PGC
PUBLISHING

Smith, M., Coppard, J. and Herrington, R., 2010 -The Geology of the Rakkurijärvi Cu-Prospect, Norrbotten County, Sweden; *in* Porter, T.M., (ed.), Hydrothermal Iron Oxide Copper-Gold and Related Deposits: A Global Perspective, v. 4 - Advances in the Understanding of IOCG Deposits; *PGC Publishing, Adelaide*, pp. 427-440.

THE GEOLOGY OF THE RAKKURIJÄRVI COPPER-PROSPECT, NORRBOTTEN COUNTY, SWEDEN

[1] Martin Smith, [2] Jim Coppard and [3] Richard Herrington.

[1] *School of Environment and Technology, University of Brighton, Brighton, U.K.*
[2] *Anglo American Exploration B.V., Malå, Sweden.*
[3] *Department of Mineralogy, The Natural History Museum, London, U.K.*

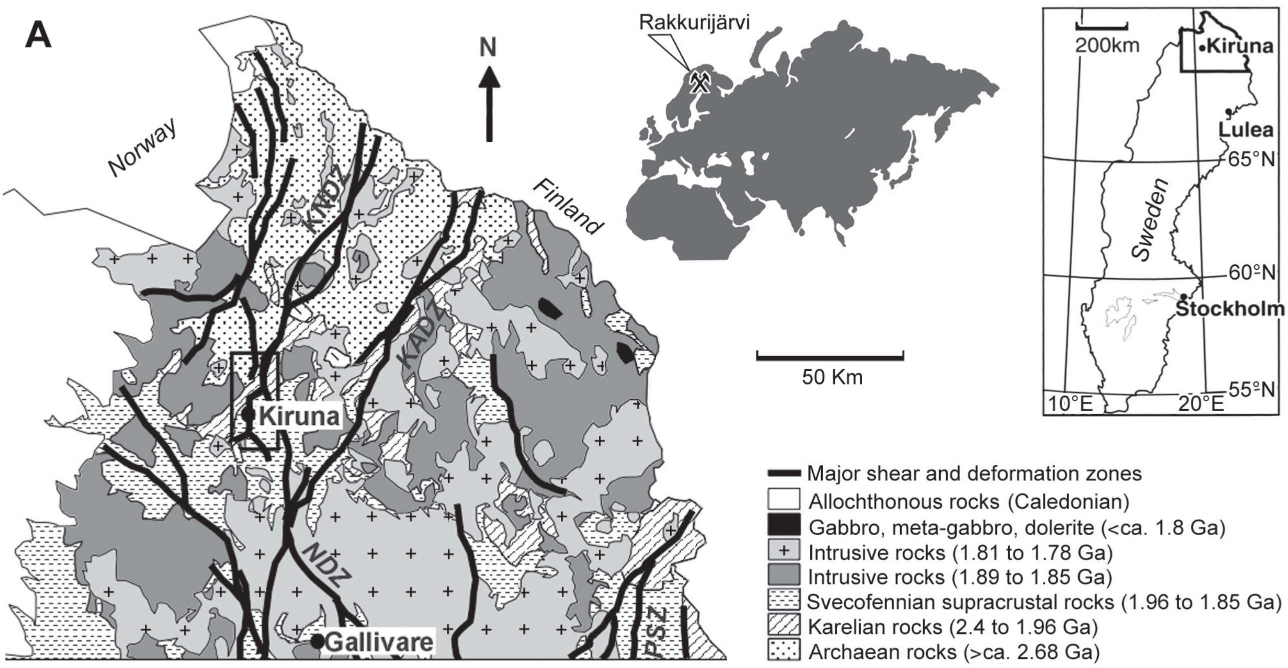
Abstract - The Rakkurijärvi prospect, Norrbotten, Sweden, is a newly discovered IOCG deposit, approximately 8 km south of Kiruna town. Exploration drilling has found mineralised intercepts including 43 m of 0.83% Cu and 0.05 g/t Au and 40.4 m of 1.41% Cu and 0.33 g/t Au, and the extent of mineralisation is currently still open. The host rocks to the deposit consist of strongly altered conglomerate and trachyandesitic lavas interbedded with thin marble bands and possible beds of pelitic sediment. These are cut by a northeast-trending shear zone which either hosts the ore bodies, or with which the ore bodies are spatially associated, and which is affected by extensive carbonate metasomatism. The ore bodies themselves consist of chalcopyrite-pyrite mineralised magnetite breccias, which grade laterally into magnetite-lithic breccias and lithic breccias, with the clasts mainly derived from the volcanic rocks. Alteration consists of early albitisation associated with actinolite and magnetite, overprinted by sodic-potassic (biotite-scapolite) and potassic (biotite-K feldspar) and finally propylitic (hematite-epidote-muscovite-chlorite-calcite) alteration. Sulphide mineralisation is associated with the propylitic stage. Both textural and chemical constraints indicate sulphide mineralisation post-dates brecciation and magnetite mineralisation. Preliminary mineralogical constraints indicate early alteration from 500 to 600°C, and chloritisation/carbonatisation from 250 to 350°C. Portions of the deposit underwent intense weathering resulting in the formation of native copper in places. Geochronological constraints (Re-Os molybdenite, U-Pb titanite and allanite) indicate sulphide mineralisation took place at around 1860 to 1850 Ma, with some LA-ICPMS analyses of allanite suggesting initial mineralisation at around 1890 to 1880 Ma, and Pb-loss from titanite via metamorphism at ~1800 Ma. The origin of fluids responsible for Fe mineralisation is currently poorly constrained, but C and O isotope analyses of calcite are consistent with a magmatic or magmatic equilibrated origin for copper-stage fluids.

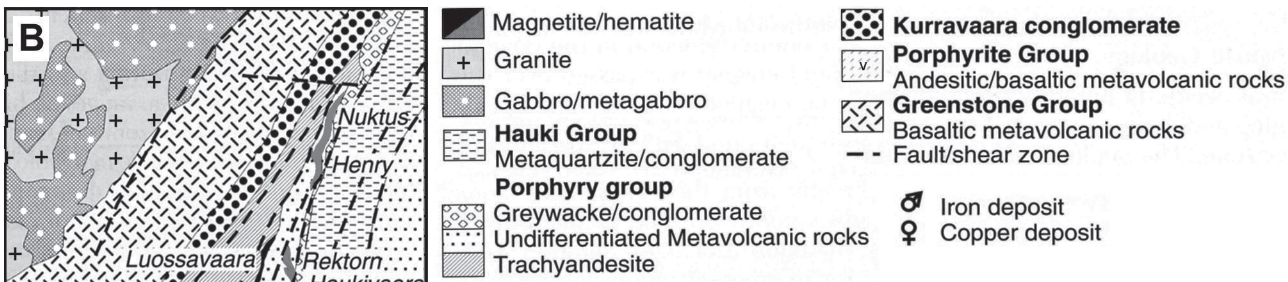
Introduction

The northern Norrbotten iron province, centred around the major iron oxide-apatite deposits at Kiruna and Malmberget (Fig. 1A), has been a focus of iron oxide-copper-gold (IOCG) deposit exploration in recent years (Carlon, 2000; Nisbet, 2000). This reflects the parallels between Kiruna and deposits such as Olympic Dam noted in early research on the deposit type (Hitzman, 1992) and the identification of deposits such as Pahtohavare (Lindblom *et al.*, 1996), Tjårrajåkka (Edfelt *et al.*, 2005) and Nautanen (Martinsson and Wanhainen, 2004) as part of the deposit spectrum. The major copper-gold deposit at Aitik has also been proposed to be a member of the group (Wanhainen *et al.*, 2003), although the in-mine geological relationships indicate a possible porphyry copper origin, with the true affinities being masked by subsequent metamorphism and deformation.

The Rakkurijärvi prospect, approximately 8 km to the south of Kiruna town and the major magnetite-apatite deposits at Kiirunavaara (Fig. 1B), is a newly identified member of the group (Smith *et al.*, 2007) and has been the focus of recent exploration activity. It represents a well preserved example of IOCG mineralisation in Norrbotten, with clear relationships to structure and with well developed alteration facies. In this paper, we present a summary of current knowledge of the Rakkurijärvi mineralisation, supplemented by new data on mineral chemistry and a synthesis with some of the most recent work on the Kiruna district IOCG province to provide new insights into the genesis of IOCG mineralisation in the region.

The site of the Rakkurijärvi prospect has been known since 1898 when it was identified on the basis of magnetic measurements. Detailed geological mapping, boulder surveys, and geochemical and geophysical prospecting by the Sveriges Geologiska Undersökning (SGU) in the 1950s and 1960s identified chalcopyrite mineralisation in the area. These investigations were followed by several drilling programs by the SGU and LKAB during the 1970s (Wägman and Ohlsson, 2000). From 1999, exploration work by Anglo American Exploration B.V. and Rio Tinto Mining and Exploration Ltd., through the Norrbotten Joint Venture, identified the IOCG potential of the area west of the known Fe mineralisation. Bodies of chalcopyrite mineralised magnetite breccias were discovered by an integrated geophysical and geochemical program focussed on IOCG-type mineralisation. The property was optioned by Lundin Mining Ltd. in 2004 and tested by a further 51 diamond drillholes. The mineralisation is still open, and the licence for the property is currently (2009) owned by the Anglo American Exploration B.V. - Rio Tinto Mining and Exploration Ltd, Norrbotten Joint Venture.





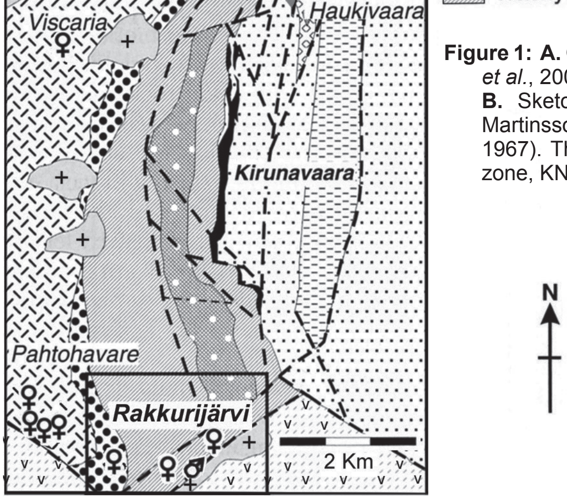


Figure 1: **A.** Outline geological map of northern Norrbotten County (adapted from Bergman *et al.*, 2001).
B. Sketch map of the geology of the Kiruna area. Based on Bergman *et al.* (2001), Martinsson and Wanhainen (2000), and Sveriges Geologiska Undersokning (SGU, 1967). The Rakkurijärvi area is highlighted. KADZ = Karesuando-Ajeplog deformation zone, KNDZ = Kiruna-Naimakka Deformation zone, PSZ = Pajala Shear Zone.

Regional Setting

The major iron ore province of northern Sweden is hosted within Palaeoproterozoic rocks, mainly Karelian (2.5 to 2.0 Ga) and Svecofennian (1.9 to 1.88 Ga) in age, which extend from northern Sweden into Finland and parts of northern Norway (Fig. 1A). The geology and metallogeny of Norrbotten have recently been reviewed by Carlon (2000) and Bergman *et al.* (2001). The Palaeoproterozoic rocks of the area were deposited over Archaean basement between 2.5 and 1.85 Ga, in environments interpreted as volcanic arcs, back-arc basins and rifts located in a supra-subduction setting (Skiöld *et al.*, 1993). The preserved Palaeoproterozoic rocks occur in a series of deformed supracrustal belts comprising clastic sedimentary and basic and intermediate to acid felsic volcanic rocks. Current models for the development of the Fennoscandian Shield in Sweden and Finland suggest rifting of the Archaean craton, continental break up and the formation of a passive margin in the period 2.45 to 2.1 Ga, followed by the inception of a juvenile arc system around 1.94 Ga. The Svecokarelian orogeny then consisted of the accretion of this arc system to the margin of the Archaean craton during the period 1.9 to 1.8 Ga (Nironen, 1997). However, Lahtinen *et al.* (2002) detected evidence for the existence of 2.1 to 2.0 Ga Proterozoic crust in detrital zircons with alkaline affinities from the Central and Southern Svecofennian sedimentary domains in Finland, and noted that potential source regions were sparse in the Fennoscandian Shield.

The lithostratigraphic sequence in the Kiruna area (Martinsson, 1997) commences with the Greenstone Group (>1.9 Ga), consisting of mainly tholeiitic (Ekdahl, 1993) to komatiitic (Martinsson, 1997) volcanic rocks related to the inferred rifting event. These are overlain by the Middle Sediment Group (Witschard, 1984), represented in the Kiruna area by the Kurravaara conglomerate. This conglomerate is overlain by the Porphyry Group (now referred to as the Kiirunavaara group; Martinsson, 2004) which consists of volcanic and subvolcanic rocks, subdivided in the Kiruna area into the dominantly andesitic Porphyrite Group, and the syenitic and quartz-syenitic Kiruna Porphyries which host the Kiirunavaara magnetite-apatite deposit. On the basis of titanite core ages determined using LA-ICPMS, Storey *et al.* (2007) proposed that the Porphyry Group in the Kiruna area was the result of volcanism and initial burial metamorphism in the period 2.1 to 1.9 Ga, in contrast to previous studies which had indicated the period 1.96 to 1.88 Ga (Bergman *et al.*, 2001; Skiöld and Cliff, 1984; Welin, 1987). This links the genesis of the Porphyry Groups to the closing stages of the Greenstone Group basic volcanism, rather than to magmatism related to accretion during the Svecokarelian orogeny. The Kiruna Porphyries may therefore actually represent part of a bimodal volcanic suite generated during the closing stages of basin inversion or the products of early arc processes in this period, which are represented by detrital zircon populations elsewhere (Lahtinen *et al.*, 2002).

The Haparanda and Perthite calc-alkaline and alkali-calcic monzonite granite suites intrude rocks of the Svecofennian sequence, and are associated with deformation and metamorphism with conditions peaking at upper greenschist or lower amphibolite facies from 1.9 to 1.8 Ga (Skiöld, 1987), concentrated around 1.88 Ga (Bergman *et al.*, 2001). In the Kiruna area, this deformation was multiphase, dominated by WNW-directed compression, and resulted in the formation of north-south trending, western side up, shear zones, steep to vertical dips of most of the strata, and southeast-plunging folds (Vollmer *et al.*, 1984; Wright, 1988; Bergman *et al.*, 2001). A second phase of granitoid magmatism, termed the Lina suite, intruded these rocks around 1.79 Ga (Skiöld, 1988; Bergman *et al.*, 2001). A second major stage of deformation occurred at a similar time (1.80 Ga), with high grade metamorphism in the south-central and south-east parts of the region (around Gällivare-Malmberget and Pajala), and deformation concentrated in and around the major deformation zones (Fig. 1). The youngest plutonic rocks in the area are TIB 2 granitoids (ca.1.71 Ga), exposed at the Swedish-Norwegian border (Romer *et al.*, 1992).

The Palaeoproterozoic rocks of the Kiruna district are affected by scapolitisation and albitisation at both the regional and deposit scale, where they are associated with iron oxide mineralisation (Frietsch *et al.*, 1997). LA-ICPMS U-Pb dating of titanite from a single site at Nunasvaara indicated preliminary ages for the sodic alteration of 1903±8Ma (Smith *et al.*, *in press*). Economic iron oxide deposits include those of the Kiruna, Svappavaara and Malmberget areas. Interpretations of their origin range from magmatic segregation followed by subsequent extrusion or intrusion (e.g., Geijer, 1931; Nyström, 1985; Nyström and Henriquez, 1994), metasomatic replacement involving late-stage magmatic (e.g., Bookstrom, 1995) or evaporite-related (Barton and Johnson, 1996) fluids, to exhalitive deposition (e.g., Parak, 1975a,b). Associated alteration includes albitisation in the footwall and hangingwall sequences and minor biotite (Geiger, 1910). Copper deposits within the area include Aitik (Wanheinen *et al.*, 2003; Wanheinen *et al.*, this volume), Viscaria (Martinsson, 1997), Pahtohavare (Lindblom *et al.*, 1996), Nautanen (Martinsson and Wanhainen, 2004) and numerous other prospects. Most of these are epigenetic (although Viscaria has been interpreted as a syngenetic exhalitive deposit; Martinsson, 1997), and they are hosted by the Karelian Greenstones and the Porphyry Group. The earliest proposed dates for iron oxide mineralisation (1884±6 Ma) overlap with the youngest possible ages for sodic alteration but this remains an area in need of further research within the Fennoscandian shield. The deposits at Malmberget and Aitik were extensively affected by the late Svecofennian (1.80 Ga) deformation and metamorphism (Romer, 1996; Wanhainen *et al.*, 2005).

Geophysical Signature

Regional targeting of the Rakkurijärvi bodies involved the use of aeromagnetic data, both in the identification of regional structure, and the initial definition of target magnetic anomalies. Area scale mapping and target identification also involved the use of airborne GeoTEM data, and Fig. 2A shows the regional apparent conductivity map derived from this data. Apparent conductivity anomalies derived from the GEOTEM data clearly indicate the geology of the area, with the northeast-trending shear zone indicated by the apparent conductivity high, and superimposed magnetic anomalies indicating magnetite breccias. Apparent conductivity highs also coincide with the extent of the Kurravaara conglomerate in the shallow subsurface. At the prospect scale, Smith *et al.* (2007) presented ground based magnetic anomaly and induced polarisation maps. The coincident magnetic and induced polarisation (chargeability) anomalies indicate the presence of sulphide mineralised magnetite breccias (see below), while chargeability anomalies outside of major magnetic anomalies indicate sulphide mineralisation in lithic and crackle breccias. Detailed geological mapping and target identification were also facilitated by gravity data (Fig. 2B, C). The residual gravity anomalies clearly delineate magnetite breccias bodies (Fig. 2C).

Deposit geology

Structural Setting

The Rakkurijärvi deposits are located in and around a northeast-trending shear zone which passes laterally into the main north-south, west side up shear zones which define the main structure of the area. The shear zone cuts near vertically dipping rocks of the Porphyry Group metavolcanics, and minor sill like intrusions either representing an intrusive facies of the Porphyry Group, or minor Haparanda Suite intrusions. The rocks themselves form part of a southeast-plunging anticline truncated by the shear zone. Mineralisation is predominantly hosted by breccias (Discovery, Tributary and Hangar zones; Fig. 2D), described in detail below, which are mainly hosted within the shear zone itself. These are deformed in places, with imbrication and elongation of the clasts, but in others preserve a dominantly random fracture pattern. This ranges from a crackle breccia with jigsaw fit of adjacent clasts on the margins of the breccia zones, outside of the main shear zone, to a matrix supported breccia in the main ore zones. The lack of preferred orientation, except in areas of subsequent deformation, suggests that the breccias were formed by hydrofracturing, possibly due to fluid pressure release during shear zone movement. Minor mineralisation also occurs in the Conglomerate zone (Fig. 2D), hosted by the Kurravaara conglomerate, which appears to have acted as a hydrothermal aquifer with major alteration of matrix and clasts (see below) throughout the geological history of the deposit.

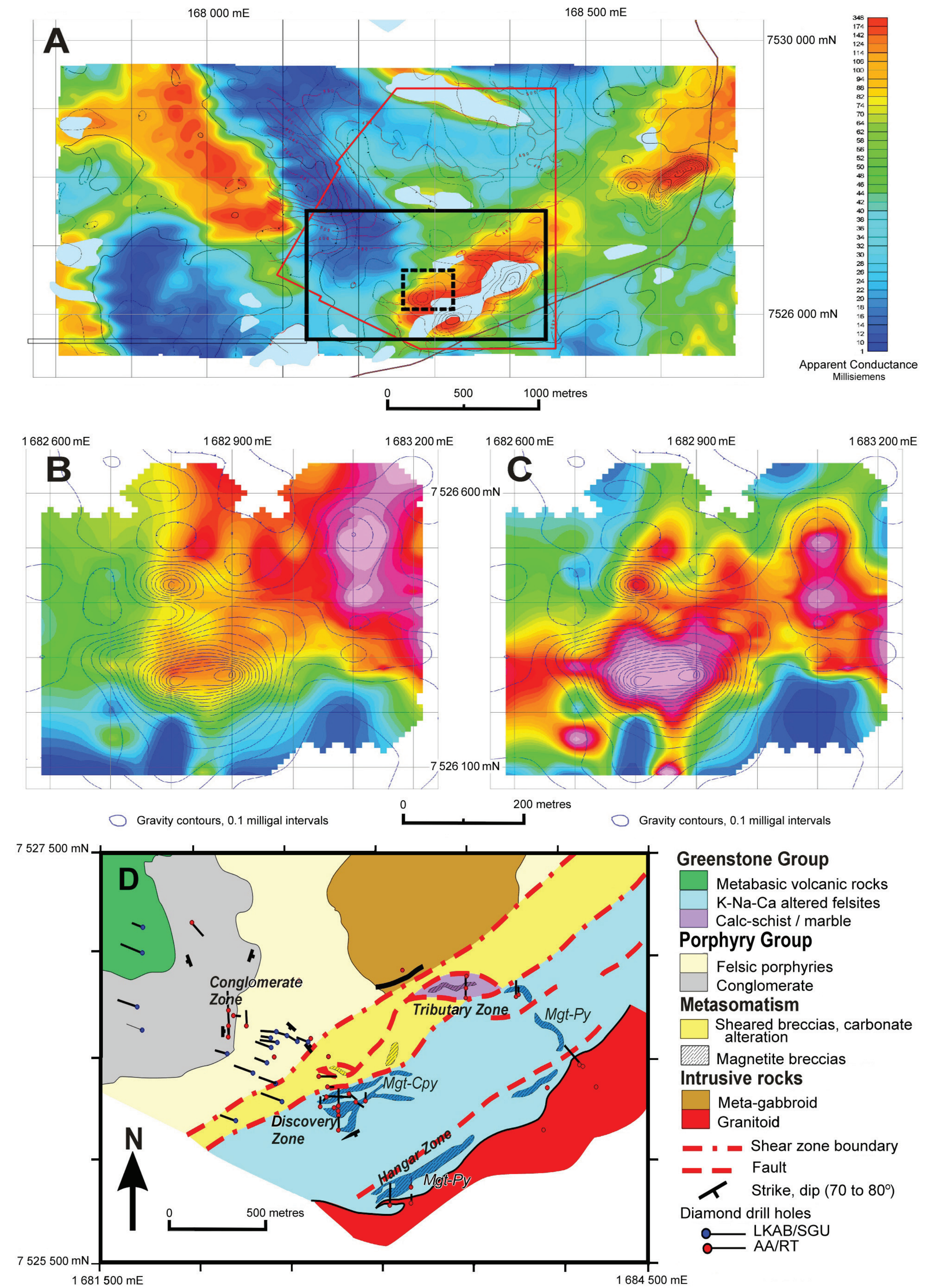


Figure 2: **A** - GeoTEM apparent conductivity map for the Rakkurijävi area (calculated using a thin sheet model). Magnetic anomaly contours (black) at 1000nT intervals and elevation contours in metres from the digital terrane model (red) are overlain. Heavy red line shows licence area. Heavy black line shows the Rakkurijärvi area from Fig.1 and Fig. 2D; dashed black line shows area of gravity survey in Figs. 2B and C. **B** - Gravity anomaly map of Rakkurijärvi, overlain by contours of magnetic anomaly from ground measurements. **C** - Residual gravity of Rakkurijärvi, overlain by contours of magnetic anomaly from ground measurements. Both B and C highlight the magnetic and gravity anomaly over the discovery zone. **D** - Interpreted geologic map of the Rakkurijävi deposit, showing the principal mineralised zones and the location of drill holes.

Host Rock Lithologies

All lithologies in the Rakkurijärvi area have undergone metasomatism to some extent. The sequence in the Rakkurijärvi area essentially consists of conglomerate (the Kurravaara conglomerate), which forms the stratigraphic marker between the Kiruna Greenstones and the Porphyry Group in the Kiruna area according to the scheme of Bergman *et al.* (2001), overlain by a sequence of porphyritic lavas and metasediments. Each of these lithologies is described in turn below.

Greenstones

The rocks to the northwest of the area are typically dominated by lower Greenschist facies metabasic rocks, comparable to those exposed around the Pahtohavare mine site, less then 3 km away (Martinsson, 1997; Bergman *et al.*, 2001). Their mineralogy is typically actinolite-albite-biotite with varying amounts of metasomatic scapolite concentrated in bands. The texture is granoblastic, with little or no development of a strong foliation. Scapolite occurs as 1 to 2 mm porphyroblasts, and also occurs alongside biotite in 1 to 2 mm fractures. Nearby exposures in the Pahtohavare area show extremely well preserved igneous textures, including virtually undeformed pillow structures, and show similar scapolite alteration of metabasic dykes in the vicinity of the ore bodies (Martinsson, 1997; Lindblom *et al.*, 1996). Late stage epidote overprints much of the metamorphic/metasomatic mineral assemblage, and minor sulphides are associated with actinolite and albite-quartz veins.

Kurravaara Conglomerate

The Kurravaara conglomerate occurs within the Kiruna area, both to the north and south of Kiruna town (Fig. 1B), and forms the stratigraphic marker between the Greenstone and Porphyry groups. As such, it has been interpreted as forming part of the Middle Sediment Group defined by Witschard (1984) as part of the regional stratigraphy of Northern Fennoscandia. The unit varies throughout the Kiruna area, probably as a result of primary variations in provenance and facies, as well as subsequent deformation and metasomatism. Regionally, the Middle Sediment Group consists of coarse pebble conglomerates, with pebbles appearing very similar to the overlying Porphyry Group volcanics but with distinct chemical affinities (Martinsson and Perdahl, 1993), meta-arenites and meta-argillites (Bergman *et al.*, 2001).

In drill core from the Rakkurijärvi area, the Kurravaara conglomerate consists of coarse pebble conglomerates, interbedded with metaarenitic units and rare marble bands. The clasts are mainly of metavolcanic provenance, with sparse clasts of polycrystalline quartz. The metavolcanic clasts are dominated by syenitic porphyry. The majority of clasts have been affected by subsequent hydrothermal alteration to some extent (Fig. 3A). In some places they have clearly been stretched by shearing, producing an imbricate fabric to the rock, extremely high aspect ratios in the clasts, and a system of *en-echelon*, calcite-filled fractures. The matrix to the conglomerate has been strongly affected by hydrothermal alteration throughout, but in places broken feldspar crystals are preserved alongside fine grained rock fragments matching the mineralogy of the main clast types. Relict sedimentary structures are preserved within these finer grained layers. Clasts of actinolite and magnetite, and layers apparently composed of magnetite sand occur within the unit. These clasts are interpreted as the results of hydrothermal alteration, rather than reflecting exposed magnetite rocks within the source area of the sediment.

Metavolcanic Rocks (Porphyries)

Within the Rakkurijärvi area, the metavolcanic rocks of the Porphyry group are mainly represented by pink to grey feldspar-phyric porphyritic igneous rocks. The highly felsic and low mafic content of the rocks suggests they may have been affected by sodic or potassic alteration, giving rise to metasomatic K feldspar and albite alongside the destruction of biotite. Feldspar phenocrysts range from 2 to 5 mm in length, are eu- to subhedral, and are enclosed in a fine grained matrix composed principally of feldspar and quartz. The phenocrysts include both K feldspar and albite. Magnetite is also present as an alteration phase. In some pink porphyries, epidote and actinolite replace a pre-existing mafic phase, probably biotite. Transitional zones exist between partially altered porphyry and biotite-scapolite schist (see below) suggesting the latter may not be a metapelitic lithology, but the result of strain partitioning into pervasively altered metavolcanics.

Marble

Calcite marble and calc-schists occur as minor lithologies throughout the Rakkurijärvi area, interbedded with biotite schists of varying mineralogies, with metavolcanic lithologies and alongside variably mineralised and altered breccias. The dominant marble types are biotite-tremolite marbles, occasionally with significant quartz and epidote contents. Biotite occurs both as individual grains within the rock, and as blocks of foliated biotite-amphibole schist enclosed within the marble (Fig. 3E). The blocks of biotite schist are interpreted as the remnants of schistose layers which where boudinaged during deformation of the less competent marble. In some places, particularly at the boundary between marble and intact biotite-schist zones, a breccia of biotite schist with a carbonate matrix occurs, with the development of a more iron rich amphibole in the matrix. Chalcopyrite and pyrite are sometimes developed in these zones. True magnetite skarn is also developed in places along these contacts. The prevalence of marble within the shear zone is suggestive of carbonate flooding producing calc-schists from the metavolcanic protoliths rather than true metasedimentary marble.

Alteration and Mineralisation

The paragenesis of hydrothermal alteration, brecciation and vein fill is summarised in Fig. 5. Within the Porphyry Group, the first alteration stage within the metavolcanics appears also to have been feldspathisation and silicification, associated with the destruction of primary igneous biotite. This resulted in a change from an initially grey porphyry to pink-red porphyry, the red colour arising from alteration of the feldspars in the matrix. Examination of the reddened porphyry in thin section shows porphyroblasts of plagioclase with incipient sericite alteration, in a matrix of albite, quartz, biotite, sericite and chlorite, with trace amounts of apatite, ilmenite, rutile and magnetite (Fig. 4A). Overprinting this initial reddening and albitisation are the development of K feldspar, scapolite and biotite replacing matrix and phenocrystic feldspar, minor actinolite alteration and the late stage development of epidote replacing both

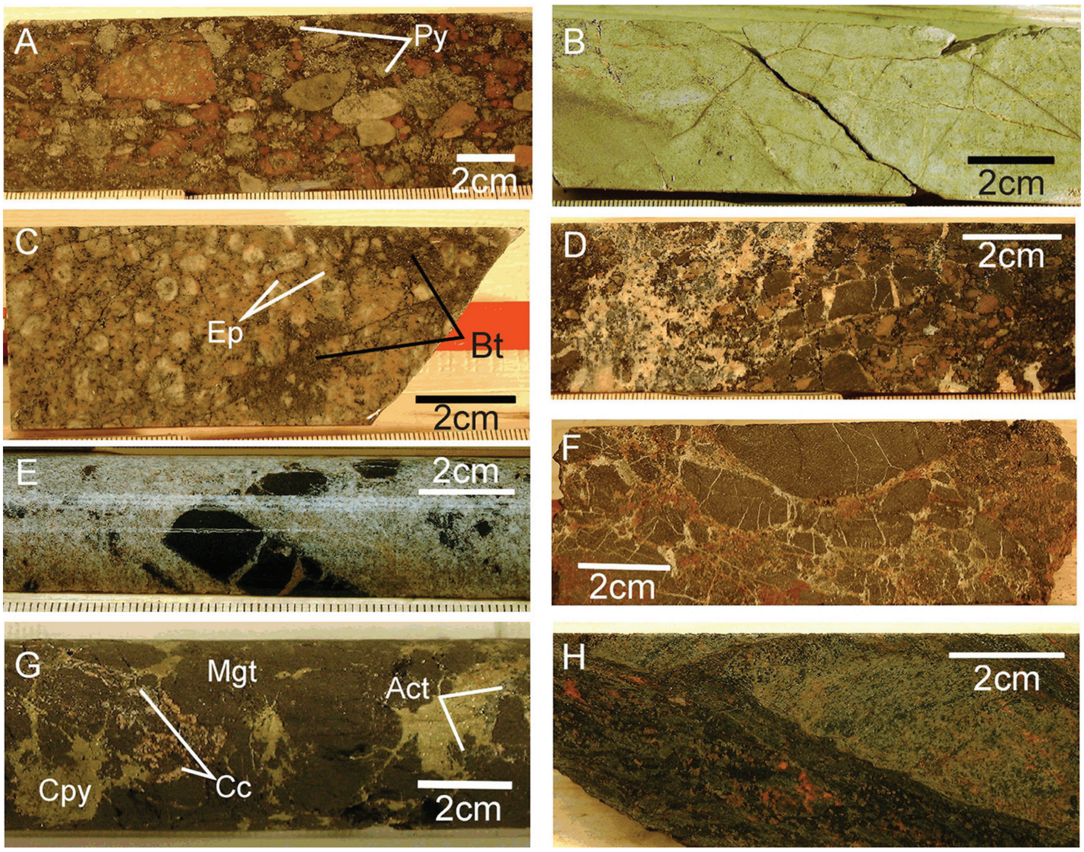


Figure 3: Photographs of drill core from Rakkurijävi. **A** - Altered Kurravaara conglomerate from the prospect are; **B** - Albitised meta-sediment with chlorite overprint; **C** - Porphyritic trachyandesite with biotite and subsequent epidote alteration; **D** - Lithic breccia with K feldspar alteration of clasts and subsequent carbonatisation of the matrix: **E** - 'Marble' with boudinaged clasts of biotite schist; **F** - Magnetite breccia with calcite matrix; **G** - Magnetite breccia with chalcopyrite-pyrite matrix; **H** - Shear zone cuting albitised porphyry, with biotite and K feldspar developed on the shear zone.

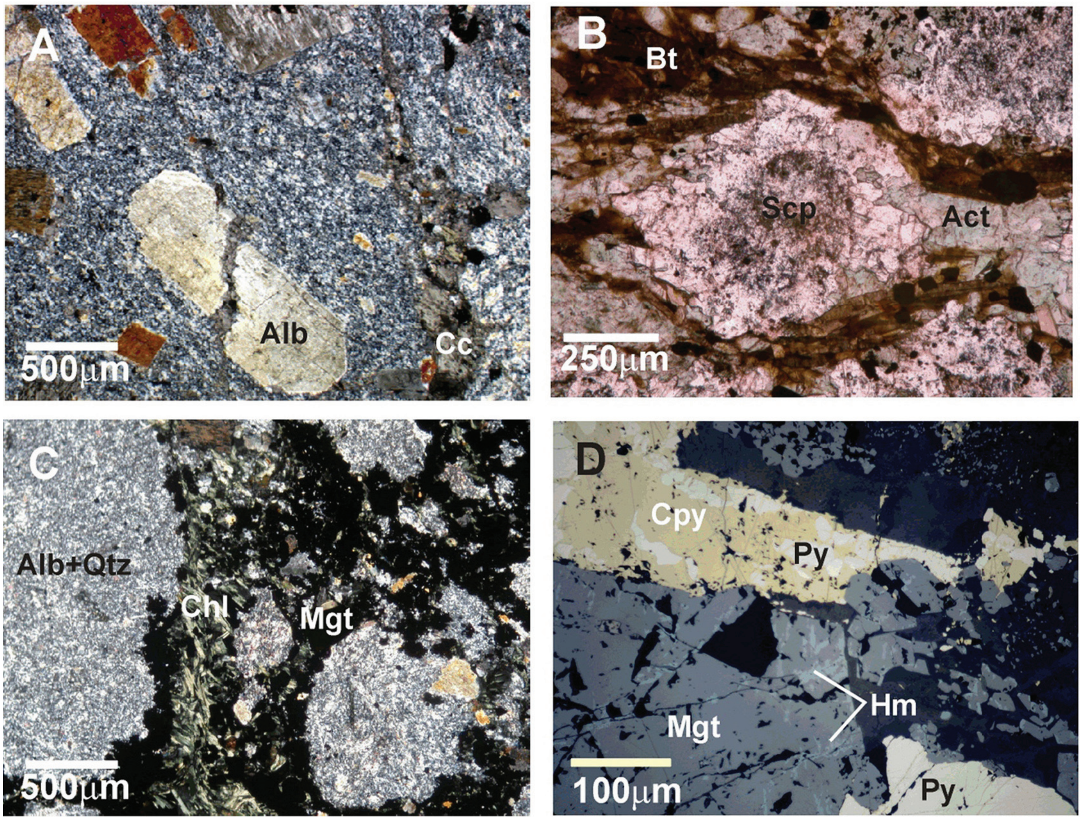


Figure 4: Representative photomicrographs from Rakkurijävi. **A** - Relatively unaltered trachyandesite porphyry; **B** - Biotite-scapolite schist; **C** - Magnetite-chlorite matrix of lithic breccia; **D** - Chalcopyrite replacing pyrite in magnetite breccia matrix. Act - actinolite; Alb - albite; Bt - biotite; Cc - calcite; Chl - chlorite; Cpy - chalcopy-rite; Hm - hematite; Mgt - magnetite; Py - pyrite; Qtz - quartz.

phenocrysts and matrix alongside minor carbonate. This alteration is developed to both the north and south of the shear zone. In extreme cases, the original porphyritic nature of the rock is obliterated, resulting in albite-biotite schists with minor scapolite and magnetite, or albite-actinolite and albite-actinolite-magnetite schists (Fig. 3B). Scapolite-biotite alteration visibly overprints these rocks (Fig. 3C). A distinctive accessory mineral assemblage is developed alongside this alteration, including titanite and apatite. The sodic-potassic alteration commonly reaches the stage of biotite-scapolite (±actinolite-magnetite) rocks with little original fabric preserved, although alteration zones appear to have preferentially concentrated strain to give a schistose fabric (Fig. 4B). The biotite-scapolite schists form the dominant alteration assemblage surrounding the mineralised lithic and magnetite breccias of the Discovery and HB zones. The Kurravaara conglomerate within the deposit area has been pervasively hydrothermally altered, to the extent that the original matrix can no longer be clearly identified. The matrix throughout contains feldspar fragments, but is dominated by fine grained biotite, actinolite and magnetite, with an epidote overprint and commonly disseminated sulphides.

Breccias

All the lithologies so far described are affected by brecciation to some extent within the deposit area, and magnetite breccias form the dominant ore hosting lithology. The porphyry sequence is affected by brecciation ranging from crackle breccia distal from the main ore-hosting magnetite breccias and to the north of the shear zone, to lithic breccias closer to the main ore zone. The least altered breccia lithologies in the metavolcanics consist of pink porphyry, with a fracture fill and matrix of biotite and minor magnetite, or actinolite. The matrix mineralogy replaces the clasts in some places. Similar breccias are developed in biotite schists. Breccias showing some degree of transport and rotation of clasts grade into crackle breccia. The matrix in both cases consists of carbonate with minor biotite, actinolite and garnet, alongside minor magnetite and sulphides. Neoformed biotite forms rims on clasts, and the proportion of biotite is raised in some clasts alongside incipient magnetite alteration. Red feldspar (K feldspar?) forms an overprint on some altered clasts (Fig. 3D). Breccias within the shear zone are associated with marble, and show the development of tremolite and actinolite in biotite schist, suggesting that at least some of the marbles and calc-schists may be metasomatic in origin.

Around the magnetite bodies, these breccias grade into lithic breccias with a high degree of transport and rotation, through lithic-magnetite breccias (Fig. 3F) to magnetite breccias (Fig. 3G). The matrix is variable and typically consists of actinolite, magnetite and minor albite, or scapolite, calcite and magnetite, or chlorite and magnetite (Fig. 4C). Actinolite-magnetite alteration of the clast rims is common (Fig. 4C). Areas also occur with calcite-rich matrices, accompanied by quartz and epidote, with varying amounts of actinolite, magnetite and albite. These grade into lithic-magnetite breccias, where complete replacement of clasts by magnetite and actinolite has taken place (Fig. 3G). The magnetite breccias which host the main ore zone consist of brecciated, fine grained (<1 mm)

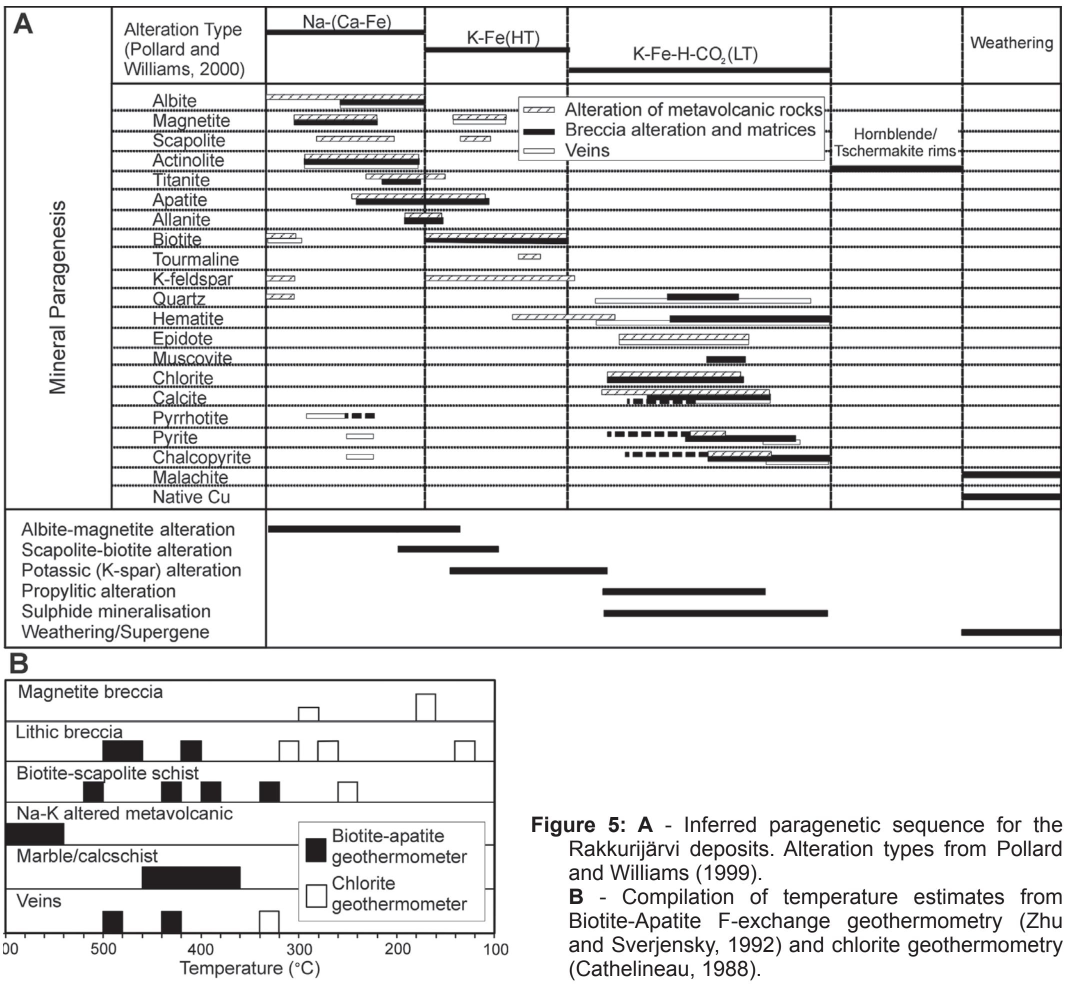


Figure 5: A - Inferred paragenetic sequence for the Rakkurijärvi deposits. Alteration types from Pollard and Williams (1999).
B - Compilation of temperature estimates from Biotite-Apatite F-exchange geothermometry (Zhu and Sverjensky, 1992) and chlorite geothermometry (Cathelineau, 1988).

magnetite rock with the majority of clasts ranging from 0.2 to 3 cm in diameter. The clasts also contain minor actinolite. The matrix shows some zonation throughout the magnetite bodies. In the outer parts it consists of calcite, actinolite, chlorite with minor epidote and biotite and accessory amounts of apatite, allanite and titanite. This grades into an albite-rich matrix with actinolite and euhedral magnetite, with albite preceding calcite as a cement. Virtually all these breccias contain some sulphide, mainly pyrite and chalcopyrite (Fig. 3G, 4D). Both lithic and magnetite breccias show evidence for shear deformation post-brecciation (Fig. 3H).

Veining and Sulphide Occurrence

Vein formation accompanies virtually all alteration types within the Rakkurijärvi area. Biotite veins appear to be paragenetically early, and are in places cut by actinolite veins. Actinolite veins vary, with central infills of albite, calcite or, more rarely, quartz. Sulphides and magnetite may be associated with central calcite infills. Calcite and quartz are later than albite infills, and may form veins without actinolite. Calcite occurs in veins with biotite lined margins, or as calcite veins with associated magnetite, sulphides or specular hematite. Quartz and epidote appear to be the paragenetically latest vein stage, and are commonly associated with reddening of feldspars in the surrounding wall rocks.

The main visible sulphide phases at Rakkurijärvi are chalcopyrite and pyrite, with minor pyrrhotite occurring in veins in the Greenstone Group metabasics. The main mineralised zones occur within the magnetite breccia bodies of the Discovery zone. Here pyrite and chalcopyrite dominate the breccia matrix, or else occur as late stage phases infilling the matrix and fractures following albite, actinolite and calcite (Fig. 3G, 4D). Chalcopyrite appears to be most strongly associated with a calcite dominated

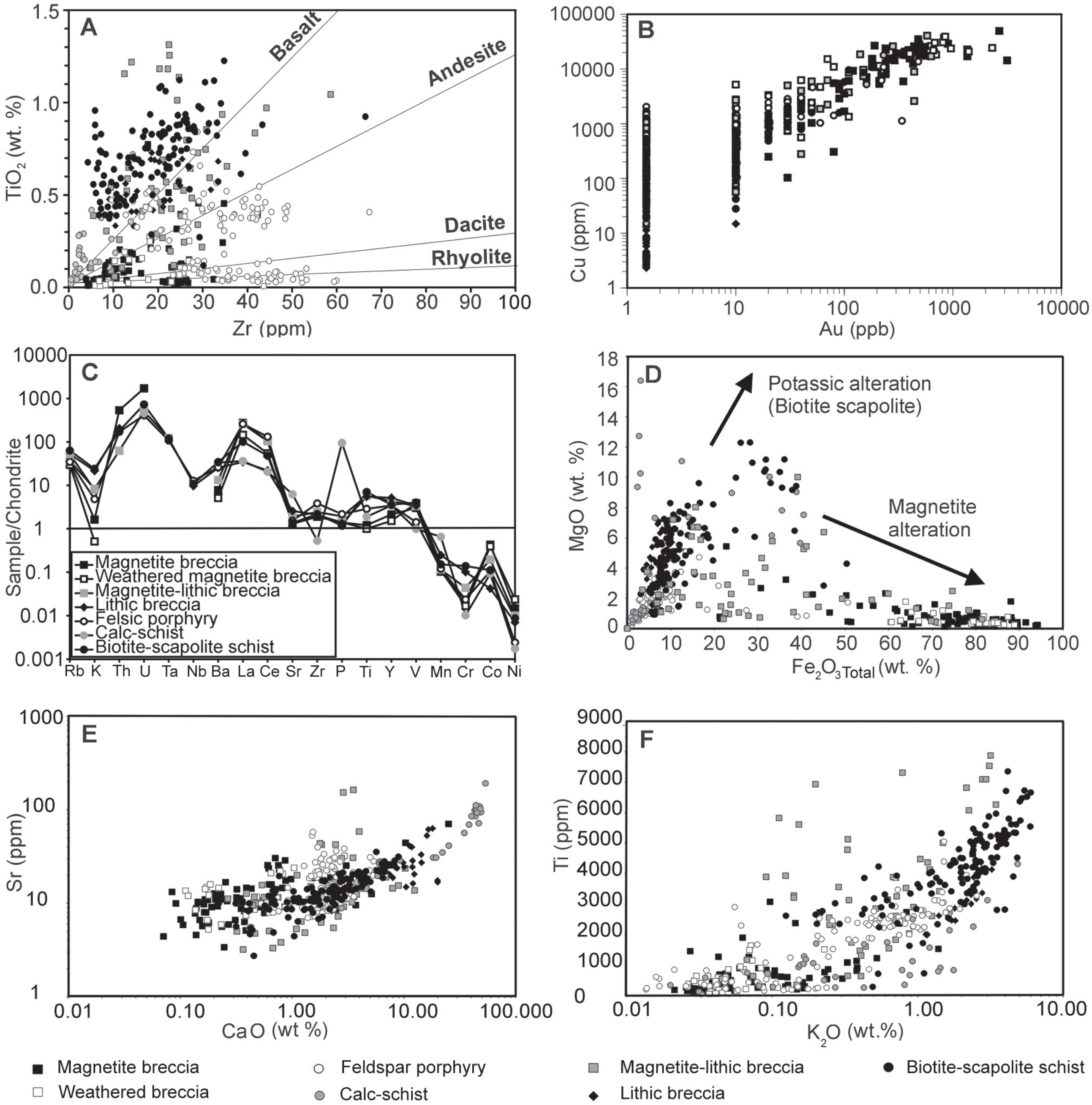


Figure 6: Bulk rock geochemistry from Rakkurijärvi. Analyses obtained by aqua-regia digestion followed by ICP-OES except for Au (fire assay) and Cu (atomic absorption).

matrix. Chalcopyrite is the paragenetically later phase, and in places occurs replacing pyrite (Fig. 4D). Minor molybdenite occurs, intergrown with magnetite.

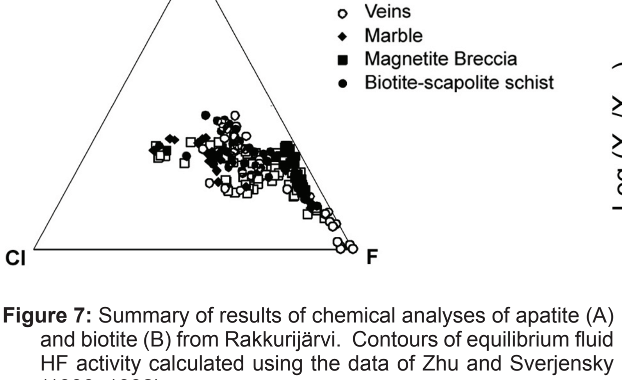
Intense weathering affects the magnetite breccias in places significantly modifying or destroying the sulphide assemblage. In the most heavily weathered portions, where magnetite appears rusty and in places has been altered to clayey hematite, the sulphide assemblage has been completely destroyed. This gives way with depth to malachite staining, and occasionally the development of native copper.

Geochemistry

Apart from full assays for Cu and Au, to date the bulk rock geochemistry of the Rakkurijärvi deposits has only been investigated as part of the exploration process using aqua-regia digestion and ICP-AES analysis (Smith *et al.*, 2007). This results in an incomplete digestion that may give low results for Na, Al and elements hosted in refractory minerals. The data are useful as a preliminary indication of the elemental changes during alteration, and for comparison with other exploration data sets. Fig. 6A, shows the TiO_2 and Zr contents of bulk rock samples, compared to rock-type ratio fields from Barrett and Maclean (1994). The concentrations are shifted to lower absolute values compared to their data set as a result of the incomplete digestion procedure, but are at least consistent with andesitic to rhyolitic protoliths. In heavily altered rocks, the ratios are shifted strongly to more Ti-rich compositions, consistent with the addition of Ti during alteration in both biotite and accessory titanite. Cu and Au grades correlate positively, and are highest in the sulphide mineralised breccias (Fig. 6B). The best mineralised intersections in drill core to date are 42 m at 0.83% Cu, 0.05g/t Au, 40.4 m at 1.41% Cu, 0.33g/t Au, 12.80 m at 2.11% Cu, 0.52 ppm Au, and 24.00 m at 1.54% Cu, 0.2 ppm Au. Overall, the trace element analyses of the bulk rocks show relatively consistent patterns with notable enrichments in U, Th and the REE (La and Ce). Co is enriched relative to Cr and Ni, probably reflecting its substitution into sulphide phases, and consistent with Co enrichment in other IOCG deposits of the area. P is notable enriched in the calc-schists and marbles relative to other rock types, reflecting the formation of metasomatic apatite (Fig. 6C). MgO and Fe_2O_3 concentrations indicate the extent of potassic (biotite) and magnetite alteration respectively (Fig. 6D). The virtually continuous variation in Sr content with CaO reflects the fact that the development of marble and calc-schist is a dominantly metasomatic process due to carbonate flooding on the shear zone (Fig. 6E). The increase in TiO_2 with K_2O indicates the control of Ti content by the formation of metasomatic biotite (Fig. 6F).

Smith *et al.* (2007) presented detailed data on the chemistry of the main silicate alteration phases at Rakkurijärvi. Feldspars are dominated by albite in relatively unaltered rocks, probably indicating pervasive Na alteration rather than initially sodium-rich volcanic rocks, and K feldspar. Scapolite is dominated by the marialite component ($X_{meionite}$= 0.15 to 0.45). The chemistry of biotite varies with paragenetic setting, with that in the magnetite breccias being relatively Mg-rich (X_{Mg} = 0.6 to 0.7) and Cl-poor compared to that in the main potassic alteration (X_{Mg} = 0.3 to 0.6). The amphibole is virtually all actinolite and may be representative of metamorphism rather than metasomatism. The exception to this is the rims of grains in the Kurravaara conglomerate which have ferro-tschermakite compositions and are relatively Cl-rich (~0.4 to 0.8 a.p.f.u.).

One issue with many models of IOCG mineralisation is the lack of direct temperature determinations for different stages of mineralisation. In order to improve the understanding of the T evolution of the system at Rakkurijärvi we have recently carried out analyses of co-existing biotite and apatite and used the geothermometer of Zhu and Sverjensky (1992) to estimate temperature (Fig. 5B). Coupled with previous work (Smith *et al.*, 2007) on chlorite chemistry using the geothermometer of Cathelineau (1988), this gives an estimate of T across the range of parageneses in the deposit. The high temperature Na-Ca and K-Fe(HT) alteration (see Pollard and Williams, 1999, for a simple classification of IOCG alteration types) occurred at ~550 to 600ºC, with potassic alteration (biotite-scapolite) continuing through cooling of the system to around 350 to 400ºC. Veining of varying mineralogy occurred through a similar temperature interval, while carbonate flooding on the shear zone took place from ~460 to -360ºC. Chloritisation accompanying the K-H-Fe-CO_2(LT) mineralisation took place from ~340 to 150ºC. Inspection of biotite and apatite halogen chemistry is indicative of higher HF activities during magnetite mineralisation, with HF activities buffered by the rock system at later stages, while the progressively later stage biotite, showing declining F- and Cl-contents, are possibly indicative of fluid dilution as the system cooled (Fig. 7A and B).



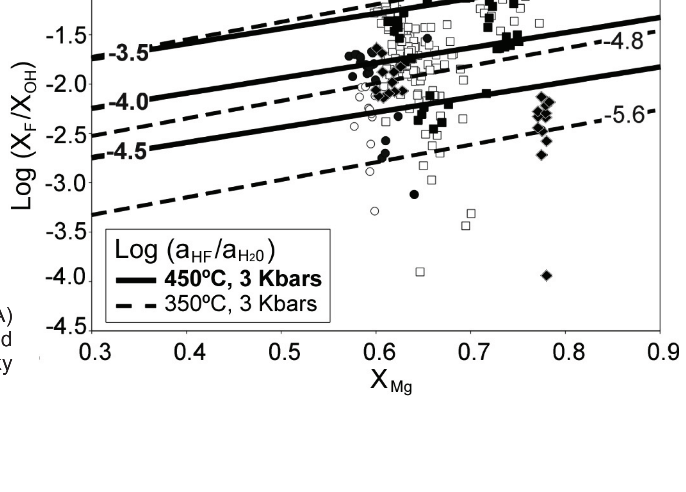


Figure 7: Summary of results of chemical analyses of apatite (A) and biotite (B) from Rakkurijärvi. Contours of equilibrium fluid HF activity calculated using the data of Zhu and Sverjensky (1990; 1992).

Timing of Mineralisation

Age determinations on the Rakkurijärvi deposit have been made using Re-Os analyses of molybdenite (Smith *et al.*, 2007) and U-Pb analyses LA-ICPMS of titanite and allanite (Smith *et al.*, *in press*). Re-Os analyses were carried out on fine grained molybdenite intergrown with magnetite. Two splits of the same sample yielded ages of 1853±6 Ma and 1862±6 Ma. The titanite and allanite analysed came from a meta-trachyandesite sample, where sodic alteration is overprinted by potassic alteration. Both titanite and allanite occurred in vug space alongside biotite, apatite and magnetite (Fig. 8A, B). Analyses of allanite defined a concordant set with a weighted mean of 1854±18 Ma, while titanite analyses extend along Concordia from the earliest individual analyses at 1896±37 Ma to the latest at 1744±42 Ma, and a weighted mean of 1806±55 Ma (Fig. 8C). The Re-Os molybdenum age, the allanite U-Pb age and the earliest analyses of titanite are all consistent and suggest sulphide mineralisation around 1860 Ma. The cumulative probability plots in Fig. 8D also suggest earlier activity at around 1880 Ma, which may indicate the initial magnetite mineralisation in the breccias. The younger ages and the overall relatively young weighted mean age of titanite may be due to the much smaller size of the grains analysed relative to allanite resulting in enhanced diffusional Pb loss, or resetting via dissolution-reprecipitation during subsequent metamorphism and fluid flow events.

The age of 1860 Ma is consistent with previously reported ages of the earliest copper mineralisation in the Kiruna area (Billstrom and Martinsson, 2000) and the earliest alteration and mineralising events at the Aitik deposit (Wanhainen *et al.*, 2005). The oldest possible Re-Os age (1862±6 Ma) and early cumulative probability peaks overlap with, or are slightly younger than, the age of iron oxide-apatite mineralisation at Kiirunavaara (1884±6 and 1875±9 Ma; Romer *et al.* (1994); 1870±24 Ma, U-Pb LA-ICPMS analyses of titanite rims, Storey *et al.* (2007)).

Discussion.

Geodynamic Setting

The timing of the Rakkurijärvi deposits determined from Re-Os analyses of molybdenite and U-Pb analyses of allanite overlaps with the major Svecokarelian deformation in the Kiruna area, and the intrusion of the Haparanda and Perthite-monzonite suite granitoids. This fixes the formation of the IOCG deposits firmly into a continental accretion setting. The host rocks to the deposits are not related to this tectonics setting (Storey *et al.*, 2007) and probably relate either to the development of a bimodal

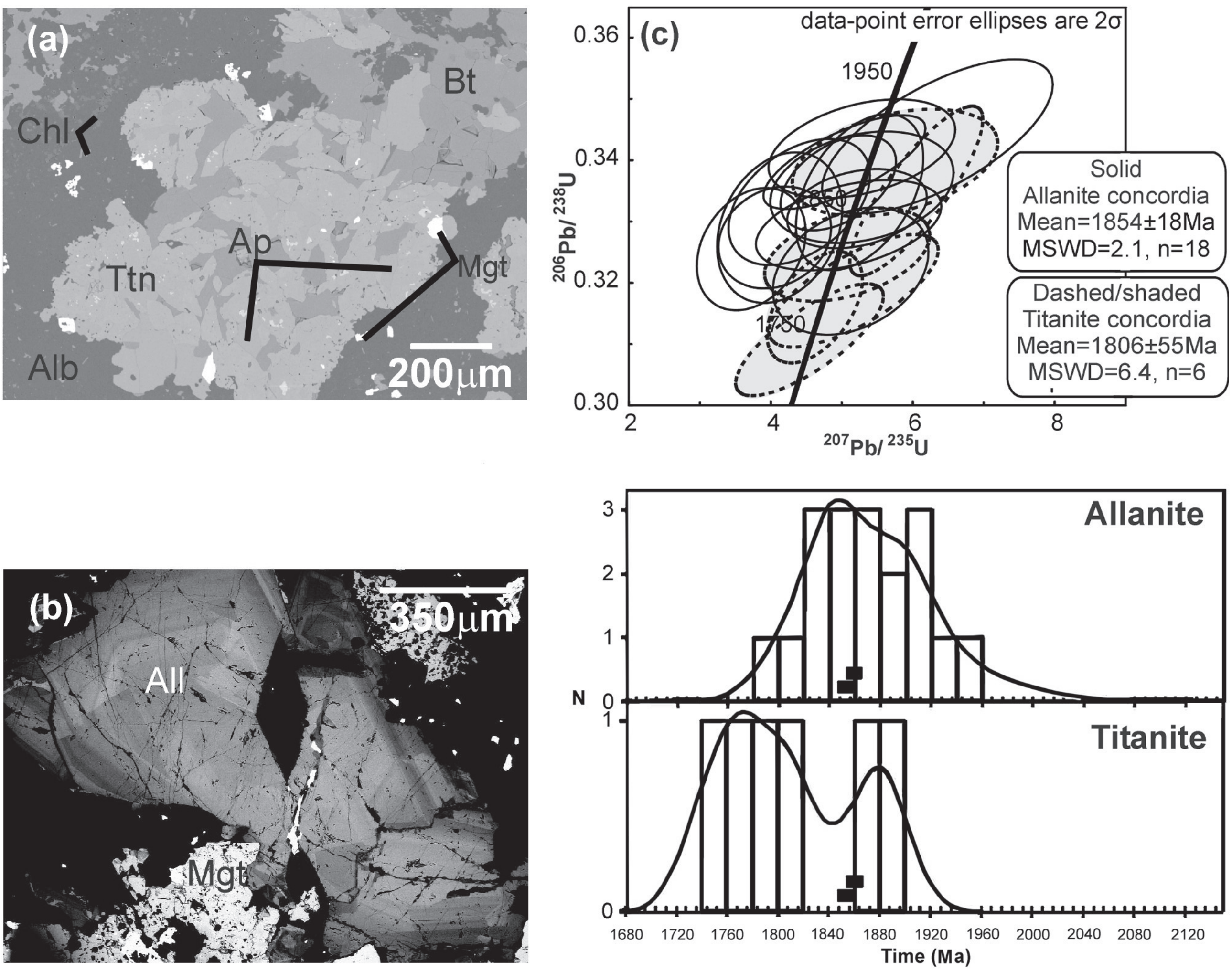


Figure 8: Results of LA-ICPMS dating of titanite and allanite from Rakkurijärvi (Smith *et al.*, in press). (a) Backscattered electron image (BEI) of titanite and apatite in vug space in K-Na altered meta-trachyandesite. (b) BEI of oscillatory zoned allanite from the same sample. (c) U-Pb Concordia diagram for titanite and allanite. (d) Cumulative probability plots for titanite and allanite 238U-206Pb data. Solid black bars show the range of molybdenite Re-Os dates from Smith *et al.* (2007). U-Pb data from Smith *et al.* (in press) Alb - albite; All - allanite; Ap - apatite; Bt - biotite; Chl - chlorite; Mgt - magnetite.

volcanic suite during Greenstone group volcanism, or to the waning stages of Greenstone group magmatism during basin shoaling and inversion (Martinsson, 1997).

The Rakkurijärvi deposit is developed adjacent to a Svecokarelian age shear zone, which is a component of the fault and shear system defining the footwall contact of the Kiirunavaara magnetite-apatite deposit. This in itself is related to the regional scale Kiruna-Arjeplog Deformation zone (Bergstrom *et al.*, 2001), and a part of the WNW-directed compressional deformation (Vollmer *et al.*, 1984; Wright, 1988; Bergman *et al.*, 2001). The resetting of titanite U-Pb systematics is consistent with reactivation of these structures during the late Svecofennian deformation event (~1.8Ga).

Mineralising Fluid Source and Characteristics.

The association with scapolite and albite alteration and the high Cl-contents of biotite and apatite indicate that alteration and mineralisation at Rakkurijärvi was the result of circulation of highly saline brines. In the Norrbotten area, such brines have been proposed to be either magmatic (Lindblom *et al.*, 1996) or metaevaporitic in origin (Freitsch *et al.*, 1997). The only direct evidence currently available for fluid at source at Rakkurijärvi is from carbon and oxygen isotope analyses of calcite in vein, breccia matrices and marble (Smith *et al.*, 2007). These are consistent with the precipitation of calcite from a high T (>400ºC), low to moderate CO_2 content (XCO_2<0.5), magmatic fluid that had interacted with metasedimentary marble in the local metavolcanic pile. This interpretation is mainly relevant to the sulphide stage of mineralisation and does not address the earlier fluids responsible for sodic alteration and magnetite mineralisation.

The apatite analyses presented here range from Cl-apatite in the altered volcanics and calcite veins, to more F-rich and ultimately fluorapatite in the magnetite breccias. This suggests contrasting fluid compositions during different stages of mineralisation, with a more F-rich fluid responsible for magnetite mineralisation. The Cl and F contents of biotite are consistent with biotite from magnetite breccias equilibrating with fluids having the highest a_{HCl}/a_{H2O}, with lower values in the lithic breccias probably relating to buffering of the HCl fugacity by the formation of Cl-bearing silicates (Smith *et al.*, 2007). The Cl content of biotite is lower in partially chloritised examples from the breccias, and may reflect OH-Cl exchange during chloritisation in the presence of a cooler, more dilute fluid. An expanded data set of biotite analyses presented here (Fig, 7B) suggests a significant, but low HF fugacity in the hydrothermal fluids. Again, chloritised examples from the lithic breccias have reduced F contents, probably relating to F-OH exchange with more dilute fluids during chloritisation. Marshall and Oliver (2006) interpreted similar variations in biotite composition to reflect the ingress of low salinity fluids in IOCG-type deposits following early, highly salinity metasomatism in deposits of the eastern Mount Isa Block, Australia.

Rakkurijärvi in the IOCG Spectrum.

The magnetite-apatite deposits of the Kiruna district and surrounding regions of northern Sweden form the type locality for the magnetite-apatite end member of the IOCG class (Hitzman *et al.*, 1992; Barton and Johnson, 1996). The initial definition of the IOCG deposit type did not distinguish between iron oxide apatite deposits and IOCG deposits proper, but more recent criteria for IOCG deposits proposed by Williams *et al.* (2005) are the presence of copper with or without gold as economic metals, hydrothermal vein, breccia and/or replacement ore styles, characteristically in specific structural sites, abundant magnetite and/or hematite, low Ti contents in iron oxides relative to those in most igneous rocks, and absence of clear spatial associations with igneous intrusions. By this definition the iron oxide apatite deposits are distinct from IOCG deposits as they lack copper and gold, although there is a late sulphide mineralisation stage in many examples. Kiruna-type mineralisation is, however, directly comparable to the early magnetite mineralisation and alteration at sites such as Rakkurijärvi, and this may therefore represent a distinct phase in activity. This is supported by initial geochronological data from Rakkurijärvi that suggests the initial alteration may have been significantly earlier than the main sulphide mineralisation stage at the site. On the basis of fluid inclusion studies at Pahtohavare, Lindblom *et al.* (1996) noted early vein fluids at temperatures >500°C and pressures around 2.4 Kbar, with salinities from ~30 to >50 weight % $NaCl_{equiv.}$, while the main stage copper-gold mineralisation was associated with a CO_2-bearing fluid with a salinity of ~30 weight % $NaCl_{equiv.}$ at a temperature of 350°C and pressures of 1 to 2 Kbar.

The Rakkurijärvi deposits are clear representatives of at least a portion of the IOCG deposits groups. In common with a number of copper-gold deposits in the surrounding area, they have a distinct association with sodic and potassic alteration (Martinsson, 1997; Frietsch *et al.*, 1997), and anomalous concentrations of the REE (e.g., Frietsch and Perdahl, 1995). The alteration characteristics of the Rakkurijärvi deposit have much in common with other iron oxide and sulphide deposits of the region, and in contiguous areas of Fennoscandia , e.g., Pahtohavare (Lindblom *et al.*, 1996; Martinsson, 1997), Bidjovagge (Bjørlykke *et al.*, 1987) and numerous other smaller copper deposits across the area (Bergman *et al.*, 2001). At both Pahtohavare and Bidjovagge, the copper-gold mineralisation is associated with calcite and ankerite alteration in addition to albitisation, scapolitisation and potassic alteration.

The alteration paragenesis at Rakkurijärvi closely corresponds to Na-(Ca-Fe) alteration overprinted by high temperature K-Fe alteration, with late stage low temperature K-Fe-H-CO_2 alteration from the classification of Pollard and Williams (1999). The overall paragenesis is closely comparable to the IOCG type deposits of the Candelaria-Punta del Cobre area (Marschick *et al.*, 2000; Marschik and Fontebote, 2001), some other deposits of the coastal cordillera of Chile and Peru (e.g., Hopper and Correa, 2000; Sillitoe, 2003) and prospects of the Curnamona and Cloncurry provinces, Australia (Williams and Skirrow, 2000), more specifically the Ernest Henry deposit (Mark *et al.*, 2000).

Conclusions

The Rakkurijärvi prospect contains copper mineralisation hosted by magnetite and lithic breccias associated with a northeast-trending shear zone linked to the main regional deformation zones in the Kiruna area. The copper mineralisation occurs as chalcopyrite in breccias matrices, predominantly associated with calcite, and clearly post-dates the initial formation of magnetite breccias. The magnetite mineralisation was accompanied by early sodic-calcic alteration (magnetite-albite-actinolite-scapolite), which was subsequently overprinted by potassic alteration (K feldspar-scapolite-biotite) and finally low temperature propylitic alteration dominated by calcite, but also leading to the formation of epidote, hematite, muscovite and chlorite. The alteration characteristics are comparable to those of a number of members of the IOCG deposit class. The sulphide mineralisation took place around 1860 to 1850 Ma (Re-Os data from molybdenite, U-Pb data from allanite), but the initial formation of breccia bodies may have been significantly earlier. U-Pb systematic of titanite indicate Pb-loss as a result of metamorphism of the deposits around 1800 Ma. Textures indicate the magnetite breccias were developed by metasomatic replacement of volcanic rocks, but no constraints are yet available for the source of fluids at this stage. Mineral chemistry clearly indicates different fluids at the magnetite and copper mineralising stages. The timing of sulphide mineralisation and the stable isotope systematics of calcite are consistent with magmatic fluids or magmatic equilibrated fluids associated with the Haparanda and Perthite-monzonite suite granitoids being responsible for copper mineralisation.

Acknowledgements

We would like to thank Anglo American Plc and Lundin Mining Limited for permission to publish the data presented in this paper. Frank van der Stijl, Brian Williams and Brett Collins contributed to the field geology, core logging, geophysical investigations and discussions presented in this paper although the authors take full responsibility for the conclusions reached.

References

Barrett, T.J. and MacLean, W.H., 1994 - Chemostratigraphy and hydrothermal alteration in exploration for VHMS deposits in greenstones and younger volcanic rocks; *in* Lentz, D.R., (ed.), Alteration and Alteration Processes Associated with Ore Forming Systems. *Geological Society of Canada*, Short Course Notes, v. 11, pp. 433-467.

Barton, M.D. and Johnson, D.A., 1996 - Evaporitic source model for igneous-related Fe oxide-(REE-Cu-Au-U) mineralization, *Geology*, v. 24, pp. 259-262.

Bergman, S., Kübler, L. and Martinsson, O., 2001 - Description of regional geological and geophysical maps of northern Norrbotten county (east of the Caledonian orogen); *Sveriges Geologiska Undersökning,* Ba 56, 110p.

Billström, K. and Martinsson, O., 2000 - Links between epigenetic Cu-Au mineralizations and magmatism/deformation in the Norrbotten county, Sweden; *in* 2nd GEODE Fennoscandian Shield Field Workshop on Palaeoproterozoic and Archaean Greenstone Belts and VMS Districts in the Fennoscandian Shield; *Luleå University of Technology*, Research Report 2000:06, p.6.

Bjørlykke, A., Hagen, R. and Söderholm, K., 1987 - Bidjovagge copper-gold deposit in Finnmark, northern Norway; *Economic Geology*, v. 82, pp. 2059-2075.

Bookstrom, A., 1995 - Magmatic features of iron ores of the Kiruna type in Chile and Sweden: ore textures and magnetite geochemistry – A discussion; *Economic Geology*, v. 90, pp. 469-475.

Carlon, C.J., 2000 - Iron oxide systems and base metal mineralisation in northern Sweden, *in* Porter, T.M., (ed.), Hydrothermal Iron Oxide Copper-Gold and Related Deposits: A Global Perspective, *PGC Publishing, Adelaide*, v. 1, pp. 283-296.

Cathelineau, M., 1988 - Cation site occupancy in chlorites and illites as a function of temperature; *Clay Minerals*, v. 23, pp. 471-485.

Edfelt, Å., Armstrong, R.N., Smith, M.P. and Martinsson, O., 2005 - Alteration paragenesis and mineral chemistry of the Tjårrojåkka apatite-iron and Cu (-Au) occurrences, Kiruna area, northern Sweden; *Mineralium Deposita*, v. 40, pp. 409-434.

Ekdahl, E., 1993 - Early Proterozoic Karelian and Svecofennian formations and evolution of the Raahe-Ladoga ore zone, based on the Pielavesi area, central Finland; *Geological Survey of Finland,* Bulletin 373, pp. 1-137.

Frietsch, R. and Perdahl, J.-A., 1995 - Rare earth elements in apatite and magnetite in Kiruna-type iron ores and some other iron ore types; *Ore Geology Reviews*, v. 9, pp. 489-510.

Frietsch, R., Tuisku, P., Martinsson, O. and Perdahl, J.-A., 1997 - Early Proterozoic Cu-(Au) and Fe ore deposits associated with regional Na-Cl metasomatism in northern Fennoscandia; *Ore Geology Reviews*, v. 12, pp. 1-34.

Geijer, P., 1910 - Igneous rocks and iron ores of Kirunavaara, Luossavaara and Tuolluvaara; *Scientific and Practical Researches in Lapland Arranged by Luossuvaara-Kiirunavaara Aktiebolag, Stockholm*; 278p.

Geijer, P., 1931 - Berggrunden inom malmtrakten Kiruna-Gällivare-Pajala; *Sveriges Geologiska Undersökning (SGU)*, Series C, 366, 255p.

Hitzman, M., Oreskes, N. and Einaudi, M.T., 1992 - Geological characteristics and tectonic setting of Proterozoic iron oxide (Cu-U-Au-REE) deposits; *Precambrian Research*, v. 58, pp. 241-287.

Hopper, D. and Correa, A., 2000 - The Panulcillo and Teresa de Colmo copper deposits: Two contrasting examples of Fe-Ox Cu-Au mineralization from the Coastal Cordillera of Chile; *in* Porter, T.M., (ed.), Hydrothermal Iron Oxide Copper-Gold and Related Deposits: A Global Perspective, *PGC Publishing, Adelaide*, v. 1, pp. 177-190.

Lahtinen, R., Huhma, H. and Kousa, J., 2002 - Contrasting source components of the Paleoproterozoic Svecofennian metasediments: Detrital zircon U–Pb, Sm–Nd and geochemical data; *Precambrian Research,* v. 116, pp. 81-109.

Lindblom, S., Broman, C. and Martinsson, O., 1996 - Magmatic-hydrothermal fluids in the Pahtohavare Cu-Au deposit in greenstone at Kiruna, Sweden; *Mineralium Deposita*, v. 31, pp. 307-318.

Mark, G., Oliver, N.H.S., Williams, P.J., Valenta, R.K. and Crookes, R.A., 2000. The evolution of the Ernest Henry Fe-Oxide-(Cu-Au) hydrothermal system, *in* Porter, T.M., (ed.), Hydrothermal Iron Oxide Copper-Gold and Related Deposits: A Global Perspective, *PGC Publishing, Adelaide*, v. 1, pp. 123-136.

Mark, G., Oliver, N.H.S. and Williams, P.J., 2006 - Mineralogical and chemical evolution of the Ernest Henry Fe oxide-Cu-Au system, Cloncurry district, northwest Queensland, Australia; *Mineralium Deposita*, v. 40, pp. 769-801.

Marschick, R., Leveille, R.A. and Martin, W., 2000 - La Candelaria and the Punte del Cobre district, Chile: Early Cretaceous Iron-oxide Cu-Au(-Zn-Ag) mineralization, *in* Porter, T.M., (ed.), Hydrothermal Iron Oxide Copper-Gold and Related Deposits: A Global Perspective, *PGC Publishing, Adelaide*, v. 1, pp. 163-176.

Marschik, R. and Fontbote, L., 2001 - The Candelaria-Punta del Cobra iron oxide Cu-Au(Zn-Ag) deposits, Chile; *Economic Geology*, v. 96, pp. 1799-1826.

Marshall, L.J. and Oliver, N.H.S., 2006 - Monitoring fluid chemistry in iron oxide-copper-gold-related metasomatic processes, eastern Mount Isa Block, Australia; *Geofluids*, v. 6, pp. 42-66.

Martinsson, O., 1997 - Tectonic setting and Metallogeny of the Kiruna Greenstones: Doctoral thesis, *Luleå University of Technology*, 1997:19.

Martinsson, O., 2004 - Geology and metallogeny of the Nothern Norrbotten Fe-Cu-Au province; *Society of Economic Geologists Guidebook Series,* 33, pp. 131-148.

Martinsson, O. and Perdahl. J.-A., 1993 - Stratigraphy of the Kiruna Porphyries; *in* Martinsson, O., Perdahl, J.-A. and Bergman, J., (eds.), Greenstone and Porphyry Hosted Ore Deposits in Northern Norrbotten, *NUTEK* Project no 92-00752P, 5p.

Martinsson, O. and Wanhainen, C., 2000 - Excursion guide. *in* 2nd GEODE Fennoscandian Shield Field Workshop on Palaeoproterozoic and Archaen Greenstone Belts and VMS Districts in the Fennoscandian Shield, *Luleå University of Technology*, Research Report 2000:06, pp. 63-76.

Martinsson, O. and Wanhainen, C., 2004 - Character of Cu-Au Mineralization and Related Hydrothermal Alteration along the Nautanen Deformation Zone, Gällivare Area, Northern Sweden; *Society of Economic Geologists Guidebook Series*, 33, pp. 149-160.

Nironen, M., 1997 - The Svecofennian Orogen: a tectonic model; *Precambrian Research*, v. 86, pp. 21-44.

Nisbet, B., Cooke, J., Richards, M. and Williams, C., 2000 - Exploration for iron oxide copper gold deposits in Zambia and Sweden; Comparison with the Australian experience; *in* Porter, T.M., (ed.), Hydrothermal Iron Oxide Copper-Gold and Related Deposits: A Global Perspective, *PGC Publishing, Adelaide*, v. 1, pp. 297-308.

Nyström, J.O., 1985 - Apatite iron ores of the Kiruna field, northern Sweden: magmatic textures and carbonatitic affinity; *Geologiska Föreningens i Stockhom Förhandlingar (GFF)*, v. 107, pp. 133-141.

Nyström, J.O. and Henríquez, F., 1994 - Magmatic features of iron of the Kiruna type in Chile and Sweden: ore textures and magnetite geochemistry; *Economic Geology*, v. 89, pp. 820-839.

Parak, T., 1975a - The origin of the Kiruna iron ores; *Sveriges Geologiska Undersökning (SGU*), Series C, 708, 209p.

Parak, T., 1975b - Kiruna iron ores are not "intrusive magmatic ores of the Kiruna type"; *Economic Geology*, v. 70, pp. 1242-1258.

Pollard, P.J. and Williams, P.J., 1999 - Short Course on Fe Oxide-Copper-Gold Deposits (The Candelaria-Ernest Henry-Olympic Dam Family); *James Cook University in collaboration with the Society for Geology Applied to Mineral Deposits and the International Association on the Genesis of Ore Deposits*. 132p.

Romer, R.L., 1996 - What is the significance of lead isotope data from stilbite, a low-temperature natural ion-exchanger? *The 22nd Nordic Geological Winter meeting, Turku, Åbo,* Abstracts, 172p.

Romer, R.L., Kjösnes, B., Korneliussen, A., Lindahl, I., Skysseth, T., Standal, H. and Sundvoll, B., 1992 - The Archaean-Proterozoic boundary beneath the Caledonides of northern Norway and Sweden: U-Pb, Rb-Sr and Nd isotopic data from the Rombak-Tysfjord area; *Norges Geologiske Undersøkelse*, Rapport 91, (225), 67p.

Romer, R.L., Martinsson, O. and Perdahl, J.-A., 1994 - Geochronology of the Kiruna iron ores and hydrothermal alterations; *Economic Geology*, v. 89, pp. 1249-1261.

Sillitoe, R.H., 2003 - Iron oxide-copper-gold deposits: An Andean view; *Mineralium Deposita*, v. 38, pp. 787-812.

Skiöld, T., 1987 - Aspects of the Proterozoic geochronology of Northern Sweden; *Precambrian Research*, v. 35, pp. 161-167.

Skiöld, T., 1988 - Implications of new U-Pb zircon chronology to early Proterozoic crustal accretion in northern Sweden; *Precambrian Research*, v. 32, pp. 35-44.

Skiöld, T. and Cliff, R.A., 1984 - Sm-Nd and U-Pb dating of early Proterozoic mafic-felsic volcanism in northernmost Sweden; *Precambrian Research,* v. 26, pp. 1-13.

Skiöld, T., Öhlander, B., Markkula, H., Widenfalk, L. and Claesson, L.-A., 1993 - Chronology of Proterozoic orogenic processes at the Archean continental margin in northern Sweden; *Precambrian Research,* v. 64, pp. 225-238.

Smith, M.P., Coppard, J., Herrington, R. and Stein, H., 2007 - The Geology of the Rakkurijärvi Cu-(Au) Prospect, Norrbotten: A New Iron Oxide-Copper-Gold Deposit in Northern Sweden; *Economic Geology,* v. 102, pp. 393-414.

Smith, M.P., Storey, C.D., Jeffries, T. and Ryan, C., (*in press)* - In-situ U-Pb and trace element analysis of accessory minerals in the Kiruna district, Norrbotten, Sweden: New constraints on the timing and origin of mineralisation; *Journal of Petrology*.

Storey, C.D., Smith, M.P. and Jeffries, T., 2007 - In situ LA-ICP-MS U–Pb dating of metavolcanics of Norrbotten, Sweden: Records of extended geological histories in complex titanite grains; *Chemical Geology,* v. 240, pp. 163-181.

Sveriges Geologiska Undersökning (SGU), 1967 - Berggrundsgeologiska och flygmagnetiska kartbladen Kiruna NV, NO, SV, SO: *Sveriges Geologiska Undersökning (SGU), Stockholm*, Sweden. Map.

Vollmer, F.W., Wright, S.F. and Hudleston, P.J., 1984 - Early deformation in the Svecokarelian greenstone belt of the Kiruna iron district, northern Sweden; *Geologiska Föreningens i Stockhom Förhandlingar (GFF)*, v. 106, pp. 109-118.

Wägman, K. and Ohlsson, L.-G., 2000 - Exploration opportunities in Norrbotten: Municipality of Kiruna; Mineral Resources Information Office, *Sveriges Geologiska Undersökning (SGU), Stockholm*, 278p.

Wanheinen, C., Broman, C. and Martinsson, O., 2003 - The Aitik Cu-Au-Ag deposit in northern Sweden: a product of high salinity fluids; *Mineralium Deposita*, v. 38, pp. 715-726.

Wanhainen, C., Billstrom, K., Martinsson, O., Stein, H. and Nordin, R., 2005 - 160 Ma of magmatic/hydrothermal and metamorphic activity in the Gällivare area: Re-Os dating of molybdenite and U-Pb dating of titanite from the Aitik Cu-Au-Ag deposit, northern Sweden; *Mineralium Deposita,* v. 40, pp. 435-447.

Welin, E., 1987 - The depositional evolution of the Svecofennian supracrustal sequence in Finland and Sweden; *Precambrian Research,* v. 35, pp. 95-113.

Williams, P.J. and Skirrow, R.G., 2000. Overview of iron oxide –copper-gold deposits in the Curnamona Province and Cloncurry district (Eastern Mount Isa Block), Australia, *in* Porter, T.M., (ed.), Hydrothermal Iron Oxide Copper-Gold and Related Deposits: A Global Perspective, *PGC Publishing, Adelaide*, v. 1, pp. 123-136.

Williams, P.J., Barton, M.D., Johnson, D.A., Fontbote, L., de Haller, A., Mark, G. and Oliver, N.H.S., 2005 - Iron oxide copper-gold deposits: Geology, space time distribution and possible modes of origin; *Economic Geology*, v. 100, pp. 371-405.

Witschard, F., 1984 - The geological and tectonic evolution of the Precambrian of northern Sweden – a case for basement reactivation? *Precambrian Research*, v. 23, pp. 273-315.

Wright, S.F., 1988 - Early Proterozoic deformational history of the Kiruna district, northern Sweden; Unpublished PhD thesis, *University of Minnesota*, 170p.

Zhu, C. and Sverjensky, D.A., 1991 - Partitioning of F-Cl-OH between minerals and hydrothermal fluids; *Geochimica et Cosmochimica Acta*, v. 55, pp. 1837-1858.

Zhu, C. and Sverjensky, D.A., 1992 - F-Cl-OH partitioning between biotite and apatite; *Geochimica et Cosmochimica Acta,* v. 56, pp. 3435-3467.