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Wanhainen, C. and Martinsson, O., 2010 - The Hybrid Character of the Aitik Deposit, Norrbotten, Sweden: A Porphyry Cu-Au-Ag(-Mo) System Overprinted by Iron-Oxide Cu-Au Hydrothermal Fluids; *in* Porter, T.M. (ed.), Hydrothermal Iron Oxide Copper-Gold and Related Deposits: A Global Perspective, v. 4 - Advances in the Understanding of IOCG Deposits; *PGC Publishing, Adelaide*, pp. 415-426.

THE HYBRID CHARACTER OF THE AITIK DEPOSIT, NORRBOTTEN, SWEDEN: A PORPHYRY Cu-Au-Ag(-Mo) SYSTEM OVERPRINTED BY IRON-OXIDE Cu-Au HYDROTHERMAL FLUIDS

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Abstract - The Aitik copper-gold-silver(-molybdenum) mine in northern Sweden is the biggest open pit operation in northern Europe, and one of Europe's largest metal producers. The open pit is 3 km long, 1 km wide and 420 m deep. Approximately 500 Mt of ore averaging 0.4% Cu, 0.2 g/t Au and 4 g/t Ag has been produced, with the metal production in year 2008 being 47 225 t of copper, 1.218 t of gold, and 32.087 t of silver.

The Palaeoproterozoic Aitik porphyry deposit and its host rocks, are situated approximately 200 km north of the Archaean-Proterozoic palaeoboundary in the Fennoscandian shield. They are considered to have formed in a volcanic arc environment related to subduction of oceanic crust beneath the Archaean craton at c. 1.9 Ga. A quartz monzodioritic intrusion, related to the formation of porphyry copper mineralisation, is situated in the footwall of the deposit. High salinity fluids (30 to 38 $_{equiv.}$ wt.% NaCl + $CaCl_2$) responsible for chalcopyrite-pyrite mineralisation was released contemporaneously with quartz monzodiorite emplacement and quartz stockwork formation at c. 1.89 Ga, and caused potassic alteration of the intrusive and surrounding volcaniclastic rocks. Remnants of this primary porphyry copper mineralisation are best preserved in the footwall intrusion, in intrusive units within the volcaniclastic rocks of the ore zone, and in quartz stockworks at the margins of the quartz monzodiorite. An overprinting mineralisation and alteration event of iron-oxide copper-gold character occurred about 100 m.y. later, when eastward subduction resulted in compression, monzonitic-granitic magmatism, ductile deformation, and block movements in northern Norrbotten. Extensive deformation of rocks and redistribution of metals occurred. Magnetite enrichment, locally found within late veins of mainly amphibole, K feldspar, tourmaline, garnet, quartz and epidote, together with late scapolite alteration within the deposit, implies that fluids responsible for iron-oxide copper-gold mineralisation and extensive sodic-calcic alteration in the region during this tectonic event also affected the Aitik deposit, and probably involved addition of copper and gold. This late mineralising fluid was highly saline (30 to >60 $_{equiv.}$ wt.% NaCl + $CaCl_2$) and contained solids of ferropyrosmalite and hematite.

Studies of the Aitik deposit reveal a multiphase origin of the ore, with multiple sources of the ore fluids and peaks of mineralisation around 1.9 and 1.8 Ga.

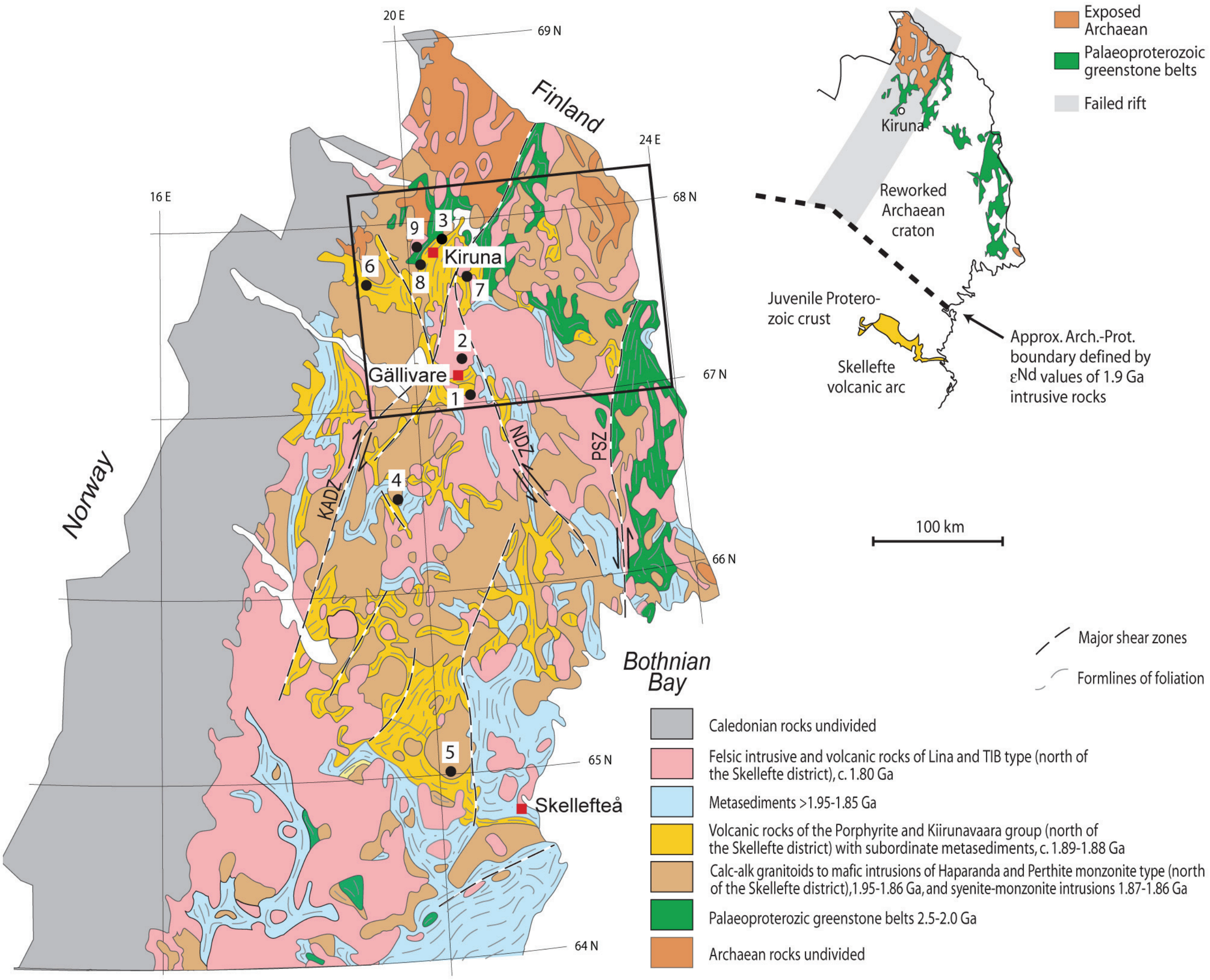
Introduction

The Aitik copper-gold-silver(-molybdenum) deposit is located about 60 km north of the Arctic Circle, at latitude 67˚07´N in northernmost Scandinavia (Fig. 1). The town of Gällivare, a historic Lappish trading centre which rose to prominence after the discovery of iron ore at Malmberget and the completion of the railway from the Baltic coast in 1888, is located 15 km northwest of Aitik (Fig. 1). A 5 to 15 m thick layer of glacial moraine covers the bedrock in this area, giving rise to a topography characterised by swamps and intervening moraine ridges. Outcrops are very scarce (Malmqvist and Parasnis, 1972).

The first boulders containing disseminated chalcopyrite were found in the Aitik area by the Boliden company in 1930 (Zweifel, 1976). Two years later, a mineralised outcrop was discovered during an electromagnetic survey, and continuation of the survey during 1933, in combination with diamond drilling, indicated zones of low-grade mineralisation which were not of commercial interest at the time. After several decades of geophysical and geochemical investigation, diamond drilling and development of mining techniques, the low-grade Aitik mineralisation was outlined and proven to be economic. A feasibility study for an open pit mine was carried out by Boliden AB in 1964 and by 1968 production of ore started at a rate of 2 Mt per year (Zweifel, 1976).

Today, the Aitik deposit is Sweden's largest sulphide mine, one of Europe's largest producers of copper, gold and silver, and the biggest open pit operation in northern Europe. The ore zone is at least 3 km long by 400 m wide, and inferred to continue to a depth of at least 800 m. Capacity expansions have been carried out several times since the mine opened in 1968 and today the annual production is 18 Mt of ore, containing 0.30% Cu, 0.14 g/t Au and 2.81 g/t Ag (average for year 2008). With current metal prices, the proven and probable ore reserves amount to about 633 Mt. A planned expansion will raise the annual output of ore to 36 Mt, and extraction of Mo will start in the near future (Nordin, 2008).

Several attempts have been made to present a genetic model for the Aitik copper-gold-silver(-molybdenum) deposit. Deformation has, however, obscured primary relationships and significantly modified the geometry of both orebody and host rocks. The protoliths of many of the lithologic units in the deposit area is therefore poorly understood, hampering the understanding of the processes responsible for the formation of the deposit. An early genetic model was outlined by Zweifel (1976), suggesting that the mineralisation was of a syngenetic sedimentary origin. According to Zweifel, the stratiform concentration of copper was later mobilised in conjunction with the intrusion of c. 1.8 Ga granites (Lina granite). By 1986, after 18 years of mining, several basic aspects of the



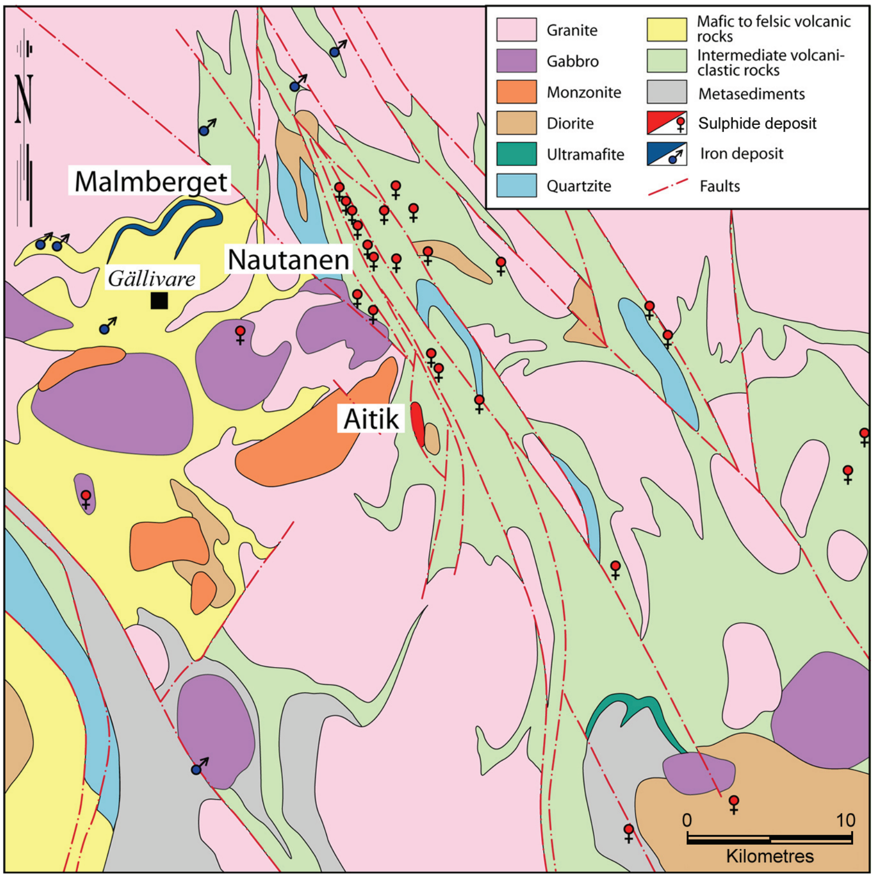


Figure 1: (above) General geology of northern Sweden and the location of the northern Norrbotten ore province (rectangle). Inset shows location of the Archaean-Proterozoic boundary zone and failed rift. Modified from Weihed and Williams (2005). 1. Aitik, 2. Malmberget, 3. Kiirunavaara, 4. Vaikijaur, 5. Tallberg, 6. Tjårrojåkka, 7. Gruvberget, 8. Pahtavaara, 9. Viscaria. KADZ = Karesuando Arjeplog Deformation Zone, NDZ = Nautanen Deformation Zone, PSZ = Pajala Shear Zone.

Figure 2: (left) Geology of the Gällivare area. Modified from Martinsson and Wanhainen (2000).

deposit were still subject to debate, and no consensus on the genesis of the deposit had been established. Based on a sulphur isotope study, a magmatic origin of the Aitik mineralisation was proposed by Yngström *et al.* (1986). This model was further developed by Monro (1988), who suggested a genetic relationship between the mineralisation and an intermediate, porphyritic intrusion occurring in the footwall. The relationship between the copper-gold mineralisation and the footwall intrusion, however, remained obscure, and a few years later, Gaál (1990) instead claimed the Aitik deposit to be of Besshi-type. During the past 15 to 20 years, a magmatic-hydrothermal origin for the deposit has been favoured, hovering between an iron-oxide copper-gold (IOCG) type (Williams *et al.*, 2003) and a porphyry copper style (Drake, 1992). A multidisciplinary approach, including field-, petrographic-, geochemical-, structural-, tectonic-, isotopic-, and fluid inclusion-investigations was undertaken on the Aitik copper-gold-silver(-molybdenum) deposit by Wanhainen (2005), concluding that the Aitik deposit is of mixed origin, with a major part of the copper ore originating from an early porphyry copper system, and a second, minor part, originating from an overprinting IOCG system.

In this paper, the complexity of the Aitik ore body arising from the mixture of two magmatic-hydrothermal systems will be discussed, as well as the character of the overprinting IOCG system.

Regional Geology

The Aitik copper-gold-silver(-molybdenum) deposit is located in the southern part of the northern Norrbotten ore province, an important mining district in northernmost Sweden that produces iron, copper and gold (Fig. 1). The province measures 120 km north-south, and 200 km in an east-west direction, and is situated about 250 km north of the Skellefte district (Fig. 1), another important mining province in northern Sweden hosting several VMS deposits. Economic deposits of apatite iron ores (Kiirunavaara, Malmberget), epigenetic copper-gold ores (Aitik, Pahtohavare) and one stratiform copper deposit (Viscaria) are mainly restricted to the Kiruna and Gällivare areas of the northern Norrbotten ore province (Fig. 1).

In the northern parts of Sweden, a Palaeoproterozoic succession of volcanic and sedimentary rocks rests unconformably on a 2.8 to 2.6 Ga Archaean granitoid-gneiss basement. Rift-related 2.5 to 2.0 Ga Karelian units at the lowest stratigraphic level are overlain by c. 1.9 Ga terrestrial to shallow water Svecofennian successions (Martinsson, 1997). These supracrustal rocks are intruded by the 1.89 to 1.87 Ga Haparanda and Perthite-monzonite suites, which have a calc-alkaline to alkali-calcic character and are considered to be comagmatic with the Svecofennian volcanic rocks (Witschard, 1984; Bergman *et al.*, 2001). The Haparanda suite intrusions were formed in a volcanic arc environment related to subduction of oceanic crust beneath the Archaean craton (Öhlander *et al.*, 1999; Mellqvist *et al.*, 2003), and the Perthite-monzonite suite intrusions in an intra-plate environment (Kathol and Martinsson, 1999). Furthermore, the Haparanda suite intrusions were affected by an early Svecofennian metamorphic and deformation event, an event that seems to mainly pre-date the Perthite-monzonite suite intrusions (Bergman *et al.*, 2001). A second phase of magmatism, termed the Lina suite, was intruded around 1.79 Ga (Skiöld *et al.*, 1988). These minimum melt granites and pegmatites (Skiöld *et al.*, 1988) are temporally related to TIB 1 (Transcandinavian Igneous Belt) intrusions in the Kiruna-Narvik area (Romer *et al.*, 1992, 1994). The c. 1.71 Ga TIB 2 granitoids close to the Swedish-Norwegian border represent the youngest plutonic rocks in the province (Romer *et al.*, 1992).

Three major ductile shear zones are present in northern Sweden, the northnortheast-directed Karesuando-Arjeplog deformation zone, the northnorthwest-directed Nautanen deformation zone, and the north to northnortheast-directed Pajala shear zone (Fig. 1). Radiometric data, together with field relationships, suggest that these major shear zones were active at c. 1.8 Ga (Bergman *et al.*, 2001).

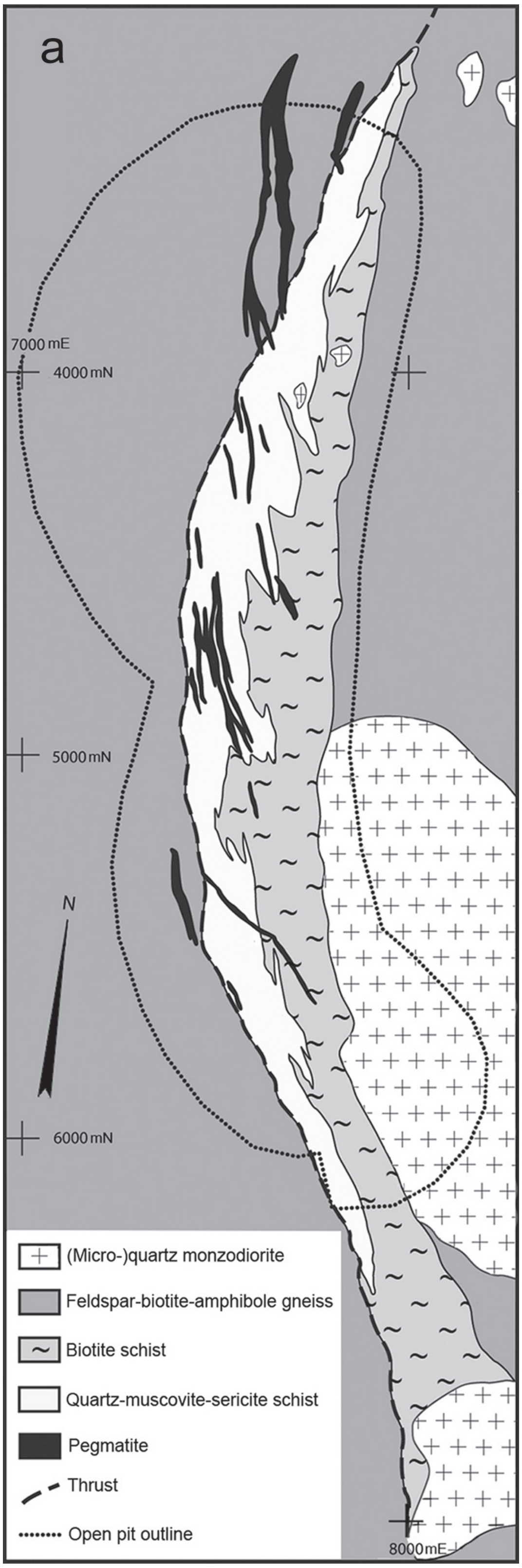
Deposit Geology

On a local scale, the bedrock in the Gällivare area consists of metamorphosed Svecofennian (c. 1.9 Ga) intermediate volcanic and clastic sedimentary rocks that were intruded by 1.9 to 1.8 Ga plutonic rocks of granitic, dioritic and gabbroic composition (Fig. 2) (Witschard, 1996). The supracrustal rocks and the c. 1.9 Ga intrusive rocks are metamorphosed to amphibolite facies (Zweifel, 1976). The Aitik deposit is situated 5 km from the structurally important Nautanen deformation zone, which is spatially associated with numerous small occurrences of copper-gold mineralisation (Fig. 2).

The Aitik mining area is divided into footwall, ore zone and hanging wall, based on structural boundaries and copper grades. The footwall consists of quartz monzodiorite, minor micro-quartz monzodiorite and diorite, and feldspar-biotite-amphibole gneiss (Fig. 3). The feldspar-biotite-amphibole gneiss is composed of large (6 to 20 mm) amphibole phenocrysts in a groundmass of feldspar, biotite and amphibole, with accessory apatite, titanite, zircon and opaque phases. The quartz monzodiorite is a 1.9 Ga old Haparanda type intrusion (Wanhainen *et al.*, 2006), typically grey and plagioclase-porphyritic with a medium grained groundmass of plagioclase, biotite, K feldspar and quartz, and trace amounts of titanite, apatite and zircon (Fig. 4a). The micro-quartz monzodiorite is macroscopically distinguished from the quartz monzodiorite only by its finer grain size (0.1 to 0.3 mm). It exhibits a porphyritic texture and a mineralogical composition similar to that of the main intrusive phase (Fig. 4b). An early foliation is present in the footwall intrusive rocks, defined by the parallel alignment of westnorthwest directed biotite laths, and overprinted by a dominant north-south oriented foliation, also characterised by biotite alignment.

The ore zone comprises biotite schist towards the footwall, and quartz-muscovite-sericite schist towards the hanging wall (Fig. 3). These rock types also interfingers throughout the entire ore zone. The dominant rock type in the ore zone is the light grey, garnet-bearing biotite schist with approximately 1 to 2% garnet porphyroblasts (Fig. 4c). The microcrystalline groundmass contains K feldspar, plagioclase, biotite, amphibole, quartz, and opaque minerals, and accessory minerals that include tourmaline, apatite, fluorite and titanite. The quartz-muscovite-sericite schist mainly comprises muscovite, K feldspar, quartz, sericite and tourmaline, with accessory apatite and opaque phases. Pyrite is common (Fig. 4d). Lenses of micro-quartz monzodiorite can be distinguished within less foliated sections of the ore zone schists (Fig. 3).

The hanging wall consists mainly of feldspar-biotite-amphibole gneiss, and is separated from the ore zone by a thrust (Fig. 3). The hanging wall feldspar-biotite-



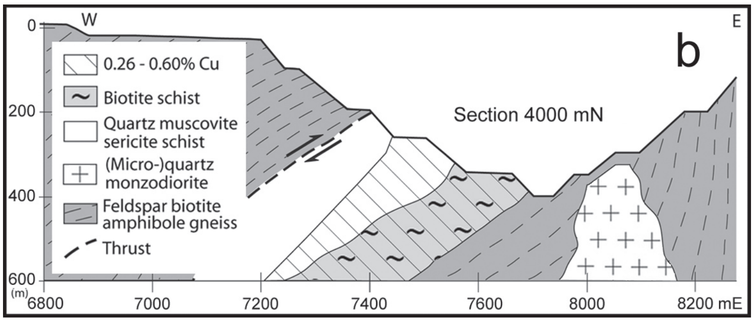


Figure 3: Geology of the Aitik Cu-Au-Ag(-Mo) deposit and its immediate surrounding. Local coordinates in metres. (a) Horizontal section at 150 m depth; (b) West-east vertical section at 4000 mN.

amphibole gneiss is grey-greenish to grey-brownish in colour and fine-grained (~ 0.2 mm). Abundant accessory magnetite and titanite occur in a groundmass of plagioclase, biotite, amphibole and quartz (Fig. 4e).

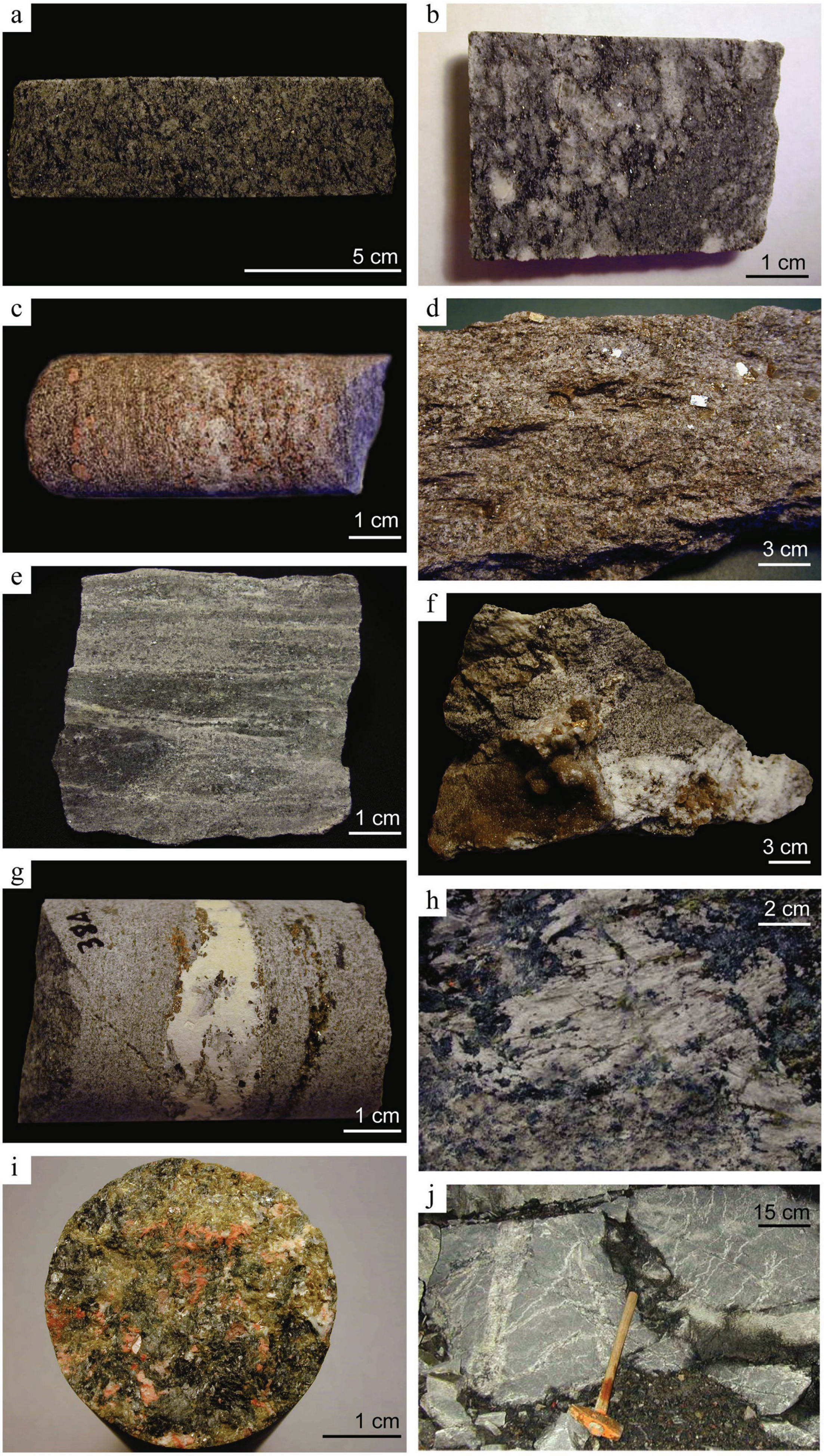
Several generations of pegmatitic dykes occur in the Aitik mining area. These pegmatites strike either north-south or east-west and range in thickness from 0.5 to 20 m. Pegmatites within the ore zone and footwall frequently contain pyrite and chalcopyrite, and occasionally some molybdenite, in addition to quartz, plagioclase, microcline, muscovite, biotite and tourmaline. Pegmatite dykes in the hanging wall are barren. Pegmatites striking north-south, i.e., along the main foliation, in places display deformation features, while those crosscutting the foliation in an east-west direction, are always undeformed. Ages of pegmatite dykes range between 1850 to 1730 Ma (Wanhainen *et al.*, 2005).

Up to 50 cm wide barite veins, containing varying amounts of magnetite, actinolite, quartz, feldspar, epidote, calcite, chalcopyrite and pyrite are locally abundant within the ore zone. They are white or light pink and commonly intensely folded. Two generations exist, an older (1875±6 Ma), which is strongly deformed, and a younger (<1730 Ma), weakly deformed or undeformed set, crosscutting the youngest pegmatite dykes (Wanhainen *et al.*, 2005).

Undeformed zeolite-quartz-veins are generally 1 to 15 cm wide, containing crystals of stilbite, chabazite, plagioclase, epidote, actinolite and opaque minerals like chalcopyrite, pyrite and magnetite in drusy vugs (Fig. 4f). Pyrite-bearing, thaumasite veinlets that are 0.5 to 5 cm wide, are also undeformed. They contain magnetite and quartz, and are commonly bordered by epidote (Fig. 4g).

With the exception of late dykes, the Aitik rocks have experienced at least two metamorphic events (Bergman *et al.*, 2001), and four main phases of alteration can be distinguished (Wanhainen *et al.*, in review). An early, pre-metamorphic potassic alteration, best preserved in the quartz monzodiorite, comprises replacement of amphibole by biotite, and microcline growth in the groundmass. The second alteration phase comprises minerals characteristic of amphibolite facies peak metamorphic conditions, such as amphibole and garnet. It is followed by a third alteration phase indicative of retrograde conditions with minerals such as biotite, sericite, chlorite, epidote and calcite that are widespread and common within the groundmass of most of the rocks. Chloritisation and sericitisation are abundant in the footwall and hanging wall rocks, while biotitisation and sericitisation dominate in the ore zone. K feldspar, magnetite, scapolite, amphibole, tourmaline, garnet, muscovite, apatite, allanite and quartz, occur locally within all rock types together with chalcopyrite and pyrite (Fig. 4h-i), and belong to the fourth alteration phase of hydrothermal origin (Wanhainen *et al.*, in review).

Figure 4: (facing page) Photographs of Aitik rock- and alteration types. (a) Quartz monzodiorite in footwall; (b) Contact between quartz monzodiorite (left) and finer grained micro-quartz monzodiorite (right); (c) Garnet-bearing biotite schist in ore zone; (d) Pyrite-rich quartz-muscovite-sericite schist in ore zone; (e) Feldspar-biotite-amphibole gneiss in hangingwall; (f) Quartz-zeolite-filled cavity in biotite schist; (g) Thaumasite veinlet containing quartz-pyrite-magnetite; (h) Scapolite-amphibole-magnetite alteration; (i) K feldspar-amphibole-epidote-magnetite-pyrite alteration; (j) Quartz stockwork veining at the contact between quartz monzodiorite and biotite schist.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The main copper-bearing mineral at Aitik is chalcopyrite. Bornite and chalcocite are present in trace amounts. Other ore minerals include (in decreasing order of frequency) pyrite, magnetite, pyrrhotite, ilmenite, and molybdenite. Chalcopyrite, pyrite and magnetite are mainly disseminated, and accompany the potassic alteration in the quartz monzodiorite. In the ore zone, disseminated chalcopyrite, pyrite and magnetite, with minor pyrrhotite, dominate the mineralisation, together with clusters of pyrite-chalcopyrite-magnetite, pyrite-chalcopyrite, and chalcopyrite-magnetite. Ore minerals also occur in several types of veins together with varying amounts of other minerals such as e.g., quartz, amphibole, garnet, magnetite, zeolite, tourmaline, barite and thaumasite, and in pegmatite dykes. The disseminated mineralisation style is quantitatively the most important. Mineralisation is absent in the hanging wall, except for minor sulphides occurring in younger veins and pegmatite dykes. Gold occurs as native metal, in amalgam and in electrum (Kontturi and Martinsson, 2000), mostly in close association with groundmass minerals such as K feldspar, biotite, plagioclase and quartz, but also with chalcopyrite and pyrite (Wanhainen and Johansson, 2008).

A quartz stockwork system, which contains two sets of quartz veins, is located along the margins of the quartz monzodiorite and in the volcaniclastic rocks of the lower ore zone (Wanhainen *et al.*, 2006). The first set consists of 2 to 5 mm wide veins of grey-white quartz containing grains of chalcopyrite and pyrite. Thin biotite selvages are in places observed along the vein-wallrock interface. These veins are overprinted by a second set of 10 to 20 mm wide quartz veins with biotite and sulphides occupying the central parts. Both vein types are deformed, randomly oriented and closely spaced (Fig. 4j). The total vein frequency increases from east to west within the intrusion, i.e., from its centre towards the western margin.

Four generations of folding, ductile shearing and brittle faulting can be recognised in the Aitik mine area (Wanhainen *et al.*, in review). D_1 deformation is defined by an westnorthwest foliation and folds with the fold axis parallel to foliation and plunging gently to the westnorthwest. These early D_1 structures are suggested by Wanhainen *et al.* (in review) to be the result of northeast-southwest compression during northeastward subduction of oceanic crust beneath the Karelian craton at c. 1.9 Ga (Fig. 1). D_2 deformation forms the dominant structural feature within the deposit area, with a prominent north-south directed foliation dipping 40 to 60°W. This orientation is probably controlled by the southsoutheast-striking Nautanen deformation zone, with the Aitik deposit located in a north-south-striking branch of the zone. Open folds in the hanging wall and tight folds in the ore zone, with fold axes of both types parallel to the north-south foliation and plunging 20°S, are characteristic for D_2 deformation, which is suggested by Wanhainen *et al.* (in review) to be the result of 1.8 Ga eastward subduction and east-west crustal shortening of the region. Major thrusting generated in the hanging wall, manifested by a several hundred metre wide zone of ductile deformation within the hanging wall feldspar-biotite-amphibole gneiss and the ore zone mica schists, constitutes D_3 deformation. The thrust plane that constitutes the western ore zone boundary strikes north-south, and dips 31°W. All brittle deformation, mainly comprising reactivation of faults, is grouped into D_4. Reactivation of the major thrust plane, with an offset of approximately 50 to 100 m, is included in this deformation phase. Faulting dominantly occurred in an east-west direction with normal subvertical dipping fault planes.

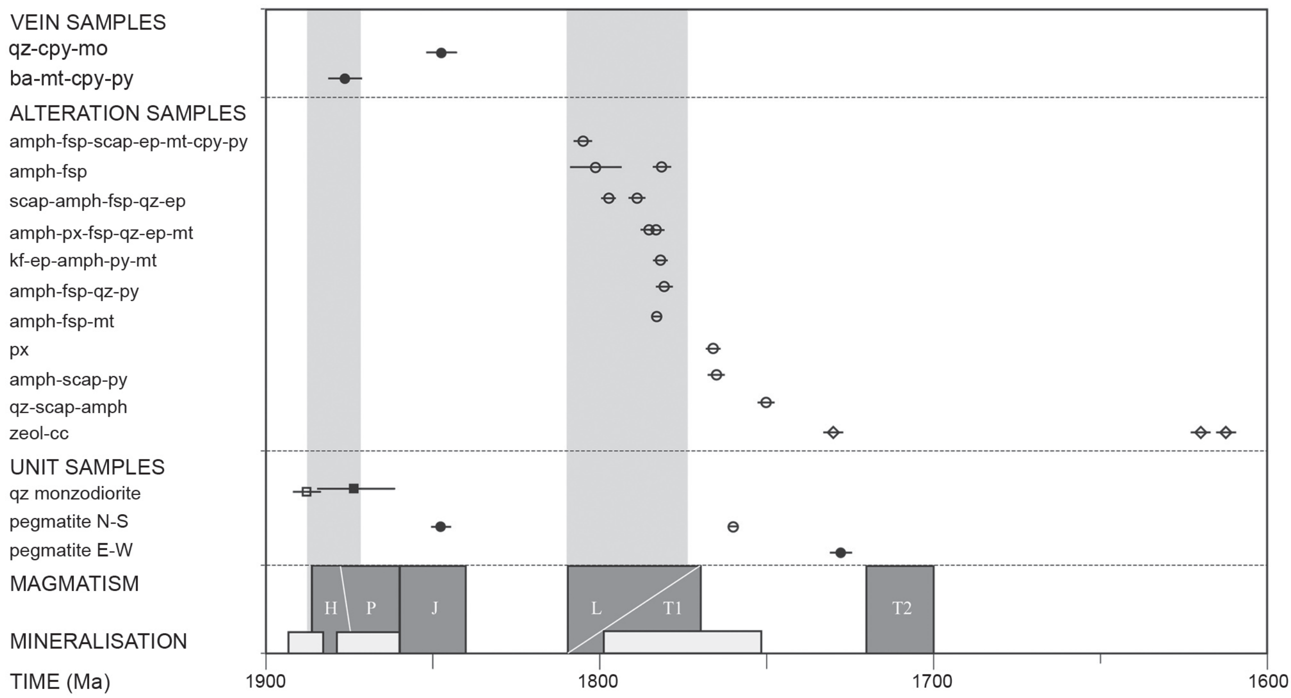

Figure 5: Evolution of the Aitik Cu-Au-Ag-(Mo) deposit in comparison with regional magmatic/hydrothermal and metamorphic events. The time table is based on U-Pb titanite dates (open circles) and Re-Os molybdenite dates (filled circles) from Wanhainen *et al.* (2005), U-Pb zircon dates from Wanhainen *et al.* (2006) (open box), Witschard (1996) (filled box), and U-Pb stilbite dates (diamond) from Romer *et al.* (1994). Age data on magmatic (dark grey boxes) and metamorphic (shaded areas) events are from Bergman *et al.* (2001). Age data on mineralising events (light grey boxes) are from Billström and Martinsson (2000) and Wanhainen *et al.* (2006). *H* Haparanda suite; *P* Perthite-monzonite suite; *J* Jyryjoki granite; *L* Lina suite; *T1* & *T2* Transcandinavian igneous belt 1 and 2 granites, respectively. Mineral abbreviations: *qz* quartz; *ba* barite; *px* pyroxene; *fsp* feldspar, *kf* K feldspar; *amph* amphibole; *ep* epidote; *scap* scapolite; *cc* calcite; *zeol* zeolite; *cpy* chalcopyrite; *py* pyrite; *mo* molybdenite; and *mt* magnetite.

Discussion

The majority of rocks in the Aitik area belong to the regionally widespread Porphyrite group of volcanic rocks and to the comagmatic Haparanda suite of intrusions (Wanhainen and Martinsson, 1999), and thus are the product of subduction and volcanic arc formation at c. 1.9 Ga. Numerous metal deposits in the Norrbotten and Skellefte mining districts were generated during this Svecokarelian orogenic event (Weihed, 2003), and many magmatic-related deposits of this age have been classified as being of either porphyry type (e.g., Tallberg: Weihed, 1992; Vaikijaur: Lundmark, 2005) or iron oxide copper-gold style (e.g., Pikkujärvi: Bergman *et al.*, 2001).

The Aitik Porphyry Deposit

The challenge in classifying an old deposit like Aitik, is to find the right combination of tools that will help to see through the deformation, alteration and metamorphism that overprints the primary features of the ore and its host- and wallrock. Nevertheless, a growing number of papers describe Precambrian porphyry systems, which although deformed and metamorphosed, often share many features with their younger equivalents (e.g., Samba: Wakefield, 1978; Kopsa: Gaál and Isohanni, 1979; Haib: Minnitt, 1986; Chapada: Richardson *et al.*, 1986; Malanjkhand: Sikka, 1989; Tallberg: Weihed, 1992; Chibougamau district: Kirkham *et al.*, 1998; Vaikijaur: Lundmark *et al.*, 2005).

At Aitik, a genetic relationship between the mineralised footwall intrusion, associated intrusive phases, and the volcaniclastic host rocks of the Aitik ore, was established by Wanhainen *et al.* (2006). These rocks are potassic (dominantly biotite) altered, and the copper mineralisation, which is mainly disseminated, is intimately associated with the potassic alteration. A zoned copper pattern can be distinguished in the intrusion, from a low-grade inner core to a higher-grade periphery, similar to the typical zoning described in porphyry copper deposits (Lowell and Guilbert, 1970). The stockwork system developed in the apex of the intrusion is also a typical feature of many young porphyry systems (e.g., Lowell and Guilbert, 1970; Sillitoe, 1973; McMillan and Panteleyev, 1986), and is also commonly found in old porphyry deposits (Gaál and Isohanni, 1979; Sikka, 1989; Lundmark *et al.*, 2005), suggesting that these quartz vein systems can endure deformation and still preserve their original character.

The Aitik intrusion contains slightly younger, but comagmatic, intrusive phases. Most common of these phases is the micro-quartz monzodiorite (Fig. 4b), which is believed to form apophyses protruding from a batholith at depth (Wanhainen *et al.*, 2006). A fundamental discovery in the genetic interpretation of Aitik was the identification of similar micro-quartz monzodiorite lenses within the ore zone schists (Wanhainen *et al.*, 2006). These lenses can be traced in the ore zone as less deformed, porphyritic rocks with strong disseminations of mainly chalcopyrite and pyrite, within the otherwise strongly foliated rocks. The occurrence of mineralised micro-quartz monzodiorite apophyses within the volcaniclastic rocks in the ore zone, together with the fact that porphyry-type mineralisation is located stratigraphically below the main ore, suggests that the ore zone represents the continuation of the copper mineralising system developed in the intrusion. Based on these observations, a porphyry copper origin, with a major part of the ore being hosted in the wallrocks to the intrusion, is suggested for the Aitik deposit (Wanhainen *et al.*, 2006).

Microthermometric data from ore-related quartz in Aitik (stockwork quartz among others) reveal an ore-forming fluid of highly saline Na-Ca-Cl-rich composition and a salinity of 30 to 38 wt.% $NaCl_{equiv.}$. This fluid composition is similar to that in many other occurrences of copper-gold mineralisation in Norrbotten, which are commonly rich in Ca and Na, but different from that in most porphyry copper deposits (Wanhainen *et al.*, 2003a, and references therein) which usually have high K-Na and low Ca contents (Table 1). A possible explanation for this is the suggested interaction of magmatic fluids with evaporitic sequences in older rift sequences in the region (Frietsch *et al.*, 1997; Martinsson, 1997).

So, although most characteristics of the Aitik deposit may be attributed to porphyry copper style mineralisation, not all features are typical (Table 1) and while some of them probably reflect the influence of evaporitic sequences on the ore fluid character, others might be the result of post-ore modification. After the initial ore-forming event at c. 1.9 Ga, metamorphism and deformation have affected the deposit and are likely to be the main cause of the present irregular distribution of sulphides within the ore. A zone rich in massive sulphide veinlets in the intensely sheared rocks towards the footwall of the ore, and gold-rich areas correlating with pyrite-rich and K feldspar-epidote-quartz altered schist close to the hanging wall, form local higher-grade zones that are suggested to be the result of multistage remobilisation (Wanhainen *et al.*, 2003b).

Overprinting Features of IOCG Character

A sulphur isotopic composition close to zero for the Aitik sulphides, irrespective of mineralisation style, favours the interpretation of magmatic and remobilised sulphides. However, overprinting mineralisation events might also have taken place contemporaneously with remobilisation, since 1.87 and 1.77 Ga magmatism is represented in the area (Fig. 5), and could theoretically generate mineralisation with similar isotopic signatures (Wanhainen and Martinsson, 2003).

U-Pb and Re-Os ages obtained from zircon, titanite and molybdenite at Aitik reveal a time span of 160 m.y. for rock formation, metamorphism and alteration within the deposit (Wanhainen *et al.*, 2005), with a peak at around 1.81 to 1.75 Ga, where samples containing metamorphic (eg. amphibole, garnet, biotite, chlorite, sericite, epidote, calcite) or hydrothermal (e.g., magnetite, garnet, quartz, amphibole, scapolite, K feldspar, epidote, REE, apatite, tourmaline, muscovite) assemblages cluster (Fig. 5). As proposed by Billström and Martinsson (2000), copper-iron deposits in the northern Norrbotten ore province constitute two major phases of ore formation, at around 1.9 Ga and 1.8 Ga respectively, in the same way as the Kiruna-type apatite-Fe ores (e.g., Malmberget) were probably followed by a later pulse of ore generation (e.g., Tjårojokka-Fe; Edfelt *et al.*, 2007). Thus, the c. 1.78 Ga event of rock formation and alteration observed at Aitik, may be temporally related to a major orogenic stage in the evolution of the Fennoscandian Shield that has affected the entire northern Norrbotten region (Fig. 5) (Weihed *et al.*, 2005). As described by Weihed *et al.* (2005), 1.8 Ga mineralisation took place when magmatism occurred during cratonisation, distal to an active north-south-trending subduction zone to the west.

Table 1: General characteristics of porphyry copper deposits (Lowell and Guilbert, 1970; McMillan and Panteleyev, 1986) and IOCG deposits (Porter, 2000, and references therein) in comparison to Aitik.

Main features	Porphyry Cu-Au	IOCG	Aitik deposit
Tectonic setting	Subduction-related island arc, continental margin	Intra-continental Extension along subduction-related continental margin	Subduction-related, continental margin
Age	Archaean to present, majority Mesozoic-Cenozoic	Archaean to present, majority Proterozoic	Early Proterozoic (c. 1.89 Ga)
Main host rocks	1. Intermediate porphyritic intrusions 2. Intermediate volcanic and sedimentary rocks	1. Felsic-intermediate volcanic and sedimentary rocks 2. Felsic intrusions	1. Intermediate volcanic rocks 2. Intermediate porphyritic intrusions
Ore paragenesis	1. Magnetite 2. Chalcopyrite, pyrite ± pyrrhotite, chalcocite, molybdenite, bornite	1. Magnetite, hematite 2. Chalcopyrite, bornite, pyrite ± molybdenite, pyrrhotite	1. Magnetite 2. Chalcopyrite, pyrite, pyrrhotite, bornite, chalcocite, molybdenite 3. Magnetite, pyrite ± chalcopyrite
Alteration paragenesis	1. Biotite, K-feldspar, quartz (potassic) 2. Quartz, sericite, pyrite (phyllic) 3. Epidote, chlorite, calcite (propylithic) 4. Quartz, kaolinite, chlorite (argillic)	1. Albite, scapolite, amphibole, biotite, magnetite 2. K-feldspar, magnetite, hematite, biotite, quartz 3. Chlorite, muscovite (sericite), calcite, quartz	1. Biotite, K-feldspar, Quartz, sericite, pyrite Epidote, chlorite, calcite 2. Amphibole, garnet 3. Biotite, epidote, chlorite, calcite 4. Scapolite, amphibole, K-feldspar, epidote, magnetite, garnet, quartz, biotite, muscovite
Mineralisation style	Disseminated, vein, quartz stockwork	Disseminated, breccia-infill, vein network, massive lenses, replacement	Disseminated, vein, quartz stockwork, patches and clots, veinlets of varying mineral compositions
Ore fluid composition	Cation: Na ± K, Fe, Ca, Mn + CO_2 Solids: halite ± calcite 30 to 50 wt.%. NaCl T: 300 to 700°C	Cation: Na ± Ca, K, Fe, Mg + CO_2 Solids: halite ± calcite, ferropyrosmalite, hematite 20 to 60 wt.%. NaCl T: 200 to -500°C	Cation: Na, Ca + CO_2 Solids: halite ± calcite, hematite, ferropyrosmalite 30 to >60 wt.%. NaCl T: >300°C
Structural control	Regional faults	Shear zones and faults	Shear zones and faults
Association with igneous activity	Temporal and spatial	Temporal	Temporal and spatial
Parental magma	I-type	I-type, oxidised A-type	I-type
Other common minerals	Tourmaline, anhydrite	REE- and U-minerals, baryte, fluorite, tourmaline, apatite	Tourmaline, anhydrite, baryte, fluorite, apatite, allanite

Locally, tectonism and deformation caused D_2 folding and faulting within the Aitik area and tilting of the Aitik porphyry intrusion. Aitik, as well as the Nautanen area, both localised within the Nautanen deformation zone (Fig. 2), constituted structurally favourable sites for magmatic-hydrothermal fluid flow, which is manifested by extensive hydrothermal alteration and IOCG mineralisation at Nautanen (Martinsson and Wanhainen, 2004). At Aitik, the hydrothermal alteration was dominated by sulphide- and magnetite-bearing scapolite-amphibole and garnet-quartz assemblages, and also by K feldspar-epidote-muscovite-tourmaline-allanite and apatite. These are mineral assemblages associated with regionally extensive Na-Ca alteration throughout the entire northern Norrbotten ore province. The regional extent is suggested by the similar scapolite-, amphibole- and K feldspar-rich mineral assemblages characteristic of 1.8 Ga mineralisation in the district. In e.g., Tjårrojåkka, extensively developed scapolite alteration is overprinted by intense K feldspar alteration in areas of copper-mineralisation and along deformation zones (Edfelt, *et al.*, 2005). The strong Na-Ca-alteration in the Gruvberget deposit also points to alteration mineral assemblages that are regional in character. Alteration in the Nautanen area is similarly manifested by extensive K feldspar and scapolite alteration (Martinsson and Wanhainen, 2004). Apart from being found as veins in mineralised areas, scapolite is also found as massive units and large porphyroblasts in rocks unrelated to mineralisation, covering hundreds of square kilometres (Frietsch *et al.*, 1997).

The occurrence of 1.8 Ga IOCG mineralisation has been widely recognised across northern Norrbotten. Consequently, it is reasonable to conclude that features at Aitik unrelated to either the porphyry mineralising event or to post-ore metamorphism and deformation, may in part, or wholly, be the result of hydrothermal overprint and/or upgrading during this late, 1.8 Ga phase (Wanhainen, 2005). Fluid inclusions found within late alteration mineral assemblages in the Aitik deposit are highly saline, Na-Ca-rich and chalcopyrite-, ferropyrosmalite- and hematite-bearing (Wanhainen *et al.*, in review). These fluids are similar to those found in IOCG mineralisation elsewhere in the region (Lindblom *et al.*, 1996; Broman and Martinsson, 2000, Williams *et al.*, 2003; Edfelt *et al.*, 2004), and worldwide (Johnson and Barton, 2000; Perring *et al.*, 2000; Smith and Henderson, 2000; Williams *et al.*, 2001). Overprinting of older systems by new mineralising fluids has been postulated for several deposits in northern Fennoscandia, e.g. Bidjovagge (Björlykke *et al.*, 1990) and Gruvberget (Lindskog, 2001). At Gruvberget, early (1.9 Ga) magmatic-derived iron oxides were mobilised and re-deposited in conjunction with shearing and subsequent copper-precipitation from hydrothermal solutions around 1.8 Ga (Lindskog, 2001). Thus, according to Lindskog (2001), copper mineralisation at Gruvberget represents a separate event, with the iron ore only acting as a chemical-structural trap. On the basis of geologic, geochronologic, sulphur isotope- and fluid inclusion data, there are strong indications of Aitik also having been subjected to multiphase mineralisation.

Taken together, the occurrence of late, 1.8 Ga magnetite, garnet, quartz, amphibole, scapolite, K feldspar, epidote, REE, apatite, tourmaline, and muscovite assemblages, together with ferropyrosmalite-bearing, highly saline Na-Ca fluid compositions, implies that IOCG type fluids of a regional nature also affected the Aitik deposit. Their relationship to earlier mineralisation of a different character also suggests that Aitik most likely formed during several stages, and from fluids of different origin. It is, however, difficult to estimate how much metal was added during the later events. Disseminated sulphides are present throughout the ore body, and constitute a major part of the mineralisation in the ore zone schists and micro-quartz monzodiorite. In the muscovite and biotite schist, mineralisation of a disseminated character is accompanied to varying degrees by massive sulphide veins, up to 10 cm wide with no associated late alteration minerals, and by patches and clots of pure sulphides, locally increasing the copper-gold grades significantly. All of this mineralisation is interpreted to originated during the porphyry phase, with the disseminated sulphides being primary, while the latter represent remobilised ore (Wanhainen *et al.*, 2003b). Sulphides within late veins of quartz ± magnetite ± scapolite ± garnet ± amphibole ± K feldspar ± epidote ± tourmaline ± apatite are not as widespread as the inferred porphyry and remobilised mineralisation, but rather, only occur locally within the deposit. This implies that the overprinting IOCG type fluids only contributed minor amounts of copper and gold to the overall metal budget of the Aitik deposit.

Acknowledgements

Boliden AB is acknowledged for the financial support of this study, and for the permission to publish this paper.

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