PART

6

THE HANNUKAINEN FE-(CU-AU) DEPOSIT, WESTERN FINNISH LAPLAND: AN UPDATED DEPOSIT MODEL

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M. Moilanen, P. Peltonen

ABSTRACT

The Hannukainen deposit in the Kolari area, western Finnish Lapland, is the largest magnetite deposit in Finland, which also contains significant Cu and Au. Together with its Kuervitikko satellite, the deposit occurs along a major structural zone and appears to be located at flexures along the major structure. The Fe-Cu-Au ore bodies are flat lenses 10–50 m in thickness hosted by calc-silicate skarn rocks, which were formed through metasomatic replacement along the contact zone between a monzonite intrusion and metabasalts. Geophysical studies indicate that the mineralized body at Hannukainen has an extensive down-plunge continuation, probably as deep as 2 km. Together with its Kuervitikko satellite deposit, the total measured and indicated open pit and underground resources are 187 Mt at an average grade of 30.04 wt% Fe, 0.18 wt% Cu, 0.11 ppm Au, and the inferred resource is 63 Mt at an average grade of 32.05 wt% Fe, 0.15 wt% Cu, and 0.05 ppm Au. A recently completed definitive feasibility study indicates that the deposit is economically viable for production of high-purity (70 wt% Fe) magnetite fines supplemented by Cu-Au concentrate.

Hannukainen and more than 10 broadly similar magnetite deposits in the Kolari area formed ~1800 Ma, when local branches of the Bothnian megashear were reactivated and the inflow of hydrothermal saline fluids occurred due to breakdown of evaporites that were earlier deposited within an intracontinental rift zone between the Norrbotten and Karelian cratons. It is hypothesized that these hydrothermal fluids progressively leached Fe, Cu, and Au from the supracrustal sequence, composed mainly of metabasalts, and then deposited metals through

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mixing with more reduced fluids. Textural analysis of mineralized rocks indicates that magnetite was deposited first, followed by precipitation of copper sulfides and gold.

Keywords: IOCG deposits; iron; copper; gold; skarn; Kolari; Finland.

INTRODUCTION

The Hannukainen project comprises two Fe-(Cu-Au) deposits: Hannukainen and Kuervitikko. They are part of an elongated cluster of magnetite deposits occurring in the Kolari-Pajala district, located in Finland and Sweden. To date, as many as 30 magnetite deposits have been identified in this district, which covers approximately 1600 km^2 (40 × 40 km). Hannukainen is the largest Fe-(Cu-Au) deposit on the Finnish side of the border and is located 25 km northeast of the municipal center of Kolari. In Sweden, Fe-(Cu-Au) deposits include the Stora Sahavaara and Tapuli deposits. The styles of mineralization in these deposits display considerable variation ranging from semimassive, skarn-hosted (calc-silicate rocks) magnetite bodies to albitite breccia-hosted magnetite-pyrite-chalcopyrite bodies and disseminated magnetite-chalcopyrite-pyrite deposits in altered mafic volcanic rocks. Copper and gold grades also vary widely among these deposits.

The Kolari-Pajala district is part of a much larger iron ore province in northern Fennoscandia. The Kiruna iron deposit, located 150 km northwest of the Kolari-Pajala area, was discovered in 1696 and has been mined on a regular basis since 1900. The Kiruna deposit consists of a 5-km-long, up to 100-m-thick, steeply dipping layer of iron oxide body with the current sole mineral of economic interest being magnetite. The proven mineral reserves are 536 Mt at 48.6 wt% Fe and probable reserves 146 Mt at 46.4 wt% Fe (LKAB, 2012). The iron oxide bodies are hosted by felsic volcanic rocks within a Svecofennian supracrustal sequence known as the Kiruna porphyry group (Offerberg, 1967). Another currently operating iron mine is the Malmberget magnetite-apatite deposit located at Gällivare in Sweden, about 100 km northwest of Kolari-Pajala. The Malmberget deposit consists of about 20 ore bodies in an area of about 5 × 2.5 km; 7 of the bodies are currently being mined. The mineralization is similar to that at Kiruna. Proven mineral reserves in Malmberget are 168 Mt at 42.3% Fe and probable reserves are 103 Mt at 41.2% Fe (LKAB, 2012). The Malmberget deposit is hosted by highly metamorphosed felsic volcanic rocks, which are considered to be metamorphosed equivalents of the Kiruna porphyry group rocks.

REGIONAL GEOLOGICAL SETTING

Several crustal-scale structures are known in the Fennoscandian Shield. One of these is the north-northeast–south-southwest-striking Kolari-Pajala shear zone, which straddles the border between Finland and Sweden, and hosts the Hannukainen and Kuervitikko deposits. The Kolari-Pajala shear zone (Fig. 6.1) is up to 50 km wide and at least a 150 km long and forms the boundary between the Norrbotten craton in the west and Karelian craton in the east. It has been suggested that the Kolari-Pajala shear zone was formed during the continent–continent collision of the Norrbotten and Karelian cratons at 1.89–1.86 Ga and was subsequently reactivated during later orogenic events between 1.83 and 1.79 Ga (Lahtinen et al., 2005).

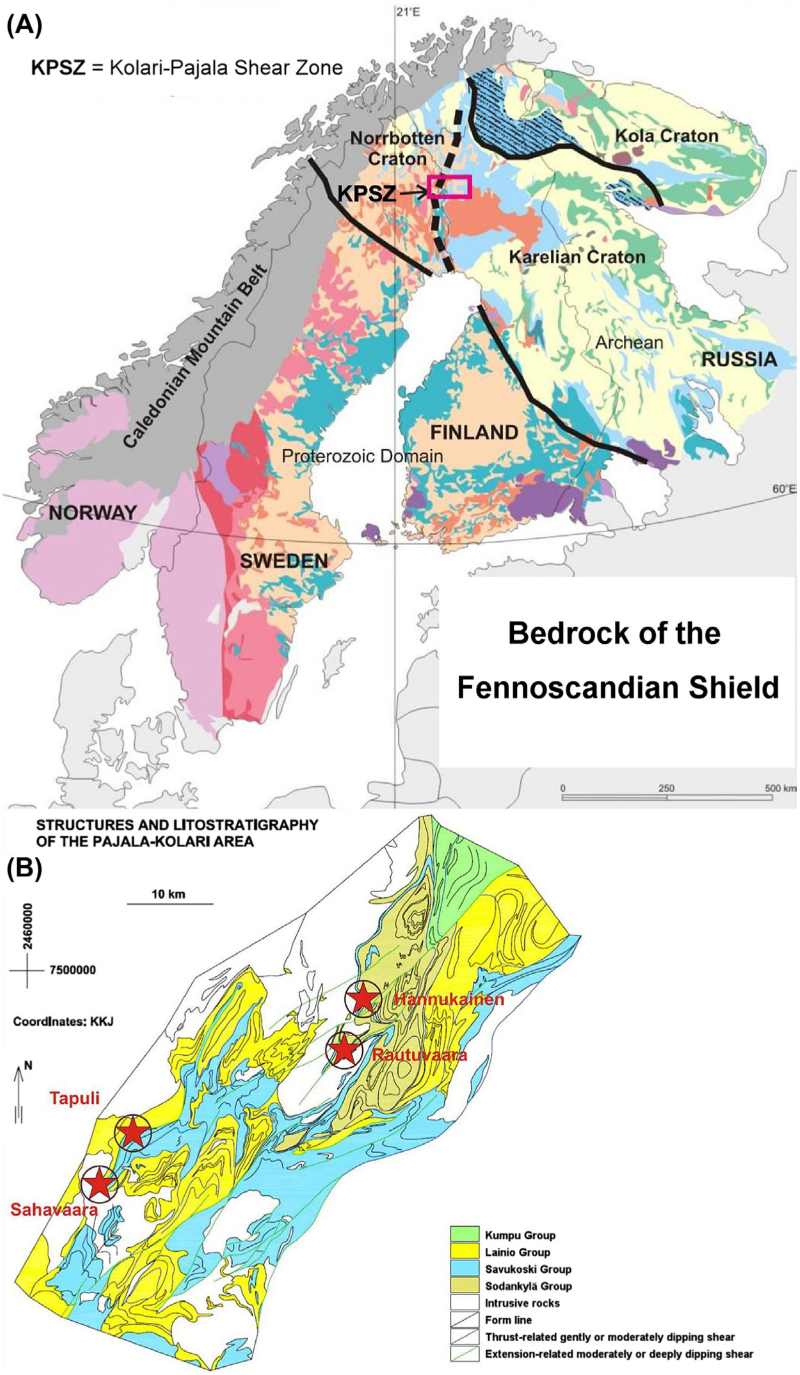

FIGURE 6.1

(A) Bedrock map of the Fennoscandian Shield; (B) Structural and lithostratigraphical map of the Kolari-Pajala region.

Sources: *(A) Modified after Koistinen et al. (2001). (B) Northland Exploration (unpublished report, 2010).*

The Kolari-Pajala area is located in the western part of the Central Lapland Greenstone Belt. The belt was formed during prolonged stages of rifting of the Archean craton, with deposition of Karelian sedimentary and volcanic rocks in intracratonic and cratonic margin rift settings between 2.5 and 2.0 Ga, and was subjected to multiphase deformation and metamorphism during orogenic events. The Haparanda suite intrusive rocks of ~1.86 Ga also occur in the Kolari-Pajala area (Lahtinen et al., 2005).

In the Kolari area, the Karelian supracrustal sequence consists mainly of gently westward-dipping quartzites, phyllites, and mica schists belonging to the Sodankylä group with an age of more than 2.22 Ga (Lehtonen et al., 1998; Hanski and Huhma, 2005). They are stratigraphically and structurally overlain by rocks of the Savukoski group, which are older than 2.06 Ga, the age of the crosscutting Kevitsa layered intrusion (Mutanen and Huhma, 2001). The Savukoski group includes pelitic metasediments, black schists, tholeiitic metabasalts, and primitive volcanic rocks of komatiitic and picritic affinity (Hanski and Huhma, 2005). The Rautuvaara formation, which is part of the Savukoski group, is the host unit for the Hannukainen Fe-(Cu-Au) deposit and other iron-base metal occurrences in the Hannukainen-Rautuvaara mining camp. The Rautuvaara formation is in structural contact with and lies below younger monzonite intrusions of the Haparanda suite (Hiltunen, 1982; Väänänen and Lehtonen, 2001; Väänänen, 1998).

EXPLORATION HISTORY OF THE HANNUKAINEN DEPOSIT

The Kolari area has been known for its iron ore resources for centuries. The first historical records indicate that in the late seventeenth century, the Juvakaisenmaa Fe deposit provided ore feed to the Köngäs ironworks at Pajala, Sweden, some 20 km west of Kolari. During World War II, Vuoksenniska Oy carried out Fe exploration in the area, which was continued by Suomen Malmi Oy in 1956–1960. The Otanmäki Oy Company continued the feasibility studies of the nearby Rautuvaara deposit until 1967 when it was merged with Rautaruukki Oy. From late 1969 to early 1970, Rautaruukki Oy reevaluated the early plans to exploit the Rautuvaara Fe deposit and a formal decision to open the mine was made in May 1970, with mining commencing in 1975. Meanwhile, Rautaruukki Oy continued exploration in the surrounding area and in 1974 exploration was focused on the Hannukainen area.

At Hannukainen, ground magnetic surveys led to the discovery of several ore bodies (Kuervaara, Laurinoja, Lauku, and Vuopio). Because the overburden thickness and stripping ratio were most favorable at the Kuervaara ore body, open-pit mining was started in May 1978. Ore was hauled 10 km to the Rautuvaara mine site to provide additional feed for the Rautuvaara plant. The most valuable ore body by in situ value was Laurinoja, which contained a significant amount of copper ore. The decision to exploit Laurinoja was made by Rautaruukki Oy in June 1981, with a flotation plant built at Rautuvaara. Production of Cu concentrate from Hannukainen started in June (Mining Magazine, 1982).

Altogether, between 1978 and 1990, Rautaruukki Oy mined approximately 4.5 Mt of iron ore from the two Hannukainen open pits. Between 1990 and 1995, the Rautuvaara mill and Hannukainen deposit were leased to Outokumpu Mining Oy, which mined an additional 0.45 Mt of magnetite ore from the Laurinoja open pit, and also processed ore from the company's other deposits (e.g., Saattopora and Juomasuo) in the Rautuvaara plant.

Since 2005, Hannukainen has been studied in great detail by Northland Resources S.A. In 2014, Northland completed the Hannukainen definitive feasibility study, which shows that the Hannukainen Fe-Cu-Au project is economically feasible.

GEOLOGY OF THE HANNUKAINEN DEPOSIT

The Hannukainen deposit consists of five ore bodies: Laurinoja, Kuervaara, Lauku, Kivivuopio, and Vuopio, as well as a satellite deposit at Kuervitikko (Figs. 6.2 and 6.3). The ore bodies form flat lenses that are oriented approximately parallel with the regional structural foliation. The location of the mineralization is strongly structurally controlled; the Fe-Cu-Au ore lenses are located at bends of the semiductile/ductile shear and thrust zone (Fig. 6.3). To the south of the deposit, the Äkäsjoki strike-slip shear zone crosscuts the thrust zone. The reverse thrust at Hannukainen dips 20–30° to the west. At Hannukainen, the lineation plunges about 30° toward the southwest.

A typical local lithological sequence in the Hannukainen deposit is from top to bottom: monzonite, diorite, different kinds of skarn rocks, amphibolite/mafic metavolcanic rocks, gneiss, and quartzite (Figs. 6.4 and 6.5). The hanging wall rocks consist of Svecofennian Haparanda suite monzonite and diorite, with the latter reinterpreted as strongly altered metabasalts/mafic metavolcanic rocks in this study, while the footwall rocks comprise supracrustal rocks, mainly mafic metavolcanic rocks (amphibolites). In association with the amphibolite units, there are thin beds of quartz-feldspar schists, which are commonly pyrrhotite-bearing and contain variable amounts of graphite. A sequence of mica schists or gneisses occurs in the eastern parts of the deposit beneath the amphibolite unit, both of which in turn overlie Sodankylä group quartzites. Quartzites form the lowermost drilled unit in the local stratigraphy. Pegmatite, aplite, and granite dikes with varying thicknesses commonly crosscut the whole sequence.

ALTERATION

In general, all rocks in the Hannukainen deposit, excluding the youngest granites, are intensively altered. Alteration has formed a deposit-scale zoned pattern where three different alteration zones can be distinguished around the ore bodies in both the hanging wall and footwall rocks. The alteration assemblages vary somewhat depending on the primary rock type, but the general pattern is that albite ± scapolite is the dominant alteration assemblage in distal zones; biotite and K-feldspar dominate the intermediate zones; and the proximal alteration zone, which encompasses the magnetite bodies, is characterized by clinopyroxene, with varying amounts of magnetite, amphibole, and calcite. Most of the sulfides occur in the proximal alteration zones, but both iron and copper sulfides can be locally present in all altered lithologies regardless of the alteration assemblage.

The main minerals in skarn rocks are clinopyroxene and hornblende. Also biotite, albite, scapolite, garnet, calcite, actinolite-tremolite, and serpentine occur in minor amounts. The main oxide mineral is magnetite, which usually occurs as disseminated grains and bands, but also massive and semimassive zones are present (see Fig. 6.9 later).

The zoned alteration pattern may repeat itself at different scales throughout the sequence. Some zones, particularly the intermediate one, may be poorly developed or even missing. Similarly, the proper magnetite skarn core is locally missing or it is very thin and pinches out. Niiranen et al. (2007) reported that the typical proximal alteration type in the Hannukainen deposit is calc-silicate dominated (Ca-clinopyroxene, actinolite, or hornblende, magnetite ± scapolite, calcite, biotite, and albite). The intermediate alteration involves biotite, K-feldspar ± albite, and scapolite, whereas the distal alteration is formed by albite ± scapolite. Figure 6.6 shows schematically typical mineral parageneses in the Laurinoja ore body.

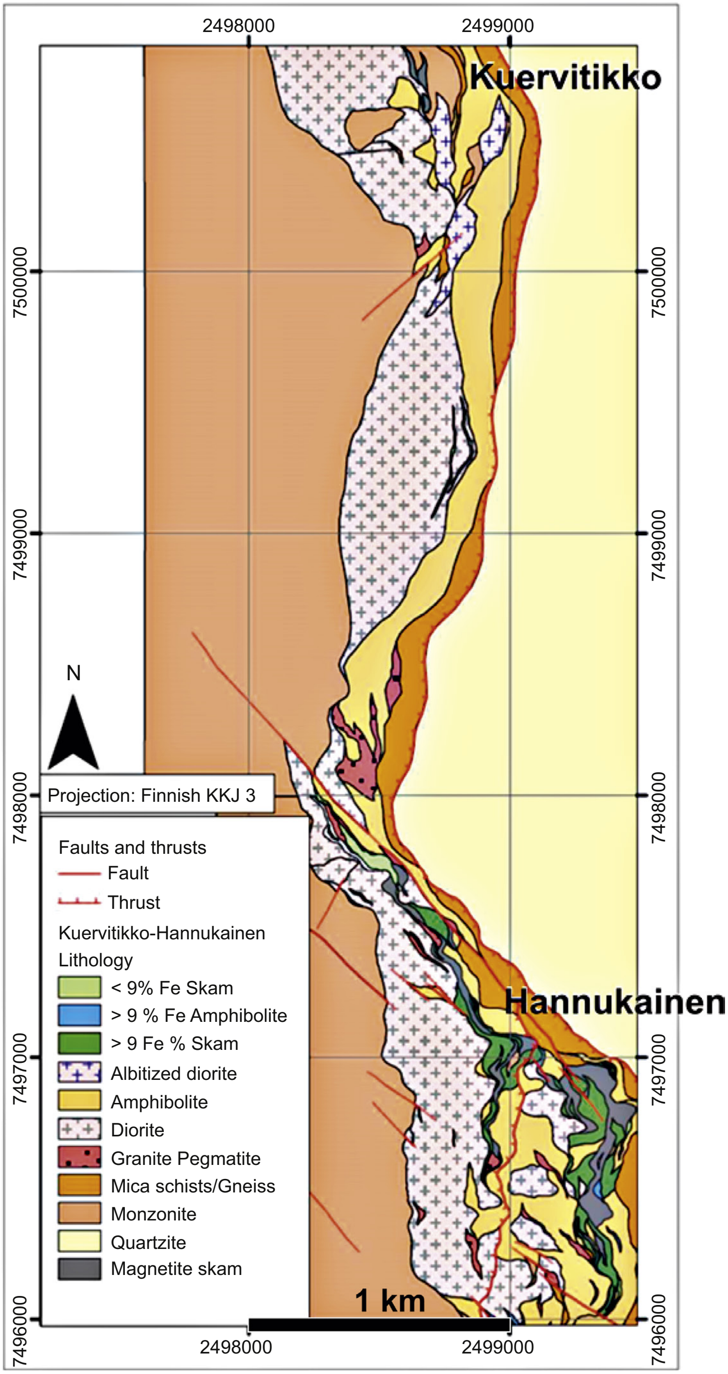

FIGURE 6.2 Surface geological map of the Hannukainen and Kuervitikko deposits.

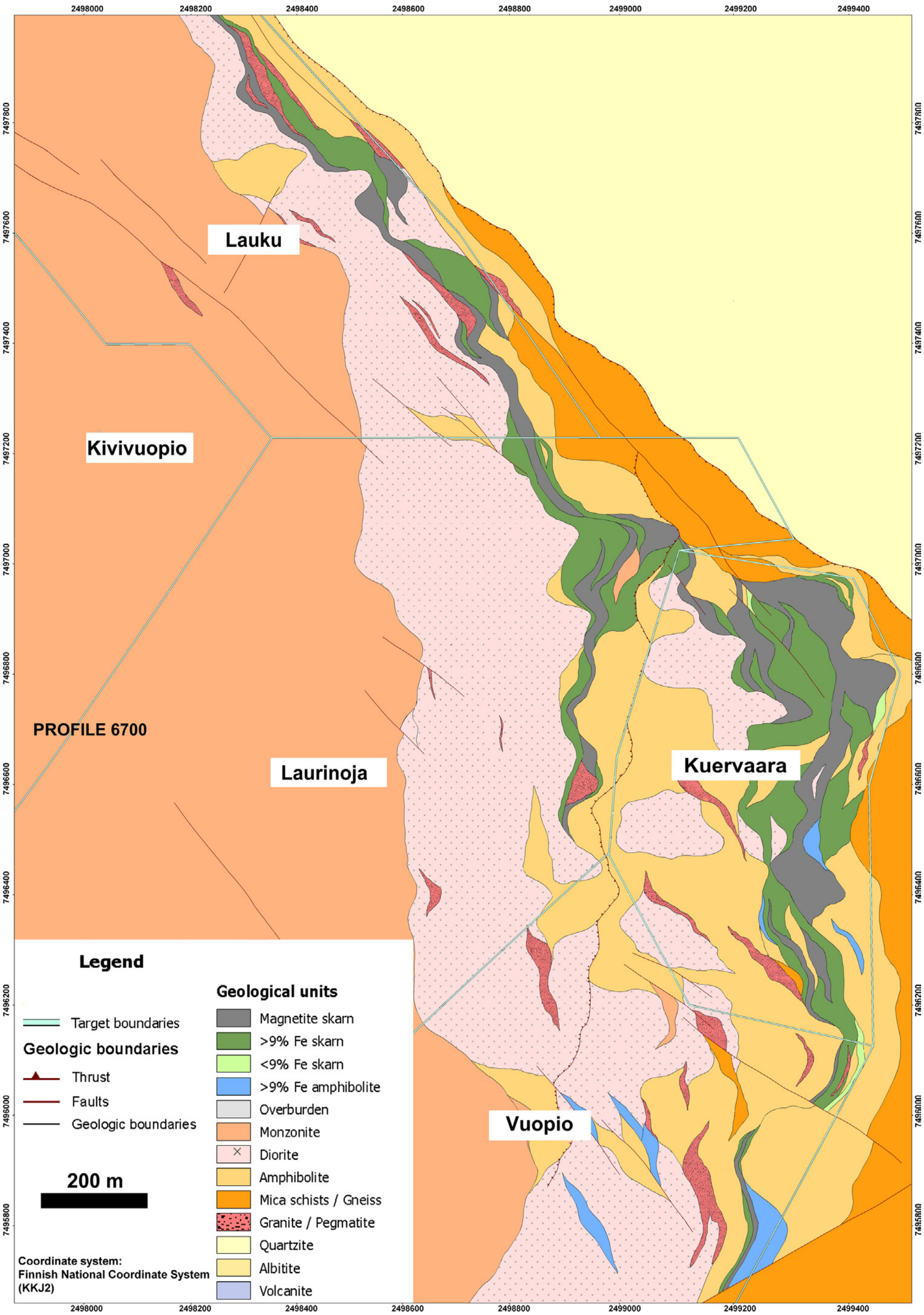

FIGURE 6.3 Surface geological map of the Hannukainen deposit.

Note that the “diorites” are not diorites sensu stricto, but have in this contribution been reinterpreted as strongly altered metabasalts/mafic metavolcanic rocks (see the following).

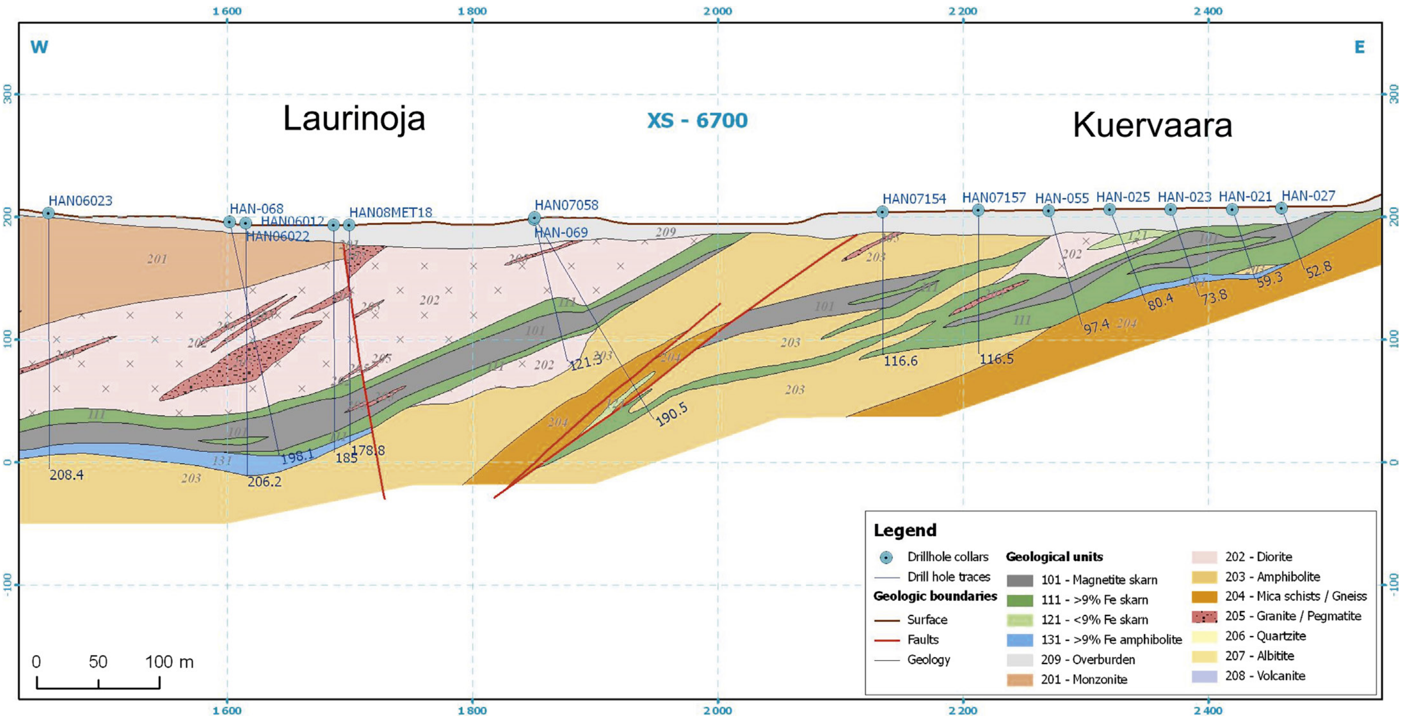

FIGURE 6.4 East–west cross section across the Hannukainen deposit

Source: *Profile 6700, northing: 7496700.*

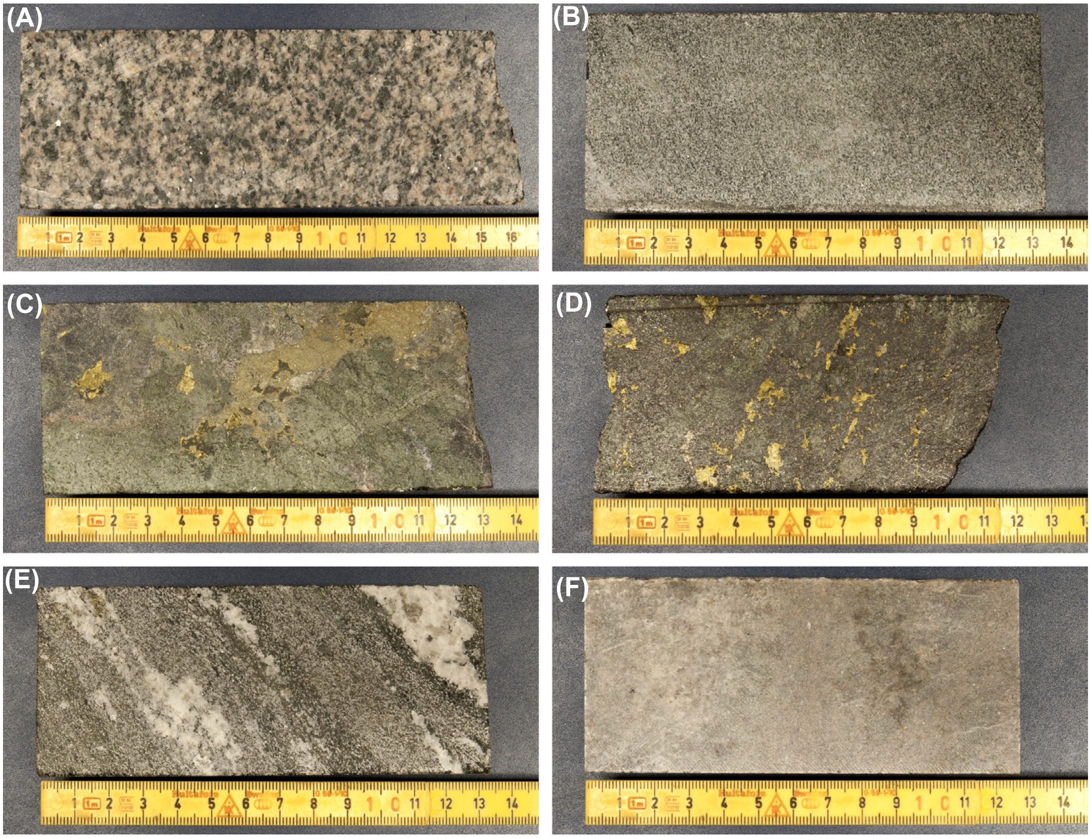

FIGURE 6.5 Photographs of major rock types from the Hannukainen deposit

(A) hanging wall monzonite, (B) hanging wall "diorite" (strongly altered metabasalts/mafic metavolcanic rock), (C) clinopyroxene skarn, (D) magnetite skarn with disseminated sulfides (chalcopyrite, pyrite, pyrrhotite), (E) footwall amphibolite, and (F) footwall quartzite.

The major rock types in the Hannukainen and Kuervitikko deposits are similar and share a common stratigraphy. The alteration assemblage in the Kuervitikko deposit defines a similar zoning as described for Hannukainen earlier. The most significant differences are that at Kuervitikko, K-feldspar and biotite are less common in the hanging wall distal alteration zone, and there is an albitite (± quartz) unit between the diorite and clinopyroxene-amphibole skarn zone. In addition, amphibole is slightly more abundant as a proximal alteration mineral than at Hannukainen. Sulfides also appear to be more abundant in the distal alteration zones, especially in the albitite.

MINERALIZATION

The Fe-(Cu-Au)-mineralized lenses are hosted by skarn rocks (calc-silicate rocks), which were formed through metasomatic replacement reactions at the lithological contact and structural shear zone between the hanging wall monzonite in the west and footwall mafic metavolcanic rocks/basalts (amphibolites) in the

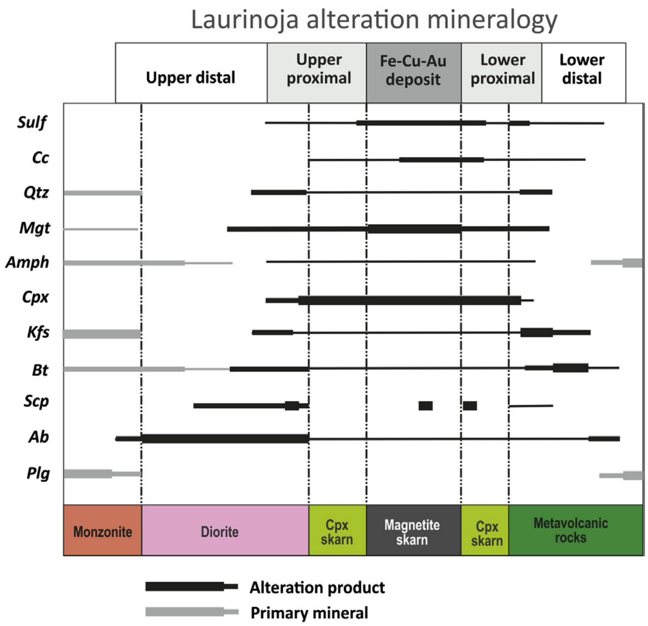

FIGURE 6.6 Schematic paragenetic diagram for minerals and alteration zones in the Laurinoja ore body, Hannukainen deposit.

Abbreviations: Sulf = sulfides, Cc = calcite, Qtz = quartz, Mgt = magnetite, Amph = amphibole, Cpx = clinopyroxene, Kfs = K-feldspar, Bt = biotite, Scp = scapolite, Ab = albite, Plg = plagioclase.

Source: *Modified after Niiranen (2007).*

Table 6.1 Physical dimensions of the mineralized ore bodies/lenses of the Hannukainen deposit and Kuervitikko satellite deposit

Mineralized lens/body	Length (m)	Down-dip width (m)	Maximum thickness (m)	Average thickness (m)
Kuervaara/Vuopio	1900	800	50	10–30
Laurinoja/Lauku/Kivi-vuopio	2100	2000	50	10–30
Kuervitikko	1200	500	50	10–20

east. Typical host rocks for the mineralization are magnetite and clinopyroxene skarns. Skarn units are well defined, with a high-grade magnetite skarn zone in the middle. The high-grade core is surrounded by a lower-grade iron mineralization, usually related to clinopyroxene skarn rocks. The average thickness of the mineralized bodies varies between 10 and 30 m, with the maximum thickness reaching approximately 50 m.

Table 6.1 summarizes the physical dimensions of the mineralized ore bodies at Hannukainen. Figure 6.7 is a 3D illustration of the Hannukainen and Kuervitikko ore bodies together with high resolution reflection seismics for ore exploration (HIRE)-line E1. Figure 6.7 implies that seismic reflectors coincide very well with the known Hannukainen Fe-Cu-Au ore lenses. This suggests that the strong

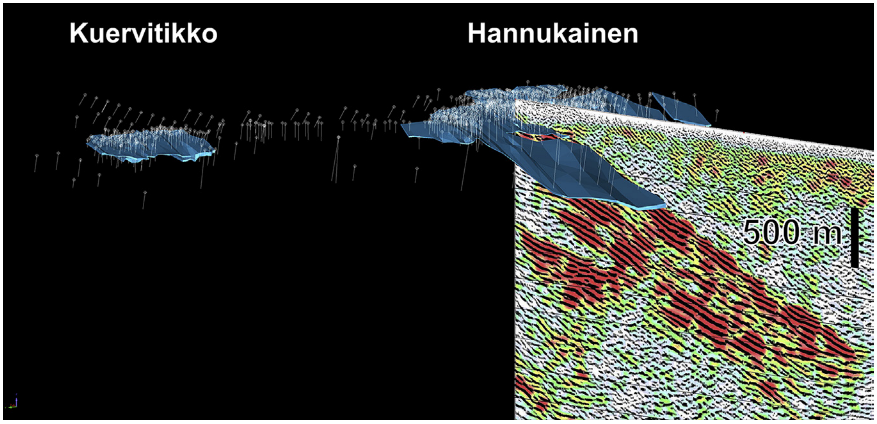

FIGURE 6.7 3D models of the Hannukainen and Kuervitikko ore bodies, diamond drill holes, and reflection seismic HIRE-line E1.

A deep ore body coincides with the top of the seismic reflector, implying that the mineralization may extend much deeper than indicated by the present drilling results. Image looking toward north-northeast.

reflectivity is due to the strong velocity contrast between monzonite and the skarn- and amphibole-dominated lithological assemblages. These seismic reflectors also correlate well with magnetic and electrically conductive layers (Kukkonen et al., 2009). Distribution of iron, copper, and gold as ore grade bodies at Hannukainen is shown in Fig. 6.8. The most recently published mineral reserves of the Hannukainen deposit are shown in Table 6.2 (SRK, 2014).

The ore mineralogy in the Hannukainen deposit is relatively simple. Magnetite is the only observed oxide mineral. Hematite has not been observed. Magnetite usually occurs as a dissemination, veins, and semimassive to massive. It is coarse grained with the grain size exceeding 0.3 mm. In sulfide-bearing zones, the dominant sulfide minerals are pyrite, pyrrhotite, and chalcopyrite. Chalcopyrite is the only significant copper mineral. The grain size of chalcopyrite is usually small but also some coarse grains and grain aggregates occur (diameter 0.02–0.03 mm). A minor amount of molybdenite occurs in association with chalcopyrite. Sulfides usually occur as a dissemination, veins, and fracture fillings (Fig. 6.9). They appear to be texturally later than magnetite, because sulfides occur as veins and veinlets around and crosscutting magnetite, and sulfide inclusions are not common in magnetite. Native gold has been detected in the silicate gangue, chalcopyrite, and magnetite. However, 95% of gold occurs as solid solution in sulfides. The copper-gold mineralization is usually hosted by magnetite skarn rocks, or, to a lesser extent, by surrounding clinopyroxene skarn rocks.

GEOCHEMISTRY AND AGE DETERMINATIONS

Average chemical compositions of major rock types in the Hannukainen deposit are listed in Table 6.3. Box-and-whisker percentile diagrams and their chondrite-normalized REE patterns are shown in Figs. 6.10 and 6.11, respectively. The monzonite intrusions that occur west of Hannukainen are metaluminous, low in Nb and Y, and have a calc-alkaline affinity (Niiranen et al., 2007). Their chondrite-normalized REE

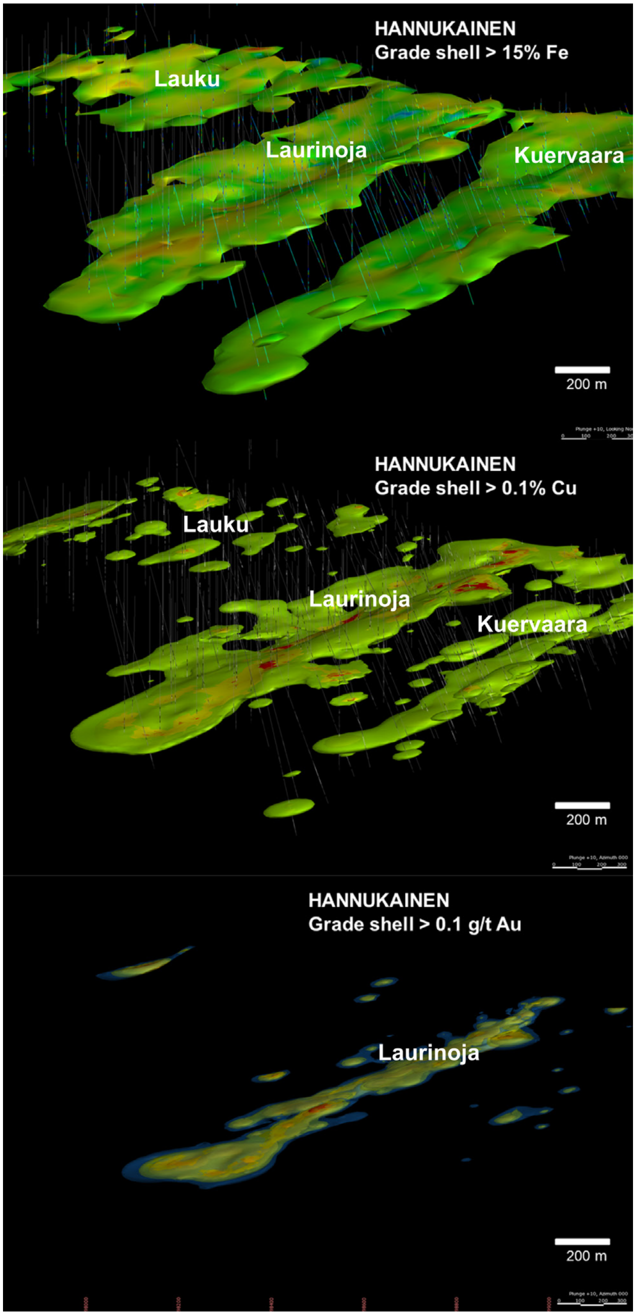

FIGURE 6.8 3D image showing the Hannukainen ore-grade lenses for iron (Fe >15 wt%), copper (>0.1 wt%), and gold (Au >0.1 g/t).

Pictures viewing toward the north. Note the prominent concentration of Cu and Au within the Laurinoja ore body. Au, in particular, is distributed along a linear feature parallel to the regional plunge direction.

Table 6.2 Open pit mineral reserves of the Hannukainen deposit

Category	Tonnes (Mt)	Fe (%)	Cu (%)	Au (ppm)
Hannukainen				
Proven	91.8	32.2	0.186	0.088
Probable	0.8	32.6	0.148	0.060
Kuervitikko				
Proven	21.9	23.6	0.183	0.216
Probable	0.3	23.8	0.177	0.194
Total				
Proven	113.7	30.5	0.185	0.112
Probable	1.1	30.0	0.157	0.100
Total	114.8	30.5	0.185	0.112

Source: *SRK, 2014*.

pattern (Fig. 6.11) shows enrichment in LREE and a weak negative Eu anomaly. The REE pattern of diorite is similar to that of monzonite with the exception that diorite has a slightly positive Eu anomaly and lower general REE abundances. Different kinds of skarn rocks in the Hannukainen deposit are the most altered rocks. Niiranen et al. (2007) showed that Ti/Al, Zr/Al, and Zr/Ti in the clinopyroxene skarn and magnetite skarn are similar, which suggests a common protolith for these rock types. Some variation in the immobile element ratios could indicate that the protoliths of these skarn rocks were locally heterogeneous and could have consisted of several different rock types. The only main difference between the clinopyroxene and magnetite skarns is that the latter contain more iron than the former.

Niiranen et al. (2007) classified mafic volcanic rocks of the Hannukainen area into two chemical groups. Based on the different Zr/Ti ratios, they distinguished type 1 (lower Zr/Ti) and type 2 (higher Zr/Ti). Type 1 mafic volcanic rocks have Zr/Ti ratios typical for basalts, whereas type 2 mafic rocks have Zr-Ti ratios that are between basalts and andesites. Mafic volcanic rocks in the distal alteration zones are rich in Na ± K, Cl, and Ba, whereas proximally altered mafic volcanic rocks are enriched in Ca ± Fe, S, Ag, Au, Bi, C, Ce, Co, Cu, La, and Te (Niiranen et al., 2007).

Magmatic zircon grains from the hanging wall monzonite and mafic volcanic rocks of the Hannukainen deposit have given U-Pb ages of 1862 ± 3 and 1864 ± 6 Ma, respectively (Hiltunen 1982; Niiranen et al., 2007). A granite dike, which brecciates and crosscuts the ore zone, has yielded a U-Pb zircon age of 1760 ± 3 Ma (Niiranen et al., 2007). These dates thus bracket the age of the alteration/mineralization event. Zircon within a skarn rock (calc-silicate rock) has been dated at 1797 ± 5 Ma, while titanites in altered wall rocks and skarns range in age between 1810 and 1870 Ma. These minerals could be original magmatic minerals or they can be hydrothermal minerals (Hiltunen, 1982; Niiranen, 2005; Niiranen et al., 2007). The dating results imply that the ore formation at Hannukainen is not directly related to the emplacement of the ~1860 Ma Haparanda suite monzonites, but probably took place close to ~1800 Ma. Zircon grains in skarn rocks may give a true age for the associated thermal event, whereas titanite ages provide a series of cooling ages ranging from the protolith age of ~1870 Ma to that of the mineralization event at ~1800 Ma (Väänänen, 1998; Väänänen and Lehtonen, 2001; Hannu Huhma, personal communication 2014).

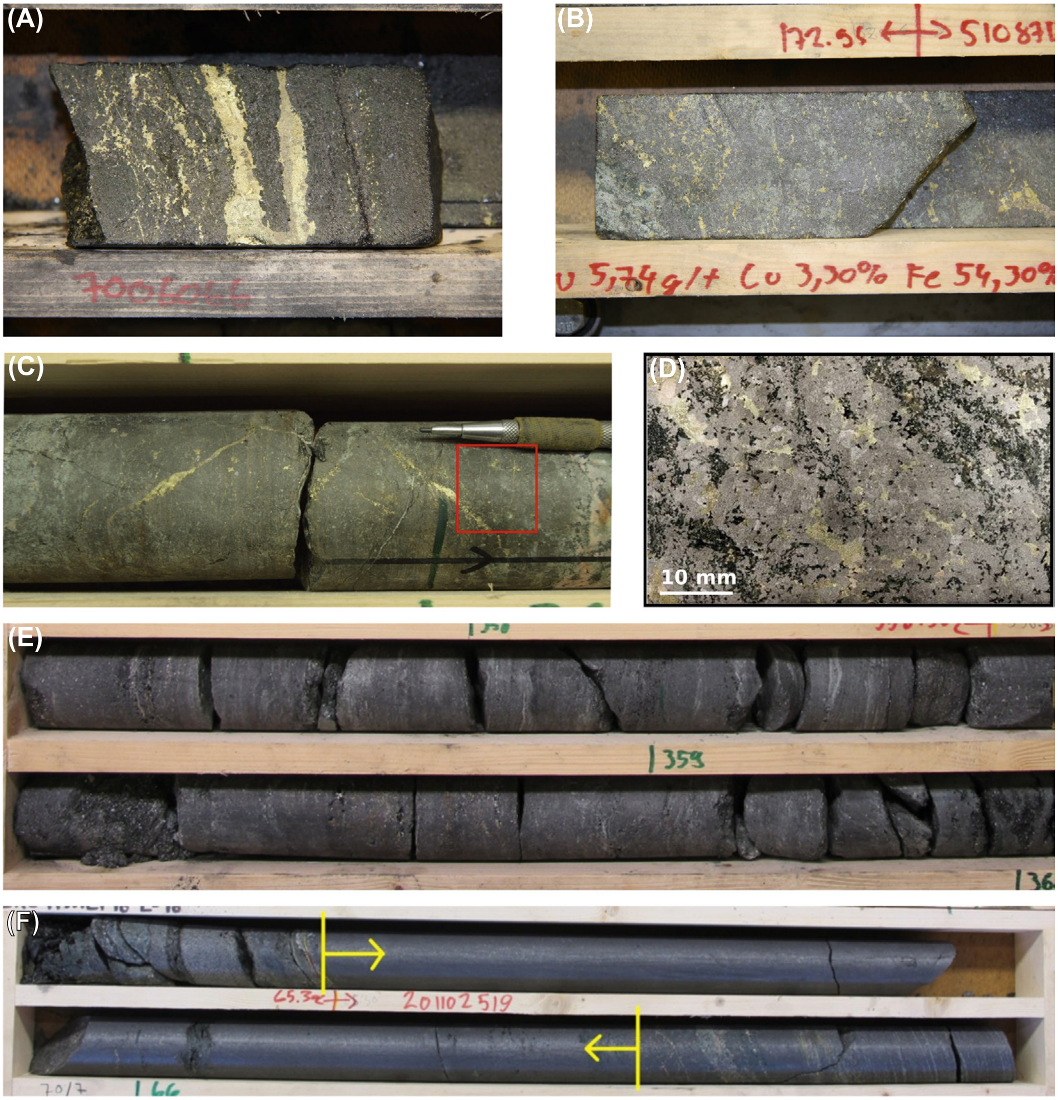

FIGURE 6.9 Different styles of oxide and sulfide occurrences in the Hannukainen deposit.

(A) Sulfide (pyrrhotite and chalcopyrite) veins and dissemination in magnetite skarn; (B) chalcopyrite dissemination in magnetite skarn; (C) chalcopyrite veins, fracture filling; (D) close-up of disseminated magnetite and sulfides; (E) banded-textured magnetite skarn; (F) semimassive and massive (inside yellow arrows) magnetite skarn.

FLUID INCLUSIONS, AND O AND C ISOTOPES

Niiranen et al. (2007) identified three main types of fluid inclusions by using a combination of textural, phase proportional, and microthermic observations. Type 1 are formed by complex aqueous or aqueous-carbonic liquid-vapor-multisolid inclusions and are subdivided into type 1A and type 1B based on their occurrence and solid contents. Type 1A occur as solitary inclusions or clusters in quartz that are

Table 6.3 Average chemical composition of major rock types in the Hannukainen deposit

	Monzonite	Diorite	Amphibolite	Skarn	Magnetite skarn
Major elements (wt.%)					
SiO_2	61.87	55.33	50.68	31.00	24.00
TiO_2	0.62	0.42	0.66	0.24	0.18
Al_2O_3	15.24	16.59	13.43	4.54	4.28
Fe_2O_3	6.31	11.11	14.01	45.53	58.64
MnO	0.06	0.07	0.12	0.26	0.33
MgO	2.06	2.15	4.67	4.98	4.62
CaO	3.48	4.96	7.16	9.88	4.67
Na_2O	5.60	5.85	4.30	1.51	1.32
K_2O	3.14	1.88	1.71	0.47	0.78
P_2O_5	0.22	0.21	0.21	0.13	0.15
Trace elements (ppm)					
Cr	74	68	141	85	31
Ni	24	36	69	82	81
Co	19	48	63	149	160
Cu	97	607	572	1913	1601
V	100	70	166	100	88
Pb	32	55	51	49	34
Zn	46	40	56	85	90
Nb	13	3.9	4.3	3.8	3.8
Zr	321	86	97	64	51
Y	20	12	17	9.0	6.1
Sr	486	348	228	104	60
Rb	111	68	71	37	61
Sc	13	11	17	9.8	10
La	39	21	27	35	33
Ce	88	53	54	64	60
Ba	706	778	348	84	107
Ga	23	18	18	17	22

associated with sulfides. Type 1B inclusions occur as networks of discontinuous inclusion trails in quartz and calcite that are associated with sulfides and also together with type 2 inclusions. Type 2 inclusions are aqueous ± carbonic liquid-vapor inclusions occurring as trails in quartz and calcite, and are associated with sulfides. Type 3 represent single phase, liquid CO_2-rich inclusions that occur in quartz as trails and around sulfides. They also occur together with type 1B inclusions. The fluid inclusion data from Niiranen et al. (2007) suggest that ore deposition took place in two distinct stages in the Laurinoja ore body.

The compositions of the first-stage fluids corresponded to moderately saline Na-Ca ± K, Fe-bearing H_2O fluids (12–22 wt% NaCl equivalent). The second stage fluids were highly saline (32–56 wt% NaCl equivalent), Na-Ca ± K-bearing H_2O-CO_2-fluids (32–56 wt% NaCl equivalent). Estimated

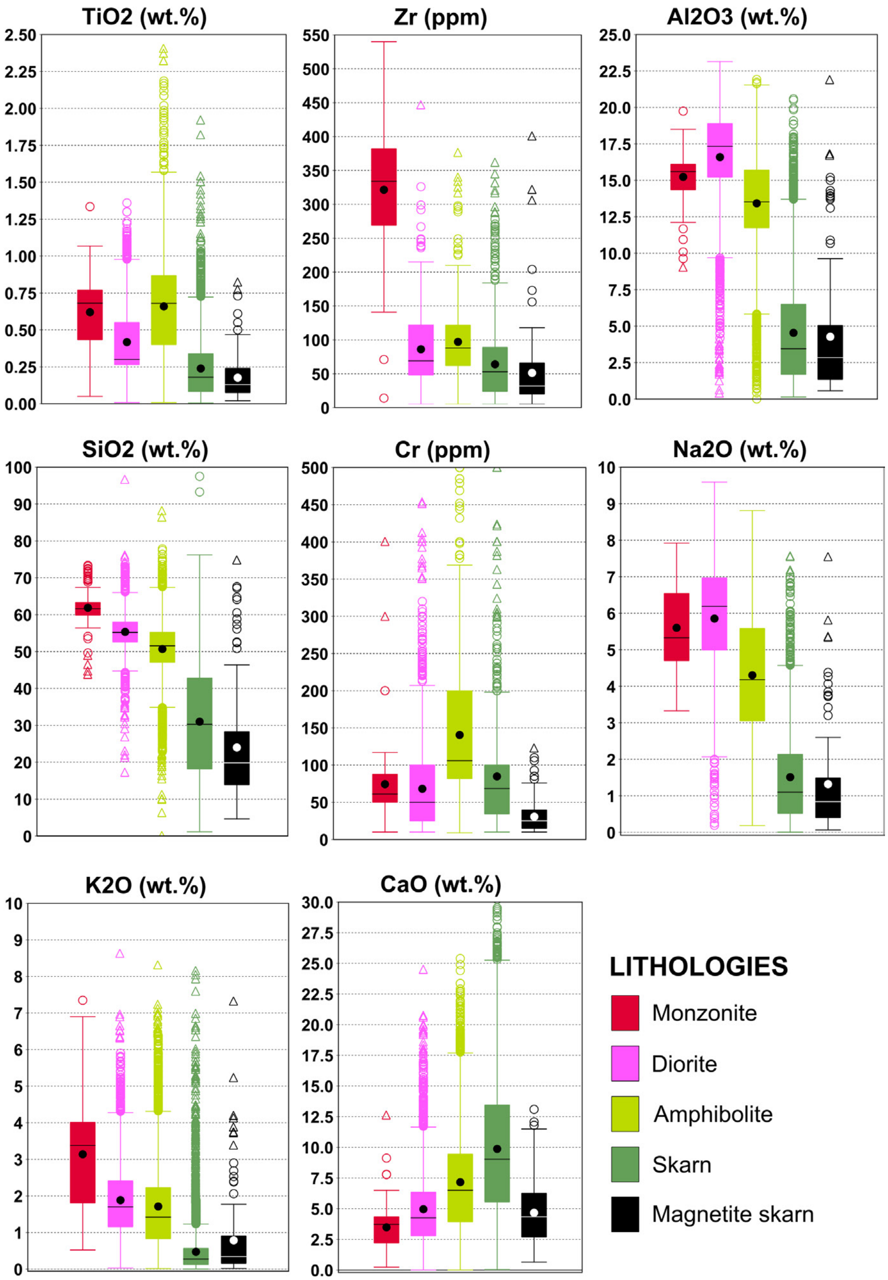

FIGURE 6.10 Box-and-whisker percentile diagrams of major elements and major rock types from the Hannukainen deposit.

The median is defined by a horizontal line within a box. The mean is represented as a black/white circle within a box. Sample points off the whiskers area are assumed to be outliers.

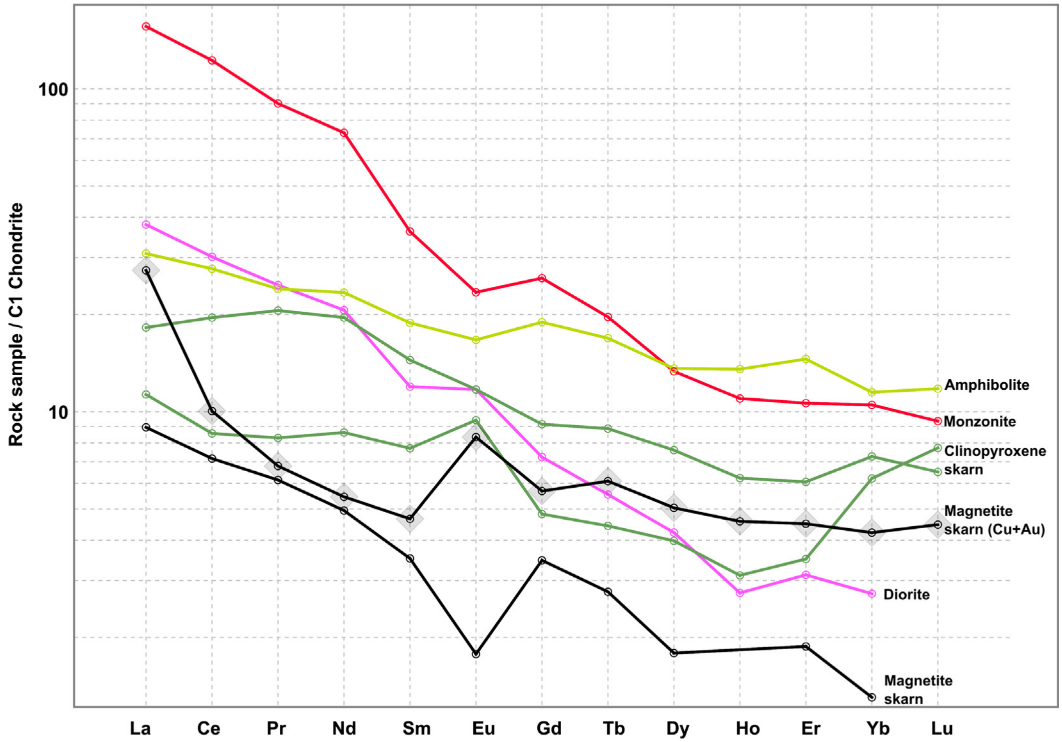

FIGURE 6.11 Examples of chondrite-normalized REE element patterns of major rock types at Hannukainen.

Red = monzonite, purple = diorite (albitized), light green = amphibolite/mafic volcanic rock (weakly albitized), green = clinopyroxene skarn (upper proximal alteration zone), black = magnetite skarn, and black with light gray squares = magnetite skarn (Cu-Au-bearing).

Source: *Normalizing values from McDonough and Sun (1995). Data from Niiranen et al. (2007).*

temperatures were in the range of 450–500 °C in the first stage and 290–370 °C in the second stage, and the pressure during both stages was between 1.5 and 3.5 kbar. Niiranen et al. (2007) and Niiranen (2005) also reported oxygen isotope compositions for oxides, silicates, and carbonates from the Laurinoja ore body. These suggest that the $\delta_{18}O$ values of the fluid phase at 500 °C are between +7.7 and +12.7 ‰ and the $\delta^{13}C$ values of the carbonates range between −3.4 and −6.9 ‰. This implies that fluids in the mineralization events were moderately to highly saline, aqueous-carbonic in composition, and that temperatures were between 290 and 500 °C, with pressure in the range of 1.5–3.5 kbar.

PROTOLITHS OF THE ORE-BEARING ROCKS

The wall rocks and host rocks of the Hannukainen Fe-Cu-Au deposit are highly altered, and hence we need to rely on immobile elements in identifying the protolith types. According to Niiranen et al. (2007), mass balance calculations indicate that Zr, Al_2O_3, and TiO_2 were immobile during the alteration event in the Hannukainen deposit. Figure 6.12 presents abundances of TiO_2 and Zr for major lithologies

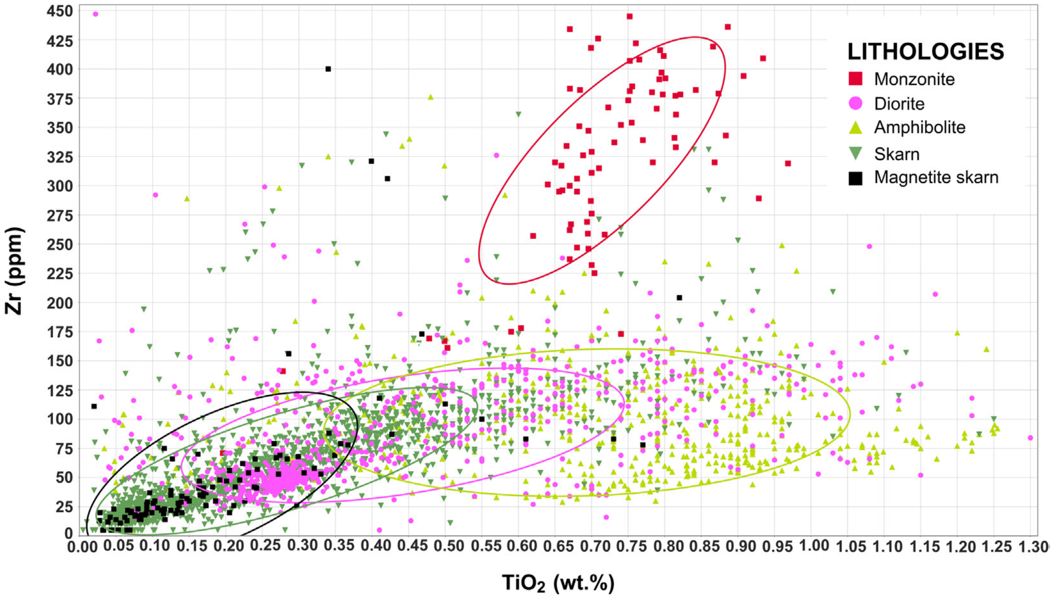

FIGURE 6.12 TiO_2 (wt.%) versus Zr (ppm) diagram for the main lithologies at Hannukainen.

of the Hannukainen deposit. It shows that magnetite skarn, skarn, diorite (strongly altered mafic metavolcanic rock), and amphibolite samples all plot along the same trend and are overlapping each other. This may indicate that these lithologies had similar protoliths (mafic volcanic rocks). On the other hand, monzonite samples plot above all other rock types and form their own distinct group. Niiranen et al. (2007) showed that there are several different protoliths for skarn rocks in the Rautuvaara-Hannukainen area. Immobile trace element ratios suggest that the dominant protolith was mafic volcanic rock. Most likely, some intercalated carbonate rocks were also present in the supracrustal sequence. They no longer exist at Hannukainen due to completion of skarn-forming decarbonation reactions, but their former presence is indicated by dolomites in other similar deposits in the region, such as Kuervitikko, Cu-Rautuvaara, Mannakorpi, and Tapuli.

Based on mass balance calculations, Kokko (2013) showed that at the Cu-Rautuvaara deposit, a similar Fe-Cu-Au deposit occurring 8 km south-southwest of the Hannukainen deposit, the protoliths for the ore-bearing skarns were also metavolcanic rocks. Ullgren (2013) came to the same conclusion for another deposit, the nearby Rautuoja Fe-Cu-Au deposit. According to Ullgren (2013), immobile element ratios in the Rautuoja deposit indicate that diorites have similar immobile element characteristics to those of the Hannukainen metavolcanic rocks. This implies a common origin for diorites and metavolcanic rocks in the Rautuoja deposit. Field evidence and chemical composition of the rocks suggest that the main protoliths for the ore-bearing skarn rocks in these deposits are metavolcanic rocks/amphibolites. Diorites in the hanging wall of the Hannukainen deposit (map shown in Fig. 6.3) are accordingly interpreted to be volcanic in origin and represent metabasalts/amphibolites altered into "diorites." Logically, along the strike of the shear zone, the diorite unit attains its maximum thickness at Hannukainen, where the strongest hydrothermal cells were located.

SUMMARY

Historically, the Fe ± Cu ± Au deposits in the Kolari-Pajala region have been classified as stratabound Ca-Mg-silicate and Mg-silicate skarn-hosted deposits that were formed by contact metasomatic events related to the intrusion of monzonites and diorites (Hiltunen, 1982), or as metamorphosed banded iron formations (e.g., Frietsch et al., 1995; Väänänen, 1998). However, as pointed out by Niiranen et al. (2007), the Hannukainen mineralization is younger than the Haparanda suite monzonite intrusions that form the hanging wall to the mineralized shear zones, and, as such, is indisputably epigenetic relative to the supracrustal sequence and plutonic rocks. The deposits comprise several bands or lenses of magnetite skarn, concordant with the surrounding skarn and sedimentary host rocks with associated Cu and Au mineralization.

The polymetallic Hannukainen Fe-(Cu-Au) deposit displays several features typical of iron oxide-copper-gold (IOCG) deposits:

- It is a magmatic-hydrothermal deposit that contains economic Cu + Au grades. The copper- and gold-rich part of the Laurinoja ore body at Hannukainen contains an average grade of 0.50 wt% Cu and 0.39 ppm Au (based on the estimation of the Laurinoja high-grade Cu ore body, above a 0.25 wt% Cu cutoff; SRK, 2014).
- The brecciated textures commonly observed in the mineralized zones indicate that magnetite is epigenetic in origin.
- Metal association Fe-Cu-Au ± Ag, Bi, Ba, Co, Mo, Sb, Se, Te, Th, U, and LREE is typical of IOCG deposits.
- Alteration styles in structurally controlled deposits define a zoning where the distal zones are characterized by sodic-potassic (Na ± Cl and K-rich) assemblages, proximal zones by calcic-iron (Ca-Fe ± CO_2-rich) assemblages, and the core, which is probably related to a structural base, is rich in magnetite (e.g., Hannukainen). In the deposits where the zoning is well developed, the Cu-Au mineralization is located within the magnetite-rich core (e.g., the Cu-Au-rich Laurinoja ore body at Hannukainen), whereas in the deposits lacking clear zoning, the Cu-Au mineralization is located in the magnetite-disseminated albitite (such as the Kuervitikko satellite deposit).
- The spatial correlation to the shear zone implies that the mineralization is structurally controlled and contains brecciated rocks.
- The deposit shows a clear temporal, but often not close spatial relationship to major magmatic intrusions.
- Although syngenetic iron formations are known in the Karelian sequence further west of the Pajala area, none are known to be present in the Kolari-Pajala district.
- Available isotopic data from the mineralization at Hannukainen suggest that the mineralization formed relatively "late," being thus consistent with an epigenetic rather than syngenetic origin.
- In the surrounding area, the Tapuli, Sahavaara, and Pellivuoma deposits are devoid of any significant Cu or Au mineralization. Nevertheless, they display some other features of an IOCG-type system. One typical feature in the known IOCG belts (for example, Cloncurry in Australia) is that numerous epigenetic magnetite and/or hematite deposits occur together with Fe-Cu-Au deposits.
- The deposit was formed from highly oxidized, saline aqueous-carbonic fluids that circulated in the system during the main alteration and mineralization event and during the subsequent brittle stage.

We interpret that Hannukainen belongs to the broad class of IOCG deposits and that most of the metals are wallrock-derived. Most likely, the Fe-Cu and Fe-Au ratios in the Hannukainen ore bodies are controlled by the wallrock background Cu and Au contents.

At Hannukainen, magnetite is stable in the skarn rocks and associated with a feldspar-actinolite-scapolite-epidote-sulfide assemblage. This assemblage is unrelated to the hematite-stable albitization. This texture-destructive albitization affects a variety of foliated and nonfoliated magmatic rocks of monzonite to diorite composition, and therefore postdates most of the magmatic activity and ductile shearing. Albite alteration is cut by the magnetite-actinolite-scapolite suite, yielding albite-actinolite rocks in the transitional zones.

The IOCG model calls for inflow of regional fluids with albitization seen as a prograde leaching alteration. During mixing with a more reduced fluid or when reacting with reduced rock, these fluids become magnetite-saturated and precipitated skarn assemblage minerals; residual dissolved metals (Cu, Au, and Na) were deposited on retrograde cooling.

For the purpose of a simple mass-balance calculation, we assume that the albitization cell around Hannukainen is approximately 3 km × 200 m × 500 m in size, corresponding to 750 Mt of rock (SG = 2.5). Because an average prealbitization Savukoski group volcanic rock contains 15.91 wt% Fe_2O_3 (Lehtonen et al., 1998), the alteration process could yield 80 Mt of dissolved Fe in hydrothermal fluids, or ~257 Mt Hannukainen-type magnetite ore (containing 31.07 wt% Fe). As the Hannukainen deposit is open at depth and has global resources of ~250 Mt at shallow levels, this mass balance seems plausible. If an average Savukoski metavolcanic rock contains 206 ppm Cu (Lehtonen et al., 1998), the same calculation would result in 155,000 t of copper metal as a total resource.

Again, this is approximately in line with the order of magnitude of Cu contained at Hannukainen (370,000 t Cu). Because there is more copper in the Hannukainen deposit than what the mass balance calculation gave, it is possible that additional copper and gold have been derived from more distal sources. The interpretation outlined here suggests that the Haparanda suite is not involved in mineralization, as also argued by Niiranen et al. (2007). Instead, the IOCG interpretation demands that the altered metasedimentary suite (Savukoski group) was once evaporite-bearing (Barton and Johnson, 1996), and perhaps was originally deposited in a rift zone located along the present Kolari-Pajala shear zone (Bothnian megashear).

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