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Metallogeny of gold in the Fennoscandian Shield

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Abstract. Gold occurs in a number of different ore types in the Fennoscandian Shield ranging in age from Late Archean to Late Proterozoic. Until recently, the metal was exploited primarily as a byproduct in volcanogenic massive sulphide deposits but during the 1980s more gold mines have been opened than during any other episode in the mining history of northern Europe. The occurrence of gold in the Fennoscandian Shield is reviewed in the context of the major tectonostratigraphic units:

1. In the Karelian Province, gold is hosted by greenstone belts of the Archean basement complex e.g. at Ilomantsi, eastern Finland. Greenstone belts of the Nordkalott Province, which are interpreted as part of an Early Proterozoic cover sequence, contain gold deposits associated with copper (Bidjovagge, Saattopora and Pahtohavare). Gold is also associated with cobalt in the metasomatically altered Early Proterozoic cover in northeastern Finland (Meurastuksenaho and Juomasuo).

2. In the Svecofennian Domain, the major gold deposits were generated during the emplacement of 1.92 – 1.87 Ga old accretional magmatism. These deposits occur in the northeastern part of the Svecofennian Domain, close to the Archean-Proterozoic boundary. They comprise two major types: (a) the porphyry-type and shear-zone gold hosted by tonalite at Tallberg, Laivakangas, Kopsa and Osikonmäki; (b) as a component of volcanogenic massive sulphide deposits (e.g. Holmtjärn, Boliden and Pyhäsalmi). Other types are: (c) gold-bearing quartz-alumina alteration zones formed during the 1.92 – 1.87 Ga magmatic period (Enåsen); (d) gold in massive sulphide and iron ore deposits in Bergslagen.

3. Gold associated with 1.84 – 1.54 Ga granites has been reported from several sites in the Shield, including quartz veins and contact-metasomatic deposits. In addition, shear-zone-related gold deposits post-datig these granites have been identified in southeastern Sweden (Ädelfors).

4. In the Sveconorwegian Domain, the gold deposits at Bleka, Eidsvoll, Glava and Harnäs are associated with shear zones which developed penecontemporaneously with the intrusion of late (1.0–0.9 Ga) granites.

These metallogenic features, deposit modelling and economic properties of the known occurrences suggest that the potential for new gold discoveries is highest in Late Archean to Early Proterozoic greenstone belts and in Early Svecofennian tonalite plutons. The gold potential of the Sveconorwegian Domain is also worth further consideration.

The Fennoscandian Shield, which occupies approximately one million square kilometers in Sweden, Finland, Norway and the westernmost USSR, is the largest Precambrian area in Europe. Although the bulk of the world's gold resources is restricted to Archean or Proterozoic shield complexes, the Fennoscandian Shield has never played a significant role as a gold producer. Nevertheless, gold has been reported from hundreds of prospects and deposits and during the last decade several gold mines have come into production. The systematic exploration for gold in the Fennoscandian Shield started in the 1980s and the results of the activities in Finland have been summarized by Nurmi (in press). Although information on the occurrence of gold in the Fennoscandian Shield is available in various publications, conference abstracts and unpublished reports (se reference list), no regional summary of gold metallogeny has been presented since Gavelin (1930) and Bugge (1935). The aim of the present contribution is, therefore, to review the available information on the occurrence of gold in the Fennoscandian Shield in order to highlight the metallogenic features of this Precambrian terrain.

History of gold mining in Fennoscandia

Gold has been mined in northern Europe for more than 200 years and detailed historical records of these activities are found in a large variety of publications. In the following summary, the oldest history has been compiled from Tegengren (1924) and Bugge (1935) whereas the history of discoveries made during the twentieth century has been compiled from available information on each specific deposit (see reference list).

The first gold deposit was discovered at Ädelfors in southern Sweden as early as 1581 but mining did not start until 1738. The mine was in operation during several stages for almost two centuries without achieving real economic importance and since the first World War it has been abandoned. The Eidsvoll gold veins in southern Norway have a similar history: they were mined for the first time in 1758 and for the last in 1907. Bleka in Telemark, southern Norway, was also mined on a small scale during the nineteenth century.

It has long been known that the copper ore at Falun contains gold, but it was not until 1790 that gold was extracted as a byproduct from the copper concentrate. In 1881 gold was also discovered in quartz veins in immediate association with the polymetallic massive sulphide deposit; these veins produced gold until 1925. Furthermore, gold has also been produced as a byproduct in many other ore deposits in the Bergslagen and Orijärvi Districts during the present century, including the massive sulphide deposits at Garpenberg and Orijärvi and the tungsten mine at Yxsjöberg. The Haveri deposit, southwestern Finland, was operated as an iron deposit at various stages until 1865. In 1935, gold ore was discovered and was mined until 1960.

Although several gold-bearing quartz veins had been known in the Skellefte Districts as early as 1901, it was not until the massive sulphide deposits were discovered after the first World War that significant gold production was implemented. The most spectacular example in this context was the Boliden deposit, which was the biggest gold producer in Europe during the 1950s. During the last decades, gold has also been recovered as an important byproduct in the Aitik, Vihanti, Pyhäsalmi and Outokumpu mines.

During the last six years five new gold mines have been opened in the Fennoscandian Shield: Enåsen, central Sweden (1984), Bidjovagge, northern Norway (1985), Björkdal, northern Sweden (1988), Saattopora, northern Finland (1989) and Åkerberg northern Sweden (1990).

General geological and metallogenetical outline of the Fennoscandian Shield

The Fennoscandian (Baltic) Shield has been subdivided into three domains. From east to west, these are the Archean Domain, the Early Proterozoic Svecofennian Domain and the Middle to Late Proterozoic Southwest Scandinavian Domain (Gaál and Gorbatschev 1987). The western margin of this Shield is concealed under the autochthonous and allochthonous units of the Caledonian Orogen. Precambrian rocks are, however, exposed in numerous tectonic windows under the Phanerozoic rock units, and large slices of Precambrian rocks are reworked and incorporated into the Caledonian mountain chain.

Table 1. Tectonostratigraphic overview of gold deposits in the Fennoscandian Shield

	Sveconorwegian Domain
1.0–0.9 Ga	Shear-zone related deposits Eidsvoll, Glava, Harnäs, Bleka
	Svecofennian Domain
1.8–1.5 Ga	Shear-zone related deposits in southeastern Sweden Ädelfors
	Deposits related to late granites Yxsjöberg, Tyfors, Van, Rautavaara, Pitkäranta
1.9–1.85 Ga	Porphyry-type shear-zone complexes and related quartz veins Kopsa, Osikonmäki, Laivakangas, Tallberg, Björkdal, Åkerberg
	Byproducts in massive sulphide deposits Outokumpu, Boliden, Holmtjärn, Kristineberg, Vihanti, Pyhäsalmi, Falun, Garpenberg, Orijärvi, Aijala, Metsämonttu
	Iron-ore-hosted gold in Bergslagen Nordmark, Malsjöberg, Riddarhyttan, Boviksgruvan
	Miscellaneous Enåsen, Kutemajärvi, Ylöjärvi, Haveri
	Karelian Province (Archean Domain)
2.1–1.9 Ga	Greenstone-hosted deposits Bidjovagge, Saattopora, Pahtohavare, Meurastuksenaho, Juomasuo, May
	Disseminations in felsic rocks Aitik, Nautanen, Fridhem
2.9–2.7 Ga	Greenstone-hosted deposits Hattuvaara, Kuittila

Gold mineralizations are known in three principal geological settings in the Fennoscandian Shield: (1) the westernmost unit of the Archean Domain, the Karelian Province, which is generally regarded as an Archean low- to medium-grade granitoid-greenstone belt terrane with a discontinuous Early Proterozoic cover; (2) the Svecofennian Domain, consisting of accreted Early Proterozoic crust; and (3) the western half of the Southwest Scandinavian Domain, composed of Mid-Proterozoic rocks which were reworked during the Late Proterozoic Sveconorwegian Orogeny (Fig. 1 and Table 1).

Karelian province

Crustal evolution

U-Pb and Sm-Nd dating of the oldest tonalites of the Fennoscandian Shield have yielded ages between 3.5 and 3.1 Ga (Jahn et al. 1984; Paavola 1986; Bibikova and Vernadsky 1988). Rifting of the Early Archean continental crust resulted in a system of linear troughs which now form strongly deformed NS- to NW- trending volcano-sedimentary belts, encompassed by tonalites, trondhjemites, granodiorites and granites (Blais et al. 1978; Gaál et al. 1978; Luukkonen 1988; Piirainen 1988). The various belts are characterized by different lithofacies: for

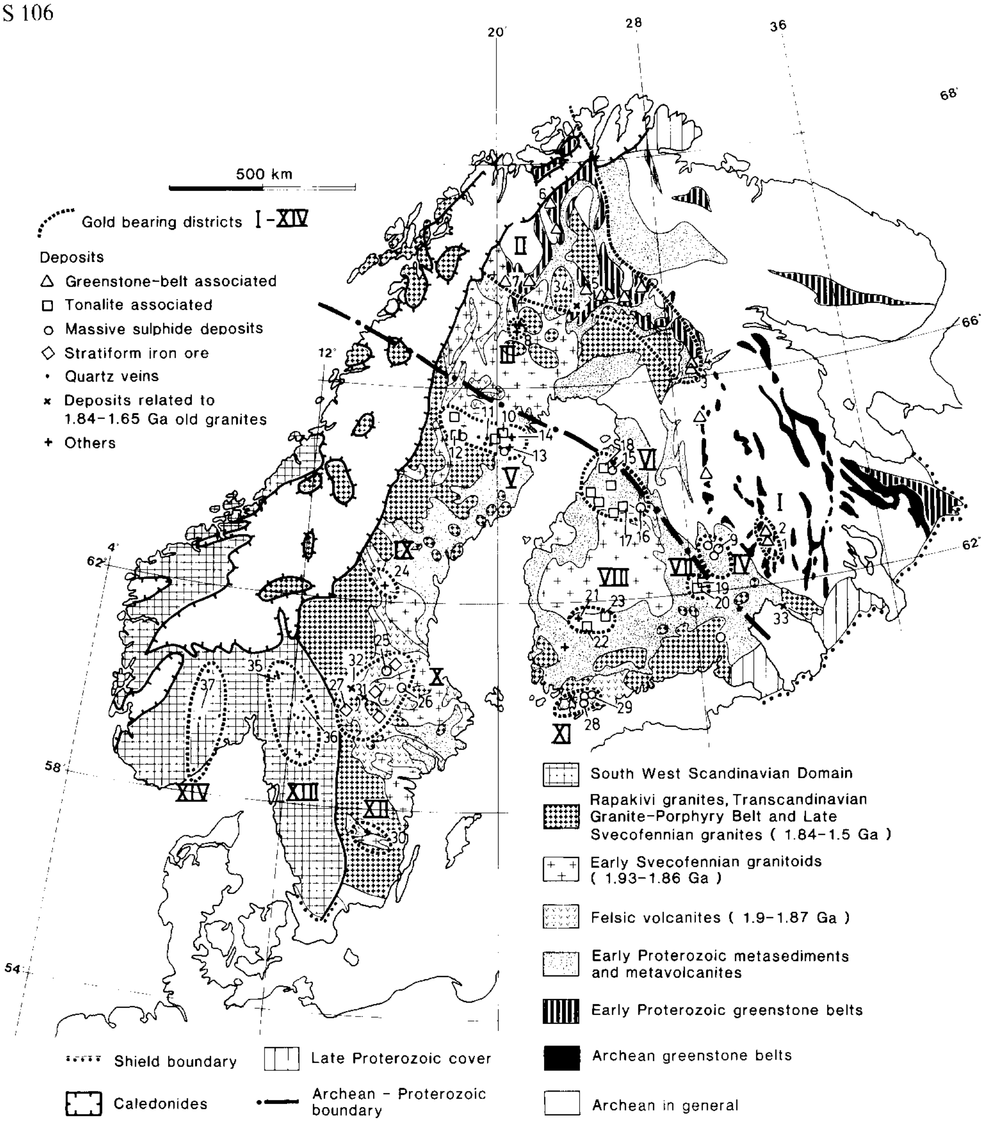

Fig. 1. Gold-bearing areas and gold deposits of the Fennoscandian Shield. *I Ilomantsi District:* 1. Hattuvaara, 2. Kuittila; *II Nordkalott Province:* 3. Meurarastuksenaho, 4. Juomasuo, 5. Saattopora, 6. Bidjovagge, 7. Pahtohavare; *III Aitik District:* 8. Aitik; *IV Outokumpu District:* 9. Outokumpu; *V Skellefte District:* 10. Boliden, 11. Holmtjärn, 12. Kristineberg, 13. Björkdal, 14. Åkerberg; *VI Pohjanmaa District:* 15. Vihanti, 16. Pyhäsalmi, 17. Kopsa, 18. Laivakangas; *VII Rantasalmi District:* 19. Osikonmäki, 20. Pirilä; *VIII Tampere District:* 21. Haveri, 22. Ylöjärvi, 23. Kutemajärvi; *IX Enåsen District:* 24. Enåsen; *X Bergslagen District:* 25. Falun, 26. Garpenberg, 27. Nordmark; *XI Orijärvi District:* 28. Aijala and Metsämonttu, 29. Orijärvi; *XII Ädelfors District:* 30. Ädelfors; *Deposits related to 1.81–1.54 granites:* 31. Yxsjöberg, 32. Tyfors, 33. Pitkäranta, 34. Rautavaara; *XIII Mjøsa-Vänern District:* 35. Eidsvoll, 36. Glava; *XIV Telemark District:* 37. Bleka

instance, the Kuhmo-Suomussalmi-Tipasjärvi belts are mainly composed of the tholeiite-komatiite association; the Kostamuska and Ilomantsi greenstone belts of metaturbidites, conglomerates and banded iron formation; and the Hautavaara greenstone belts of pyroclastic calc-alkaline volcanites. Volcano-sedimentary deposition took place at 2.9–2.7 Ga, while the age of metamorphism and granitoid plutonism is bracketed between 2.8 and 2.5 Ga. These estimates are based on U-Pb ages (Tugarinov and Bibikova 1980; Hyppönen 1983); WR Rb-Sr isochrons in contrast seem to indicate, more or less consistently, 200 Ma younger ages (Martin and Querré 1984). Plate tectonic models have been applied to explain Late Archean crustal evolution (Taipale 1983; Gaál and Gorbatschev 1987; Martin 1987).

The greenstone belts, partly with similar lithologies, in the northern part of the Fennoscandian Shield are more problematic. Gaál et al. (1978) have correlated the greenstone belts of Finnish Lapland with the Late Archean Kuhmo-Suomussalmi and Ilomantsi greenstone belts of eastern Finland. More recently, however, the greenstone belts of northern Finland have been assigned to the Lapponian Supergroup (Silvennoinen 1985). Silvennoinen (1985) places the Lapponian Supergroup into the Late Archean (2.75–2.45 Ga). The equivalent greenstone belts in Norway and Sweden have been dated with the U-Pb method to 1932±45 Ma at Kiruna (Skiöld 1986) and with the Sm-Nd method to 2085±85 Ma at Karasjok (Krill et al. 1985). Although Ward and Nurmi (1988) interpret the Lapponian greenstone belts as Early Proterozoic, the question has still not been satisfactorily answered since available geological and geochronological data do not put enough constraints on the age limits of the greenstone belts of the northern part of the Fennoscandian Shield. Correlation of at least part of these belts with the Late Archean greenstone belts in eastern Finland, as suggested by Muradymov et al. (1988), cannot be excluded.

The Archean crust of the eastern part of the Fennoscandian Shield was consolidated by 2.5 Ga. Nevertheless, Early Proterozoic tectonic-magmatic reactivation affected the Archean, and periods of rifting and compression alternated before and during the ensuing Svecofennian Orogeny. A tensional regime at around 2.45 Ga ago resulted in intrusion of tholeiitic magma, forming extensive, layered plutonic complexes (Alapieti

1982; Gorbunov et al. 1985) which were dismembered during subsequent tectonic movements. The volcano-sedimentary cover-sequence of the Sumi-Sariola Group was deposited on the rifted basement 2.5–2.3 Ga ago, after which there was a period of denudation and weathering. Quartzites, conglomerates, tholeiitic lava flows and carbonate rock of the Jatul Group, 2.3–2.1 Ga in age, complete the sequence upwards (Sokolov and Heiskanen 1985). The Archean crust and its cratonic cover were invaded by subparallel N-NW-trending swarm of doleritic dykes at 2.25–2.0 Ga, marking the initial stage of the formation of an Early Proterozoic continental margin (Gaál and Gorbatschev 1987).

Metallogeny

Most gold deposits in the Karelian Province are associated with greenstone belts of various ages (Fig. 1). The oldest greenstone belts are located in the Ilomantsi District (I), southeastern Finland, where several gold occurences are currently being prospected (Nurmi et al. 1988). The most extensive greenstone belts occur in the Nordkalott Province (II), which is distributed over the northernmost parts of Norway, Sweden, Finland and the westernmost part of the USSR. Economic to sub-economic gold deposits have been discovered in all four countries; Bidjovagge (Bjørlykke et al. 1987), Pahtohavare (Carlsson et al. 1988), Saattopora (R. Hugg, personal communication 1988) and May (Turchenko et al. in press). In addition to these greenstone-hosted gold deposits, gold-bearing copper ore occurs in felsic volcanic rocks in the Aitik District (III), northern Sweden.

I Ilomantsi District. Late Archean greenstone belts in southeastern Finland host numerous small gold mineralizations (e.g. the Hattuvaara and Kuittila deposits) in a N-S-trending, roughly 40 km long, linear belt which is currently the target of intensive exploration (Pekkarainen 1987; Nurmi and Ward 1988). The age of the greenstone belts is constrained by U-Pb dating on zircons to 2.9–2.7 Ga. Gold is hosted by various lithologies, including metagreywacke, conglomerate, pyroclastic rocks, tonalite and quartz veins. Hydrothermal alteration is indicated by sericitization, tourmalinization, carbonatization, silification, chlorite and biotite. The ore minerals accompanying gold are pyrite, pyrrhotite, arsenopyrite, chalcopyrite, molybdenite and sphalerite.

II Nordkalott Province. Tholeiitic and subordinate komatiic volcanites are the dominant rock types of the Karelian Province in the northern part of the Shield for which Pharaoh et al. (1987) coined the name "Nordkalott Tholeiitic Province". Mafic-ultramafic rocks in association with meta-turbidites and other epiclastic rocks form a greenstone-belt association which, according to the prevailing view, is mostly of Early Proterozoic age (Krill et al. 1985; Skiöld 1986). These rocks were deposited on rifted, attenuated continental crust in a whithin plate environment (Pharaoh et al. 1987). Rifting may also have led to restricted ocean opening (cf. Krill 1985).

Cu ± Au deposits of the region are associated with tholeiitic volcanites and have a typical mafic signature with anomalous Zn, Co, Ni and As values. Gold-bearing deposits of this type are decipted in Fig. 1 as the Nordkalott Province. Five deposists (Pahtohavare, Bidjovagge, Saattopora, Meurastuksenaho and Juomasuo) have a total of 10 million tonnes of ore grading, on average, 2.25 ppm Au and with varying Cu contents. This amounts to known reserves of 225 tonnes of gold metal in the Nordkalott Province. Hydrothermal alteration of the country rocks is a typical feature manifested in albitization, sericitization, carbonatization and silicification. Host rocks of the mineralization are altered tholeiitic volcanites and meta-sediments (Pankka and Vanhanen 1986; Bjørlykke et al. 1987; Carlsson et al. 1988; Korkiakoski et al. 1988; Pankka 1988; Turchenko et al. in press).

III Aitik District. In the Gällivare region (100 km southeast of Kiruna), a number of auriferous copper deposits including Aitik, Nautanen and Fridhem have been known since the turn of the century (Geijer 1918, 1923 a; Zweifel 1976; Danielsson and Lindroos 1986). The deposits are hosted by a sequence of meta-sediments and felsic volcanic rocks, which have been dated by the U-Pb method to 1909 ± 17 Ma (Skiöld and Cliff 1984). The Aitik Cu mine is the largest of these deposits (3 km long and 400 m wide) and has been mined from an open pit since 1967. The deposits in the Aitik District are characterized by large, disseminated low-grade copper bodies with gold as a significant by product. Besides chalcopyrite and gold, which are the main ore minerals, several other opaque phases such as bornite, chalcocite, sphalerite, and bismuth- and silver-tellurides have been reported (Zweifel 1976; Danielsson and Lindroos 1986).

Svecofennian domain

Crustal evolution

The Early Proterozoic volcano-sedimentary cover of the Karelian Province and the sedimentary rocks constituting the Svecofennian Domain are tectonically juxtaposed in a NW-trending zone extending from Lake Ladoga across the Bothnian Bay in Finland and continuing north of the Skellefte District up to the Caledonian Front. No isotopically defined Archean rocks are known southwest of this Ladoga-Bothnian Tectonic zone, and Nd, Hf, U-Pb and Rb-Sr isotopes indicate that Early Proterozoic crust was generated and accreted to the Archean crust 1.93–1.85 Ga ago (Huhma 1986; Patchett and Kouvo 1986; Vaasjoki and Sakko 1988). The junction between the Archean craton and the associated Proterozoic crust can be constructed somewhere along a line north of Savonlinna-Raahe to south of the Lofoten islands (Fig. 1). The Archean-Proterozoic boundary controls the most significant metallogenic provinces of the Fennoscandian Shield – gold included.

The following five crustal evolution stages and metallogenic epochs are distinguished: (cf. Gaál and Gorbatschev 1987; Vaasjoki and Sakko 1988, Gaál 1990):

1. Thinning and rifting of the Archean continental crust and intrusion of dolerite dykes (2.45 – 2.0 Ga)
2. Disruption of the continental crust, ocean opening and development of a continental margin; deposition of carbonate rock and BIF on the shelf and turbidites on the continental rise (2.0 – 1.95 Ga); Outokumpu and Jormua ophiolites 1.97 Ga
3. Early subduction of ocean crust leading to generation of trondhjemite-tonalite magma (1.93 – 1.9 Ga) followed by generation and intrusion of nickel-bearing tholeiitic magma (1.9 – 1.87 Ga) in the tectonic setting of oceanic island arcs
4. Second phase of subduction towards east (and retreating towards west) leading to development of calc-alkaline island arcs with 1.91 – 1.87 Ga old volcanites intruded by large granitoid batholiths of 1.89 to 1.87 Ga age. Collision of these island arcs with Archean crust was followed by the main deformation and metamorphism and obduction of ophiolites
5. Magmatic underplating manifested by the intrusion of S-type Late Svecofennian granites (1.84 – 1.74 Ga)

Metallogeny

In terms of gold, there are eight different metallogenetic districts in the Svecofennian Domain: IV Outokumpu, V Skellefte, VI Pohjanmaa, VII Rantasalmi, VIII Tampere, IX Enåsen, X Bergslagen and XI Orijärvi. Three of these districts – Skellefte, Pohjanmaa and Rantasalmi – form a linear belt parallel to the southwestern boundary of the Archean crust. This trend constitutes a major geological and metallogenic structure along which a number of gold and massive sulphide deposits and Ni-bearing mafic-ultramafic bodies occur. The Bergslagen District forms another complex mining district with numerous iron, base, alloy and noble metal deposits.

IV Outokumpu district. Cu-Zn-Co-bearing massive sulphide deposits occur in the Outokumpu region in a rock association composed of serpentinite, dolomite, calc-silicates, cherty quartzite, graphitic schists and mica schists. The geological setting is envisaged as a linear rift zone with ocean opening and hydrothermal fluids leaching underlying ultramafic rocks and precipitating metals along a fissure zone (Koistinen 1981). The serpentinites in Outokumpu have been interpreted as part of a dismembered ophiolite complex. The associated gabbro has been dated in Outokumpu and the analogous Jormua ophiolite complex to 1.97 Ga by the U-Pb method on zircons (Koistinen 1981; Kontinen 1987). Economically significant gold abundances have been reported from the Outokumpu mine (28 million tonnes grading 0.6 ppm Au), and from the recently discovered Kylylahti deposit (4 million tonnes of massive sulphide ore grading 0.95 ppm Au).

V Skellefte district. The Skellefte District forms a 200 km long belt which has been interpreted as an Early Proterozoic volcanic arc (Rickard 1986). The volcanic rock units, as well as the adjacent I-type tonalitic-granodioritic intrusions, have been dated by the U-Pb method to 1.89-1.88 Ga (Welin 1987; Wilson et al. 1987) and comagmatic relationships between these rock units have been suggested. The area is one of the most important mining districts in Sweden with respect to base metals and gold and two kinds of gold occurrence can be distinguished:

1. Byproducts of massive sulphide deposits. These deposits, which include Boliden, Renström, Långdal, Kristineberg and Holmtjärn, have been described in some detail by a number of authors, see Rickard (1986) and references therein. A volcanogenic model, first postulated by Rickard and Zweifel (1975), is now generally accepted for their formation. Gold in relation to the ores in the Skellefte District was first discussed by Mörtsell (1931) and has recently been treated in greater depth by Nysten (1986), Nicholson et al. (1988) and Bergman et al. (1989). Some of the very high gold values recorded in the Boliden deposit were partly caused by tourmaline-bearing veins crosscutting the massive sulphide ore (Ödman 1941), but the massive sulphide ore in the Skellefte District often shows anomalously high gold values compared with massive sulphide deposits elsewhere in the world. Although the gold values may be lower than 1 ppm in some deposits, gold grades in the range 1 – 8 ppm have been recorded at Holmtjärn, Österbäcken, Renström, Långdal, Kristineberg and Norrliden (Gavelin 1939; Rickard 1986; Nicholson et al. 1988).

2. Quartz veins. Auriferous quartz veins $\pm$tourmaline are commonly associated with the 1.89 Ga granitoid intrusions and include the Björkdal, Tallberg, Fäbodliden, Storklinten, Vinliden and Grundfors deposits (Löfgren 1987; Weihed et al. 1987; Markkula 1988; Weihed and Bergström 1988; Bergman in press) but gabbro-hosted veins have also been found at Åkerberg. The auriferous quartz veins at Tallberg (Weihed et al. 1987) are closely related to Cu-Mo-Au disseminations in the granitoid host rock accompanied by propylitic and phyllic alteration around subvolcanic quartz-feldspar porphyritic stocks.

VI Pohjanmaa district. The calc-alkaline island arc environment in the Pohjanmaa District is characterized by numerous semi-circular batholith complexes of tonalitic to granodioritic composition. Most gold mineralizations in the district are hosted by quartz veins and stock works within tonalitic batholiths and stocks or in their contact zones. Mineralization is accompanied by hydrothermal alteration such as silicification, propylitization and potassic alteration. Gold is accompanied by copper, molybdenum and arsenic, and the deposits have been classified as the porphyry type (Gaál and Isohanni 1979; Nurmi and Haapala (1986). The low-grade, porphyry-type Kopsa Cu-Au deposit, which is hosted by a tonalite-porphyry rock, contains 25 million tonnes of ore grading 0.6 ppm Au and 0.18% Cu. The Laivakangas deposit is of similar type and ore reserves have been estimated to be 400 000 tonnes with 3.5 ppm Au (Mäkelä et al. 1988). Gold has also been recovered as a byproduct of the massive sulphide deposits in the Vihanti and Pyhäsalmi mines (Ekberg and Penttilä 1986).

VII Rantasalmi district. Several gold prospects in this district are genetically related to tonalitic batholites. The largest deposit, Osikonmäki, is hosted by a folded shear zone in tonalite (Kontoniemi and Ekdahl 1990). The Pirilä gold deposit is hosted by silicified and potassium-altered supracrustal rocks in contact with tonalite. The deposit has been interpreted by Makkonen and Ekdahl (1988) as volcanogenic.

VIII Tampere district. South of the 1.90–1.89 Ga old Granitoid Complex of Central Finland (Huhma 1986), several gold deposits are known in the E-W-trending Tampere district. In the Haveri Au-Cu mine a mafic meta-volcanite hosts magnetite, pyrrhotite, chalcopyrite and pyrite ore with 2.8 ppm Au and 0.37% Cu (Stigzelius 1944; Ore Deposit Databank of Finland, GSF). The exhausted Cu-W deposit of Ylöjärvi is hosted by a tourmaline breccia which has been compared with Phanerozoic tourmaline breccia pipes of porphyry copper affinity (Himmi et al. 1979; Gaál et al. 1981). Mined reserves were 4 million tonnes grading 0.67 ppm Au, 0.71% Cu and 0.01% W. At Kutemajärvi, gold occurs together with a number of tellurides in a quartz-sericite-topaz rock in contact with tonalite. Estimated reserves have been calculated to 0.6 million tonnes of ore grading 9 ppm Au (Ollila and Kojonen 1990).

IX Enåsen district. This district consists of one single deposit, Enåsen, which was discovered during a prospecting campaign for base metals during the 1930s. In 1984, the mine was opened for gold production (Lundqvist et al. 1986). The ore consists of native gold and gold-tellurides associated with chalcopyrite and pyrrhotite in an amphibolite facies topaz-bearing quartz-sillimanite gneiss (Nysten and Annersten 1984; Hallberg 1988). Hallberg (1989) has shown that the deposit was formed semi-contemporanously with the major ore-forming events in the Skellefte and Bergslagen districts, and Hallberg (1988) has also suggested that the deposit is of the epithermal hot-spring type with gold precipitation in siliceous sinters during advanced argillic alteration.

X Bergslagen district. Bergslagen has been the most active mining district in Fennoscandia and includes a number of different ore types which were formed during several geological events. Most iron- and base metal deposits are closely associated with 1.9 Ga old felsic volcanics, but significant alloy metal deposits were also formed in conjunction with the intrusion of younger granites. Gold has concentrated in several different environments in connection with these ore-forming events and is associated partly with 1.9 Ga stratiform iron oxide or massive sulphide deposits and partly with late (1.84–1.65 Ga) granitic intrusions. Since gold occurrences related to the late granites are not restricted to the Bergslagen District, these deposits will be discussed separately.

1. Byproducts in volcanogenic massive sulphide deposits. This groups includes several important mines, e.g. Falun, Garpenberg, Saxberget, Kaveltorp and Svärdsjö. The metals in these deposits, including gold, are generally considered to have concentrated as a result of volcanogenic processes (Koark 1962; Vivallo 1985). The lead contents in these deposits are generally much higher than in the massive sulphide deposits in the Skelllefte District (Table 2), which probably reflects a continental margin affinity in Bergslagen. The gold values are generally lower than 1 ppm and are comparable to those of many other massive sulphide deposits in the world.

Gold-bearing quartz veins with a number of Bi- and Se-minerals have been reported from the northeastern part of the Falun mine (Nordenström 1882; S. Adolfsson, personal communication 1989). Preliminary fluid inclusion data presented by Åberg (1990) have indicated an evolution from hot gold-bearing fluids with CO_2 to cooler barren fluids. Although these veins have been regarded informally as a stringer zone to the massive ore, they show many characteristics which differ from volcanogenic stringer systems which indicate that the Falun veins may be considerably younger than the stratabound massive sulphide ore.

2. Gold in iron ore. Stratiform iron ore layers including "banded iron formation" and "skarn iron ore" occur at numerous sites in the Bergslagen District. These deposits are considered to have formed by exhalations on the sea floor in either quartz-rich, lime-rich or lime/clay-rich environments (Magnusson 1970). The calc-silicate assemblages in the skarn iron ores are the result of regional metamorphism, and the skarn concept used for these ores

Table 2. Known mineable gold reserves (mined and not mined) in sulphide deposits of the Fennoscandian Shield

Ore-bearing area	Major metals	Average grade of ore					Total ore million tons	Total metal (tons)	
		Au	Ag	Zn	Cu	Pb		Au	Ag
II, III Nordkalott Province and Aitik District	Cu±Au±Co	0–5			0.47		525	1 486	25 000
IV Outokumpu District	Cu, Zn, Co	0–1		1.0	2.7		50	21	
V Skellefte District	Cu, Zn, As	2.7	61	3.6	0.9	0.3	80	216	4 880
VI Pohjanmaa District (Vihanti-Pyhäsalmi)	Cu, Zn	0.3	20	3.4	0.65	0.15	70	21	1 400
X Bergslagen District	Zn, Cu, Pb	0.4	46	5.5	0.65	1.8	75	30	3 450
								1 774	34 730

should not be confused with the nomenclature for calc-silicate assemblages formed as a result of intrusion-related contact-metasomatic processes.

The occurrence of gold in these iron skarn deposits was first recognized by Löfstrand (1894) and Flink (1908), who described the occurrence of native gold together with bismuthinite and pyroxene in the Nordmark and Ludvika areas. A similar assemblage was noted by Geijer (1923 b) for an iron ore deposit in the Riddarhyttan area. Further discoveries of this type of gold occurrence have recently been made at other sites in the Nordmark, Riddarhyttan and Svärdsjö (Boviksgruvan) areas (Hammergren et al. 1986; Bergman 1990). Gold is found at all these sites intimately intergrown with bismuth minerals and pyroxene. Although high gold grades have been encountered locally, none of these deposits is of economic importance at present. The origin of this type is still not understood, but Hammergren et al. (1986) and Bergman (1990) consider that the gold was precipitated by a hydrothermal event that postdated the iron ore deposition.

XI Orijärvi district. The Orijärvi District, with four small volcanogenic massive sulphide Zn-Cu-Pb-Ag deposits, can be considered to be the eastern continuation of the Bergslagen District. Gold has been reported as a byproduct from Aijala (0.7 ppm) by Warma (1975) and from Metsämonttu (1.4 ppm) by Latvalahti (1979).

Late granites (1.84 – 1.54 Ga) in the Karelian Province and the Svecofennian Domain

Late granites occur throughout the Archean and Svecofennian Domains of the Fennoscandian Shield. Marked concentrations of these granites are met with in two E-W-trending zones in the southern part of the shield, extending from Lake Ladoga to the Bergslagen District, and in the northern part of the shield, associated with the Nordkalott Province. A third zone of concentration trending N-S runs parallel to the western boundary of the Svecofennian Domain. On the basis of a number of recent age determinations (Huhma 1986; Vaasjoki 1977; Wilson et al. 1985; Jarl and Johansson 1988; Patchett et al. 1987; Skiöld 1988; Billström and Öhlander 1989; Mansfeld in press), these granites can be classified into two age groups. The older group includes the Late Svecofennian granites and the Transscandinavian Granite-Porphyry Belt (1.84 – 1.77 Ga), and the younger group the Rätan-Siljan-Rapakivi granites (1.75 – 1.54 Ga). The Late Svecofennian granites are generally anatectic S-type microline granites with some alkaline affinities, whereas the Transscandinavian Granite-Porphyry Belt shows I-type characteristics (Wilson and Åkerblom 1982). The Rapakivi granites have been classified as A-type granites (Nurmi and Haapala 1986).

Metallogeny

Ore deposits associated with these young granites comprise tungsten, molybdenum, tin, iron and REE mineralizations at a number of sites in the Shield. Gold has been reported in small quantities from several of these different deposits and two types of environment can be distinguished; auriferous quartz veins and contact-metasomatic skarn deposits.

Gold-bearing veins hosted by granites are generally very small and their gold values are usually of no more than mineralogical interest. Such veins have been reported at Tyfors and Van (Ohlsson 1979; Ohlsson, personal communication 1987), where small amounts of native gold occur together with wolframite ± cassiterite and Bi-minerals. The Tyfors and Van veins are hosted by a granite of the Rätan-Siljan-Rapakivi group.

Contact-metasomatic skarn deposits related to 1.84 – 1.54 Ga granites occur at various places in the Fennoscandian Shield and have been subject to mining for W, Sn and Fe. Gold has either been extracted as a byproduct in these mines or has been observed microscopically, as at Pitkäranta (Saksela 1953), Yxsjöberg (S. Månsson, personal communication 1989) and Rautavaara (Hiltunen 1982).

Structurally related gold deposits in southeastern Sweden

XII The Ädelfors District. The auriferous quartz veins at Ädelfors are hosted by Svecofennian mafic volcanic rocks adjacent to a major WNW-ESE-trending shear zone separating the volcanics from 1.8 Ga granites. Gold is closely associated with pyrite and various bismuth minerals (Bergman, 1986) and the wall-rock has been enriched in potassium but depleted in sodium (Sundblad 1990). The geological setting of these veins has been compared with that of the Mother Lode system in California and the Ädelfors veins are considered to have been emplaced in conjunction with shear movements shortly after the emplacement of the 1.8 Ga granitoids (Sundblad 1990).

Southwest Scandinavian Domain

Crustal evolution

Southwestern Scandinavia is dominated by various gneiss units which are separated from the Svecofennian Domain by a tectonic zone referred to as the "Protogine Zone". Several thrust contacts have been identified within this gneiss complex and the magmatic and metamorphic evolution ranging from > 1.6 Ga to 0.9 Ga has been established. The last metamorphic event, which was related to the Sveconorwegian Orogeny, took place at 1.1 Ga. Magmatic activity ceased with the intrusion of S-type granites and associated U-rich pegmatites in the Bohus, Østfold, Blomskog and Telemark areas (Killeen and Heier 1974; Wilson and Åkerblom 1982). A Rb-Sr determination of the Bohus Granite has yielded an age of 0.89 Ga (Skiöld 1976) whereas U-Pb determinations on pitchblende from some of the associated pegmatites have yielded ages in the range 1.06 – 0.88 Ga (Chyssler and Kresten 1979). This Precambrian terrain is geographically divided into two parts by the Permian Oslo Paleorift.

Metallogeny

A number of shear-related gold-bearing quartz veins have been recognized in the Southwest Scandinavian Domain on both sides of the Permain Oslo Paleorift. The veins cut through the main foliation in the host rocks and an age of ca. 1.0 Ga has been obtained from a Pb-Pb galena isochron in the Värmskog-Vänern area by Johansson (1985). Furthermore, a U-Pb age of 0.96 Ga on pitchblende from the the Långvattnet (Härserud) Au-Mo-W-Bi-Te-U deposit (Chyssler and Kresten 1979; Hammergren 1980) agrees well with the ages obtained on the Bohus granite and their associated pegmatites, which indicate a close temporal relationship between emplacement of the late granites, development of the shear structures and ore-forming processes in this area. This is consistent with observations of Nordrum (1978), Ihlen (1986) and Lundegårdh (1989). Two ore-bearing districts can be recognized in the Southwest Scandinavian Domain:

XIII Mjøsa-Vänern district. This district comprises the ancient gold mines at Eidsvoll, Norway (Ihlen 1978, 1986), a number of abandoned copper deposits farther southeast in Sweden such as Glava (Oen and Kieft 1984) and Harnäs (Lundegårdh 1989) and the lead-silver veins at Värmskog (Johansson 1985).

XIV Telemark district. The only deposit in this district to have been investigated in some detail is Bleka in the Telemark area, Norway. These gabbro-hosted quartz veins are associated with shear zones and alterations, and native gold, chalcopyrite, pyrite and various bismuth minerals have been identified (S. Jensen, personal communication 1989). Other gold-bearing veins in this district include Haukum, Haukedal, Hisø and Romelien (Foslie 1925).

Conclusions

From the above facts it is clear that gold has been concentrated in the Fennoscandian Shield by a large variety of geological processes during a number of epochs ranging from the Late Archean to the Late Proterozoic. Many of the conventional ore types contain enough gold to be extracted as a byproduct. In addition, specific geological features, such as major tectonic breaks, and certain key lithologies govern the distribution of many of the most important gold deposits.

The known mineable gold reserves – mined and not mined – are estimated at 1800 tonnes (Table 2); the major part of this figure is arrived at as.byproducts from various sulphide deposits. Furthermore, this estimate is dominated by the gold content of the large, low-grade Cu-Au deposit of Aitik in northern Sweden. It is likely that the figure will be augmented as gold exploration continues in the Fennoscandian Shield.

From the review presented in this paper, we can predict that the most prospective areas for further gold discoveries are the greenstone belts of both Archean and Proterozoic age. This is indicated by recent discoveries at Pahtohavare, Saattopora and Ilomantsi and also by analogues with other greenstone belts in Canada, Brazil, southern Africa and Australia.

A distinctive feature of the Fennoscandian Shield is the occurrence of gold in association with Early Proterozoic tonalites and granodiorites along the Archean-Proterozoic boundary. Although the deposits so far discovered are of low grade (Tallberg, Kopsa and Osikonmäki), this deposit type can be regarded as having the most economic potential in the Svecofennian Domain.

The recognition of large amounts of auriferous quartz veins in southwestern Scandinavia has been one of the pleasant surprises in this work. It is, thus, possible that this part of the Fennoscandian Shield may attract more interest from prospecting companies in the future.

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