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Metallic mineral deposits in the Nordic countries

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The Nordic countries, including Greenland, have a long tradition in mining. Documented mining dates back to the 8th century AD. Today this region is the most important metallic mining district of the European Union. Metals are produced from active mines in all countries except Iceland and related industries are thriving in all countries.

Important ore deposit types include: volcanogenic massive sulphide deposits (Cu, Zn, Pb, Au, Ag), orogenic gold deposits (Au), layered intrusions (Ni, PGE, Ti±V), intrusive hosted Cu-Au, apatite-Fe deposits, Cr- and anorthosite hosted Ti deposits. Besides these well-documented deposits, new kinds of deposits are being explored, e.g., iron oxide-copper-gold (IOCG), shale-hosted Ni-Zn-Cu and different types of uranium deposits.

Introduction

The Fennoscandian Shield, which forms a large part of the Nordic countries (see descriptions elsewhere in this volume), has historically been one of the most active mining areas in Europe. For example, archaeological evidence shows that copper was produced from the Falun mine in the Bergslagen province, Sweden, early in the 8th century AD (Eriksson and Qvarfort, 1996). Since the industrial revolution in the 19th century, numerous iron mines were exploited in Bergslagen and, during the 20th century, mining of both base metals and iron ore started in several new mining districts such as the Skellefte and Northern Norrbotten districts in Sweden, the Vihanti-Pyhäsalmi and Outokumpu districts in Finland, the Pechenga district in Russia, Tellnes and Sulitjelma in Norway, and Ivittut (Ivigut) in Greenland. However, Fennoscandia (the Precambrian Shield together with the Caledonides) can still be regarded as under-explored and having a good potential for major new discoveries, as shown by the discovery of metal, industrial mineral and natural stone deposits made every year in the region.

Figure 1 Location of major ore deposits of the Nordic countries. Map from Lahtinen et al. (2005).

Table 1 Data on major mineral deposits of the Nordic countries (Greenland included with Denmark).

	Type ²	Size (Mt)	Cu %	Zn %	Pb %	Co %	Au ppm	Ag ppm	Fe %	Ni %	Cr %	V %	TiO ₂ %	Status	Reference ³
Fennoscandian Shield															
Bidjovagge	Cu-Au	2	1.2	-	-	-	3.6	-	-	-	-	-	-	Closed mine	Eitner et al. (1994)
Viscaria	Strat. Cu	12.54	2.29	-	-	-	-	-	-	-	-	-	-	Closed mine	Martinsson (1997)
Stora Sjöfjärden	Fe-Cu-Au	145	0.08	-	-	-	-	-	43.1	-	-	-	-	Prospect	Eilu et al. (2007)
Hannukainen	Fe-Cu-Au	170.7	0.2	-	-	-	0.1	-	35.5	-	-	-	-	Closed mine	Niiranen et al. (2007)
Aitik	Porphy.	1600	0.4	-	-	-	0.2	4	-	-	-	-	-	Active mine	Wanhai et al. (2003)
Boliden	VMS	8.3	1.4	0.9	0.3	-	15.5	50	-	-	-	-	-	Closed mine	Bergman Wehsted et al. (1996)
Renström	VMS	12.6	0.8	7.3	1.5	-	2.8	155	-	-	-	-	-	Active mine	Allen et al. (1996a)
Petkänäs S	VMS	6.5	1.1	4.8	0.9	-	2.3	108	-	-	-	-	-	Active mine	Allen et al. (1996a)
Räkäjaur	VMS	20.7	0.3	2.4	0.2	-	1.0	45	-	-	-	-	-	Closed mine	Allen et al. (1996a)
Kristineberg	VMS	31.4	1.1	3.2	0.4	-	1.2	37.8	-	-	-	-	-	Active mine	Allen et al. (1996a)
Vihanti	VMS	37.1	0.48	4.0	0.36	-	0.44	25	-	-	-	-	-	Closed mine	Helovuori (1979)
Pyhäsalmi	VMS	71	0.79	2.47	-	-	0.4	15	-	-	-	-	-	Active mine	Wehsted (2001)
Outokumpu region	VMS	42.1	1.1	-	-	0.22	0.6	8.3	-	0.12	-	-	-	Closed mines	Gaál 1985
Kylälahti	VMS	7.8	1.17	0.5	-	0.24	0.7	-	-	0.22	-	-	-	Prospect	Eilu et al. (2007)
Falun	VMS	28.1	~3	4	1.5	-	~3 ⁴	~20	-	-	-	-	-	Closed mine	Allen et al. (1996b)
Garpenberg	VMS	21.5	0.3	5.3	3.3	-	0.65	98	-	-	-	-	-	Active mine	Allen et al. (1996b)
Zinkgruvan	VMS	51	-	8	3.5	-	-	70	-	-	-	-	-	Active mine	Allen et al. (1996b)
Kiruna	FeOx	>2000	-	-	-	-	-	-	>60	-	-	-	-	Active mine	Martinsson (1997)
Malmberget	FeOx	840	-	-	-	-	-	-	51-61	-	-	-	-	Active mine	Martinsson (1997)
Grängsberg	FeOx	227	-	-	-	-	-	-	58-64	-	-	-	-	Closed mine	Allen et al. (1996b)
Tellnes	Ti	408	-	-	-	-	-	-	-	-	-	18	-	Active mine	Charlier (2005)
Björkdal	Orog. Au	23.5	-	-	-	-	2.6	-	-	-	-	-	-	Active mine	Wehsted et al. (2003)
Pahlaavaara	Orog. Au	>3	-	-	-	-	3	-	-	-	-	-	-	Active mine	Eilu et al. (2003)
Kuopijärvi	Epith. Au	2.0	-	-	-	-	9	-	-	-	-	-	-	Active mine	Poutainen and Grönholm (1996)
Suuri-Kuusikko (Kittilä)	Orog. Au	24.3	-	-	-	-	4.75	-	-	-	-	-	-	Active mine	Pattison (2007)
Kotilahti	Ni-Cu	13	0.27	-	-	0.03	-	-	-	0.72	-	-	-	Closed mine	Papunen and Gorbunov (1985)
Hittura	Ni-Cu	13	0.2	-	-	0.02	-	-	-	0.59	-	-	-	Closed mine	Papunen and Gorbunov (1985)
Ahnaavaara	PGE	78.1	0.23	-	-	-	0.08	1.52 ppm PGE	-	0.09	-	-	-	Prospect	Wehsted et al. (2005)
Kemi	Cr	158	-	-	-	-	-	3	-	0.26	-	-	-	Active mine	Alapieti et al. (1989)
Talvivaara	Ni-Zn	338	0.14	0.56	-	0.02	-	-	-	0.3	-	-	-	Active mine	Loukola-Ruskeeniemi and Heino (1996)
Kevitsa	Ni-Cu	207	0.46	-	-	0.01	0.13	-	-	-	-	-	-	Prospect	Mutanen (1997)
Mustavaara	Fe-Ti-V	43.5	-	-	-	-	-	-	21.5	-	-	0.2	5	Closed mine	Alapieti (1982)
Onamäki	Fe-Ti-V	36.1	-	-	-	-	-	-	34	-	-	0.26	6.78	Closed mine	Eilu et al. (2007)
Björnevatn	BIF	140	-	-	-	-	-	-	31	-	-	-	-	Closed mine	Eilu et al. (2007)
Caledonides															
Lokken	VMS	30	2.3	1.8	0.02	-	0.2	19	-	-	-	-	-	Closed mine	Grenne et al. (1999)
Stekeljokk-Levi	VMS	25.7	1.43	2.55	0.23	-	0.3	50	-	-	-	-	-	Closed mine	Grenne et al. (1999)
Tverrfjellet	VMS	19.0	1.0	1.2	0.2	-	-	-	-	-	-	-	-	Closed mine	Grenne et al. (1999)
Jonia, Grong	VMS	22.5	1.49	1.7	tr.	-	-	-	-	-	-	-	-	Closed mine	Grenne et al. (1999)
Skorvas, Grong	VMS	10.0	0.8	1.6	tr.	-	-	-	-	-	-	-	-	Closed mine	Grenne et al. (1999)
Giken, Sulitjelma	VMS	9.5	2.25	0.70	tr.	-	-	-	-	-	-	-	-	Closed mine	Grenne et al. (1999)
Blackvassli	SEDEX	6	0.2	4.2	2.5	-	-	25	-	-	-	-	-	Closed mine	Grenne et al. (1999)
Bruvann, Rana	Ni-Cu	7	0.1	-	-	-	-	-	-	-0.53	-	-	-	Closed mine	Grenne et al. (1999)
Ørffjell, Rana	BIF	417	-	-	-	-	-	-	34	-	-	-	-	Active mine	Grenne et al. (1999)
Nordli	Porphy	200	-	-	-	-	-	-	-	-	-	0.14 % Mo	-	Prospect	Eilu et al. (2007)
Laisvall	MVT	64.5	0.1	0.5	3.9	-	-	11	-	-	-	-	-	Closed mine	Grenne et al. (1999)
Greenland															
Black Angel	SEDEX	-	-	-	-	-	-	-	-	-	-	-	-	Closed mine	Thomassen (1991)
Citronen Fjord	SEDEX	-	-	-	-	-	-	-	-	-	-	-	-	Prospect	van der Stijl & Mosher (1998)
Fiskensæset	Cr	-	-	-	-	-	-	-	Chromium	-	-	-	-	Prospect	Stendal et al. (2005)
Isua	Fe	-	-	-	-	-	-	-	Iron	-	-	-	-	Prospect	Stendal et al. (2005)
Brogedal	Cu	-	-	-	-	-	-	-	-	-	-	-	-	Prospect	Stendal et al. (2005)
Malmberget	Mo	-	-	-	-	-	-	-	-	-	-	-	-	Prospect	Stendal et al. (2005)
Nalunaq	Orog. Au	-	-	-	-	-	-	-	-	-	-	-	-	Active mine	Stendal et al. (2005)
Platinova Reef	Ni-Cu	-	-	-	-	-	-	-	Gold, Palladium	-	-	-	-	Prospect	Stendal et al. (2005)

1) This table lists major deposits in Norden where deposit data are available. Data for deposits 4, 5, 19, 20, 21, 22, 23, 35-55 from the Geological Survey of Finland deposit database, data for deposit 1, 2, 7-18 from Wehsted (2001), data for deposit 6 from Boliden Mineral AB, data for deposits 24-27 from Allen et al. (1996), data for deposits 28-30 from Geological Survey of Sweden mineral deposit database and data for deposit 31 from Charlier (2005).

2) Abbreviations: Strat. Cu = Stratiform Cu deposits; Porphy. = Porphyry type deposit; VMS = Volcanogenic massive sulphide deposit; FeOx = Fe-oxide deposit; Epith. Au = Epithermal Au deposit, BIF = banded iron formation.

3) There is only one reference for each deposit listed in the table. Where possible this is a recent reference containing more references to the deposit concerned.

4) Grade for epigenetic quartz vein hosted gold part of deposit.

The present economic mineral deposits (Figure 1) are largely concentrated in the Paleoproterozoic parts of the Fennoscandian Shield. Nickel-PGE, orogenic gold, and VMS (including some of uncertain classification), Pb-Zn, Cr and Fe-oxide deposits are the main types of economic interest in the Shield (Table 1). Large tonnage-low grade Cu-Au deposits (e.g., Aitik) are associated with intrusive rocks in northern areas. The latter have been described as porphyry style or as hybrid porphyry-IOCG style deposits (Weihed, 2001; Wanhainen et al., 2003). Also Fe-Ti oxides occurring in anorthosites and chromite in layered intrusions are major deposit types in the region. Besides these, mining of tungsten, molybdenum, REE and lithium has taken place during the last decades on smaller scales.

Greenland, with many terranes of Archean and Proterozoic age, is currently also being explored for similar commodities and the first gold mine is now in production. Also the Caledonian orogen hosts many major mineral occurrences in Norway and Sweden. This short review of ore deposit types in the Fennoscandian Shield and their geodynamic setting is chiefly derived from Weihed et al. (2005).

The main metal mining areas in Norden are described below and the metallogeny is put into a geodynamic context.

Greenland

Greenland's first gold mine, Nalunaq, located in the Nuuk region (Stendal and Secher, 2002) in southern Greenland, was officially opened in August, 2004 (Figure 2). Since the systematic exploration for minerals in Greenland started in the 1800s, moderate-size to major deposits of chromium, copper, gold, iron, lead, molybdenum, phosphorous, PGE, rare-earth metals, yttrium, silver, and zinc have been discovered but only a few have been mined (Table 1). Exploration for kimberlite pipes, with a potential for diamonds, is being carried out in west-central Greenland, and diamonds have been recovered in two areas (Jensen and Secher, 2004). Mining occurred in the last century at the Mestersvig lead-zinc deposit, the Maarmorilik (Black Angel mine) lead-zinc-silver deposit (Thomassen, 1991), and the Innatsiaq, Josva, and Lillian copper deposits in the Kobbminebugt. A new exciting discovery, the Citronen Fjord lead and zinc deposit, occurs near the Navarana Fjord Escarpment in north Greenland (Van der Stijl and Mosher, 1998).

Greenstone belts in Greenland are found in both Archean and Paleoproterozoic terranes, where they are generally rather small in volume compared to similar belts in Canada, Australia, and the Fennoscandian Shield. The Greenland Archean gneiss complex, a part of the 3.8–2.5 Ga North Atlantic Craton, contains fragmented belts (maximum 10 vol. %) of supra-crustal rocks within the gneisses. In addition, within Greenland's granite-greenstone terranes, mafic to ultramafic magmatic intrusions occur hosting major deposits, such as chromitite ($\pm$ PGE) in anorthosites, and gabbro complexes with V and Ti in magnetite and ilmenite.

Banded iron formations (BIF), mostly Algoma type, and gold mineralizations are typical for the Archean greenstone belts in Greenland. BIFs occur in three main localities with the most famous in the Isua supracrustal belt (~3805 Ma), and the two others of rather large size, at Itilliarsuk (~2850 Ma) and Melville Bugt (2700 Ma). The latter locality can be correlated with similar deposits on Baffin Island, Canada, which are subject now to feasibility studies.

Gold is a potential commodity in most of the Archean and some of the Paleoproterozoic greenstone belts and other supracrustal sequences. Most of the known Archean gold occurrences in Green-

Figure 2 Major metallic mines and prospects in Greenland. Map from *Greenland Mineral exploration letter (GEUS, 2007)*.

land are older than 2.7 Ga, and they are all smaller than similar deposits in Canada and Australia. The favourable areas are the southwestern edge of the Mesoarchean block at Sermiligaarsuk fjord within the Tartoq Group greenstone belt, and the Meso-Neoproterozoic belts in the Nuuk region where there are two interesting areas: One is a Mesoarchean arc-related system with a Cu-Au association (Qussuk), and the other is on Storø with a typical As-rich orogenic

gold-style mineralisation. To the north of the Archean block, the Paleoproterozoic mobile belts contain large amounts of reworked Archean rocks and Proterozoic intrusions. Within this belt, a Mesoarchean block is preserved in the northeastern part of Disko Bugt area containing both stratabound and orogenic types of gold deposits (Stendal and Garde, 2005; Stendal et al., 2007).

The juvenile Ketilidian orogen is considered to be a gold province with several prospects in different settings and the only gold mine in Greenland. The gold is thought to be related to the later stages of a batholith intrusion (1800–1770 Ma), but is found both in supracrustal rocks and granitoids (Stendal and Frei, 2000). The greenstone belts in the Paleoproterozoic domains outside South Greenland are at present considered to have a low potential for gold deposits. Supracrustal suites in the northern Nagssugtoqidian orogen (1950–1920 Ma) contain syngenetic massive sulphide occurrences (Natanaq and Ataneq), and the Ataneq area contains prominent graphite deposits. The Karrat Group comprises the SEDEX-style Black Angel deposit (Thomassen, 1991) and sulphide-gold occurrences at Karrat Isfjord. In Inglefield Land gold mineralisation is related to shear zones and hosted by Paleoproterozoic deformed gneisses and supracrustal rocks (Stendal et al., 2005).

Mineral occurrences in Greenland's magmatic environments are very promising, with giant porphyry molybdenum deposits related to a Paleogene alkaline intrusion in East Greenland and associated vein systems with gold and silver. Another giant deposit is the Skaergaard gabbroic intrusion containing a world-class deposit of Au, Pd, Pt, V and ilmenite. Except around known deposits, the Paleogene alkaline and mafic igneous rocks in East and West Greenland are, in general, frontier areas, providing optimism for the discovery of new deposits.

The alkaline Mesoproterozoic intrusions in the Gardar province contain large deposits of niobium, tantalum, zirconium, rare earth elements, and cryolite. Of these, the eudialite (zirconium) deposit at Ilimaussaq ('Kringlerne') has been thoroughly investigated. Within Greenland's Mesoproterozoic magmatic province an equivalent to the Voisey's Bay deposit in Labrador has still to be found. The carbonates of both Neoproterozoic and Jurassic age have a great potential for niobium, tantalum, REE and apatite. The Neoproterozoic kimberlite dykes and sills in the Kangerlussuaq area have promising diamond potential and are currently under exploration (Stendal et al., 2005).

Examples of sediment-hosted mineralizations are: (1) copper in Neoproterozoic and Triassic sandstones, (2) lead and zinc in shale/carbonate sequences, (3) fossil placer deposits and evaporite deposits and (4) lead-zinc veins in sediments in the Mesters Vig area in East Greenland, including the closed Blyklippen Pb-Zn mine.

SEDEX-type Pb-Zn deposits in shale sequences are found in the sedimentary basin in North Greenland. Carbonate-hosted Pb-Zn (MVT) is known from platform carbonates both in North and East Greenland. Celestite and barium deposits are related to basins with evaporites in East Greenland. Many of the sedimentary basins are situated in remote areas and are still frontier regions with respect to exploration. The geological setting in these remote areas is highly favourable for SEDEX- and MVT-type deposits (Stendal et al., 2005).

Fennoscandian Shield

Ni-Cu-PGE deposits

Ni-Cu±PGE deposits occur in several different settings within the Fennoscandian Shield (Weihed et al., 2005 and references therein). Nickel has been and still is mined on a large scale in northwestern Russia, (e.g., Pechenga) and Finland (e.g., Kotalahti, Hitura and Vammala) and to a lesser extent in Sweden (e.g., Lainejaur). The age and geodynamic setting of these deposits can be subdivided into: (1) Archean greenstone belts (2.74 Ga), (2) older Paleoproterozoic (2.49–2.45 Ga) mafic layered intrusions in Finland and Russia, also containing large Cr deposits and stand-alone PGE deposits, akin to Bushveld, (3) younger Paleoproterozoic (2.2 to 2.05 Ga) greenstone belts, (4) Paleoproterozoic ophiolite complexes (1.97 Ga), (5) rift-related ultramafic volcanism (1.97 Ga), (6) Svecofennian orogenic mafic-ultramafic intrusions (1.88 Ga), and (7) post-orogenic diabase dykes.

VMS deposits

Volcanogenic massive sulphide (VMS) deposits are currently the most exploited base metal ore type in the Fennoscandian Shield. Five deposits are currently mined in the Skellefte district in northern Sweden, one in the Pyhäsalmi area in central Finland and two in the Bergslagen region of south-central Sweden. However, it is unclear (as discussed below) whether or not some of the major deposits in the Bergslagen region should be classified as VMS deposits (e.g., Garpenberg and Zinkgruvan). Also an open question is whether or not the Outokumpu deposits (Kontinen, 1998; Sorjonen-Ward et al., 2004) really are VMS deposits *sensu stricto*. Significant VMS potential also exists in the northern Paleoproterozoic supracrustal belts, as shown by the now closed Viscaria and Pahtavaara Cu-Zn mines in Sweden and Finland, respectively.

Orogenic gold

Most of the gold occurrences of the Fennoscandian Shield belong to the orogenic category, following the terminology of Groves et al. (1998). These are present in practically all Archean and Proterozoic supracrustal belts. Some gold deposits have been described with alternative genetic models. For example, Enäsen (Hallberg, 1994) and Kutemajärvi (Poutiainen and Grönholm, 1996) have been interpreted as metamorphosed epithermal deposits. Today's largest gold deposit in the Fennoscandian Shield, Boliden, has also been described as a hybrid epithermal VMS deposit (Bergman Weihed et al., 1996). In the northernmost part of the Fennoscandian Shield, Cu-Au ores, such as Bidjovagge (Ettner et al., 1994), Pahtohavare (Lindblom et al., 1996) and Saattopora (Grönholm, 1999), have been described as orogenic gold deposits, although their high Cu content and saline mineralising fluids are more akin to IOCG deposits (Weihed, 2001; Eilu et al., 2003).

Almost all currently economic deposits are in the Paleoproterozoic domains (Sundblad, 2003). The apparent scarcity of Archean economic deposits may be due to the paucity of exploration for gold in the Russian part of the Shield, and that all gold exploration is recent within the region; also that the largest greenstone belt of the Shield (the Central Lapland greenstone belt) is Paleoproterozoic in age.

Age data on orogenic gold mineralizing events are scarce, but it is possible to constrain three major periods of mineralization: 2.72 to 2.67 Ga, 1.90 to 1.86 Ga and 1.85 to 1.79 Ga (Eilu and Weihed, 2005). The age data appear to define a rough zonation from northeast to southwest, which seems to be related to the southwestward growth of the Fennoscandian Shield with time.

Recent discoveries of orogenic gold deposits include the "Gold line" in northern Sweden with two active mines (Svartliden and Blaiken, currently in January 2008 the Blaiken deposit is put on hold due to technical and economic difficulties) and one deposit (Fäbodliden) in the feasibility stage. Suurikuusikko, in the Central Lapland greenstone belt of Finland, with a current *in situ* resource of 115 t gold, is the largest deposit in northern Europe and will start production in 2008 (Patison, 2007).

Fe deposits (including IOCG), porphyry Cu-Au and stratiform Cu±Au

The northern Paleoproterozoic part of the Fennoscandian Shield, including parts of Finland, Norway and Sweden, is an economically important metallogenic province dominated by Fe oxide and Cu±Au ores. Based on the style of Fe and Au-Cu mineralization and the extensive albite and scapolite alteration, the region has been regarded as a typical IOCG province (e.g., Martinsson, 2001; Williams et al., 2003; Niiranen et al., 2007). Four major types of deposits exist, namely skarn-like Fe±Cu±Au deposits, Kiruna type Fe oxides (apatite iron ores), and epigenetic and porphyry style Cu±Au and Au deposits. In strictly genetic terms, only some of these can be classified as typical iron oxide-Cu-Au (IOCG) deposits, whereas others only share a few characteristic features with this, rather loosely defined, ore class (cf. Hitzman et al., 1992; Hitzman,

2000). For example, the Kiruna-type deposits could also be interpreted as magmatic, or magmatic-hydrothermal occurrences (Nystrom and Henriquez, 1994).

Economically, the most important deposit type for the region is the apatite-iron ore, presently with an annual production of about 31 Mt of ore from the Kiirunavaara and Malmberget mines and a total production of about 1,600 Mt from 10 mines during the last 100 years. Copper and gold have been mined on a large scale in Sweden (Aitik), whereas other Cu-Au mines (e.g., Bidjovagge, Saattopora) have been small. All of the sulphide deposits are hosted by Paleoproterozoic greenstones and are small- to medium-sized except for Aitik, which occurs in Svecofennian volcanoclastic rocks and is a world-class deposit with a total resource of >1,000 Mt and an annual production of 18 Mt. At present, Aitik is seen as a porphyry-style deposit possibly with a subordinate IOCG-style overprint (Wanhainen et al., 2003).

The Bergslagen region in south-central Sweden, and its extension in southwestern Finland, hosts a number of Fe deposits of various types. Currently there is no mining of Fe in this historically important iron province (e.g., major deposits like Grängesberg and Dannemora), but the recent increase in metal prices has led to a feasibility study to re-open the Dannemora mine. Also the Stora Sahavaara IOCG-style (?) Fe deposit in northern Sweden is currently being investigated, together with similar deposits in the neighbouring Kolari area in Finland.

Fe-Ti oxides in anorthosites

Magmatic ilmenite deposits are typically hosted by anorthosite massifs. The second largest deposit of this type in the world is the Tellnes ilmenite norite deposit which was intruded into the central part of the Neoproterozoic Åna-Sira anorthosite massif, in the Rogaland Anorthosite Province of southwestern Norway (Bingen and Stein, 2003). Smaller Fe-Ti occurrences are widespread in the area. Among them, the most important are Storgangen and Blåfjell (Duchesne, 1999), but mining activities are currently confined to Tellnes where the average grade is slightly above 18 % TiO₂ for >380 Mt of ore.

Other deposit types

Other types of metal occurrences in the Nordic countries include Cr, Li, Mo, Nb, REE, Sn, Ta, W and U. The Kemi chromite mine in Finland is one of the largest chromium deposits in Europe. Recent promising exploration results include the 340 Mt Talvivaara Ni-Cu-Zn deposits hosted by metamorphosed black shales in the Paleoproterozoic Kainuu Schist Belt, Finland (www.talvivaara.com; Eilu et al., 2007). Talvivaara is an example of a previously unexploited style of mineralization which may prove, globally, to be a major new source for base metals.

During the last decade, diamond exploration has been successful in delineating diamondiferous kimberlite pipes especially in the Archangelsk area in Russia, but also in the eastern Finland (see <http://en.gtk.fi/ExplorationFinland/Commodities/Diamonds.html>).

Uranium is known to occur in several mineralization types in both vein-type deposits in Precambrian rocks, primarily in Finland and in Paleozoic shales overlying the Precambrian basement in Sweden. Substantial low-grade reserves are known in Cambrian alum shales (Wilson, 1979; Andersson et al., 1985; Gustafsson, 2007). Many of these deposits are now being investigated, although it is uncertain whether or not mining of uranium will be permitted in Sweden or Finland.

Caledonide metallogeny

The Caledonide nappe complexes in western Fennoscandia contain several major ore deposit types, some of world-class dimensions. In the post-world war era, massive Cu-Zn-Pb sulphide deposits in both volcanic and sedimentary settings comprised the backbone of the mining industry in Norway. The last massive sulphide mine was closed in the mid-1990s and large-scale exploration for new deposits of any kind has been minimal since the 1980s. Currently, the Ørtfjell iron deposit is the only Caledonian metallic deposit being mined.

Systematic exploration and research on Norwegian metallic deposits had a low priority since the mid-1990s, although the diversity of fertile geological terrains and large expanses of mostly unexplored territory provide an incentive for new exploration. Slowly, this situation is changing and currently there is active exploration in both the Fennoscandian Shield and the Caledonides of Norway, although far below the level now observed in Sweden and Finland. Most of the activities in the Caledonides concern hydrothermal gold deposits (e.g., Bindal and Mofjellet), but recently also polymetallic tungsten skarn deposits in the Nordland tungsten province and orthomagmatic Ni-Cu deposits in the Caledonides as well as the komatiite lithologies of Finnmark County in the Shield. According to Grenne et al. (1999), the Nordic Caledonian mineral deposits can be subdivided into:

- Stratabound, partly stratiform, massive to disseminated deposits of mainly Zn-Pb±Cu sulphides in mixed metasedimentary-metavolcanic successions (Bleikvassli, Mofjellet).
- Stratabound magnetite-hematite deposits in metasedimentary carbonate-pelite successions—so-called metasedimentary iron ores (Ørtfjell).
- Carbonatite-hosted Nb-Fe-P-REE deposits (Fen Complex).
- Organic-rich black shale deposits with concentrations of U, V, Mo, Ni.
- Stratabound, partly stratiform, massive pyritic deposits of Cu-Zn (±Pb) sulphides (VMS deposits, Stekenjokk-Levi, Lökken, Røros and Sulitjelma).
- Stratabound magnetite-(pyrite-chalcocopyrite) deposits (volcanic-hosted iron ores).
- Orthomagmatic Ni-Cu-S and Cr deposits with locally high PGE (Bruvann, Råna).
- Minor Cu-Mo stockwork mineralisation in felsic magmatic rocks.
- Stratabound, disseminated to semi-massive accumulations of Pb±Zn sulphides in quartz-arenites (MVT, sandstone lead deposits, Laisvall).
- Various, small, vein- and replacement type deposits characterised by Au, Ag, Pb, Zn, Sb, As, W, Mo or U, in metamorphic and plutonic complexes.

Geodynamic settings from the Archean to the Paleozoic

Throughout the evolution of the Fennoscandian Shield, the orogenic gold deposits also reflect the orogenic younging of the Shield towards the southwest and west. Most orogenic gold deposits formed during periods of crustal shortening, and the mineralization processes peaked at 2.72–2.67 Ga, 1.90–1.86 Ga, and 1.85–1.79 Ga.

Between ca. 2.5 to 2.4 Ga, the Archean craton rifted on a large scale, possibly for the first time, facilitating the emplacement of extensive layered intrusions and mafic dyke swarms. At this stage and, to some extent, also during later rifting stages at 2.2 to 2.05 Ga, Ni-Cu±PGE deposits formed both as part of layered igneous complexes and associated with mafic volcanism in rifted basins with komatiite volcanism in the Karasjokk, Kautokeino and Central Lapland greenstone belts. However, small Ni±Cu±PGE deposits also occur in the Neoarchean greenstone belts of eastern Finland (possibly also in Russia), and also these may be related to rifting of the Archean crust. Synorogenic mafic-ultramafic intrusions formed during the peak of the Svecokarelian orogen at ca. 1.89 to 1.88 Ga. These host numerous Ni-Cu deposits and are confined to linear belts that slightly post-date the regional arc volcanism.

Nearly all VMS-style deposits in the Fennoscandian Shield formed between 1.97 and 1.88 Ga in extensional settings during basin inversion and accretion. The oldest, the Outokumpu-type Cu-Co±Au±Ni±Zn deposits were formed at 1.97–1.95 Ga in mantle rocks that were subsequently obducted onto the Archean continent during onset of convergence. The next, more typical VMS deposits formed at 1.93 to 1.91 Ga in an accreted, primitive, bimodal arc setting which formed during extension of only slightly older volcanic crust in the Pyhäsalmi area in central Finland. Their host rocks are tholeiitic basalts and transitional to calc-alkaline rhyolites, including

high-silica varieties, and the deposits broadly fit within the “bimodal mafic type” classification of Barrie and Hannington (1999). The Skellefte VMS deposits are 20 to 30 million years younger and Allen et al. (2002) suggest that, in contrast to the deposits in the Pyhäsalmi area, the former district is a remnant of a strongly extensional intra-arc region that developed on continental or mature arc crust where the basement was only slightly older. The Bergslagen-Uusimaa belt, with a much more diverse metallogeny compared to the Skellefte and Pyhäsalmi areas, is coeval with the Skellefte area, but was formed within or at the margin of a microcontinent that collided with Fennoscandia at ca. 1.88 to 1.87 Ga. The Bergslagen region is interpreted as an intra-continental extensional or continental margin back-arc region developed on older continental crust (Allen et al., 1996b).

IOCG occurrences in the Fennoscandian Shield are diverse in style. At least the oldest mineralizing stages at ca. 1.88 Ga are coeval with magmatism having a monzonitic fractionation trend and calc-alkaline to alkaline subaerial volcanism more akin to continental arc, or magmatism inboard of an active arc. There also is evidence for multiple metal introduction or remobilization between ca. 1.80 and 1.77 Ga, related to late- to post-orogenic magmatism distal to an active N-S subduction zone further to the west (Weihed et al., 2002). Also, the interaction of magmas with evaporitic sequences in older Paleoproterozoic rift sequences could be significant for forming fluids able to carry large amounts of Fe, Cu and Au (Martinsson, 1997).

Large volumes of anorthositic magmas characterize the Sveconorwegian Orogeny, in the southwestern part of the Fennoscandian Shield. The best example of a major concentration of Ti associated with these anorthosites is the Tellnes deposit. The Tellnes ilmenite deposit belongs to the Mesoproterozoic (930 to 920 Ma) Rogaland Anorthosite Province in SW Norway. The rocks of this province were emplaced in the southwestern part of the Sveconorwegian orogenic belt under granulite facies conditions, ca. 40 million years after the last regional deformation (Bingen and Stein, 2003). Many massive, but small Ni-Cu sulphide occurrences also formed during emplacement of the anorthosite complexes associated with noritic melts (e.g., the Homsevatn deposit). Otherwise, more important orthomagmatic Ni-Cu deposits are associated with the early Sveconorwegian Iveland-Gautestad norite (1279±3 Ma) in Setesdalen comprising the Flåt Ni-deposit and several smaller occurrences. In addition, sub-economic Mo-occurrences are associated with Sveconorwegian granites, mostly in the southwestern part of this orogenic belt.

Ore deposits associated with the Scandinavian Caledonides may tentatively be divided into three groups: (1) formation during continental rifting and/or ocean floor spreading with emplacement as integral parts of the nappes during the Caledonian orogeny, (2) formation during plate convergence and ocean closure, or (3) formation during continent-continent collision and subsequent extensional orogenic collapse (Grenne et al., 1999). Accordingly, the deposits occur in the accreted Laurentia terrains to the west (now the Uppermost Allochthon), the outboard Iapetus oceanic sequences (Upper Allochthon), the outer continental margin sequences (Upper Allochthon, lower part) and the inner continental margin and shelf successions of Baltica (Middle and Lower Allochthon and Autochthon).

During Neoproterozoic to Cambrian pre-Caledonian divergent tectonics, massive to disseminated volcanosedimentary-hosted Zn-Pb±Cu and Cu-Zn sulphide deposits were formed in an Atlantic-type margin environment (Grenne et al., 1999). In the Shield, rift-type tholeiitic to carbonatitic magmatism gave rise to Nb, P and Fe mineralization in carbonatites of the Fen Complex. Late Cambrian epicontinental sedimentation deposited vast, but so far uneconomic resources of U, Mo, Ni and V in alum shales. Minor stratabound base metal sulphide and orthomagmatic Cr and Ni-Cu±PGE occur only in oceanic environments and continental margin and oceanic successions host many Cu-Zn sulphide ores in tholeiitic basalts. The earliest subduction-related sequences of major ore-forming importance are the Early Ordovician Stenokjokk-Fundsjö arc (ca. 490 Ma) and immature arc and ophiolitic assemblages formed between 500 and 480 Ma. In Early to Middle Ordovician times, magmatism gradually changed to a predominantly calc-alkaline character. Major granodiorites intruded the mature-arc sequences at an advanced stage of

development (ca. 460 Ma), occasionally containing sub-economic vein- and stockwork-type Cu-Mo mineralisation. By the end of the Ordovician, obduction of the arc-and-arc-basin systems on to the edge of the Laurentian plate took place. Thick clastic sequences were intruded by rift-type, mainly tholeiitic to alkaline, magmas with Ni-Cu mineralization and stratabound sulphides associated with volcanic rocks. The final, collisional stage of the Caledonian orogeny (Scandian) is represented by MVT-type Pb-sandstone deposits and Au, Ag, Pb, Cu, Zn, Fe, As, Sb, W, Mo±U vein deposits (Grenne et al., 1999). Post-collisional magmatism is associated with a regional mineralization event in the western parts of the Uppermost Allochthon, characterised by polymetallic W-Mo-Au occurrences (Larsen, 1991; Grenne et al., 1999). Recent Re-Os dating of the Bjellåtinden W-Mo skarn has provided evidence of a long-lived mineralization stage from 430±5 to 401±3 Ma, i.e., beginning at Scandian peak metamorphism and continuing through lower-grade extensional shearing (Larsen and Stein, 2007). Also the Målvika W-Mo-Au and the Bindal Au-deposits (currently in test production) belong to this latest Caledonian mineralizing event.

Concluding remarks

The Fennoscandian Shield is one of the most intensely mineralized Paleoproterozoic areas in the world. Important ore deposit types include volcanogenic massive sulphide deposits, orogenic gold deposits, layered intrusions, intrusive hosted Cu-Au, apatite-Fe deposits, and anorthosite-hosted Ti deposits. Currently all these types of deposits are exploited and exploration expenditure is at an all time high level in 2007. Investment in exploration in the Fennoscandian Shield in 2007 will probably be close to 100 million euros. Besides the well documented deposit types, new kinds of deposits are being explored, e.g., iron oxide-copper-gold (IOCG) and shale-hosted Ni-Zn-Cu and different types of uranium deposits. Greenland is still a frontier area concerning mineral exploration and mining, however, present high activity of exploration is promising for the country. Two mines are in operation (gold and olivine) and feasibility studies are in progress for five deposits.

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