

**Iron Oxide-Copper-Gold Deposits in Finland:
case studies from the Peräpohja schist belt and
the Central Lapland greenstone belt**

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Academic dissertation

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Cover: Laurinoja Fe-Cu-Au ore. Polished drill core half. ~ 45 % Fe, ~ 2.5 % Cu, and ~ 5 g/t Au. Chalcopyrite (yellow), magnetite (gray), and clinopyroxene (green) comprise the main minerals. Field of view is 17 mm.

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Abstract

Iron oxide-copper-gold (IOCG) deposits define a group of diverse, epigenetic Cu-Au deposits to which several economically important deposits belong. Their typical characteristics are: (1) Fe-Cu-Au-Co-U-REE-Ba-F element association, (2) high Fe-S ratio manifested by magnetite- and/or hematite-rich host rocks of the ores, (3) extensive, commonly spatially and temporally zoned Na-Ca-K-Fe metasomatism in and around the deposits, (4) highly saline aqueous \pm carbonic fluids related to alteration and mineralisation, and (5) spatial correlation with crustal-scale fault and shear zones. Host rock sequence, fO_2 , and depth as well as temperature of the mineralisation events vary extensively between the known deposits causing considerable diversity in their characteristics.

The purpose of this work is to evaluate the IOCG potential of northern Finland. This is done by studying five iron oxide-rich deposits from two different regions: (1) Raajärvi and Puro magnetite deposits in the Misi region located in the easternmost part of the Peräpohja schist belt, and (2) Hannukainen, Kuervitikko and Cu-Rautuvaara Fe-Cu-Au deposits in the Kolari region located in the western part of the Central Lapland greenstone belt. The study covers alteration, mineralogy, geochemistry, fluid inclusion characteristics, and geochronology. The data achieved are further compared to the existing data on the IOCG deposits elsewhere and to genetic models that have been proposed for IOCG deposits.

In both Kolari and Misi regions, the geological features of the deposits are comparable to the IOCG deposits elsewhere and consistent with proposed magmatic source models. The Kolari deposits also contain Cu and Au in grades typical for IOCG deposits and thus they best fit to the IOCG category. Although at least Cu was mobile during the mineralisation and alteration events related to magnetite deposits in the Misi region, only anomalous values of Cu and Au have been detected. However, the alteration style, fluid inclusion composition, O- and C-isotope characteristics, and the proposed genetic model of the magnetite deposits at Misi are consistent with what has been described with IOCG deposits. Therefore, the magnetite deposits in the Misi region are considered to be representatives of IOCG deposits barren with respect to Cu and Au.

According to the data presented, northern Finland is a IOCG potential region. The most prospective district for IOCG is the western part of the Central Lapland greenstone belt, the area adjacent to the major Kolari shear zone system. Based on the age data on the studied deposits, favourable time periods for IOCG mineralisation in northern Finland were 2.44 – 2.05 Ga and 1.83 – 1.77 Ga. These periods represent the crustal-scale rifting stage that predates the 1.92 – 1.77 Ga Svecofennian orogenic events, and the D₃-stage thrusting event(s) of the Svecofennian orogeny post-dating the peak of regional metamorphism, respectively. The most prospective locations for IOCG deposits in northern Fennoscandia are old cratonic margins and intracratonic regions with abundant rift-related magmatism and extensive, metal-depleting sodic alteration.

Keywords: *IOCG deposits, Skarn deposits, Iron deposits, Copper deposits, Gold deposits, Hydrothermal alteration, Palaeoproterozoic, Peräpohja Schist Belt, Central Lapland Greenstone Belt, Misi, Kolari, Finland, Geochemistry, Fluid inclusions, U-Pb age, O-isotopes, C-isotopes, SIMS, PIXE*

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Preface

Iron oxide-copper-gold deposit class (IOCG) include world class deposits like Olympic Dam (Gawler craton, Australia), Ernest Henry (Cloncurry district, Australia) and Candelaria (Punta del Cobre, Chile). The mentioned deposits are very large in size (e.g. Olympic Dam, about 3 Gt) and their origins controversial, hence their discovery has captured the attention of exploration companies and academics, and the number of deposits classified into the IOCG category has drastically increased as is the understanding of the genesis of this enigmatic deposit class during the past 15 years.

This work is part of the project “Iron oxide-copper-gold in northern Finland” of the Geological Survey of Finland (GTK), initiated in 2001. The aim of the project is to verify the occurrence of this ore type in Finland, and to create genetic models and exploration tools applicable to the Fennoscandian Shield. The ultimate goal is to locate economically interesting prospects for private industry and to promote mineral exploration by providing information on host rocks, genetic ore models, and exploration indicators of IOCG mineralisation in Finland.

The original GTK project scheme focused the research to northern Finland because the geological environment is similar to the regions where IOCG deposits are known to occur. Furthermore, the plan was to focus the research to the known iron oxide-rich deposits that have at least anomalous concentrations Cu and Au and have previously been classified as skarn deposits. Therefore, the scientific part of the project was focused on deposits in the Misi region in the easternmost corner of the Peräpohja schist belt, and on deposits in the Kolari region in the western part of the Central Lapland greenstone belt.

On my account, this project was initiated by a phone call in the late autumn 2000. Caller was Dr. Pasi Eilu from the Geological Survey of Finland who told me briefly about the IOCG project that was due to start in January 2001, and asked whether I was interested in doing a PhD work on the topic as a part of the GTK’s project. This was the first time ever I had heard about the IOCG de-

posits, and some of the methods I was supposed to use I knew only by their name. However, without fully realising what I was up to do, I answered yes to Pasi’s question. And so it began.

The time spent on this project has certainly been interesting and challenging for me. I’ve been in places I probably otherwise would never winded up, met number of interesting people, and had opportunity to work with some of the top-ranking ore geologists. So I am happy that I took the challenge. Now, writing this, I am even happier that it is done and I never have to do it again.

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I am very grateful to Dr. Pasi Eilu (GTK) who acted as a leading supervisor during my work, introduced me to the world of altered rocks and mass balance calculations. Besides that he was a co-author in one paper, he reviewed all my manuscripts with an amazing efficiency and rigor. I am also grateful to Professor Nick Oliver (James Cook University) for the efforts he put into my work and for his hospitality during my stay in Oz. Dr. Matti Poutianen was one of the key persons in the project and deserves very big thanks. Besides introducing me to the world of fluid inclusions and being an inspiring co-author, Matti supported me during the frustrating times (yes, there were quite a few) of the project. I am also very grateful to Dr. Irmeli Mänttari (GTK) who did a tremendous work on the age determinations and was a co-author in two of the papers. I am also grateful to Professor Eero Hanski (University of Oulu) who introduced me to the geology of the Misi region and acted as a co-author in one paper. Mr. Akseli Torppa (University of Helsinki) is appreciated for the carbonate isotope analyses. Professor Martti Lehtinen (University of Helsinki) is thanked for the XRD work and Dr. Bo Johansson (GTK) for the microprobe work. I am grateful for Dr. Jodie Miller (University of Cape Town) for the stable isotope analyses and Dr. Satu Mertanen (GTK) for the AMS measurements. Mr. Riku Raitala (University of Helsinki) owes my gratitude for the assistance in the ore microscopy and for “turning-that-one-diagram”. Dr. Arto Luttinen (University of Helsinki) is thanked for enlightening discussions on the geochemical issues. Dr. Chris Ryan and Mrs. Esme van Achterberg at the CSIRO laboratories in North Ryde, Sydney are thanked for the kind assistance with the PIXE.

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This work was carried out mainly in the University of Helsinki and I am very grateful to the following persons at the University of Helsinki not directly related to my project but for the inspiring and/or hilarious coffee table discussions

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The work was done in co-operation with the Geological Survey of Finland Rovaniemi and Espoo offices where the following persons are thanked for their support during my work: Dr. Raimo Lahtinen, Dr. Juhani Ojala, Dr. Pekka Nurmi, Dr. Erkki Vanhanen, and Mr. Jorma Isomaa.

I am grateful to all organisations from which I have received financial support during the project. Outokumpu Oyj Foundation was the main financial supporter. I also received funding from the Finnish Academy (project n:o 202628), Finnish Graduate School in Geology, Australian Research Council Discovery Grant, and a three months grant from the University of Helsinki for finishing the doctoral thesis. The Geological Survey of Finland provided most of the geochemical and age dating analyses and thin sections. Management of the Geological Survey of Finland is thanked for the possibility to finish my work.

My very good friends Mr. Sami Partamies and Mr. Jouni Rautiainen are thanked for all their mental support during the work and for reminding me that there is life outside the work, too. My spouse, Ms. Virve Heilimo deserves very special thanks for all her patience during the project and enjoyable life outside the office.

Stein um Stein

Helsinki, October, 21st, 2005.

Tero Niiranen

Contents

List of publications.....	8
1 Introduction.....	9
1.1 Element association.....	9
1.2 Iron-rich hosts.....	15
1.3 Alteration.....	15
1.4 Proposed genetic models for IOCG deposits.....	16
1.5 Fennoscandian IOCG deposits.....	18
2 Review of the original papers.....	19
2.1 Paper I.....	19
2.2 Paper II.....	19
2.3 Paper III.....	20
3 Discussion.....	21
4 Summary.....	23
4.1 Conclusions.....	23
4.2 Implications for exploration.....	23
5 References.....	24
Papers I-III	

List of Publications

This thesis consists of a synopsis and the following three papers that are referred in the synopsis in roman numerals:

- I** Niiranen, T., Hanski, E., Eilu, P., 2002. General geology, alteration, and iron deposits in the Palaeoproterozoic Misi region, northern Finland. *Bulletin of the Geological Society of Finland* 75, pp. 69-92.
- II** Niiranen, T., Mänttari, I., Poutiainen, M., Oliver, N.H.S., Miller, J. Genesis of the early Proterozoic iron skarns in Misi region, northern Finland. *Mineralium Deposita* 40, pp. 192-217.
- III** Niiranen, T., Poutiainen, M., Mänttari, I. Geology, Geochemistry, Fluid inclusion characteristics, and U-Pb age studies on Iron oxide-Cu-Au deposits in the Kolari region, northern Finland. *Ore Geology Reviews* (Accepted).

T. Niiranen's contribution to paper I includes everything except the construction of the geological map of the region and part of the field observations and sampling related to the regional geological survey. T. Niiranen contributed everything except U-Pb age determinations and stable isotope analytical work for paper II. Furthermore, the majority of the fluid inclusion descriptions and heating-freezing measurements were carried out by a co-author. Everything except U-Pb age determinations and fluid inclusion work in paper III was done by T. Niiranen.

1 Introduction

Iron oxide-copper-gold deposits (IOCG) are now a widely recognised ore class into which hundreds of iron and copper-gold deposits around the world have been included since the synthesis of the concept by Hitzman et al. (1992). The IOCG deposits form a group with diverse age, tectonic setting, host rock package, and mineralisation style (e.g. Hitzman et al. 1992; Haynes, 2000; Williams and Skirrow, 2000; Pollard, 2001; Williams and Pollard, 2001; Tables 1 and 2). Nevertheless, there appear to be features that are characteristic for all deposits, although none of them alone is diagnostic by itself. The most common features include: (1) the element association Fe-Cu-Au-Co-U-REE-Ba-F, (2) host rock for Cu-Au mineralisation is typically rich in iron oxides, (3) an extensive metasomatism in and around the deposits, (4) high-salinity aqueous \pm carbonic ore fluids, (5) high mineralisation temperature (up to 600°C for oxide stage) evolving towards moderate temperatures (500 – 300°C for sulphide stage), (6) deposits appear to be located in the regions with voluminous igneous activity but, with some exceptions, lack intimate relationship with intrusions, and (7) deposits are located in or next to fault or shear zones, and in regional scale appear to be proximal to crustal-scale faults, shear zones

or lineaments (e.g. Hitzman et al., 1992; Barton and Johnson, 1996; Pollard, 2000; Williams and Pollard, 2001; Oliver et al., 2004; Tables 1 and 2). Below is a brief description of some the most essential features and their genetic significance.

1.1 Element association

Copper and gold are the main commodities IOCG deposits are mined for. The grades for Cu and Au are commonly relatively low (0.5 – 1.5 wt.% Cu, 0.2 – 1 g/t Au, cf. Table 1) similar to porphyry systems, but high grade IOCG deposits (> 1.5 wt.% Cu, > 1 g/t Au) are known, too (e.g. Starra, Osborne, Mt Elliott, Eloise; Table 1). Average iron concentration, where reported, is usually between 15 – 35 wt.% Fe, but also over 40 wt.% concentrations in the ironstone hosts are common (e.g. Hitzman et al., 1992; Marschik et al., 2000; Requía and Fontboté, 2000; Wang and Williams, 2001; Paper III). In addition to the Fe-Cu-Au association, the deposits typically display at least elevated values, if not ore grades, of Ag, Ba, Bi, Co, F, Mo, P, Se, Te, U and REE (Table 1). Less frequently, the deposits are enriched in As, B, Ni, Sn, W, or Zn. In some deposits, which in other respects clearly are of IOCG type, even Cu or Au may occur in concentrations only in slightly over local background levels (e.g. NICO, Goad et al., 2000).

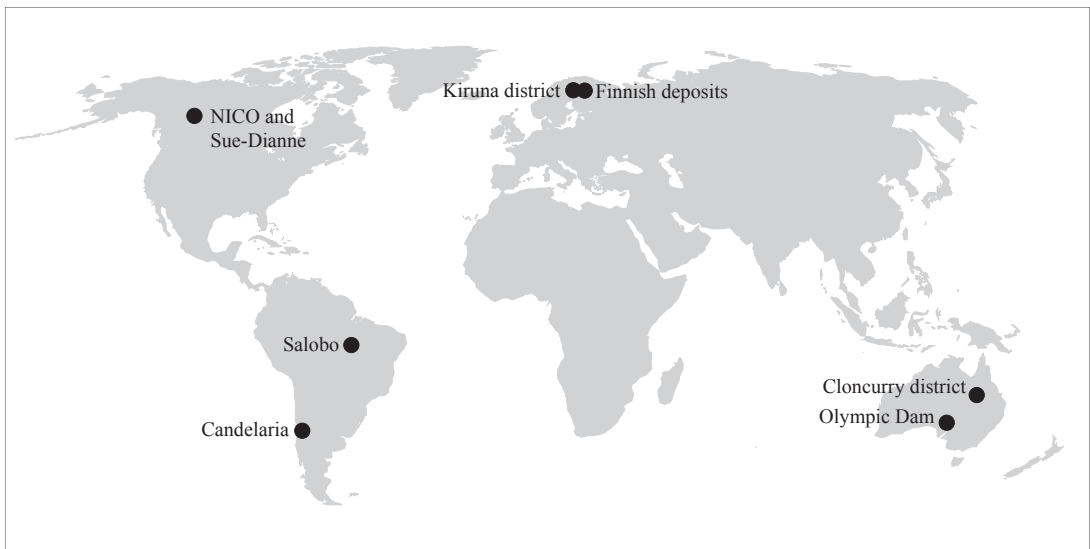


Figure 1. Location of the deposits listed in Tables 1 and 2.

Table 1. Characteristics of selected IOCG deposits. Geographical locations are given in Figure 1; Ernest Henry, Starra, Osborne, Mt Elliott, and Eloise are all in the Cloncurry district.

Deposit and references	Size and grade, element association¹	Ore mineralogy²	Structures, host sequence	Age and P-T estimates³
Australia Olympic Dam (Oreskes and Einaudi, 1990 & 1992; Reynolds 2000; WMC Ltd Annual Report 2003)	2950 Mt at 1.2% Cu, 0.5 g/t Au, 6 g/t Ag, 0.04 % U ₃ O ₈ , 0.05 % REE; Fe, Cu, Au, F, Ba, LREE, U, Ag, Co, P	Hm, cpy, bor, cha, py, ura ± cofl, bran; Ser, qtz, sid, bar, flu ± chl, tou, mnz, bast	Diatreme breccia at intersection of major lineaments; A-type granite, felsic metavolcanic rock	1590 Ma (U-Pb, zr in the granite host); Ca. 400°C (early), 200-400°C (late) (O isotopes, F.I.), shallow level deposition
Ernest Henry (Mark and Crookes, 1999; Mark et al., 2000; Oliver et al., 2004)	167 Mt at 1.1% Cu, 0.5 g/t Au; Fe, Cu, Au, Mn, Mo, As, Co, Ba, F, U, W, LREE	Cpy, py, mgt ± hm; Kfs, ce, bt, gr, bar, ± ser, sca	Hydrothermal breccia in bend in brittle-ductile shear zone; Intermediate metavolcanic rock, diorite, psammite, calc-silicate rock	> 1514-1504 Ma (Ar-Ar, bt); 1.5-3.7 kbar (F.I.), 450°C (F.I. and O isotopes)
Starra (Rotherham et al., 1998; Mark et al., 2001; Williams et al., 2001; Oliver et al., 2004)	7.4 Mt at 1.9% Cu, 3.8 g/t Au; Fe, Cu, Au, Co, W, Sn, F, Mo, LREE	Mgt, hm, cpy, py, cha, ± gold, bor; Bt, qtz, cc, anh, chl, mu, ser	Ductile shear zone, breccia; Mica schist	> 1505 Ma (Ar-Ar, bt); > 1.3 kbar (F.I.), 400-550°C early, 220-360°C late (F.I.)
Osborne (Adshead et al., 1998; Mark et al., 2001; Oliver et al., 2005)	15.2 Mt at 3.0% Cu, 1.1 g/t Au; Fe, Cu, Au, Co, Mo, LREE, Ni, Se, Te, Ag, Hg, Bi, W	Mgt, cpy, py ± po, hm; Bt, qtz, ab, hbl, mu, cc	In bend or fold in ductile shear zone; BIF(?), meta-arenite, pelitic schist, amphibolite	1600-1590 Ma (Re-Os, mo, U-Pb, tit), 1570-1540 Ma (Ar-Ar, hbl and bt); 1.5 kbar, >450°C (F.I.)
Mt Elliott (Mark et al., 2001; Wang and Williams, 2001; Oliver et al., 2004)	3.3 Mt at 3.6% Cu, 1.8 g/t Au; Fe, Cu, Au, Co, Ni, F, P, LREE, Mo, Se, Te, U	Mgt, py, po, cpy; Cpx, sca, ab ± am, adr, cc, ap, tou, all	Breccia and veins in dilational jog in shear zone; Amphibolite, carbonaceous schist, siltstone	1510 Ma (Ar-Ar, act); 350-550°C
Eloise (Baker, 1998; Baker et al., 2001)	3.1 Mt at 5.5% Cu, 1.4 g/t Au, 16 g/t Ag; Cu, Au, Fe, Ag, Co, Ni, As, Bi, Zn, Se, Te	Cpy, po, py, mgt ± gold, sph, gal; Hbl, bt, cc, chl ± mu, act, tou, Kfs, ep, sid, hm	In dilational jog associated with shear zones; Meta-arkosite, qtz-bt schist, amphibolite	1530 Ma (Ar-Ar, hbl); 1-3.5 kbar (F.I.), 430-550°C (F.I., O isotopes)

Table 1. Continued

Deposit and selected references	Size and grade, element association ¹	Ore mineralogy ²	Structures, host sequence	Age and P-T estimates ³
Chile				
Candelaria (Marschik et al., 2000; Marschik and Fontboté, 2001)	470 Mt at 1.0% Cu, 0.2 g/t Au, 3.1 g/t Ag; Fe, Cu, Au, Ag, Mo, LREE, Zn, As	Mgt, cpy, py ± hm, po, sph, apy, mo, gold; Bt, Kfs, qtz, am ± ab, ep, tou, cc	Near to intersection between lithostratigraphic boundary and major shear zone; Andesitic-basaltic metavolcanic rocks, diorite, dacite dykes, limestone	115 Ma (Ar-Ar, bt & hbl); >470-330°C (F.I.)
Brazil				
Salobo (Requia and Fontboté, 2000; Requia et al., 2003)	789 Mt at 1.0% Cu, 0.5 g/t Au; Fe, Cu, Ag, As, F, Mo, Mn, U, Co, LREE	Mgt, cpy, bor, cha ± hm, mo, cob, ura, gold; Cum-gru, bt, Kfs, gr ± qtz, tou, flu, ap, all, chl	within a major shear system; Metagreywackes, amphibolite; quartzite, BIF, gneiss, dolerite	2576-2562 Ma (Re-Os, mo); 550°C
Canada				
NICO (Goad et al., 2000)	42 Mt at 0.1% Co, 0.5 g/t Au, 0.1% Bi; Fe, Au, Co, As, Bi, W, Te, Ba, B, P, F, LREE	Mgt/hm, apy, cob, bis, py, po, cpy; Bt, am, Kfs ± carb, chl, tou	Diatreme and fracture breccia at intersection of structural lineaments; Sub-arkosic wacke, rhyolite, siltstone	1850 Ma; shallow level deposition.
Sue-Dianne (Goad et al., 2000)	17.3 Mt at 0.72% Cu, 2.7 Ag, 0.06 g/t Au; Fe, Cu, Ag, U, Mo, Ba, P, Bi, Co, F, REE	Hm/mgt, cpy, bor ± cha, cov, ura, py, gold, mo; Kfs, ep, chl, gr, flu, qtz, all	Diatreme breccia at intersection of structural lineaments; Rhyodacite ignimbrite, marginal to rapakivi pluton	1850 Ma; shallow level deposition.
Sweden				
Tjäröjåkka-Cu (Edfelt and Martinsson, 2003; Edfeldt et al., 2005)	3.2 Mt at 0.9% Cu; Cu, Fe, P, F, Ba ± Au, Ag, Te, Mo, Th, REE	Cpy, bor, mgt ± py, cha, cov, mo; Kfs, act, qtz, cc, ap	Shear/fault next to intersection of two major shear zones, ca. 700 m from 53 Mt (52% Fe) magnetite body; Andesitic metavolcanic rock, dolerites	Palaeoproterozoic
Nautanen (Martinsson and Aaltonen, 2004)	0.63 Mt at 2.4% Cu, 1.3 g/t Au, 11 g/t Ag; Cu, Fe, Au, Ag, Ba ± B, Co, Zn, W	Cpy, mgt, py ± sph, gal, carr, mo, bor, cha; Am, px, ep, qtz, ser, tou	Shear zone; Intermediate metavolcanic rock(?)	Palaeoproterozoic

Table 1. Continued

Deposit and references	Size and grade, element association¹	Ore mineralogy²	Structures, host sequence	Age and P-T estimates³
Finland				
Vähäjoki (Korvuo, 1982; Liipo and Laajoki, 1991; Niiranen and Eilu, 2003; Niiranen and Poutainen, 2003; Niiranen, unpublished data)	Up to 30 ironstone bodies with total ca. 11 Mt at 40% Fe, 0.4% Cu, 0.1% Co, <0.2-2.0 g/t Au; Fe, Cu, Au, Co, Ba, Ag, Mo, Bi, Te, Zn	Mgt, po, py, cpy, cob, apy ± hm, limn, sph, gold, bor; Tre/act, cum, hbl, chl, bt, cc	Shear/fault zone, breccia; Dolomitic marble banded mica schist, black schist, mafic metavolcanic rock,	Palaeoproterozoic; 2-4 kbar, 400-500°C
Laurinoja (Hannukainen) ⁴ (Hiltunen, 1982; Niiranen, 2004; Paper III)	33 Mt at 43% Fe, <0.1-11.0% Cu, <0.1-6.6 g/t Au, <0.1-17.7 Ag; Fe, Cu, Au ± Ag, Bi, Ba, Co, Mo, Sb, Te, LREE	Mgt, py, po, cpy ± gold, mo; Cpx, hbl, act ± sca, cc, bt, ab, qtz, Kfs, all, mnz	Bend in reverse thrust/fault zone; Mafic metavolcanic rock, diorite, mica gneiss, quartzite, marble(?)	Ca. 1800 Ma (U-Pb, zr, tit); 1.5-3.5 kbar (F.I.), 450-550°C (F.I.)
Kuervitikko (Hiltunen, 1982; Niiranen, 2004; Paper III)	1.2 Mt at 36-53% Fe, <0.1-8.3% Cu, <0.1-6.0 g/t Au, <0.1-2.1 g/t Ag; Fe, Cu, Au ± Ag, Bi, Ba, Co, Mo, Se, Te, LREE	Mgt, py, cpy, po ± gold, mo; Cpx, act, hbl, cc ± sca, bt, ab, qtz, Kfs, all, mnz	Bend in reverse thrust/fault zone; Mafic metavolcanic rock, diorite, mica gneiss, quartzite, marble	Ca. 1800 Ma (U-Pb, zr, tit); 1.5-3.5 kbar (F.I.), 450-550°C (F.I.)
Cu-Rautuvaara (Hiltunen, 1982; Niiranen, 2004; Paper III)	4 Mt at <0.1-1.5% Cu, <0.1-2.6 g/t Au, <0.1-1.2 g/t Ag; Fe, Cu, Au ± Ag, Ba, Bi, Mo, Se, Te, Th, U, LREE	Mgt, cpy, po, py ± ura; Ab, atp, bt ± tit, sea, Kfs, chl, cpx, qtz	Next to reverse thrust/fault; Mafic metavolcanic rock, diorite	Ca. 1800 Ma (U-Pb, zr, tit); Probably similar to P-T conditions as with the Laurinoja and Kuervitikko
Raajärvi & Puro (Papers I and II)	Total 7.2 Mt at 46% Fe, 0.11% V; Fe, V, P, in sulphur bearing parts anomalous Au, Cu, Co, Te	Mgt ± py, cpy, tell, late hm, bor; Tre/act, chl, srp, cc, bt, ± di, tlc, ap	Shear/fault zone; Dolomitic marble, quartzite, mica schist, gabbro (Raajärvi); gabbro, quartzite (Puro)	2062-2017 Ma (U-Pb, tit); 2.2-3.5 kbar (F.I.); 390-490°C (F.I. and O isotopes)

1) Note that an element that is not noted to be enriched in a particular ore system may not actually have been analyzed from the deposit. 2) Mineral abbreviations: ab = albite, act = actinolite, adr = andradite, am = amphibole, all = allanite, anh = anhydrite, ap = apatite, apy = arsenopyrite, atp = anthophyllite, bar = barite, bast = bastnaesite, bis = bismuthite, bor = bornite, bran = brannerite, bt = biotite, carb = carbonate, carr = carrollite, cc = calcite, cha = chalcocite, chl = chlorite, cob = cobaltite, coff = coffinite, cov = covellite, cpx = clinopyroxene, crd = cordierite, cum = cummingtonite, di = diopside, do = dolomite, ep = epidote, flu = fluorite, gal = galena, gr = garnet, gru = grunerite, hbl = hornblende, hm = hematite, Kfs = K-feldspar, mgt = magnetite, mnz = molybdenite, mu = muscovite, po = pyrrhotite, px = pyroxene, py = pyrite, qtz = quartz, saff = saffrolite, sca = scapolite, ser = sericite, sid = siderite, sph = sphalerite, srp = serpentine, tell = telluride, tit = titanite, tlc = talc, tou = tourmaline, tre = tremolite, ura = uraninite, zr = zircon. 3) F.I. = fluid inclusion data. 4) Laurinoja is the largest of the five ore bodies comprising the Hannukainen deposit and the only one that is known to contain significant Cu and Au.

Table 2. Alteration, fluid inclusion and stable isotope data on deposits shown in Table 1

Deposit	Alteration	Fluid inclusion chemistry	S, C, O isotopes (‰)
Australia			
Olympic Dam	Early: K-Fe (ser-hm-qtz) Intermediate: Cu-Au-U-Ba-F-S (qtz-hm-sid-bar-flu-sulphides) Late: Ca-Ba-F-CO ₂ (bar, flu, sid, do, sulphides)	(A) High salinity L-V-halite, up to 42 wt.% NaCl _{eq} [?] (B) Moderate salinity L-V, 7-24 wt.% NaCl _{eq} [?] (C) CO ₂ -rich	$\delta^{13}\text{C}_{\text{sid}} = -4$ to -2 , $\delta^{18}\text{O}_{\text{sid}} = 14$ to 21 , $\delta^{18}\text{O}_{\text{fluid}} \sim 10$ (early) and < 9 (late)
Ernest Henry	Distal: Na \pm Ca (ab \pm act, di) Proximal: (I) K-Fe (Kfs-mgt-bt-cc-gr), (II) K-Fe-Cu-Au-S-CO ₂ (Kfs, mgt, carb, qtz, py, cpy). Post mineralisation: cc, do, qtz \pm hm veining	(A) hypersaline L-V-halite \pm 5 daughter minerals, 33-55 wt.% NaCl _{eq} . (B) moderate salinity L-V \pm halite, ca. 20 wt.% NaCl _{eq} . (C) CO ₂ -rich	$\delta^{34}\text{S}_{\text{py}} = -2$ to 4 , $\delta^{34}\text{S}_{\text{cpy}} = -1$ to 4 , $\delta^{13}\text{C}_{\text{cc}} = -6$ to 0 , $\delta^{18}\text{O}_{\text{cc}} = 10$ to 13 , $\delta^{18}\text{O}_{\text{fluid}} = 8$ to 11
Starra	Distal: Na-Ca (ab-qtz-act-sca) Proximal: (I) K-Fe (bt-mgt-qtz \pm hm, py), (II) CO ₂ -SO ₄ -S-Au-Cu (anh-cc-hm-chl-sulphides \pm ser, mu)	(A) hypersaline L-V-halite \pm 3 daughter minerals, 34-52 wt.% NaCl _{eq} . (B) hypersaline L-V-halite \pm 4 daughter minerals, 29-42 wt.% NaCl _{eq} . (C) CO ₂ -rich	$\delta^{34}\text{S}_{\text{cpy}} = -10$ to -3 , $\delta^{13}\text{C}_{\text{cc}} = -7$ to -1 , $\delta^{18}\text{O}_{\text{cc}} = 10$ to 13 , $\delta^{18}\text{O}_{\text{fluid}} = 7$ to 10
Osborne	Distal/Regional: Na-Ca (ab-sca-act) Proximal: Fe-K-Ca-CO ₂ -S (mgt-bt-qtz-ab-cpy-py-po \pm am, cc, mu, hm)	(A) hypersaline L-V-halite \pm 4 daughter minerals, ≤ 70 wt.% NaCl _{eq} . (B) CO ₂ -CH ₄ -rich	$\delta^{34}\text{S}_{\text{cpy}} = -4$ to 3 , $\delta^{18}\text{O}_{\text{fluid}} = 5$ to 12
Mt Elliott	Distal: Na (ab \pm sca), Proximal: (I) Ca-Fe \pm Na (di-mgt-sca-act), (II) Ca-Cu-S-CO ₂ -Au (cpy-act-sca-cc \pm adr, tou, all, ap, mgt, py, po)	(A) hypersaline L-V-halite \pm 4 daughter minerals, (B) CO ₂ -rich	$\delta^{34}\text{S}_{\text{py}} = 0$ to 2 , $\delta^{34}\text{S}_{\text{cpy}} = 1$ to 2 , $\delta^{13}\text{C}_{\text{cc}} = -10$ to -8 , $\delta^{18}\text{O}_{\text{cc}} = 12$ to 13 , $\delta^{18}\text{O}_{\text{fluid}} = 9$ to 10
Eloise	Distal: ab \pm ap, qtz and bt-hbl, Proximal: hbl-bt-qtz-mgt-cpy-po-py Late/post-ore: chl, Kfs, cc, qtz, bt, cpy, py, mu, tou, sph, gal, flu, hm, sid	(A) hypersaline L-V-halite \pm 4 daughter minerals, (B) CO ₂ -rich	$\delta^{34}\text{S}_{\text{py}} = 0$ to 2 , $\delta^{34}\text{S}_{\text{po}} = 1$ to 2 , $\delta^{34}\text{S}_{\text{cpy}} = 1$ to 2 , $\delta^{13}\text{C}_{\text{cc}} = -10$ to -8 , $\delta^{18}\text{O}_{\text{cc}} = 9$ to 10 , $\delta^{18}\text{O}_{\text{fluid}} = 5$ to 10
Chile			
Candelaria	Distal: Na-Ca (ab-qtz-bt-mgt & sca \pm gr, px, Ca-am); Proximal: (I) K-Fe \pm Ca (bt-mgt-qtz-gru/cum \pm Kfs, gr, crd), (II) Cu-Au-Ca-S (sulphides \pm Ca-am, anh)	(A) hypersaline, (B) CO ₂ -rich	$\delta^{34}\text{S}_{\text{cpy}} = 0$ to 3 , $\delta^{34}\text{S}_{\text{anh}} = 15$ to 18 , $\delta^{18}\text{O}_{\text{fluid}} = 6$ to 9
Brazil			
Salobo	Distal (pre-mineralisation): weak Na (ab); Proximal: (I) K-Fe-Ca (Kfs-cum/gru-bt-mgt \pm tou, flu, apa, all) (II) Cu-Au-S \pm K, Ca (cpy-cha-bor \pm cum/gru, bt, mo, cob, gold, saff)	(A) hypersaline, up to 58 wt.% NaCl _{eq} . (B) low to moderate salinity, 1-29 wt.% NaCl _{eq} . (C) CO ₂ -CH ₄ -rich,	$\delta^{34}\text{S}_{\text{cpy \& bor}} = 0$ to 2

Table 2. continued.

Deposit	Alteration	Fluid inclusion chemistry	S, C, O isotopes (‰)
Canada			
NICO	Distal: extensive & intense K ± Fe (Kfs ± mgt) Proximal: K-Fe ± Ca (mgt-bt-hbl/act-hm-Kfs ± carb, chl, tour) in multiple stages accompanied with sulphides and gold	no data	no data
Sue-Dianne	Distal: extensive & intense K ± Fe (Kfs ± hm) Proximal: K-Fe (hem-mgt-kfsp ± ep, qtz, gr, flu) accompanied with sulphides	no data	no data
Sweden			
Tjärrojäkka-Cu	Distal: Na (sca ± bt and ab-mgt-ap); Proximal: K-Cu-S ± Ca, Fe (Kfs-sulphides ± am, qtz, mgt, ap, carb)	high to moderate salinity	no data
Nautanen	Distal (?): Na-K (sca-bt), Proximal(?): K-Fe ± Ba-Cu-Au-S (Kfs-bt-gr-mgt and ser-gr-mgt-tou-qtz)	no data	no data
Finland			
Vähäjoki	Proximal: tre/act-cum-chl-mgt ± bt, gr, hbl, qtz, hm, cc, bar; sulphides and gold overprint(?)	(A) low salinity L-V ± nahcolite 2-14 wt.% NaCl _{eq} . (B) CO ₂ -rich	no data
Laurinoja (Hannukainen)	Distal: Na (ab ± sca) Inner distal: K ± Na (bt-Kfs ± ab, sca) Proximal: Ca-Fe-Cu-Au-S (cpx-act/hbl-mgt-sulphides-gold ± sca, cc, bt, ab)	(A) hypersaline L-V-halite ± 5 daughter minerals, 45-48 wt.% NaCl _{eq} . (B) hypersaline L-V-halite 32-56 wt.% NaCl _{eq} . (C) CO ₂ -rich	$\delta^{34}\text{S}_{\text{py}} = -1$ to 7, $\delta^{34}\text{S}_{\text{cc}} = 2$ to 6, $\delta^{13}\text{C}_{\text{cc}} = -7$ to -3, $\delta^{18}\text{O}_{\text{cc}} = 10$ to 14, $\delta^{18}\text{O}_{\text{fluid}} = 8$ to 13
Kuervitikko	Distal: Na (ab ± sca) Inner distal: K ± Na (bt-Kfs ± ab, sca) Proximal: Ca-Fe-Cu-Au-S (cpx-act/hbl-mgt-sulphides-gold ± sca, cc, bt, ab)	(A) hypersaline L-V-halite ± 5 daughter minerals, 45-48 wt.% NaCl _{eq} . (B) hypersaline L-V-halite 32-56 wt.% NaCl _{eq} . (C) CO ₂ -rich	no data
Cu-Rautuvaara	Distal: Na ± K, Ca (ab ± bt, kfs, sca cpx, am) Proximal: Na-Fe-Cu-Au-S ± K (ab-mgt-atp ± bt) accompanied with sulphides and gold	no direct data, probably similar to Laurinoja and Kuervitikko	$\delta^{34}\text{S}_{\text{epy, py, po}} = 4$ to 6
Raajärvi & Puro	Distal: Na ± Ca (ab ± sca, act), Proximal: act/tre-chl-mgt ± cc, bt, ab, ap, Retrograde post-ore srp-chl-tlc-cc-hm	(A) hypersaline L-V-halite ± 4 daughter minerals, 29-58 wt.% NaCl _{eq} . (B) low to moderate salinity 0-22 wt.% NaCl _{eq} . (retrograde stage) (C) CO ₂ -rich	$\delta^{13}\text{C}_{\text{cc}} = -8$ to 11, $\delta^{13}\text{C}_{\text{unaltered marble}} = 13$, $\delta^{18}\text{O}_{\text{cc}} = 12$ to 19, $\delta^{18}\text{O}_{\text{fluid}} = 6$ to 10

For references and mineral abbreviations see Table 1. The stable isotopes are given relative to CDT, PDB and SMOW for S, C, and O, respectively.

al., 2004).

1.2 Iron oxide-rich hosts

The role and origin of the ironstones that host the Cu-Au mineralisation in IOCG systems has been under debate ever since the IOCG concept was created. Hitzman et al. (1992) included Kiruna apatite-iron ores in the IOCG class. On the other hand, some authors consider that the giant Kiruna ores were formed via direct crystallisation from Fe-O-(P-Ca-F) melts (e.g. Nyström and Henriquez, 1994), and there is still controversy whether there is a link or continuum between “Kiruna-type” apatite-iron ores and IOCG deposits. Typically, the ironstone hosts are metasomatic replacement bodies, and numerous barren examples of these are known to occur in conjunction with IOCG occurrences (Williams, 1994). Even in deposits that display a broad spatial relationship with syngenetic iron formations (i.e. BIFs) the iron oxide-rich hosts for Cu-Au mineralisation are considered epigenetic (e.g. Salobo, Requía and Fontboté, 2000).

In a number of deposits, iron oxides appear to be paragenetic precursors to the copper-gold assemblages, and in some cases it has been proposed that magnetite-rich ironstones have acted as a redox trap for the sulphur-rich fluids (e.g. at Starra, Rotherham et al., 1998). Sulphidation of the pre-existing iron-rich assemblages is proposed in some deposits as a precipitation mechanism of Cu and Au (e.g. Eloise, Baker, 1998). Groves and Vielreicher (2001) suggest that the complex and repetitive nature of the ore-paragenesis reflect a prolonged and discrete hydrothermal event related to multiple intrusive stages with an alkaline magmatic fluid source. Recent geochemical modelling suggests that precipitation of iron oxides and Cu-Au minerals in IOCG deposits did not necessarily take place in discrete episodes, but rather the Fe and Cu-Au assemblages express prolonged evolution of a single hydrothermal system (Oliver et al., 2004). Nevertheless, the ultimate role of the iron-rich hosts in the genesis of the IOCG deposits is still unclear. While in some deposits they appear to be the cause for precipitation of the Cu and Au bearing minerals, in others they may just be a “by-product” of Cu and Au mineralisation (e.g. Williams and Pollard, 2001; Oliver et

1.3 Alteration

The IOCG deposits typically are surrounded by hundreds of meters to kilometre-scale hydrothermal alteration haloes and the immediate wall rocks are intensely altered. The alteration styles vary from sodic to potassic to calcic or combination of these (Table 2). The distal alteration is typically characterised by extensive sodic \pm calcic mineral assemblages, chiefly albite \pm scapolite, actinolite, and it is accompanied by a loss of a number of elements, especially Fe, K \pm Ca and gain in Na (e.g. Williams, 1994; Oliver et al., 2004; Paper II). The styles of the proximal alteration somewhat depends on the lithology of the host rock sequence, varying between potassic and calcic assemblages and accompanied by precipitation of iron oxides (Table 2). The potassic alteration products are K-feldspar and biotite or sericite, and the calcic alteration assemblages are dominated by skarn minerals, i.e. diopside-hedenbergite, andradite-grossular, and Ca-amphiboles. In some cases, such as parts of the Candelaria (Marschik et al., 2000; Marschik and Fontboté, 2001), the skarn assemblages are related to the presence of carbonate rocks in the host rock package, whereas in others (e.g. Mt. Elliott, Wang and Williams, 2001) calcium is externally derived. In some shallow-level breccia-style deposits (e.g. Olympic Dam, NICO, Sue-Dianne; cf. Table 1), the sodic distal alteration zone is missing or not exposed, and the distal alteration is dominantly potassic.

Hitzman et al. (1992) suggested that the alteration patterns depend on the depth of alteration, sodic alteration prevailing at deep levels, potassic at intermediate to shallow levels, and sericitic alteration and silicification at very shallow levels (Fig. 2). The level of deposition also appears to be reflected in the ore mineralogy (Table 1). In deeper levels, the dominant iron oxide is magnetite, and chalcopyrite, pyrite, and pyrrhotite are the main sulphide minerals. In shallow-level deposits, the mineral assemblages indicate more oxidized conditions, hematite being the dominant iron oxide, and chalcocite and bornite comprising the typical Cu-sulphide minerals.

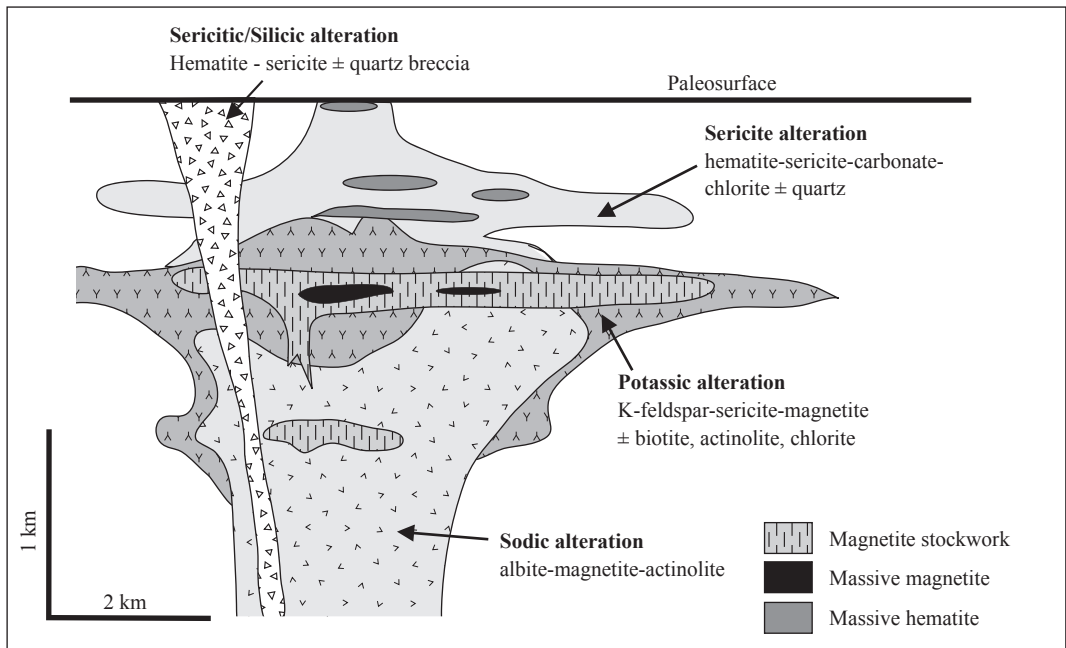


Figure 2. Schematic cross section of alteration zoning in IOCG deposits after Hitzman et al. (1992).

1.4 Proposed genetic models for IOCG deposits

The original proposal by Hitzman et al. (1992) was that IOCG deposits are expressions of deep-seated, volatile-rich igneous-hydrothermal systems tapped by deep crustal structures and possibly related to global-scale rifting events chiefly during the Mesoproterozoic. Since that work, both Archaean and Phanerozoic IOCG deposits and districts have been recognized and recent age data indicate that some deposits are linked to orogenic processes (e.g. Williams, 2000; Oliver et al., 2004). Therefore, it is becoming more and more apparent that IOCG deposits are not limited to a certain time period or tectonic environment, but were formed throughout the geological history in various tectonic environments.

Several genetic models for the IOCG deposits have been proposed during the past 15 years. Release of the ore constituents, especially the constituents of the iron oxide-rich hosts via albitisation reactions caused by circulating high salinity brines is emphasised in number of these models (e.g. Hitzman et al., 1992; Williams, 1994; Barton and Johnson, 1996; and 2000; Oliver et al., 2004). The main contradicting issue between the presented models is the ultimate source of the

albitising brines (i.e. magmatic versus non-magmatic source). Volatile-rich alkaline magmas enriched in incompatible elements (e.g. A-type or shoshonitic felsic intrusives) are favored in the magmatic fluid source models (e.g. Pollard et al., 1998). A genetic link to carbonatite intrusives has also been proposed (Groves and Vielreicher, 2001). Brief reviews are given below on the genetic models by Barton and Johnson (2000) and Oliver et al. (2004) which suggest non-magmatic and magmatic brine sources for the mineralising fluid, respectively (Figs 3 and 4).

Barton and Johnson (1996 and 2000) proposed that the ore fluids are connate basal brines and the ligands carried by these brines are possibly derived from ancient evaporates. The circulation of the brines is controlled by thermal convection, and extensive albite alteration (with metal depletion) is expected in the inflow and down flow zones of the brine (Fig. 3). Near magmatic heat sources the fluids focus into structurally and/or lithologically favourable locations producing intense sodic (mafic host) or potassic (felsic host) proximal alteration and the metals are precipitated. Mixing of surface-derived fluids with brines can be a significant factor in metal precipitation at shallower levels. Barton and

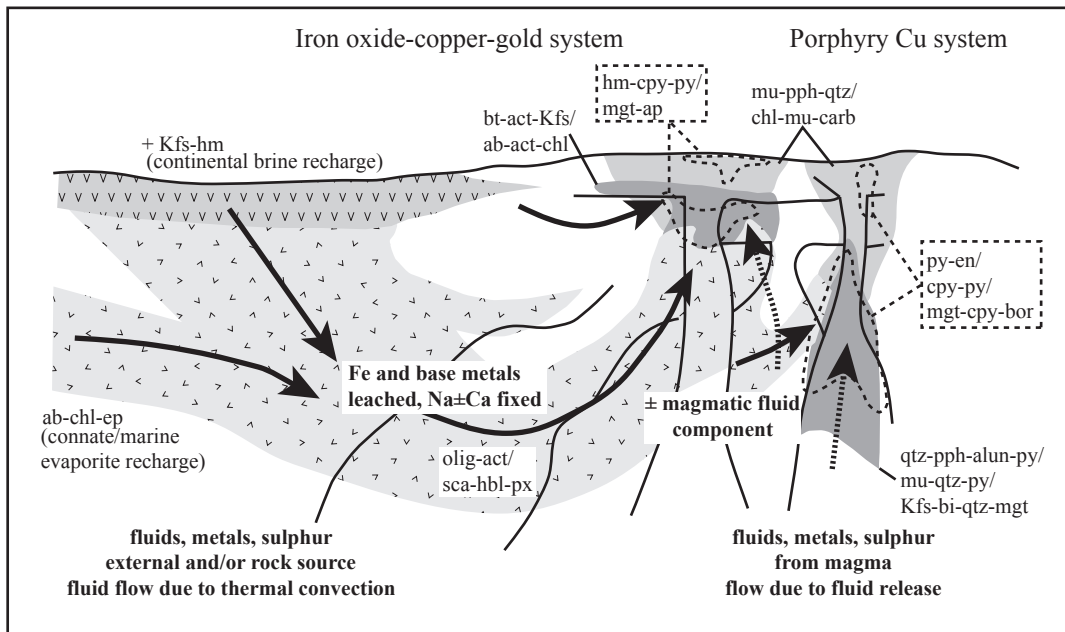


Figure 3. Conceptual genetic model for IOCG deposits, and a possible link to porphyry Cu-Au deposits, by Barton and Johnson (1996 & 2000). Solid arrows display the path of the externally derived brines, dashed arrows the path of fluid derived from magmatic source. Mineral abbreviations as in Tables 1 and 2, except alun = alunite, en = enargite, olig = oligoclase. Figure modified after Barton and Johnson (2000).

Johnson (2000) point out that this kind of system tends to produce sulphide poor deposits with only geochemically anomalous concentrations of chalcophile elements. Therefore, they propose that magmatic metal, sulphur, and fluid input mixing with the externally derived fluids or superimposing the oxide-rich system is probably significant in Cu-Au-richer deposits. Although the model by Barton and Johnson (1996) does explain the extensive sodic alteration noted in number of the IOCG districts, it fails to explain the almost consistent magmatic stable isotope signatures in the majority of the deposits (Table 2).

Oliver et al. (2004) compiled the data on the deposits from the Cloncurry region and made the following observations. (1) Several albitisation stages exists in the region covering temporally both the metamorphic events related to the 1600 – 1580 Ma Isan orogeny and the thermal events related to Williams Suite intrusives during 1550 – 1500 Ma. (2) Most of the IOCG deposits in the region post-date the peak of regional metamorphism being contemporaneous with the Williams Suite intrusives. Thus the evaporate source model for the deposits is unlikely since the evaporate

units would have been consumed in albite and scapolite producing reactions prior to or during the peak of regional metamorphism. (3) Geochemical data on the albitised country rocks of the Cloncurry deposits suggest consistent gain in Na and loss of Fe, K, Ba, Rb ± Ca, Sr, Co, V, Mn, Pb, and Zn during the alteration. Most the elements lost from the albitised rocks are found enriched in the metasomatic ironstones that host the Cu-Au occurrences, and are also detected in elevated concentrations in the fluid inclusions in the IOCG deposits of the region. Thus a genetic link between sodic alteration, high-salinity brines, and the IOCG deposits appears evident. However, Cu is not consistently lost from the albitised rocks suggesting that another source(s) is needed.

Based on this data and geochemical modelling, Oliver et al. (2004) propose a genetic model for IOCG deposits in the Cloncurry region where: (1) brines are released from crystallising Williams Suite intrusives, (2) circulating brines evolve via albitisation reactions where Na is fixed and constituents that are enriched in proximal alteration zones and ironstones (especially K and Fe) are stripped to the brine, (3) the circulation of

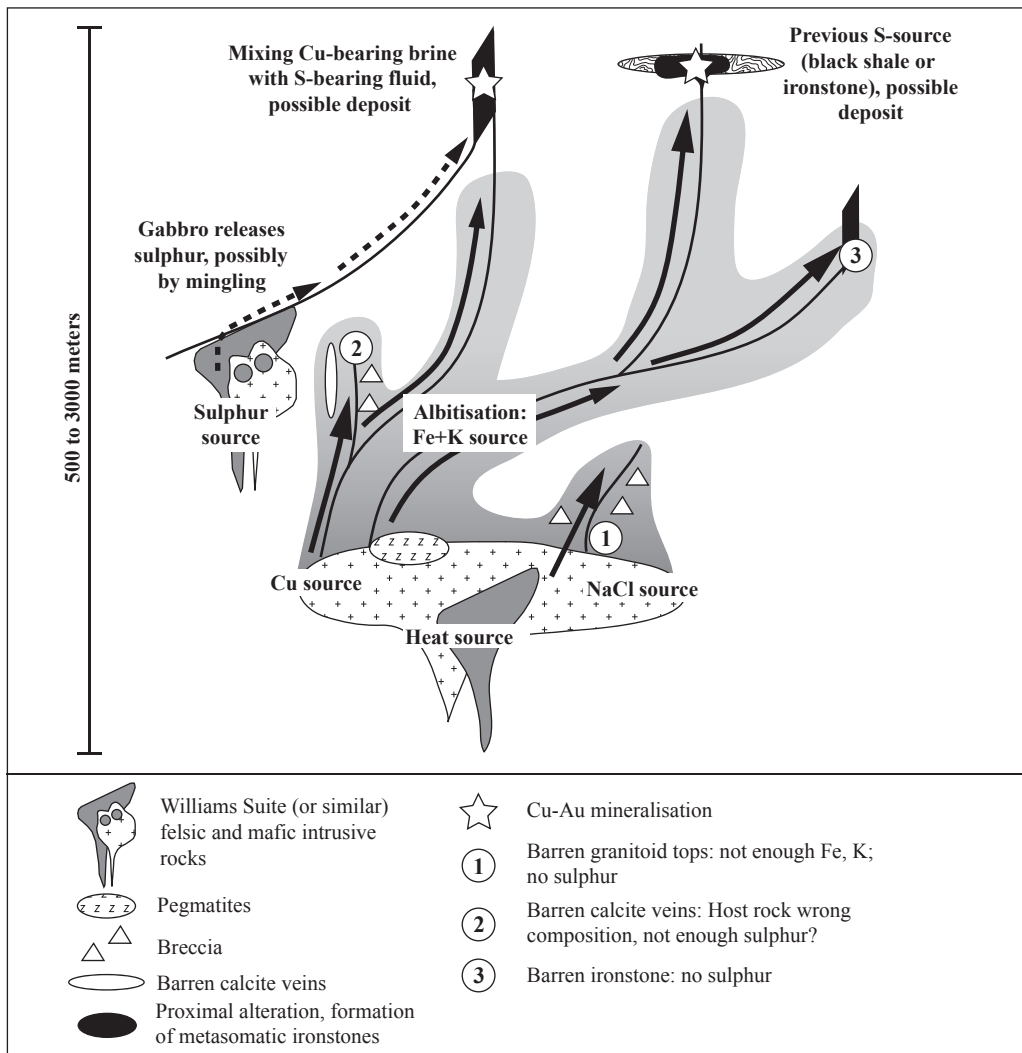


Figure 4. The genetic model for IOCG deposits in the Cloncurry region, Queensland, Australia by Oliver et al. (2004). Solid arrows illustrate the path of the brines derived from intrusions. Dashed arrows illustrate path of the sulphur bearing fluids. Figure modified after Oliver et al. (2004).

the metal-enriched brine is aided and focused by faulting and/or shearing, (4) metals are precipitated in structurally (e.g. dilational jogs) and/or lithologically favourable locations possibly aided by mixing with external lower-salinity fluid (Fig. 4). Barren ironstones are produced if the albitising fluids were initially poor in Cu or S or both. For formation of large tonnage chalcopyrite deposits in the region (e.g. Ernest Henry), mixing of a metal-rich brine with S-bearing wall rocks or an external S-bearing fluid is probably required.

1.5 Fennoscandian IOCG deposits

Besides the Kiruna-type magnetite-apatite ores,

several deposits in the northern Fennoscandia have been proposed to belong to the IOCG class (e.g. Hitzman et al., 1992; Pollard, 2000; Weihed and Eilu, 2003). In northern Finland, numerous, chiefly orogenic, Au ± Cu deposits are known (Eilu, 1999), and the Fe-Co-Au-(U) deposits in the Kuusamo schist belt have been suggested to belong to the IOCG class (Vanhanen, 2001). However, until recently, the main focus of exploration and research in northern Finland has been in PGE and orogenic gold deposits and little effort has been put on the IOCG deposits. The purpose of this work is to establish the IOCG potential of the northern Finland – whether such deposits ex-

ists there, and if so, what are their characteristics, and how do they compare to IOCG deposits elsewhere.

2 Review of the original papers

2.1 Paper I

Paper I describes (1) the general geological features of the Misi region, (2) geological and the geochemical features of the magnetite occurrences in the area focusing on the Raajärvi and Puro deposits, and (3) regional and local alteration styles.

The bedrock of the Misi region consists of a supracrustal sequence of dolomitic marbles, quartzites, mafic metalavas, mafic tuffs, mica schists, black schists, calc-silicate rocks and meta-arkosite. Gabbros and granites comprise the intrusives in the region. Based on their chemical composition, the mafic metavolcanic units are divided into LREE-depleted and slightly LREE-enriched tholeiitic lavas, and a tuff unit which has a flat chondrite-normalised REE pattern. Two geochemically different gabbros occur in the region: differentiated, LREE-enriched, 2117 ± 7 Ma gabbros, and gabbros of unknown age with a flat chondrite-normalised REE pattern. The granites, that occur mainly in the northern part of the region, are the youngest rocks in the area and belong to the ca. 1800 Ma aged intrusive suite of the Central Lapland Granitoid Complex. The geochemical and stable isotope features of the Misi supracrustal rocks display similarities with the Kivalo Group rocks in the western part of the Peräpohja schist belt.

Several skarn-like magnetite occurrences exist in the Misi region. Of these, the Raajärvi and Puro deposits were investigated in more detail. The magnetite occurrences are hosted by skarn rocks within a ca. 2.22 – 2.12 Ga dolomitic marble-quartzite sequence and within albitites which are highly altered varieties of the LREE-enriched gabbro intrusions and their granophyric roof zones. The main opaque mineral in the occurrences is magnetite with minor hematite, pyrite and chalcopyrite. Besides iron, the occurrences contain elevated concentrations of V (≤ 2400 ppm),

and locally elevated values of P (≤ 1.44 wt.%). The average sulphur concentration at Raajärvi and Puro is 0.1 wt.% and 0.3 wt.%, respectively. However, locally up to 3.7 wt.% S was assayed from pyrite- and chalcopyrite-bearing parts of the deposits. The sulphide-bearing parts of the ores and skarn hosts also show elevated concentrations of Au, Cu, Co, and Te.

Characteristic for the Misi region is a regional-scale, multistage sodic alteration (albite-scapolite) that has affected all rocks in the region except the granites in variable degrees. Alteration in and around the Raajärvi and Puro deposits is dominated by intense, pervasive sodic alteration (albite-scapolite) and skarn-alteration (actinolite-tremolite-chlorite-serpentine). The intense sodic alteration and the skarn-alteration are related to faulting or shearing before or during the regional D_1 deformation stage.

Based on the alteration features, and geochemical and mineralogical constraints of the Raajärvi and Puro deposits and their country rocks, it is suggested that the iron in the deposits may well have been derived from the altered country rocks.

2.2 Paper II

Paper II (1) tests if it is possible that the iron in the magnetite deposits in the Misi region was derived from the mafic country rocks via albitisation by circulating high-salinity brines, (2) investigates whether the albitisation and mineralisation took place during the crustal-scale extensional stages pre-dating the 1.9 – 1.8 Ga Svecofennian orogeny or during the Svecofennian orogenic events, (3) evaluates the sources of the fluids related to the albitisation and mineralisation events, and (4) evaluates the possible mechanisms of mobilisation and precipitation of the metals in the magnetite deposits. This work is done based on the geochemical, fluid inclusion, stable isotope (O and C), U-Pb and Pb-Pb isotopic data presented in Paper II.

Mass balance calculations on variably albitised gabbro next to the Raajärvi and Puro deposits indicate that significant amounts of Fe, Ca, Mg, K, Cu, V, and Ba were lost, and Na and Si were gained during the alteration of the rock with

Al, Ga, Ti, and Zr remaining immobile. Calculated loss of $\text{Fe}_2\text{O}_3(\text{t})$ in respect to 100 g of rock is 3.3 g and 14.7 g for moderately and intensely albitised gabbro, respectively. This indicates that only one km^3 of gabbro with a density of $2.9 \text{ kg} \times \text{dm}^{-3}$ can release 67 Mt of Fe through moderate albite alteration. This is more than 20 times the iron in the Raajärvi and Puro deposits combined and, considering the extent of the albite alteration around the deposits (i.e. at least 3 km^2 moderately to intensely albitised rock in the immediate vicinity), the iron in the deposits could easily have been derived from the country rocks. Mass balance calculations on skarn-alteration indicate that significant quantities of Si, Ca, Fe, Na, Cr, and Ba were gained, K, Mg, and V were lost and Al, Ti and Zr remained immobile during the skarn-alteration of a mica schist at Raajärvi.

Fluid inclusion data from the Raajärvi and Puro deposits suggest that fluids related to ore formation, albitisation, and skarn-alteration were highly saline (up to 58 wt.% NaCl_{eq}), oxidizing, aqueous-carbonic fluids. Based on heating-freezing measurements and proton induced X-ray emission (PIXE) analyses, the fluids contained high concentrations of Na, Cl, Ca, K, Fe, and Ba, as well as elevated concentrations of Mn, Sr, Cu, Zn, and Pb. The fluids that circulated during the post-ore serpentinisation were low to moderate salinity aqueous-carbonic fluids containing moderate concentrations of Na, Cl, Ca, and K. The Br-Cl ratio of the fluids that circulated during the mineralisation and the post-ore retrograde stages differ significantly suggesting a different origin for the fluids.

Based on oxygen isotope thermometry, the temperature during the skarn-alteration and formation of the magnetite deposits was between 390° and 490°C . Based on the analysed $\delta^{18}\text{O}$ values of the magnetites, and silicates from the ores and skarns the calculated $\delta^{18}\text{O}_{\text{fluid}}$ during the mineralisation stage was between 6.1 and 9.8 ‰ SMOW at 450°C . This, together with the analysed $\delta^{13}\text{C}$ values of the calcites in the ores and skarns that are between -7.7 and 10.9 ‰ PDB, most likely reflect admixture of magmatic- or mantle-derived carbon with the marble wall rocks that show $\delta^{13}\text{C}$ values of around 13 ‰ PDB.

SIMS U-Pb age data on zircons from the albitised gabbro next to the Raajärvi and Puro deposits suggest that the intrusion of the gabbro took place at $2123 \pm 7 \text{ Ma}$. TIMS U-Pb data on metamorphic titanites in the albitised gabbro related to albite alteration yield ages of $2062 \pm 2 \text{ Ma}$ and $2017 \pm 3 \text{ Ma}$. These ages are roughly contemporaneous to magmatic events related to crustal-scale extensional stages in northern Finland.

Based on the data presented, the following conclusions are made. (1) The oldest skarn assemblage, the diopside skarn, was formed due to contact metasomatic reactions caused by the intrusion of the $2123 \pm 7 \text{ Ma}$ gabbro into the Raajärvi formation supracrustal sequence. (2) The ironstones and actinolite-dominated skarns were formed during metasomatic events that took place between $2062 \pm 2 \text{ Ma}$ and $2017 \pm 3 \text{ Ma}$. The hot, highly saline, fluids that circulated during this stage caused the wide spread albite alteration and stripped the mafic country rocks of Ca, Fe, K, Cu, Ba, and V. The fluid was possibly derived from a deep-seated magmatic source. The circulation of the metal-rich fluid was aided and focused by faulting related to crustal-scale extension and the metal precipitation was due to a drop in temperature, wall rock reaction, or mixing of the brine with cooler, less-saline fluids, or combination of these. (3) The present low-temperature mineral assemblages at Raajärvi and Puro were formed during the later Svecofennian orogenic events that post-date the iron mineralisation in the Misi region.

2.3 Paper III

Paper III (1) describes the geology of three iron oxide-copper-gold deposits in the Kolari region, northern Finland, (2) describes the alteration in and around the deposits, (3) presents new geochemical data on the deposits and altered rocks, (4) presents new fluid inclusion data, and (5) presents new U-Pb age data. Based on the previously reported data and the new data presented, a new genetic model, alternative to the previous skarn model, for the Kolari deposits is presented.

Several iron oxide-copper-gold deposits are known in the Kolari region, in the western part of the Central Lapland greenstone belt, northern

Finland. They are hosted by clinopyroxene-dominated skarns overprinting the > 2.05 Ga Savukoski Group supracrustal rocks and the ca. 1.86 Ga Haparanda Suite intrusions. All deposits are located within or next to shear and fault zones forming parts of the major, NNE-trending, Kolari shear zone (KSZ) which in turn form the northernmost part of the Baltic-Bothnian Megashear (BBMS). Paper III focuses on three of the deposits which contain significant amounts of Cu and Au: the Laurinoja ore body at the Hannukainen mine, and the Kuervitikko and Cu-Rautuvaara deposits. At Laurinoja and Kuervitikko, the copper and gold are hosted by ironstone and skarn. At Cu-Rautuvaara, the host rock is a magnetite-disseminated albite.

The deposits have a distinct metal association of Fe-Cu-Au \pm Ag, Bi, Ba, Co, Mo, Sb, Se, Te, Th, U, LREE. The concentration of copper and gold is 0.1 – 4.5 wt.% and 0.1 – 6.6 g/t, respectively. The wall and host rocks are intensely altered and display a deposit-scale zonation at Laurinoja and Kuervitikko where the structural control is the most prominent. The outer distal alteration zone is characterised by albite \pm Na-scapolite, the inner distal alteration zone by biotite-K-feldspar \pm albite, scapolite, and the proximal alteration zone by clinopyroxene-magnetite \pm Ca-amphibole, scapolite, calcite, sulphides.

The ratios of the immobile Al, Ti, Zr indicate that the dominant protolith for the clinopyroxene-dominated skarns and ironstones is the mafic metavolcanic rock of the > 2.05 Ga supracrustal sequence. Mass balance calculations suggest that significant quantities of Fe, Ca, CO₂, S, Cu, Au, Bi, and Te were added to the proximally altered rocks (skarn and ironstone) at near constant Al, Ti, and Zr. Mass balance evaluations for the distally altered rocks suggest gains in Na, K, and Ba and loss in Ca.

Fluid inclusion data from Laurinoja and Kuervitikko suggest that fluids that circulated in the rocks during the main mineralisation event and the subsequent brittle stage(s) were complex high-salinity (\leq 56 wt.% NaCl_{eq}) aqueous-carbonic fluids. The temperature during the mineralisation event was between 450° and 550°C which is consistent with the high-temperature mineral

assemblages of the skarn. The pressure at the time of the mineralisation was between 1.5 and 3.5 kbars.

The age limits for the alteration and ore formation are defined by the 1864 ± 5 Ma age of magmatic zircons in the hanging wall diorite and the 1797 ± 5 Ma age of the magmatic zircons in the granite that brecciates the ore at Hannukainen mine. The 1797 ± 5 Ma age of the zircons in skarn combined with the 1.81 – 1.78 Ga ages of the metamorphic titanites in the altered wall rocks and skarns suggest that the deposits were formed at ca. 1.80 Ga. This age post-dates the regional metamorphic peak in northern Finland, and is interpreted to be broadly contemporaneous with the eastward directed, 1.83 – 1.77 Ga D₃ thrusting event in the Kolari region during which the KSZ was (re-)activated.

The data presented is inconsistent with the previous models of the Kolari deposits which suggested that the deposits either are metamorphic expressions of syngenetic iron formations or skarn deposits formed under contact-metasomatic conditions related to ca. 1.86 Ga monzonite intrusions. Instead, the alternative model presented here is that the Kolari ironstones and Cu-Au occurrences are epigenetic deposits structurally controlled by the KSZ fault and shear zones. The new data suggest that the deposits best fit into the category of the iron oxide-copper-gold deposits.

3 Discussion

Characteristics of five potential IOCG occurrences from northern Finland are shown in Tables 1 and 2: Laurinoja, Kuervitikko, and Cu-Rautuvaara from the Kolari region, western part of the Central Lapland greenstone belt (CLGB), Raajärvi with its small satellite (Puro) from the Misi region, eastern part of the Peräpohja schist belt (PSB), and Vähäjoki in the western part of the PSB (Fig. 5). All, except Vähäjoki which is beyond the scope of this work, are described in more detail in papers I, II, and III.

The general characteristics of the Kolari deposits best fit into the IOCG category; they display similar element association, alteration pattern, and fluid inclusion characteristics to the

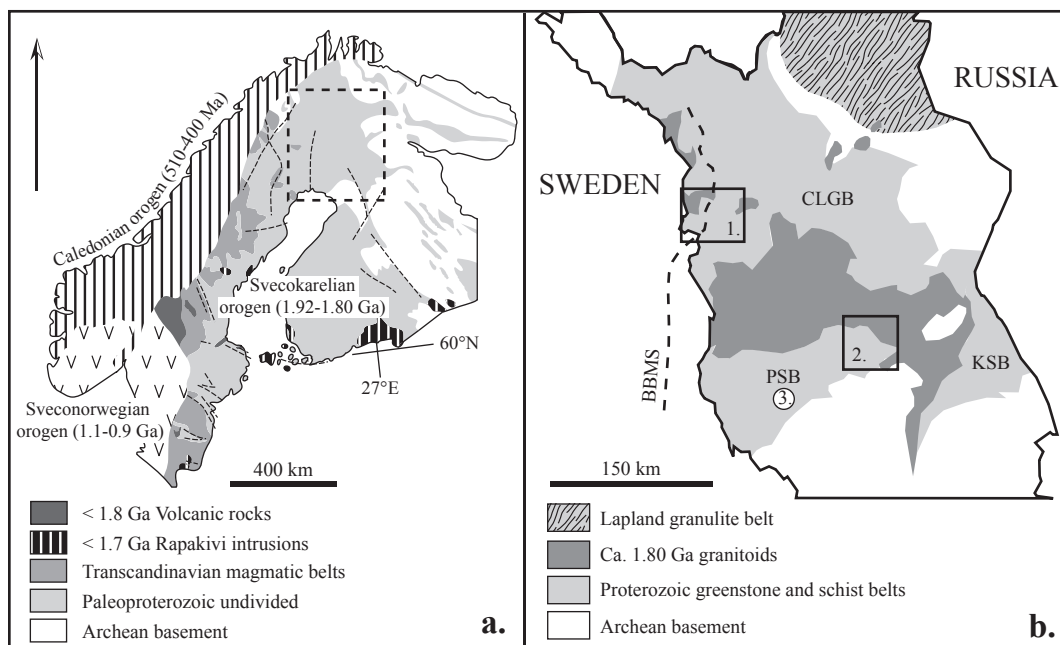


Figure 5. (a) General geological features of northern Fennoscandia. Dashed lines indicate major structural lineaments. Dashed box indicates the area covered in (b). Modified after Gorbachev and Bogdanova (1993). (b) General geological features of northern Finland and the location of the Kolari region (1), Misi region (2), and Vähäjoki deposit (3). CLGB = Central Lapland greenstone belt, KSB = Kuusamo schist belt, PSB = Peräpohja schist belt. BBMS = Baltic-Bothnian megashear (after Berthelsen and Marker, 1986).

other deposits listed in Tables 1 and 2. The Kolari deposits are related to a major crustal scale shear zone system (Berthelsen and Marker, 1986) that is considered to represent the continent-continent collisional boundary between the Norrbotten and Karelian cratons in the recent plate tectonic model of the Fennoscandian shield by Lahtinen et al. (2003). The deposits were formed during the late part of the continent-continent collisional stage (1.85 – 1.79 Ga), near to the extensional orogenic collapse and stabilisation stage (1.79 – 1.77 Ga) in the tectonic model. The preliminary C- and O-isotope data on the Kolari deposits suggest that the fluid source was dominantly magmatic, S-isotopic values implying a combination of magmatic and sedimentary sources for the sulphur (Hiltunen, 1982; Table 2). The proposed 1.80 Ga age of the Kolari deposits (Paper III) is contemporaneous to a thermal event related to the intrusion of the voluminous S-type potassic granitoids throughout northern Finland and Sweden (e.g. Hanski et al., 2001). Another interesting, but poorly known, group of roughly contemporaneous intrusions in northern Finland are the ca. 1.79 Ga appinites that display enrichment in K, Na,

Ba, Sr, P, Cl, F, and LREE, and locally contain abundant Cu-Ni-Fe sulphide dissemination with elevated PGE-Au-Te concentrations (Mutanen and Väänänen, 2004). Regardless of whether the brine source for the Kolari deposits was the felsic intrusives, appinites or some other, possibly deep-seated magmatic source, the genetic model by Oliver et al. (2004) best fits with the characteristics of the Kolari deposit.

The barren ironstones in the Misi region show a number of features common for IOCG deposits despite containing only locally geochemically anomalous concentrations of Cu, Au, Co, and Te (Tables 1 and 2; Paper I and II). The data suggest that it is likely that the Misi ironstones were formed by a mechanism proposed by Oliver et al. (2004) for ironstone hosts for IOCG deposits (see Fig. 4). In addition, the data from the Raajärvi and Puro deposits indicate that Cu and possibly Au were mobile during the alteration and precipitation of iron but, possibly due to lack of S, the chalcophile elements did not precipitate (see Paper II).

The age data suggests that the sodic alteration and formation of the ironstones in the Misi region

took place in an intracratonic rift setting prior to the 1.92 – 1.79 Ga Svecofennian orogenic events. Thus, if the local supracrustal sequence did contain evaporate beds as it has been suggested (e.g. Frietsch et al., 1997), the sodic alteration in the Misi region could have been related to the brines released from the evaporates by a mechanism similar to that proposed by Barton and Johnson (1996). However, the stable isotope data and halogen ratios of the brines at Raajärvi and Puro suggest that the fluid source was dominantly magmatic (Paper II). Therefore, like with the Kolari deposits, it appears that also in the Misi region the magmatic-source model is more probable.

4 Summary

4.1 Conclusions

Following conclusions can be made based on the data presented:

1. Northern Finland is a potential region for the formation of IOCG deposits. Of the Fe-Cu-Au deposits presently known in the region the Kolari occurrences best fit into the IOCG category.

2. The metasomatic ironstones in the Misi region are formed by mechanism similar to the ironstone hosts for IOCG deposits elsewhere. Copper and probably gold was mobile during the alteration and formation of the ironstones in the Misi region, but due to a low amount of sulphur in the system they did not precipitate. Therefore, the ironstones at Misi are considered to represent barren examples of IOCG deposits.

3. In light of the current data, it appears that the most favourable periods for formation of IOCG deposits in northern Finland were: (1) during the extensional events at 2.44 – 2.05 Ga, and (2) during tectonic events at 1.83 – 1.77 Ga that post-date the peak of the regional metamorphism.

4. The data supports magmatic source models of the mineralising fluids and that the elements enriched in the ironstones were derived from the country rocks of the ores by albitisation process.

5. Sodic alteration in northern Finland took place in multiple stages, especially during the crustal scale extensional events between 2.44 and 2.05 Ga, but also during post-peak metamorphic

tectonic events at 1.83 – 1.77 Ga.

6. The sodic alteration events in northern Finland were accompanied by massive flux of mobilised metals, especially iron, which may have focused to structural and/or lithological locations suitable for metal precipitation. Great care should be taken in interpretation of the origin of iron oxide-rich lithologies in regions with abundant albite alteration, especially if the host rock is highly altered, before labelling them to “metamorphic expressions of syngenetic iron formations”. Epigenetic origin should also be considered.

4.2 Implications for exploration

1. In the light of current data, the most promising area for exploration of IOCG type deposits in northern Finland is the area around the Kolari Shear Zone system in the western part of the Central Lapland greenstone belt. Also the Misi region appears interesting with barren ironstones indicating that favourable hydrothermal activity did take place in there. However, the focus of the exploration at Misi should perhaps to be put into the areas with sulphur-rich lithologies.

2. Sodic-altered rocks indicate activity of high-salinity brines and mobility of metals. Regions with albitised and scapolised rocks should be favored. However, in shallower-level systems sodic-altered rocks may not be exposed, instead potassic-iron and or calcic-iron alteration may prevail and indicate high-prospectivity areas.

3. Key locations for exploration are fault and shear zones, lithological contacts, and intersections of these.

4. Numerous ironstones that have been interpreted, in some cases only based on their banded appearance, to be syngenetic iron formations (i.e. BIFs) do occur in northern Finland. These should be reviewed, especially if they do contain even small amounts of Cu, Ba, Co, Au, and S, and if there appears to be a spatial correlation with fault or shear structures.

5. Geophysics and till geochemistry should be used to focus the exploration. A number of the currently mined large IOCG deposits are blind and were discovered by using geophysics and soil geochemistry. The combination of distal sodic alteration and iron oxide-rich host rocks should give

good response in magnetic maps. In addition, U, K, and/or Th anomalies in radiogenic maps and Au, Cu, Co, Ba, U, Th, and/or P anomalies in soil geochemistry may indicate the presence of a proximal alteration zone and mineralisation.

6. Drilling should not be limited to ironstones only. Cases like Cu-Rautuvaara in Finland and Tjärrojåkka in Sweden suggest that Cu-Au mineralisation and ironstones may be located tens or hundreds of meters away from each other.

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