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# A Review of Gold Mineralization Styles in Finland

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## Abstract

A wide range of styles of gold mineralization has been recognized in Finland, including orogenic, metamorphosed epithermal, skarn- or epigenetic ironstone-hosted, intrusion-related (nonskarn), massive sulfide-hosted, paleoplacer, and placer deposits. Gold production in the past was principally as a byproduct from the mining of Paleoproterozoic base-metal massive sulfide deposits. This situation has changed during the last decade with the closure of some base metal mines and the commencement of production from recently discovered, gold-only deposits.

Gold mineralization occurred during distinct episodes of crustal evolution in Finland. Several late-Archean greenstone belts in the Karelian craton in eastern and northern Finland contain orogenic gold deposits dated at about 2.75 to 2.70 Ga, suggesting a coherent and pervasive tectonic and metallogenic event. In the Paleoproterozoic, low-grade (<1 ppm) concentration of gold occurred within the Outokumpu Cu-Co-Ni massive sulfide deposits, associated with ophiolites formed during rifting of the Karelian craton at 1.97 to 1.95 Ga. Svecofennian magmatism between 1.91 and 1.87 Ga, attributed to the formation and accretion of a number of volcanic arcs adjacent to the Karelian craton, is associated with syngenetic massive sulfide mineralization, commonly with gold grades between 0.1 and 1.0 ppm. The Tampere schist belt in southern Finland, which formed within this accretionary setting, is host to the Kutemajärvi gold deposit, which appears to be a metamorphosed high-sulfidation epithermal deposit that formed within a subsiding felsic volcaniclastic and subvolcanic sill complex during the transition from calc-alkaline through more alkaline volcanism.

The main accretionary stage of the Svecofennian orogeny in Finland culminated with metamorphism and deformation between 1.89 and 1.86 Ga. During that time, intrusion-related Au-Cu mineralization took place in both syntectonic porphyry stocks and their wall rocks in and close to the Archean-Proterozoic margin. Orogenic gold mineralization took place at or slightly after the metamorphic peak throughout the Svecofennian domain, possibly also overprinting massive-sulfide and intrusion-related occurrences. It is notable that the largest orogenic deposits are located within discrete plutons, rather than hosted by supracrustal sequences. This may be a consequence of the rheological contrasts between plutons and the supracrustal lithologies.

The Paleoproterozoic Lapland domain in the northern part of the country records a protracted and complicated evolution involving multiple episodes of rifting, magmatism, sedimentation, and alteration, culminating at around 1.9 Ga with the collision of the Karelian craton, the Svecofennian fold belt to the south, and the Kola craton to the north. These deformational events led to orogenic gold mineralization throughout the Proterozoic greenstone belts of northern Finland at about 1.89 to 1.86 Ga, during and soon after the peak of metamorphism and deformation. Skarnlike or epigenetic ironstone-hosted deposits were also formed during the orogeny, in the western and southwestern parts of the Lapland domain, probably somewhat later, at around 1.86 Ga. The most favorable sites for mineralization are regionally extensive zones of early albitization that predate gold mineralization. The deposition of molasselike sediments during the terminal stages of the Svecofennian orogeny and weathering of both orogenic and syngenetic sulfide mineralization, also prior to 1.8 Ga, produced placer accumulations (now paleoplacers) in the conglomerates of the uppermost formation of the Central Lapland greenstone belt. Placer deposits of controversial origin and provenance have also been worked for many years in the glaciofluvial sediments of northernmost Finland.

The areas with greatest potential for the discovery of new orogenic gold deposits in Finland are the late Archean and Paleoproterozoic greenstone belts in eastern Finland and Lapland, respectively. Some Fe-Cu-Au skarns or epigenetic ironstone-hosted deposits have been mined in the past, and there may be potential for the discovery of larger iron oxide-copper-gold systems in the western Central Lapland greenstone belt. For intrusion-related (nonskarn) mineralization, the most promising areas are close to the Raahe-Ladoga Suture, and the potential for additional metamorphosed and deformed epithermal mineralization exists in the Tampere schist belt. The significant number of gold occurrences already known in these areas highlights the potential for new discoveries.

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## Introduction

Prior to the 1980s, very few gold occurrences were known in the Fennoscandian Shield, the most significant having been the Boliden deposit in the Skellefte district of northern Sweden (Bergman Weihed et al., 1996). In Finland, there was little understanding or awareness of the potential for gold mineralization (e.g., Kahma, 1973; Isokangas, 1978; Mikkola, 1980). This situation was reflected in the special issue of *Economic Geology* on mineral deposits in Fennoscandia (1979, vol. 64, no. 5), in which only one deposit with gold as a significant commodity is described (Gaál and Isohanni, 1979). Prior to 1988, only two deposits, Haveri and Kivimaa (Fig. 1), had been mined chiefly for gold (Rouhunkoski and Isokangas, 1974; Mäkelä, 1980).

This perception has changed since the early 1980s, in response to the increase in the price of gold during the 1970s, extensive research into the formation of gold deposits, which

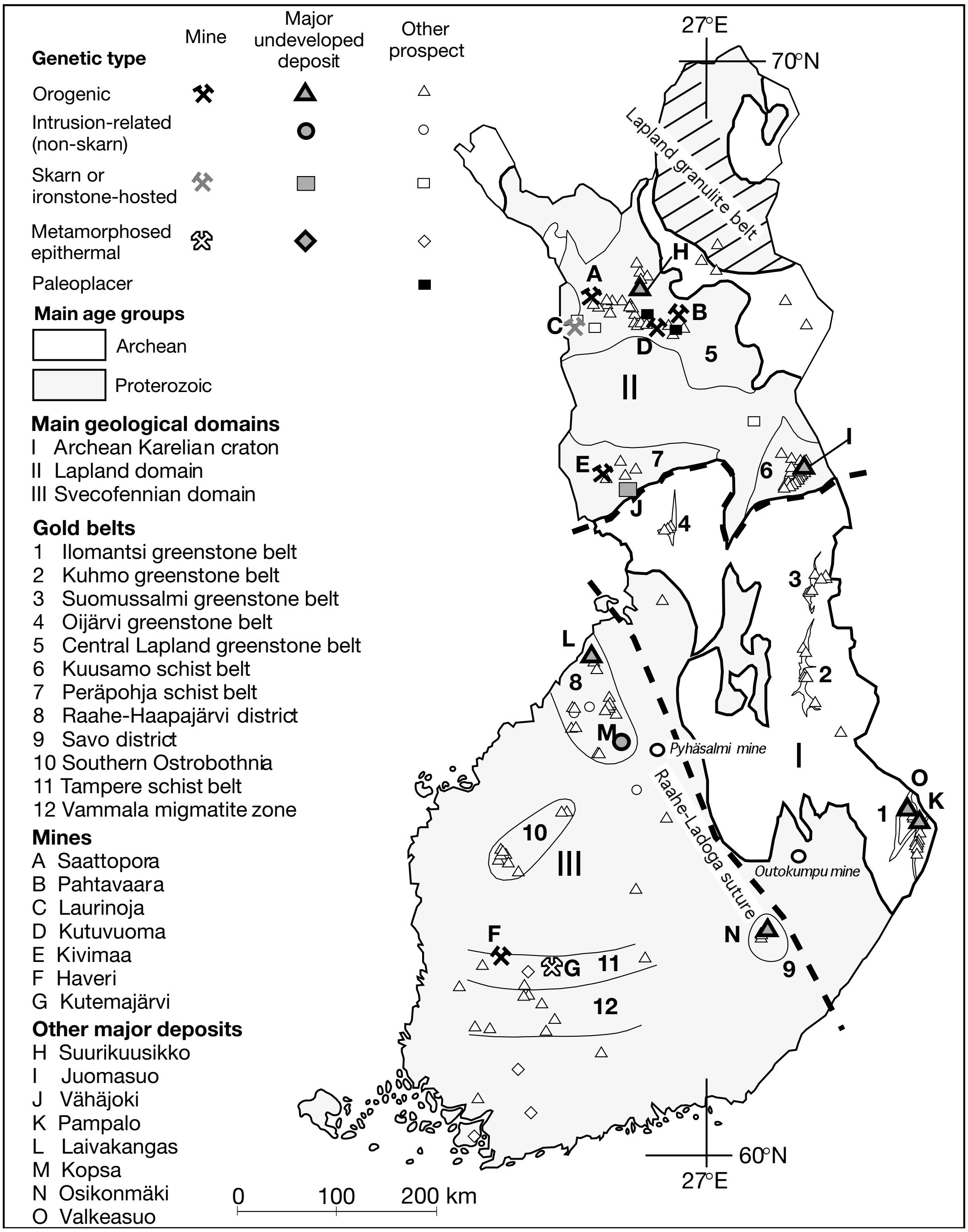


Fig. 1. Three major geologic domains (I–III) of Finland, with their boundaries marked by thick dashed lines. The distribution of gold mines (A–G), other major gold deposits (H–O), and drilled prospects is shown. Also, the two base-metal mines mentioned in Table 2 are indicated. The extent of geological subdomains with gold deposits (greenstone and schist belts and other areas; 1–12) is marked by thin boundary lines. Modified from Eilu (1999); geology based on Korsman et al. (1997).

produced a range of genetic exploration models applicable to Finland, and technical developments in exploration and analytical methods appropriate for Finnish geology (e.g., Kontas, 1981; Niskavaara and Kontas, 1990). Research on the orogenic or mesothermal lode gold mineralization style (e.g., Colvine et al., 1988; McCuaig and Kerrich, 1998; Goldfarb et al., 1998; Groves et al., 1998) has been particularly important for recent exploration successes in Finland (Nurmi and Sorjonen-Ward, 1993; Korkiakoski and Kilpelä, 1997).

Although orogenic gold deposits have been the most important exploration target in Finland, increasing attention has been given to other types of gold mineralization. For example, there is growing interest in epigenetic iron oxide-copper-gold and metamorphosed epithermal Au deposits (Poutiainen and Grönholm, 1996; Kojonen et al., 1999; Vanhanen, 2001).

Recent exploration investment and drilling have led to the discovery of more than 150 gold prospects in Finland (Fig. 1). These include both gold-only mineralization, which represents the majority of occurrences, and cases where gold is the main commodity, accompanied by Ag, Co, Cu, or Sb as significant minor constituents. Three discoveries have resulted in full-scale mining (Saattopora, Pahtavaara, and Kutemajärvi), and a number of others are undergoing or have undergone extensive feasibility studies including test mining (Table 1). Large parts of Finland, both in the Proterozoic and Archean domains, are still under explored for gold, and recent research has provided a more precise characterization of the types of deposits that may be expected in these areas. Approximately 500 public documents and hundreds of confidential reports on gold occurrences and exploration in Finland have been compiled during the past 15 yr (Eilu, 1999). Although reports have been published on individual deposits or gold belts (Korkiakoski, 1992; Pankka and Vanhanen, 1992; Nurmi and Sorjonen-Ward, 1993; Poutiainen and Grönholm, 1996; Kontoniemi and Nurmi, 1998; Vanhanen, 2001), and on limited aspects of Finnish gold deposit types (Gaál and Sundblad, 1990; Nurmi, 1991; Puustinen, 1991; Nurmi et al., 1991; Mänttäri, 1995; Sorjonen-Ward and Nurmi, 1997; Sorjonen-Ward et al., 1997a), a comprehensive review of all gold occurrences in Finland has not yet been compiled.

In this review, we have attempted to synthesize and reinterpret the existing geological database on Finnish gold deposits in terms of major geological characteristics, mineralization style, genetic type, and tectonic settings. The data used in this review, including detailed information on each drilled gold deposit and prospect in Finland, are from the original database compiled by Eilu (1999), the references therein, and more recent updates of the database available from the Geological Survey of Finland at the following web site: <www.gsf.fi/explor>. Included in the database is information on location, holding, resources, exploration, ore mineralogy and composition, structure, alteration, and geological setting.

## Archean and Paleoproterozoic Geological Evolution of Finland

Finland occupies the central part of the predominantly late Archean and Paleoproterozoic Fennoscandian Shield, which is exposed over an area of more than 1 million km$^2$. The Finnish bedrock can be broadly subdivided into three domains (Fig. 1) that have shared a common history since about 1.8 Ga. These three crustal units essentially comprise a late Archean nucleus (Karelian craton) flanked on both sides by Paleoproterozoic mobile belts. Their geodynamic evolution is summarized in Table 2. The Lapland domain, together with

TABLE 1. Gold Mines and Major Undeveloped Deposits in Finland

| Deposit (alternative name in brackets) | Original resource: Tonnage (M) | Grade: Au (ppm) | Grade: Other metals (%) | Status of development as of mid-2002 | Reference |
|---|---|---|---|---|---|
| Haveri | 1.5 | 2.8 | 0.37 Cu | Mined 1942–1960 | Isokangas (1978) |
| Juomasuo | 1.8 | 3 | 0.2 Co | Pilot mining 1992 | Vanhanen (2001) |
| Kivimaa | 0.022 | 5.3 | 1.87 Cu | Mined 1969 | Rouhunkoski and Isokangas (1974) |
| Kopsa | 25 | 0.57 | 0.18 Cu | Preliminary feasibility study | Gaál and Isohanni (1979) |
| Kutemajärvi (Orivesi) | 2.0 | 8 | | Active mining 1994– | H. Saarnio, pers. commun. (2001) |
| Kutuvuoma | 0.07 | 6.7 | | Mined 1999 | |
| Laivakangas | 0.7 | 4 | | Preliminary feasibility study | Mäkelä et al. (1988) |
| Laurinoja | 4.6 | 0.95 | 0.88 Cu | Mined 1974–1992 | Hiltunen (1982) |
| Osikonmäki | 2.2 | 3.1 | | Preliminary feasibility study | Kontoniemi (1998) |
| Pahtavaara | 3 | 3 | | Mined 1996–2000 | H. Alaniska, pers. commun. (1998 and 1999) |
| Pampalo (Ilomantsi) | 1.2 | 8.0 | | Pilot mining 1996, 1998, 2000–2001 | Unpub. report for Outokumpu Oyj (2001) |
| Saattopora | 2.163 | 3.0 | 0.24 Cu | Mined 1988–1995 | Korvuo (1997) |
| Suurikuusikko | 11.5 | 5.4 | | Under feasibility study | Riddarhyttan Resources AB, press release, 12/12/2002 |
| Vähäjoki | 10.5 | 0.1–2.0 | 0.1–1 Cu, ≤0.2 Co | Preliminary resource estimate | E. Korvuo, unpub. report for Lapin Malmi (1982) |
| Valkeasuo (Hosko) | 4.8 | 3.7 | | Preliminary resource estimate | Unpub. report for Endomines Oy (1999); see also: <www.endomines.fi> |

Locations shown in Figure 1

TABLE 2. Gold Mineralization in Finland in Relation to Geodynamic Evolution of the Fennoscandian Shield

| Age (Ma) | Event | Predominant process | Implications for gold mineralization | | |
|---|---|---|---|---|---|
| | | | Svecofennian domain | Karelian domain | Lapland domain |
| 0 | Holocene deglaciation[1,2] | Deposition of till and glaciofluvial reworking[1,2] | Till deposition | Till deposition | Till deposition; placer reworking in glaciofluvial systems |
| 0–2 | Pleistocene glaciation[1,2] | Glacial erosion and transport[1,2] | Dispersal of regolith enrichment and formation of till anomalies | Dispersal of regolith enrichment and formation of till anomalies | Regolith commonly preserved beneath till |
| 0–80 | Rifting and sea-floor spreading in North Atlantic[3] | Topographic rejuvenation, denudation, and regolith formation[3] | Regolith enrichment and depletion, transport | Regolith enrichment and depletion, transport | Regolith enrichment and depletion, transport |
| 60–300 | Exhumation of shield[4] | Weathering and erosion[4,5] | No record preserved | No record preserved | No record preserved |
| 300–380 | Ural collision, rifting, and alkali magmatism[4,5] | Erosion, syenite, and carbonatite emplacement[4,5] | No known record | No known record | Alkaline intrusions emplaced at shallow depths; no gold mineralization |
| 400–560 | Iapetus rifting and Caledonian orogeny[4,6] | Carbonate platform and transient foreland basin with Zn-Pb mineralization and fluid infiltration into basement[4,6,7] Kimberlite emplacement[8] | Local resetting of Pb isotopes | Kimberlite magmatism; no known effects on gold mineralization | Local resetting of Pb isotopes |
| 1100 | Sveconorwegian orogeny[6] | Possible burial beneath foreland basin[6] | No effects documented | No effects documented | No effects documented |
| 1550–1640 | Gothian orogenic event and lithospheric extension with anorogenic rapakivi magmatism[9] | Metamorphism and nappe emplacement in southern Sweden, rapakivi granites, and extension elsewhere[9,10] | Rapakivi granites and mafic sills; lower crustal extension; no demonstrated links with gold mineralization | Rapakivi granites and mafic sills; lower crustal extension; no demonstrated links with gold mineralization | No record documented |
| 1780–1800 | Emplacement of Transscandinavian igneous batholith[9] | | No defined record | No defined record | Fractionated granites with Archean inheritance, minor Mo but no Au |
| 1800–1840 | Late-collisional, intracrustal melting followed by postcollisional bimodal shoshonitic magmatism (lithosphere delamination)[10,11] | Crustally derived granites and high-T–low-P metamorphism, followed by metamorphism and anatexis in domains of high T and low P, associated with monzodioritic and local mafic intrusions[11] | Metamorphic dehydration and granite crystallization, few examples of Au mineralization recognized; metamorphic overprint on older orogenic vein deposits well documented | Present erosion level records metamorphic dehydration and granite crystallization | Granites as thermal and potential fluid sources for IOCG; metamorphic overprint on older orogenic vein deposits well documented |
| 1860–1890 | Transition from initial Svecofennian collision to orogen-parallel shear regime with bimodal volcanics and plutons[10,12,13,14] | Tectonic imbrication of craton margin, with local granulite facies in Svecofennian domain; predominantly I type and ilmenite series TTG plutons, intruded at greenschist-amphibolite facies[10,12,,14,15] | Structurally controlled Au mineralization in late to postcollisional tonalite plutons; orogenic and epithermal Au systems | Isolated, crustally derived granite intrusions and major ductile shear zones; no Au mineralization recognized; peak metamorphic overprint on Archean Au deposits | Late orogenic molasse-type red bed deposits with Au paleoplacer accumulations and potential hydrothermal overprint; extensive orogenic Au mineralization; possible IOCG mineralization in western Lapland; regional albitic alteration? |
| 1900–1930 | Initial Svecofennian collision with Karelian domain[9,12,15,16] | Thin-skinned deformation over craton foreland, with prograde metamorphism and tectonic thickening[12] | Bimodal arc magmatism; volcaniclastic hosted Cu-Zn (Au) deposits | Deposition and deformation of turbidite wedge at craton margin; no Au deposits | Timing of deformation and complex hydrothermal alteration not constrained; Au deposits not identified |
| 1950–2010 | Cratonic magmatism and breakup[12,17] | Attenuation of craton margin and exhumation of mantle lithosphere; formation of oceanic crust[17] | No record | Continental flood basalts and picrites-ophiolites, including protoliths hosting the Outokumpu Cu-Co-Ni-Zn-(Au) deposits | Komatiites and picrites in autochthon, tholeiites in oceanic allochthon; albitic hydrothermal alteration? |

TABLE 2. (*Cont.*)

| Age (Ma) | Event | Predominant process | Implications for gold mineralization: Svecofennian domain | Karelian domain | Lapland domain |
|---|---|---|---|---|---|
| 2050–2100 | Rifting and subsidence at Karelian craton margin[12,18] | Transgressive sedimentation and tholeiitic magmatism[12,17,219] | No record | Volcaniclastic hosted Cu-Zn (Au) deposits | Mafic polymetallic intrusions; albitic hydrothermal alteration |
| 2200 | Intraplate mafic magmatism[18,19] | Extensive mafic sills, terrestrial to shallow marine sediments[19] | No record | Albitic hydrothermal alteration | Albitic hydrothermal alteration |
| 2400–2440 | Rifting and bimodal magmatism[18,19,20] | Extensive mafic sills, terrestrial to shallow-marine sediments[19,20,21] | No record | Mafic layered intrusions, alkali granites, and bimodal volcanism | PGE in layered intrusions |
| 2630–2700 | Thermal reworking and stabilization of Karelian craton[22] | Granulite metamorphism, cooling, and exhumation[22] | No record | Currently exposed high-grade gneiss terranes have a limited gold endowment | Currently exposed high-grade gneiss terranes have a limited gold endowment |
| 2700–2750 | Formation and accretion of crustal elements in Karelian craton[18,21,23] | Transition from volcanism to deformation and peak metamorphism in low-grade supracrustal terrains[18,21,23] | No record | Main orogenic gold event coincides with late tectonic strain partitioning under peak metamorphic conditions | Juxtaposition of high-grade gneiss terranes with TTG and greenstones; Au deposits not identified |
| 2800 | Greenstone belts formed superimposed on earlier orogenic substrate[18,21] | Submarine komatiitic, tholeiitic and felsic volcanism[18,21] | No record | Komatiite-hosted Ni and felsic Ag-Zn deposits, no Au | No distinct events recognized |
| 2840 | Thermal reworking of earliest recorded crust[21,22] | High-strain migmatite complexes derived from amphibolite protoliths[21,22] | No record | No Au mineralization recognized | No Au mineralization recognized |
| 3000–3340 | Segregation of earliest preserved continental crustal material; geodynamic context and processes unknown[7,21] | | No record | No Au mineralization recognized | No Au mineralization recognized |

IOCG = iron oxide-copper-gold

References: [1] = Hirvas (1991), [2] = Nenonen and Huhta (1993), [3] = Vågnes et al. (1998), [4] = Nikishin et al. (1996), [5] = Vartiainen and Paarma (1979), [6] = Larson et al. (1999), [7] = Vaasjoki (1981), [8] = O'Brien and Tyni (1999), [9] = Gaál and Gorbatschev (1987), [10] = Korja et al. (1993), [11] = Väisänen et al. (2000), [12] = Ward (1987), [13] = Kähkönen et al. (1989), [14] = Lahtinen (1994), [15] = Korsman et al. (1999), [16] = Gaál (1990), [17] = Kontinen (1987), [18] = Sorjonen-Ward et al. (1997b), [19] = Vaasjoki (ed.; 2001), [20] = Alapieti and Lahtinen (1989), [21] = Luukkonen (1992), [22] = Hölttä et al. (2000), [23] = Nurmi and Sorjonen-Ward (1993) contiguous terranes in the adjacent Kola Peninsula, records the amalgamation of several distinct crustal units of both Proterozoic and Archean age to the northeast margin of the Karelian craton at around 1.9 Ga (Gaál et al., 1989; Ward et al., 1989; Gaál, 1990; Sorjonen-Ward et al., 1997b; Lehtonen et al., 1998). In contrast, the Svecofennian domain, to the southwest of the Karelian craton, is entirely Paleoproterozoic in age, with a history of relatively rapid formation and accretion of new crust between about 1.97 and 1.86 Ga (Huhma, 1986; Patchett and Kouvo, 1986; Nironen, 1989; Kähkönen et al., 1989; Gaál, 1990; Sorjonen-Ward et al., 1997b). Extensive crustal reworking between 1.84 and 1.80 Ga is recorded in all three domains, represented mainly by potassic monzogranitic magmatism and low-pressure, high-temperature metamorphism.

*Archean evolution of the Karelian craton*

The Karelian craton is characterized by narrow, northerly trending greenstone belts surrounded by granitoids and gneisses (Fig. 1). Although rocks up to 3.2 Ga are present throughout the craton (Table 2), the earliest well-documented magmatic and metamorphic event took place at around 2.84 Ga (Kröner et al., 1981; Kröner and Compston, 1990; Luukkonen, 1992; Vaasjoki et al., 1993, 1999; Huhma et al., 1995). The lower metamorphic-grade greenstone sequences formed after this event and were variably deformed and intruded by tonalitic to granitic magmas between 2.75 and 2.70 Ga (Luukkonen, 1992; Vaasjoki et al., 1993). Granulite facies domains formed in association with later stages of pluton emplacement and were exhumed and juxtaposed against lower-grade domains by around 2.63 Ga (Hölttä et al., 2000). Four distinct northerly trending greenstone belts are recognized in the Finnish part of the Karelian craton, separated by higher-grade gneisses and granitoid domains. From southeast to northwest, these are the Ilomantsi, Kuhmo, Suomussalmi, and Oijärvi greenstone belts. Extensive, structurally controlled alteration systems have recently been delineated and found to contain numerous gold targets of orogenic type in each of these greenstone belts (Luukkonen, 1993; Nurmi, 1993; Nurmi and Sorjonen-Ward, 1993).

The Kuhmo and Suomussalmi greenstone belts are the most extensive, with a combined strike length of nearly 200 km, though seldom exceeding 10 km in width. These belts are also prospective for nickel, and both contain abundant tholeiitic and komatiitic volcanic rocks, together with related intrusive and subvolcanic cumulates, and lesser felsic volcanic and volcaniclastic units (Luukkonen, 1992; Nurmi and Sorjonen-Ward, 1993; Sorjonen-Ward et al., 1997b). The Ilomantsi greenstone belt felsic to intermediate volcaniclastic sedimentary rocks record rapid crustal growth and deformation between 2.76 and 2.72 Ga (O'Brien et al., 1993a). The lithofacies, as well as the geochemistry of granitoids and some basalts in this belt, are consistent with a collisional arc setting (Sorjonen-Ward, 1993). Although the structural framework and evolution of these belts is relatively well constrained, there is as yet no basis for defining large-scale crustal elements within a plate-tectonic context. The Oijärvi greenstone belt consists of mafic to ultramafic volcanic and felsic sedimentary units, and its geodynamic origin and setting are likewise unclear (Tolppi, 1999).

*Paleoproterozoic development of the Karelian craton*

The northern part of the Karelian craton records a prolonged and episodic history of sedimentation, rifting, and magmatism throughout the Paleoproterozoic (Table 2). The Central Lapland greenstone belt (Fig. 1) is the largest mafic volcanic-dominated province preserved in Finland. A sequence of bimodal komatiitic and felsic volcanic rocks dated at around 2.5 Ga unconformably overlies the Archean basement and represents the onset of rifting (Manninen et al., 2001). Continued rifting of the Archean crust resulted in the widespread emplacement of gabbro-norite layered intrusions between 2.45 and 2.39 Ga (Alapieti and Lahtinen, 1989). Terrigeneous clastic sedimentary rocks discordantly overlie these layered intrusions, with further episodes of mafic magmatism recorded as local flows and sills with ages of 2.2 Ga, 2.10 Ga, and 2.05 Ga (Huhma, 1986; Vuollo et al., 1992; Huhma et al., 1996; Vaasjoki, 2001; Hanski et al., 2001). This latter phase of mafic magmatism coincided with rifting, subsidence, and transgression along the whole of the Karelian craton margin, recorded by carbonates, iron formations, graphitic schists, and coarse clastic turbidites. Continued rifting culminated in extensive mafic and ultramafic volcanism and the formation of oceanic crust between 2.01 and 1.95 Ga. Fragments of oceanic crust were subsequently emplaced back onto the Karelian craton, as the Nuttio ophiolite in Lapland and the Jormua and Outokumpu ophiolites further south, the latter being best known for its Cu-Co-Zn deposits and chrome skarns (Kontinen, 1987; Gaál, 1990; Sorjonen-Ward et al., 1997b and 2001; Lehtonen et al., 1998).

Rifting of the Karelian craton was followed by the main phase of compressional deformation and mineralization, associated with Svecofennian synorogenic plutonism, between 1.89 and 1.86 Ga (Vaasjoki, 2001). The Svecofennian orogeny in this region was accompanied by extensive orogenic gold mineralization at about 1.89 to 1.86 Ga (Mänttäri, 1995). Gold deposits in Lapland are concentrated in the Central Lapland greenstone belt and Kuusamo schist belt (Fig. 1; Ward et al., 1989; Korkiakoski, 1992; Pankka and Vanhanen, 1992; Vanhanen, 2001). In the western part of the Central Lapland greenstone belt and in the Peräpohja schist belt, synorogenic, skarn, or epigenetic ironstone-hosted Au-Cu deposits have been found and, in western Lapland, mined chiefly for iron (Hiltunen, 1982). A spatial association exists between the ironstones and 1.89 to 1.86 Ga calc-alkaline granitoids in western Lapland, but more felsic potassic granites are also abundant in this region, with ages between 1.82 and 1.80 Ga. An outstanding problem in Lapland geology is whether these deposits might form a continuum with the more typical orogenic-style deposits in the greenstones of central Lapland, or whether several superimposed mineralization events are present.

Paleoplacer gold deposits are hosted by quartz-pebble conglomerates of the uppermost Kumpu Formation of the Central Lapland greenstone belt. These sediments are typical late-orogenic terrestrial red beds that are clearly discordant with respect to the main deformation event in the underlying greenstones. They were deposited after or perhaps during the formation of the orogenic gold occurrences. Radiometric dating and structural evidence indicate that deposition of the conglomerates took place sometime between 1.91 and 1.80 Ga (Härkönen, 1984; Lehtonen et al., 1998; Rastas et al. 2001).

*Paleoproterozoic evolution of the Svecofennian domain*

Northeast-vergent emplacement of the Outokumpu ophiolite onto the Karelian craton is inferred to record the initial collision with a Svecofennian oceanic island arc (Kontinen, 1987; Ward, 1987), generating primitive tonalites from a low-K tholeiitic source (Kontinen, 1987). Continued volcanism within this arc at 1.92 to 1.87 Ga led to the formation of volcanic-hosted massive sulfide (VHMS) deposits, including the Pyhäsalmi Zn-Cu deposit, with hydrothermally altered host rocks subsequently being metamorphosed to distinctive cordierite-orthoamphibole lithologies (Helovuori, 1979; Gaál, 1990). Reversal of subduction polarity following collision (Gaál, 1990), or a further arc-arc collision, is invoked to explain the rapid orogenic evolution, with the most extensive phase of volcanism, magmatism, and deformation occurring in southern and western Finland between 1.89 and 1.86 Ga (Nironen, 1989; Kähkönen et al., 1989; Kähkönen, 1994; Lahtinen, 1994; Kähkönen and Nironen, 1994; Kilpeläinen et al., 1994; Mänttäri et al., 1997).

Deep seismic studies in combination with geochemical and isotopic data indicate that postcollisional extensional collapse and widespread crustal melting took place in the period of 1.84 to 1.80 Ga (Korja et al., 1993; Sorjonen-Ward and Nurmi, 1997; Väisänen et al., 2000). This is interpreted as a thermal and gravitational response to tectonic thickening of the lithosphere, although the role of lithospheric delamination and mafic underplating as an additional heat source is the subject of much speculation (Lahtinen, 1994; Väisänen et al., 2000). A distinctly separate thermal input from the mantle is nevertheless invoked to account for later extension and rapakivi magmatism at 1.6 Ga (Rämö and Haapala, 1995).

Gold mineralization in the Svecofennian domain occurs within several environments: 1) as enrichments in 1.91 to 1.87 Ga VHMS deposits (Kähkönen et al., 1989; Gaál, 1990; Kähkönen and Nironen, 1994); 2) as metamorphosed epithermal deposits in the Tampere schist belt (Luukkonen, 1994; Poutiainen and Grönholm, 1996; Sorjonen-Ward et al., 1997a); and 3) 1.89 to 1.86 Ga synorogenic orogenic gold deposits, commonly hosted by syntectonic intrusions (Mäkelä et al., 1988; Nurmi et al., 1991; Rosenberg, 1997; Kontoniemi and Nurmi, 1998). Crustal reworking and melting at 1.84 to 1.80 Ga clearly postdates both orogenic and intrusion-related gold mineralization within the Finnish part of the Svecofennian domain. Shoshonitic magmatism has been recognized in spatial and temporal association with this younger metamorphic and anatectic event (Väisänen et al., 2000). However, field and structural evidence from Finland so far only indicate local remobilization and recrystallization within preexisting gold deposits during this time interval, rather than a separate mineralizing event coincident with alkaline magmatism (Rosenberg, 1997; Kontoniemi, 1998).

## Genetic Types of Gold Mineralization in Finland

Of the several types of gold mineralization recognized in Finland, orogenic deposits predominate (Fig. 1; Table 3), similar to other Precambrian terranes (cf. Foster and Piper,

TABLE 3. Genetic Types of Gold Mineralization in Finland

| Deposit type | Age group[1,2,3,4] | Schist belt or other geological subarea | Examples |
|---|---|---|---|
| Orogenic | 2700 Ma<br>1900–1850 Ma | Archean: Ilomantsi, Kuhmo, Suomussalmi, Oijärvi<br>Proterozoic: Central Lapland, Kuusamo, Peräpohja, Ostrobothnia, Savo, Tampere, Vammala | Pampalo,[2] Valkeasuo[2]<br>Haveri,[5,6] Kivimaa,[1] Osikonmäki,[7] Pahtavaara,[3] Saattopora,[3,8] Suurikuusikko[3] |
| Metamorphosed epithermal[5] | 1900 Ma | Tampere | Kutemajärvi[4] |
| Skarn- or epigenetic-ironstone hosted[5] | 1900–1800 Ma | Central Lapland, Peräpohja | Laurinoja,[8] Vähäjoki[8] |
| Intrusion-related (nonskarn)[9] | 1900–1800 Ma | Central Ostrobothnia | Kopsa[1,5] |
| Massive sulfide | 1920–1870 Ma | Raahe-Ladoga Suture | Outokumpu,[1] Pyhäsalmi[1] |
| Paleoplacer | 1900–1800 Ma | Central Lapland | Kaarestunturi,[8,10] Outapää[8,10] |
| Placer | Tertiary–Quaternary | Northern Lapland | Ivalojoki,[11] Lemmenjoki[11] |

[1] Gaál (1990)
[2] Nurmi and Sorjonen-Ward (1993)
[3] Mänttäri (1995)
[4] Mänttäri et al. (1997)
[5] There is some controversy regarding certain deposits or presence of deposit types; these are such cases; massive sulfide deposits are included, as they have played a significant part in the production of gold in Finland, although gold has only been a byproduct of these deposits
[6] T. Strauss, pers. commun. (1997)
[7] Kontoniemi and Nurmi (1998)
[8] Lehtonen et al. (1998)
[9] Deposit type as defined by Sillitoe (1991)
[10] Härkönen (1984)
[11] Puustinen (1991)

1993; Robert and Poulsen, 1997; Groves et al., 1998). About 90 percent of the drilled gold deposits and prospects in Finland can be classified as orogenic. Gold mineralization styles more typical of Phanerozoic terranes (e.g., Sillitoe, 1991; Berger and Bagby, 1991; Hedenquist et al., 1996; Robert et al., 1997) are more difficult to identify or correctly classify in metamorphosed and deformed rocks. One notable exception is the Kutemajärvi deposit which, despite high strain and amphibolite-facies metamorphism, retains characteristics suggestive of an epithermal origin. Deposits with porphyry-style characteristics also have been recognized in the Svecofennian domain, more particularly in the Skellefte district of northern Sweden (Weihed, 1992).

In the Svecofennian domain, there are two larger deposits of which the genesis has not been unambiguously explained. The Haveri Cu-Au deposit in the Tampere schist belt (Fig. 1; Table 1) is either entirely of VHMS type (Mäkelä, 1980) or is a VHMS-type Cu deposit overprinted by orogenic gold mineralization (T. Strauss, pers. commun., 1997). The Kopsa deposit in the Raahe-Haapajärvi district has been considered to be porphyry-type Cu-Au mineralization (e.g., Gaál and Isohanni, 1979), but there are structural indications that it is a porphyry-Cu deposit overprinted by orogenic gold mineralization.

## Orogenic Gold Mineralization

### *Distribution*

In the Archean domain, orogenic gold has been recognized in all greenstone belts (Fig. 1). The largest number and the best-known examples are from the Hattu schist belt that forms the central part of the Ilomantsi greenstone belt in eastern Finland (Fig. 2). The existence of gold deposits in this extensively explored greenstone belt and in the Kuhmo and Suomussalmi greenstone belts has been known since the 1980s (e.g., Luukkonen, 1993; Nurmi and Sorjonen-Ward, 1993), whereas the first signs of gold mineralization in the Oijärvi greenstone belt were only discovered in 1996 (Tolppi, 1999).

In contrast to many other Precambrian shields, the largest number of orogenic gold occurrences and nearly all gold mines in the Fennoscandian Shield are in Paleoproterozoic rocks (see also Sundblad, 2003). The most important of the Proterozoic gold-enriched belts in Finland are the Central Lapland greenstone belt and Kuusamo schist belt (Figs. 1 and 3). Both of these belts contain more than 25 deposits, within a relatively small area, that have been drilled. This number includes undeveloped deposits with significant reserves (e.g., Juomasuo and Suurikuusikko) and three mines: Kutuvuoma, Pahtavaara, and Saattopora (Table 1; Pankka and Vanhanen, 1992; Korvuo, 1997; Korkiakoski and Kilpelä, 1997; Härkönen et al., 1999). In the Lapland domain, additional orogenic occurrences are also known in the Peräpohja schist belt, including the small Kivimaa deposit (Table 1; Rouhunkoski and Isokangas, 1974).

In the Svecofennian domain, significant gold belts or camps include the Raahe-Haapajärvi and Savo districts along the Archean-Proterozoic boundary zone (commonly referred to as the Raahe-Ladoga zone or suture), the area known as Southern Ostrobothnia near the western coast of Finland, which is contiguous with the Skellefte district of Sweden, and the Tampere schist belt and Vammala Migmatite zone in southern Finland (Fig. 1). These areas also contain deposits that may be of other genetic types or cases where syngenetic base-metal mineralization is overprinted by orogenic gold mineralization, such as at Haveri and Kopsa (Fig. 1; Tables 1 and 3; Gaál and Isohanni, 1979; Mäkelä, 1980; Nironen, 1994).

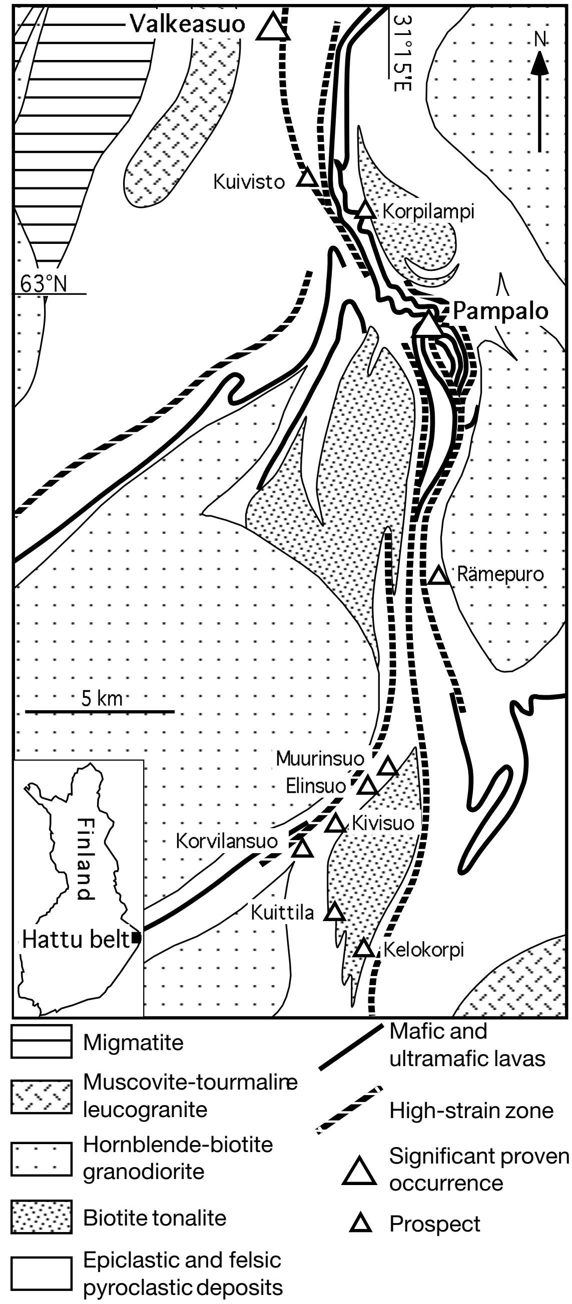


FIG. 2. Geology of the Hattu schist belt, Ilomantsi, and the locations of most of the reported gold deposits in the belt. In addition, a few deposits in the belt have been discovered to the south of the area shown here. Modified from Nurmi et al. (1993).

### *Host rocks*

Sedimentary and mafic rocks predominate as hosts to orogenic gold in Finland (Fig. 4A; Table 4). In most cases, there

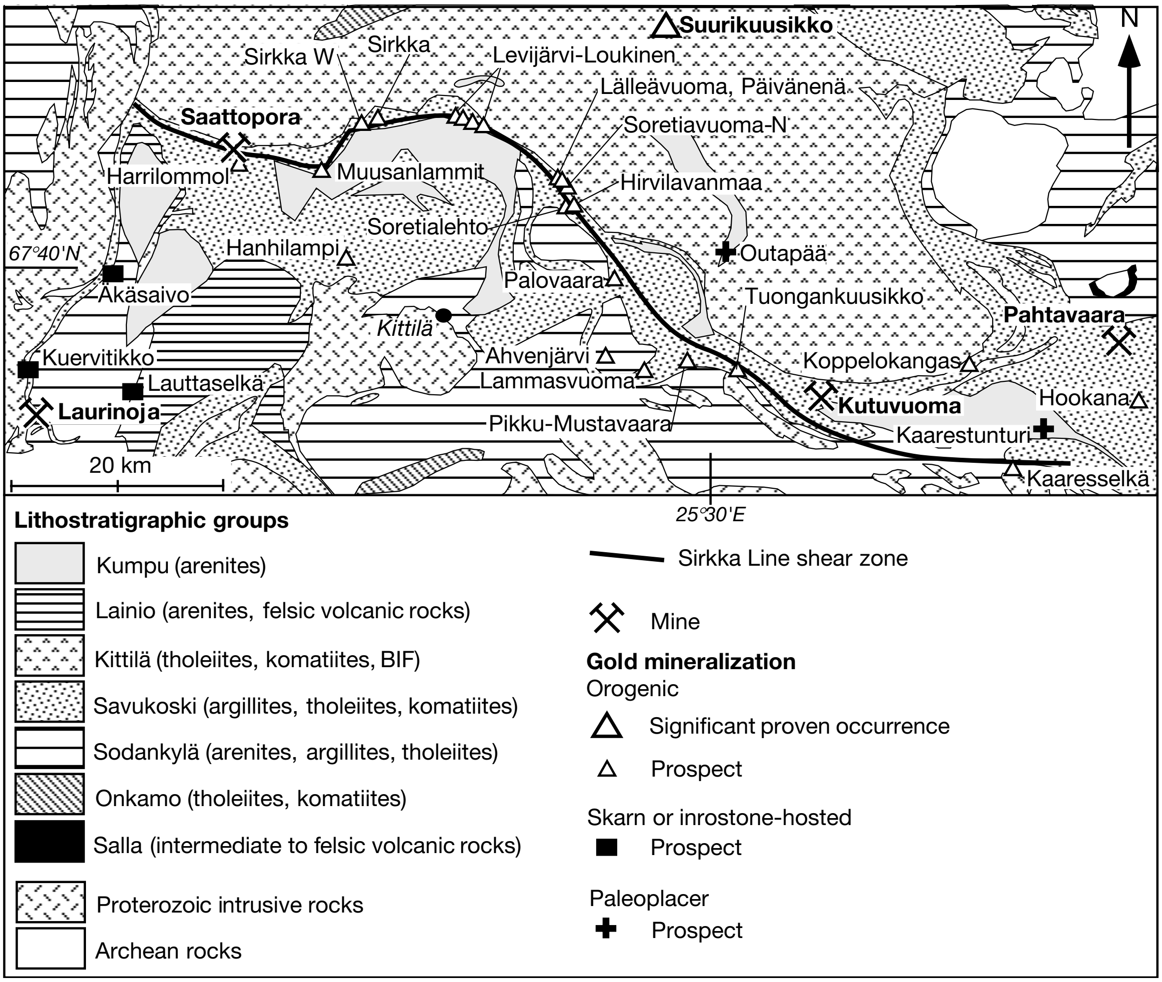


FIG. 3. Geology and gold occurrences drilled and reported in the central parts of the Central Lapland greenstone belt. In the legend, rock types most characteristic for each group are given in brackets. Modified from Lehtonen et al. (1998).

is more than one host rock, as at Pampalo, Saattopora, and Juomasuo (Figs. 5–7), although, in all cases, one rock type is dominant. Deposits hosted by a single rock type include Pahtavaara (komatiite), Kivimaa (dolerite), and Osikonmäki (tonalite). In the Peräpohja schist belt, dolerite is the main host rock in all occurrences.

In contrast to many other Precambrian shields (e.g., Groves et al., 1990), there is nearly a complete lack of banded iron formation (bif)-hosted gold deposits, komatiite is a main host in Proterozoic (in Central Lapland only; Fig. 4A) but not in Archean deposits, and sediment-hosted deposits predominate over volcanic-hosted deposits in several belts (Fig. 4A; Table 4). There is only one prospect, Palovaara in the central part of the Archean Kuhmo greenstone belt, where a bif is the main host. The dominance of clastic-sedimentary host rocks is exemplified by the Hattu and Kuusamo belts (Figs. 1 and 2), where more than 80 percent of reported gold occurrences are in sedimentary rocks derived from volcanic sources (Nurmi and Sorjonen-Ward, 1993; Vanhanen, 2001).

The importance of different host-rock types mainly reflects the distribution and abundance of rock types in the gold belts; bif is relatively uncommon, komatiites are more abundant in the Central Lapland greenstone belt than elsewhere in Finland, metasedimentary units in the Hattu and Kuusamo belts are extensive and located in structurally favorable position for gold mineralization (Vanhanen, 2001), and many orogenic belts in the Svecofennian domain are dominated by sedimentary and igneous rocks of intermediate to felsic composition (e.g., Korsman et al., 1997). Extensive and intense albitization predating gold mineralization characterizes metasedimentary rocks in some areas in Central Lapland and especially in Kuusamo (Pankka, 1992; Grönholm, 1999; Vanhanen, 2001). This albitization is thought to have rendered the metasedimentary units more competent than other lithological units and, hence, mechanically favorable for localizing orogenic gold mineralization.

*Ore mineralogy and metal associations*

Gold is usually the only metal present in economically significant amounts; in a few cases, economically recoverable Ag, Co, Cu, or Sb are present. The Saattopora mine in Lapland and the Haveri mine in the Tampere schist belt (Fig. 1) also produced copper, and in most of the deposits in Kuusamo, Co (± Cu) is potentially a valuable byproduct.

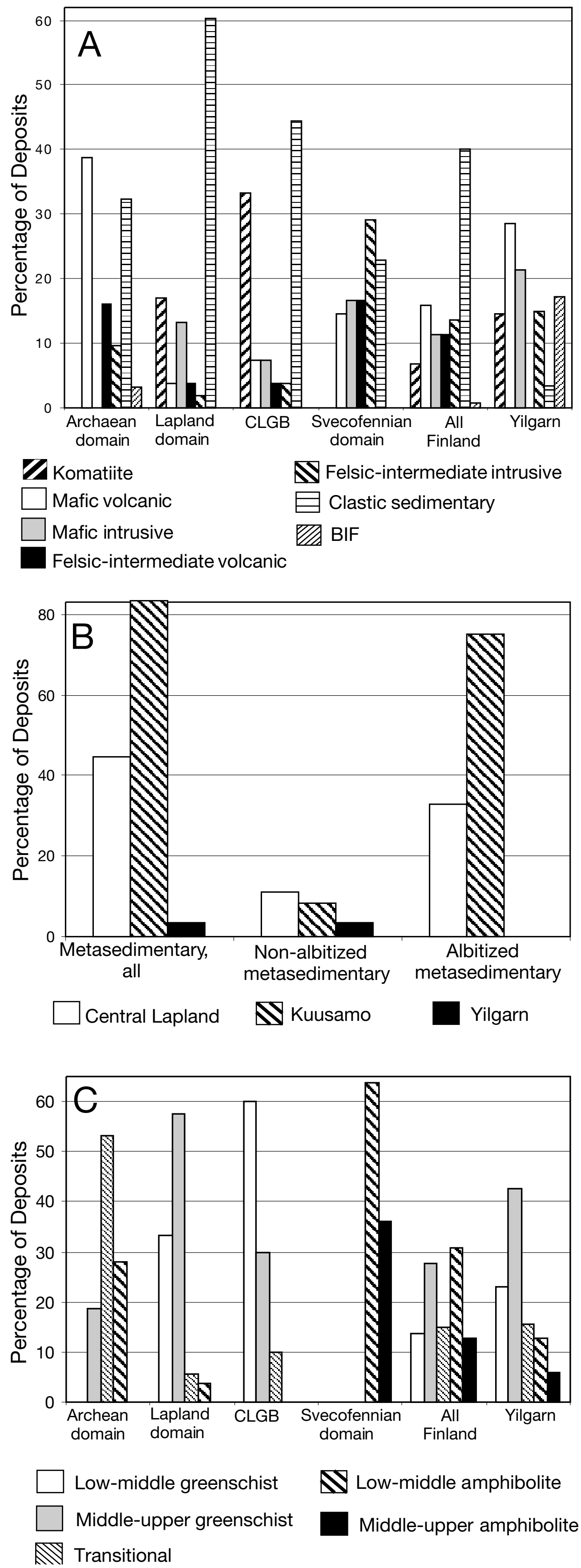


FIG. 4. Comparison of rock types and metamorphic grade of mineralization in Finland and in the Archean Yilgarn craton of Western Australia. Percentage values in the vertical axis in all plots. Data for the Finnish occurrences are from the FINGOLD database at <www.gsf.fi/explor> (2002); the Yilgarn (Western Australia) data are from Groves et al. (1990). Data from the Central Lapland greenstone belt (CLGB) are included in the Lapland domain data, but also shown separately. A. Relative importance of a rock type as the main host to orogenic gold. B. Effect of pregold albitization on the potential of a metasedimentary rock to be the main host to ore. C. Orogenic gold occurrences formed at different metamorphic grades.

Antimony, Ag, and U may also occur in individual deposits in considerable concentrations (Table 5).

Geochemically, Finnish gold deposits show distinct signatures in different domains and camps. Nurmi et al. (1991) analyzed bulk samples from 42 gold deposits in Finland for about 70 elements. Archean deposits are uniformly enriched in Te and commonly also in S, W, As, Ag, and Bi. Deposits in Lapland fall into two major geochemical types. Those in Central Lapland are moderately enriched in As, Ag, Bi, Te ± Cu, and Co, whereas the sedimentary rock-hosted deposits in Kuusamo are very low in Ag and As but enriched in B, Bi, LREE, Pb, Se, Te, U, and W. Svecofennian deposits are characterized by high abundances of Ag, As, Bi, Sb, Se, and Te, and lesser amounts of Cu and Co. Detailed studies indicate that gold in most cases correlates closely with Te and Bi in and around individual deposits. This is demonstrated by distinct geochemical correlations and grain-scale intergrowths of native gold with Te and Bi minerals, such as, for example, in the Archean Ilomantsi deposits (Bornhorst and Rasilainen, 1993; Kojonen et al., 1993) and in the Svecofennian Osikonmäki deposit (Kontoniemi et al., 1991; Bornhorst et al., 1998).

Characteristic geochemical features of different subdomains include minor As in the Tampere schist belt, significant As and Cu enrichment in the Savo district, Sb enrichment in the Southern Ostrobothnia, and enrichment of Cu, Ag, and As ± Bi and Sb in the Raahe-Haapajärvi district (Nurmi et al., 1991; Appelqvist, 1993; Luukkonen, 1994; Kontoniemi, 1998). The similarities between deposits within a schist belt suggest common fluid and metal sources at the domain scale. The similar metal association of intrusion-related deposits within the Southern Ostrobothnia and Raahe-Haapajärvi districts suggests that felsic to intermediate intrusions may have been important sources of metals in these areas (Gaál and Isohanni, 1979; Nurmi et al., 1991).

The different metal associations are reflected in the major ore minerals present in the deposits, as shown in Table 6. Metamorphic grade is a major factor controlling the mineralogy of Fe sulfides and arsenic sulfides. Pyrite is the major Fe sulfide in greenschist-facies orogenic gold mineralization, but pyrrhotite and loellingite may be the only phases present in the amphibolite-facies rocks.

Arsenopyrite and loellingite are commonly major ore minerals. However, regional-scale correlations between Au and As are not always reflected at local scale (Korkiakoski, 1992; Nurmi and Sorjonen-Ward, 1993; Luukkonen, 1994). For example, As is enriched regionally in altered volcanic and sedimentary rocks in the Ilomantsi area, but it is typically very low in ore-grade Au bodies, and arsenic is of little concern in beneficiation (Nurmi and Sorjonen-Ward, 1993). A similar

TABLE 4. Main Host Rocks for Orogenic Gold in Finland

| Main host rock | Schist belt or other geologic subarea (Fig. 1) | No. of deposits |
|---|---|---|
| Volcanic | | |
| Komatiitic | Central Lapland | 9 |
| Mafic | Central Lapland, Kuusamo, Ilomantsi, Kuhmo, Suomussalmi, Oijärvi, Raahe-Haapajärvi, Tampere | 21 |
| Intermediate | Ilomantsi, Suomussalmi, Central Lapland, Kuusamo, Southern Ostrobothnia, Savo, Tampere | 13 |
| Felsic | Southern Ostrobothnia | 2 |
| Intrusive | | |
| Mafic | Central Lapland, Kuusamo, Peräpohja, Raahe-Haapajärvi, Southern Ostrobothnia | 15 |
| Felsic to intermediate | Ilomantsi, Oijärvi, Central Lapland, Raahe-Haapajärvi, Savo, Vammala, miscellaneous cases in central and southern Finland | 18 |
| Clastic sedimentary | Central Lapland, Kuusamo, Ilomantsi, Raahe-Haapajärvi, Southern Ostrobothnia, Savo, Tampere, Vammala, miscellaneous cases in central and southern Finland | 53 |
| Banded iron formation | Kuhmo | 1 |
| Not reported | | 4 |
| Total | | 136 |

Based on Eilu (1999), and the FINGOLD database at <www.gsf.fi/explor> (2002)

relationship between Au and As is indicated for most of the occurrences in the Kuhmo and Suomussalmi greenstone belts, as well (A. Hartikainen, K. Pietikäinen, and M. Tenhola, unpub. reports for Geological Survey of Finland, 2001–2002). In other deposits, detailed mineralogical studies indicate that gold grains may occur intergrown with As minerals, although in most cases it is in the free-milling form (Nurmi et al., 1991). In some of the Proterozoic deposits in the Svecofennian domain and Lapland, however, arsenic can be abundant and problematic, as in the Suurikuusikko deposit, in Central Lapland, where about 95 percent of Au occurs in the crystal lattice of arsenopyrite and As-rich pyrite (Kojonen and Johansson, 1999; Härkönen et al., 1999). Here, laboratory-scale tests have shown that a combined process including flotation, bio-oxidation, and cyanide leaching gives a total gold recovery of about 85 percent (Härkönen et al., 1999).

*Alteration, metamorphism, and structural style*

Orogenic gold mineralization in Finland occurs in rocks metamorphosed, altered, and mineralized under lower-greenschist to upper-amphibolite facies (Fig. 4C; Table 7). This P-T range is similar to that documented in other Precambrian shields (Anhaeusser and Maske, 1986; Groves et al., 1990; McCuaig and Kerrich, 1998; Eilu et al., 1998). However, there is a larger proportion of deposits formed under amphibolite-facies conditions than in Precambrian shields in

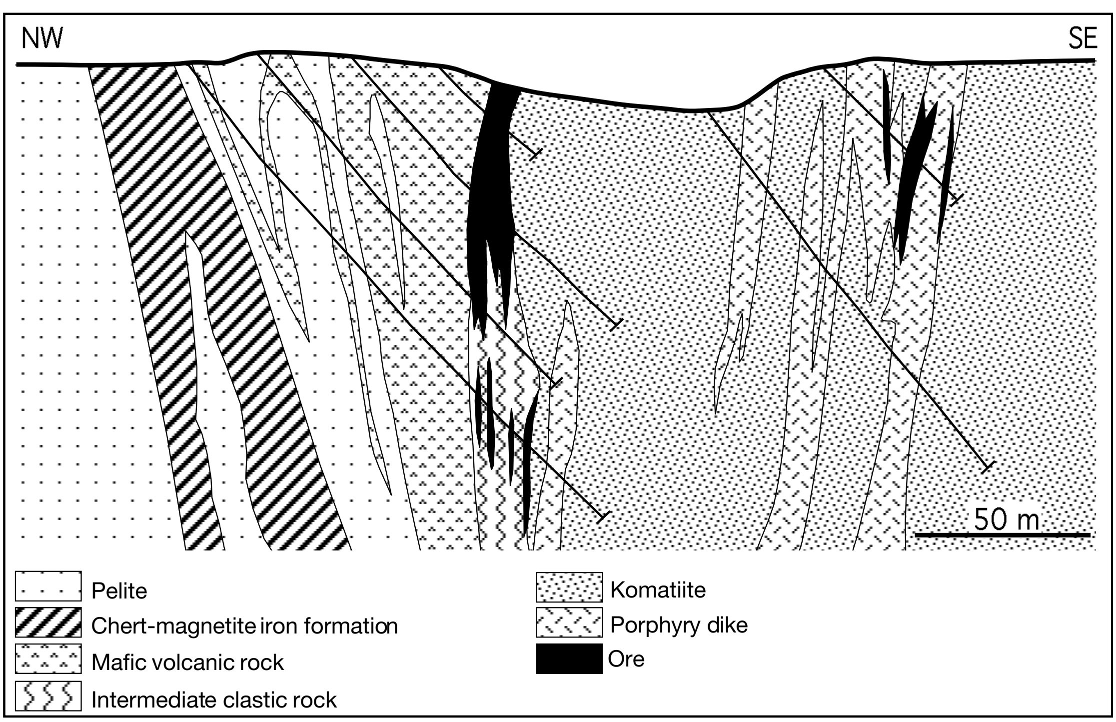


FIG. 5. Cross section through the Pampalo deposit in the Hattu schist belt, Ilomantsi (Nurmi et al., 1993).

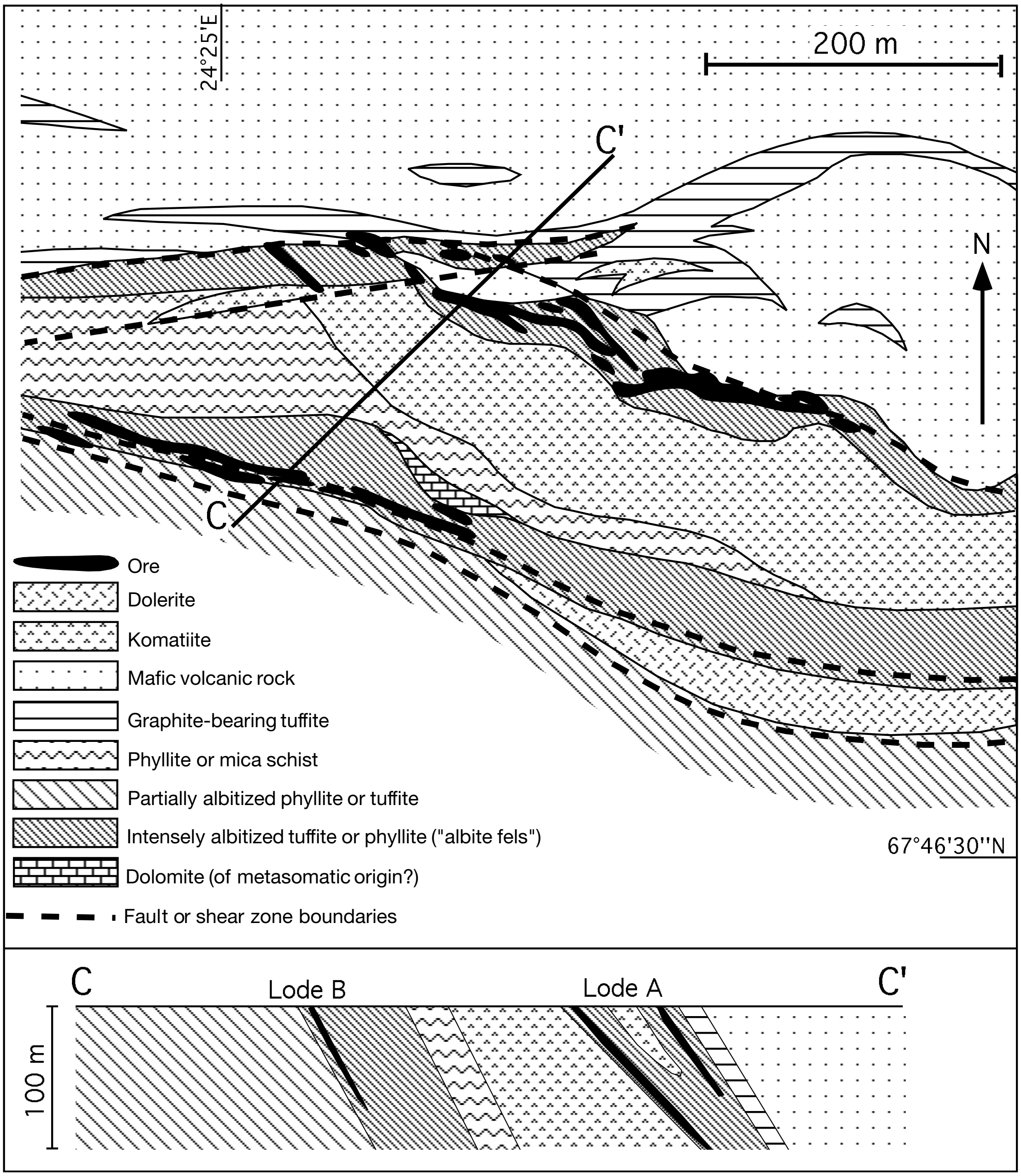


FIG. 6. Geologic map of the Saattopora area, Central Lapland greenstone belt. Modified from Korvuo (1997).

Canada and Western Australia (Fig. 4C). All orogenic gold mineralization in the Svecofennian domain took place at amphibolite facies P-T conditions, whereas the situation in the Archean and Lapland domains is more similar to that in Precambrian shields in Canada and Western Australia (Fig. 4C).

In nearly all cases, mineral assemblage, texture, and structure indicate that mineralization was either contemporaneous with or slightly later than the peak of regional metamorphism (Rastas et al., 2001; Sorjonen-Ward et al., 2001). However, many of the deposits also show a postmineralization metamorphic overprint (e.g., in the Archean Ilomantsi and Oijärvi greenstone belts, and locally in the Proterozoic areas at Pahtavaara in Lapland and in several deposits in southern Finland; Table 2). This overprint is indicated by porphyroblast growth and minor remobilization of the ore minerals and gold, typically without significant deformation, indicating fairly static metamorphic conditions (Korkiakoski, 1992; Nurmi and Sorjonen-Ward, 1993; Kilpeläinen et al., 1994; Rosenberg, 1997; Sorjonen-Ward et al., 1997a; Tolppi, 1999). Pervasive recrystallization and deformation with complete destruction of mineralization-related mineral assemblages, at about 1.83 Ga, have only been observed at Osikonmäki in the Savo district (Fig. 1; Kontoniemi, 1998).

Styles of alteration, chemical changes, fluid inclusion characteristics, deformation, and the relationship between alteration mineral assemblages and metamorphic grade in the

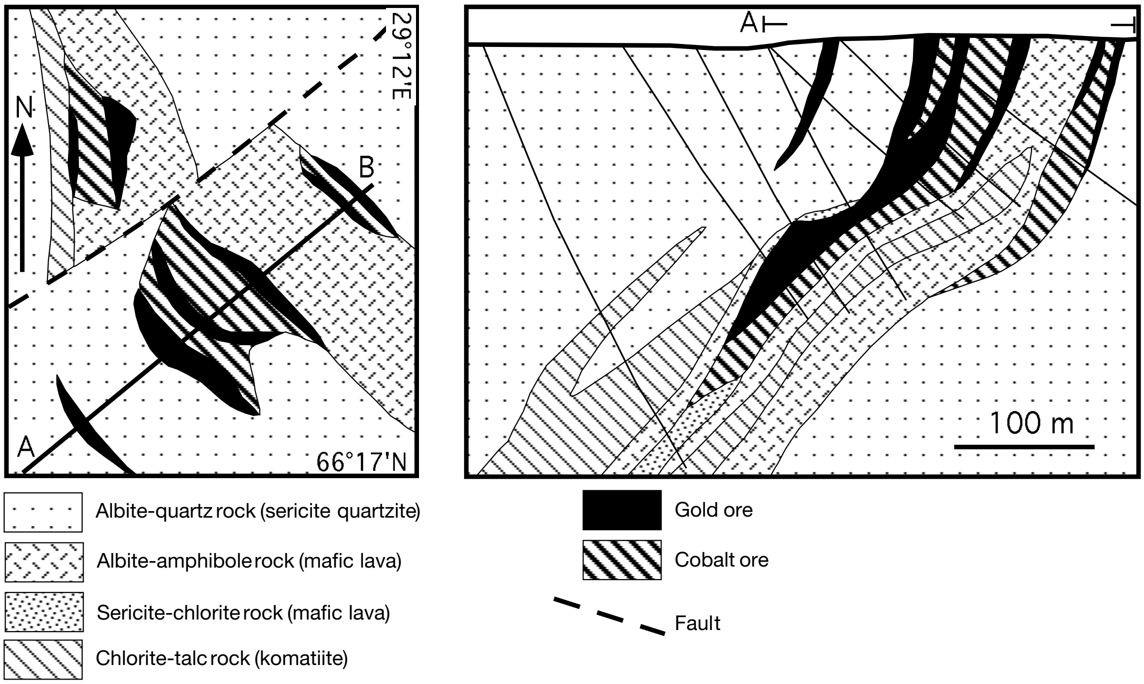


FIG. 7. Surface geology and a cross section through the Juomasuo deposit, Kuusamo schist belt. In the legend, the interpreted primary rock types are given in brackets. After Pankka (1992).

Finnish orogenic gold deposits (Rasilainen, 1996; Eilu, 1999; Hölttä and Karhu, 2001) are similar to those recorded in other parts of the world. Alteration includes sericitization and carbonatization at lower- to middle-greenschist facies, biotitization and carbonatization at upper-greenschist to lower-amphibolite facies, and biotitization and formation of K feldspar and calc silicates in higher metamorphic-grade rocks. This alteration is associated with enrichments in Ag, As, Au, Bi, Ba, $CO_2$, K, Rb, S, Sb, Se, Te, and W. The style of deformation varies from brittle through brittle-ductile to ductile with increasing pressure and temperature, with the brittle-ductile style being the most common. Almost all deposits are elongated along the host structure. Lodes within mineralized shear or fault zones tend to form en echelon swarms and follow the dominant lineation within the structure.

*Regional albitization*

Many deposits in Central Lapland and Kuusamo are associated with extensive and spectacular albitization extending for up to tens of kilometers along major structures and, laterally, kilometers away from them (Pankka and Vanhanen, 1992; Frietsch et al., 1997). Extensive albitization, carbonate alteration, and scapolite formation, with enrichment of Cu and Co, also are common within the orogenic gold deposits of the northern parts of Sweden and Norway, in the western and northern extensions of the Lapland domain of Finland (Ettner et al., 1994; Frietsch et al., 1997; Bergman et al., 2001).

Synvolcanic spilitization of volcanic rocks is typical throughout the greenstone and schist belts of the northern Fennoscandian shield. Within sedimentary units, feldspars are also commonly partially to completely albitized (Eilu, 1994; Vanhanen, 2001). However, this early spilitization and diagenetic albitization are overprinted by much more extensive albite and scapolite alteration and variable carbonatization across the Central Lapland greenstone belt and Kuusamo schist belt. This alteration is interpreted to be a product of greenstone belt-scale hydrothermal circulation of magmatic and/or basinal brines prior to or during the peak deformation (Pankka and Vanhanen, 1992; Vanhanen, 2001).

Presently, there are two views on the timing of this style of alteration in northern Fennoscandia: 1) it is coincident with the peak of the main compressional deformation associated with the Svecofennian synorogenic plutonism at 1.89 to 1.86 Ga and orogenic Au ± Cu, Co mineralization (e.g., Ettner et al., 1994; Frietsch et al., 1997), or 2) it is pre- or early-metamorphic and syndeformational, but predates the peak of

TABLE 5. Metal Association, Based on Potentially Exploitable Commodities, in Orogenic Gold Deposits in Finland

| Metal association | Schist belt or other geologic subarea | Examples | No. of deposits |
|---|---|---|---|
| Au only | All areas | Pahtavaara, Pampalo, Suurikuusikko, Valkeasuo | 98 |
| Au-Cu | Central Lapland, Peräpohja, Savo | Kivimaa, Osikonmäki, Saattopora | 13 |
| Au-Sb | Southern Ostrobothnia | Kalliosalo | 3 |
| Au-Cu-Ag | Raahe-Haapajärvi | Vesiperä | 7 |
| Au-Co-Cu ± U | Kuusamo | Juomasuo | 15 |
| Total | | | 136 |

Based on Eilu (1999), and the FINGOLD database at <www.gsf.fi/explor> (2002)

TABLE 6. Major Ore Mineral Associations in Orogenic Gold Deposits in Finland

| Major ore mineral assemblage | Schist belt or other geologic subarea | No. of deposits |
|---|---|---|
| Pyrite | Central Lapland, Kuusamo, Peräpohja, Raahe-Haapajärvi | 18 |
| Pyrite-arsenopyrite | Central Lapland, Raahe-Haapajärvi, central Finland | 4 |
| Pyrite-chalcopyrite | Central Lapland, Peräpohja | 3 |
| Pyrite-pyrrhotite | Ilomantsi, Oijärvi, Central Lapland, Kuusamo, Raahe-Haapajärvi | 29 |
| Pyrite-pyrrhotite-chalcopyrite | Central Lapland, Peräpohja, Tampere | 5 |
| Pyrite-pyrrhotite-chalcopyrite-arsenopyrite | Central Lapland, Raahe-Haapajärvi, Southern Ostrobothnia | 4 |
| Pyrite-pyrrhotite-chalcopyrite-cobaltite-Co pentlandite | Kuusamo | 5 |
| Pyrrhotite | Kuhmo, Suomussalmi, Oijärvi, Kuusamo, Raahe-Haapajärvi, Vammala | 9 |
| Pyrrhotite-arsenopyrite | Kuhmo, Raahe-Haapajärvi, Southern Ostrobothnia, Tampere, Vammala, central and southern Finland | 17 |
| Pyrrhotite-antimony-arsenopyrite | Southern Ostrobothnia | 3 |
| Pyrrhotite-arsenopyrite-loellingite-chalcopyrite | Raahe-Haapajärvi, Savo | 10 |
| Not reported | | 27 |
| Total | | 136 |

Based on Eilu (1999), and the FINGOLD database at <www.gsf.fi/explor> (2002)

TABLE 7. PT Conditions of Alteration and Mineralization in Orogenic Gold Deposits in Finland

| P-T conditions | Schist belt or other geological subarea | No. of deposits |
|---|---|---|
| Lower to middle greenschist | Central Lapland | 18 |
| Middle to upper greenschist | Oijärvi, Central Lapland, Kuusamo, Peräpohja | 37 |
| Transitional between greenschist and amphibolite | Kuusamo, Ilomantsi, Kuhmo | 20 |
| Lower to middle amphibolite | Suomussalmi, Kuusamo, all areas in Svecofennian domain | 41 |
| Middle to upper amphibolite | All areas in Svecofennian domain, except Tampere | 17 |
| Not reported | | 3 |
| Total | | 136 |

Based on Eilu (1999), and the FINGOLD database at <www.gsf.fi/explor> (2002); metamorphic classes as in Groves et al. (1990)

deformation and orogenic gold mineralization (Ward et al., 1989; Pankka, 1992, 1997; Grönholm, 1999). If the latter is correct, then the intense albitization prepared ground for orogenic gold mineralization near structurally favorable locations, such as along and around the Sirkka Line shear zone (Fig. 3) and the central antiforms of the Kuusamo schist belt. Because the gold-mineralizing fluids were low salinity, near neutral, and $H_2O$-$CO_2$ rich (Korkiakoski, 1992; Grönholm, 1999), it is unlikely that these fluids could have been responsible for the albitization.

### *Controls on orogenic gold mineralization*

Structure: At both regional and local scale, the main control on all orogenic gold mineralization in Finland is structural. All occurrences are either in or close to a distinct fault or shear zone. The host structure itself is rarely a major, first-order structure, but typically a smaller, second- or third-order fault or shear zone branching from the major structure (Makkonen and Ekdahl, 1988; Ward et al., 1989; Kontoniemi, 1998).

Most of the orogenic gold deposits in the Kuhmo, Suomussalmi, and Central Lapland greenstone belts, and in the Raahe-Haapajärvi and Savo districts, are located close to first-order, crustal-scale shear zones. At Kuhmo and Suomussalmi, mineralization occurs in second- or third-order ductile $D_3$ and brittle-ductile $D_4$ shear zones and, also, at the junctions of these two (Luukkonen, 1993). In Lapland, at least 20 deposits have been discovered within 3 km from the west- to northwest-trending Sirkka Line (Fig. 3), a transcrustal shear zone (Lanne, 1979; Ward et. al., 1989; Lehtonen et al., 1998). Most of these deposits are in minor faults branching from the Sirkka Line, but a number lie within the main structure (e.g., the Saattopora mine). Others occur up to 35 km away (e.g., the Pahtavaara mine and the Suurikuusikko deposit; Fig. 3), hosted by faults at a high angle to the Sirkka Line, and interpreted as reactivated transfer faults or reoriented early thrusts (Ward et al., 1989). The Svecofennian deposits of the Raahe-Haapajärvi and Savo districts are in secondary and tertiary fault and shear zones branching from northwest-trending major faults (Makkonen and Ekdahl, 1988; Mäkelä et al., 1988; Weihed and Mäki, 1997; Kontoniemi, 1998). The major faults can be followed along strike for more than 100 km and are an integral part of the Raahe-Ladoga Suture, which forms the boundary between the Karelian craton and the Svecofennian domain (domains I and III in Fig. 1).

A major, although not necessarily crustal-scale, structural control is evident in other mineralized belts as well. In the Ilomantsi greenstone belt (Fig. 2), all known deposits are within 1 km of distinctive high-strain zones (>10 km long) within the greenstone belt (Nurmi et al., 1993). These zones represent progressive localization of strain on fold limbs, with a significant vertical component to the strain paths. Gold mineralization is commonly, although not exclusively, located at geometrical and lithological perturbations with dilational jog or releasing bend characteristics (Sorjonen-Ward, 1993). In the Kuusamo district (Fig. 1), nearly all deposits are located within two parallel, northeast-trending antiforms located in the central part of the greenstone belt, at or near intersections between the antiforms and crosscutting faults (Pankka, 1997). In the Svecofennian of southern Finland, at least one shear zone several kilometers long can be found within 1 km of every deposit (Lestinen et al., 1991; Luukkonen, 1994; Korsman et al., 1997), although the timing of deformation with respect to mineralization has not always been established.

Lithology: Locally, there may also be a lithological control on the siting of the lodes, reflecting contrasting competency or chemical composition between the rock types. Competent rock types appear to be the most favorable host rocks, particularly where they are chemically reactive. At Saattopora, where all lodes are in rocks that were pervasively albitized prior to gold mineralization (Fig. 6), the early albitization significantly increased the competency of the host tuffites and phyllites, providing pathways for the mineralizing fluids where these units were brecciated (Grönholm, 1999). Grönholm (1999) further suggested that precipitation of gold at Saattopora was induced by reduction-oxidation reactions between the mineralizing, $H_2O$-$CO_2$–dominated fluid and graphite in the albitized wall rock. Increased competency due to albitization has also been suggested for most of the Kuusamo deposits (Fig. 4B; Pankka and Vanhanen, 1992; Pankka, 1997). Localization of mineralization within more competent rock units, such as felsic to intermediate volcanic and intrusive rocks, is also evident within some deposits in the Ilomantsi greenstone belt (Nurmi and Sorjonen-Ward, 1993).

Tectonic setting: The most productive hydrothermal systems are interpreted to have been of regional, greenstone-belt scale and related to regional tectonics rather than local, deposit-scale systems (Rasilainen, 1996; Pankka, 1997; Grönholm, 1999; Vanhanen, 2001).

Most of the greenstone belts in the Archean Karelian craton formed after the earliest magmatic and metamorphic event at 2.84 Ga and were deformed and intruded by tonalitic to granitic magmas between 2.76 and 2.70 Ga (O'Brien et al., 1993a; Vaasjoki et al., 1993, 1999; Table 2). In the Hattu schist belt (Fig. 2), gold is hosted by extensive, structurally controlled alteration systems, and there is textural and structural evidence that gold mineralization preceded or was synchronous with the peak of the regional metamorphism (Sorjonen-Ward, 1993; Rasilainen, 1996). The geometry in the Hattu schist belt suggests a transpressional regime in which the mineralization occurred under conditions transitional between greenschist and lower-amphibolite facies; peak metamorphism was at lower-amphibolite facies, but did not cause complete recrystallization of the rocks (Sorjonen-Ward, 1993). The presence of mineralization in syntectonic tonalites is evidence that introduction of gold was likely synchronous with deformation (Nurmi et al., 1993). The Ilomantsi greenstone belt was reheated to greenschist facies by burial beneath a sequence of nappes in the foreland of the Svecofennian orogeny around 1.9 Ga. There is, however, no evidence for a distinct Proterozoic gold mineralization event in the area, despite the Proterozoic disturbances to isotopic systems (Kontinen et al., 1992; O'Brien et al., 1993b). Several generations of Paleoproterozoic dolerites, metamorphosed at greenschist facies, crosscut the gold deposits, but show no indication of mineralization or alteration (Nurmi et al., 1993).

The Archean Kuhmo and Suomussalmi greenstone belts (Fig. 1) had a more prolonged and complex evolution than the Ilomantsi greenstone belt (Luukkonen, 1992). However, gold mineralization seems to have taken place within shear systems that developed at the same time and with the same kinematics as those affecting the Ilomantsi greenstone belt (Luukkonen, 1993; Sorjonen-Ward and Nurmi, 1997). This suggests that a pervasive and coherent tectonic and mineralizing event occurred throughout the Archean craton at about 2.75 to 2.70 Ga.

The main compressional deformation associated with synorogenic plutonism in the Lapland domain took place during the period from 1.89 to 1.86 Ga (Rastas et al., 2001; Sorjonen-Ward et al., 2001). The compressional stage was accompanied, and possibly followed, by extensive orogenic gold mineralization (Mänttäri, 1995). A similar geotectonic and mineralization history is likely for both the Kuusamo and Peräpohja schist belts (Vanhanen, 2001; Perttunen and Vaasjoki, 2001).

Synorogenic processes (ca. 1.89–1.80 Ga) also were responsible for orogenic gold mineralization within the Svecofennian domain (Mäkelä et al., 1988; Luukkonen, 1994; Rosenberg, 1997; Kontoniemi and Nurmi, 1998). These deposits formed under amphibolite-facies conditions and postdate the earliest Svecofennian deformation, but were recrystallized and deformed to varying degrees after mineralization during the period from 1.84 to 1.80 Ga (Sorjonen-Ward and Nurmi, 1997; Kontoniemi, 1998).

## Metamorphosed Epithermal Gold Mineralization

At the Kutemajärvi mine and Järvenpää prospect, 35 km to the west (Fig. 1) in the Tampere schist belt, many features have been documented that are consistent with a metamorphosed epithermal gold deposit of the high-sulfidation (acid-sulfate) subtype (Poutiainen and Grönholm, 1996; Kojonen et al., 1999). The following description is based mainly on the Kutemajärvi deposit, because it is currently being mined and has been more extensively investigated than other occurrences in the region.

The Tampere schist belt is a Paleoproterozoic, continental-type island arc in an accretionary setting, dominated by intermediate, alkaline and calc-alkaline magmatism and turbiditic, fore-arc–type sedimentary rocks (Kähkönen et al., 1989; Kähkönen, 1994; Sorjonen-Ward et al., 1997b). Zircon U-Pb data indicate a rapid evolution of the belt, with volcanic rocks formed between 1904 and 1889 Ma and the synorogenic plutonic rocks intruded at 1885 to 1878 Ma (Nironen, 1989; Kähkönen et al., 1989). The Kutemajärvi deposit (Fig. 8) is hosted by intermediate, calc-alkaline, volcanic, or volcanogenic sedimentary rocks that form a part of a felsic to intermediate volcanosedimentary sequence in the central part of the Tampere schist belt (Luukkonen, 1994; Poutiainen and Grönholm, 1996). A hypabyssal, synvolcanic porphyritic intrusion of intermediate composition is also an integral part of the rock sequence (Poutiainen and Grönholm, 1996). The porphyry is 1 to 2 km wide and 15 km long at the present surface, and it is located only a few hundred meters to the north of the gold deposit, possibly crosscutting the alteration halo around the ore (Fig. 8).

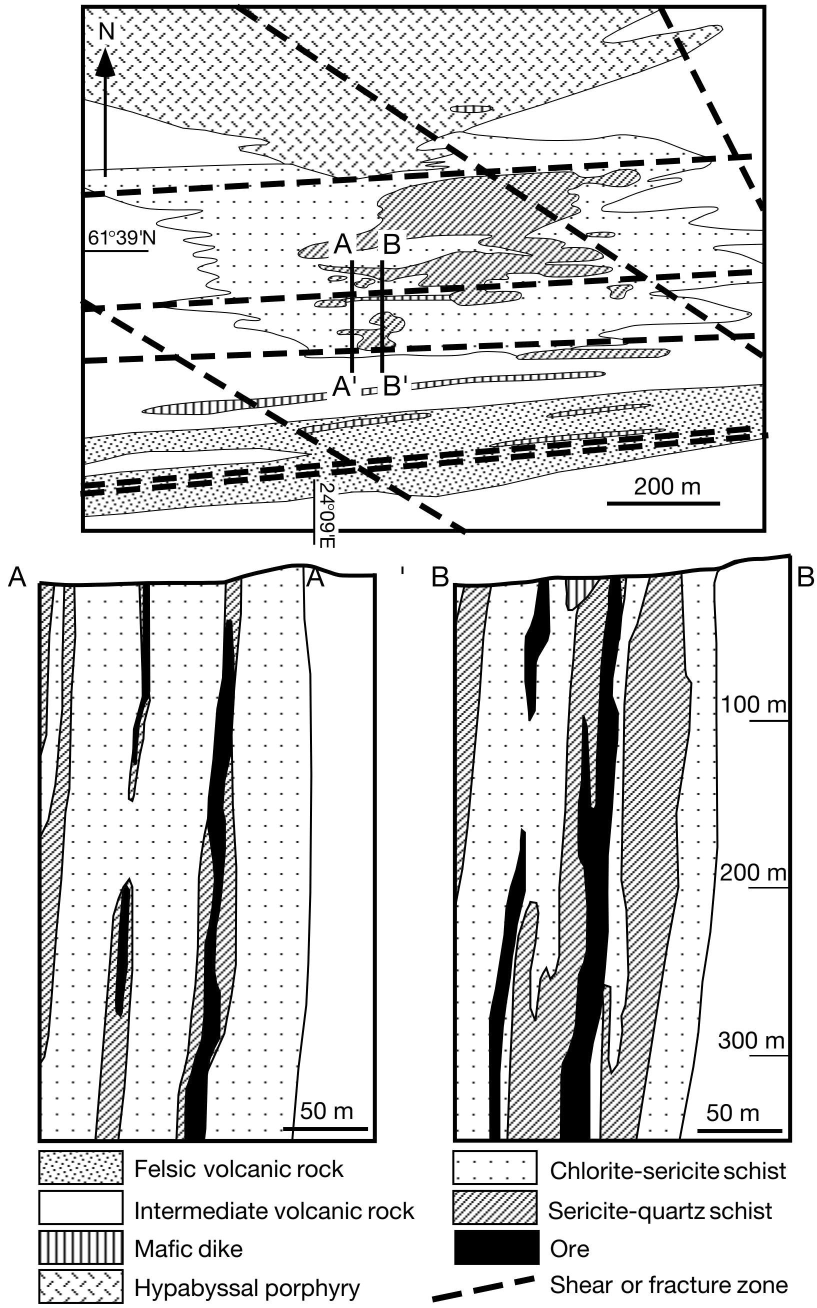


FIG. 8. Surface geology and two cross sections at Kutemajärvi, Tampere schist belt. After Poutiainen and Grönholm (1996).

The deposit is in an area metamorphosed to lower-amphibolite facies and characterized by multistage ductile to brittle-ductile deformation (Kilpeläinen et al., 1994). The Kutemajärvi ore bodies consist of five pipe-shaped, subvertical lodes (Kojonen et al., 1999) hosted by quartz and quartz-pyrophyllite rocks with variable amounts of andalusite, kaolinite, topaz, and fluorite (Luukkonen, 1994; Poutiainen and Grönholm, 1996). The host rocks are enveloped by a distal alteration zone consisting of sericite, quartz, and chlorite. Sericitic alteration can be traced regionally, along a particular horizon that appears to coincide with a transition in depositional setting and volcanic characteristics, including the advent of potassic volcanism (Kähkönen, 1994). Fluid inclusion investigations indicate the involvement of several types of syn- and postpeak metamorphic, $H_2O$-$CO_2$ ± $CH_4$, $N_2$, low-salinity fluids (Poutiainen and Grönholm, 1996) and minimum pressures and temperatures of regional metamorphism between 200° and 400°C and 0.5 to 2.5 kbar (Poutiainen et al., 1999).

Native gold and altaite are the main gold-bearing minerals at Kutemajärvi. Minor amounts of pyrite, arsenopyrite, and traces of a large number other Au tellurides, and chalcopyrite, sphalerite, galena, cubanite, native tellurium, electrum, and rutile have also been detected in the ore (Luukkonen, 1994; Poutiainen and Grönholm, 1996; Kojonen et al., 1999). The fineness of the gold is 950, on average, with Au/Ag ratios in the ore of 2 to 4, and Te/Se ratios of 7 to 20 (Luukkonen, 1994; Poutiainen and Grönholm, 1996).

In the ore, Au, Bi, F, S, Si, and Te are strongly enriched, and minor but distinct enrichment is evident in Ag, As, Hg, Sb, Se, and Zn (Luukkonen, 1994). Altered wall rocks are also enriched in Ag, Au, As, Bi, F, S, Si, and Te, and depleted in Fe, Mg, Ca, Na, and K. The most quartz rich rocks also show Al depletion. Locally in the altered domain, there also are signs of Cu, Sb, Se, and Zn enrichment (Luukkonen, 1994). On the other hand, there are no indications of K or $CO_2$ enrichment, and the Cu- and Au-enriched domains only show minor overlap.

The alteration zonation and geochemical features at Kutemajärvi are best explained by premetamorphic, epithermal-style alteration and metamorphic recrystallization of the altered rocks, possibly reflecting originally vuggy(?) quartz rock in the innermost zone, followed by advanced argillic alteration and distal propylitic alteration typical of high-sulfidation, epithermal deposits (cf. Hedenquist et al., 1996). During regional metamorphism at lower-amphibolite facies, these mineral assemblages would have been converted to the quartz, quartz-pyrophyllite-andalusite, and sericite-quartz-chlorite rocks present at Kutemajärvi. This interpretation is similar to that proposed for the Boliden deposit by Bergman Weihed et al. (1996), and for the Enåsen deposit in central Sweden by Hallberg (1994).

Lack of $CO_2$ enrichment, and intense depletion of Fe, Mg, Ca, Na, and K contrasts with the alteration normally related to orogenic gold deposits. Silicification of the host rock, formation of F-rich minerals, and significant pyrite in the alteration halo, but not in the ore, are also unusual. The F-rich minerals suggest a significant magmatic component in the fluid, and the source for heat and acidic fluids could potentially have been any of the intrusions abundant in the region.

The preservation potential of epithermal deposits in metamorphosed, deformed, and eroded terrain would be inherently low, unless associated with rapid subsidence, such as during arc extension. This has been inferred for Hope Brook in Newfoundland (Dube et al., 1998) and is consistent with the stratigraphic and volcanic context around Kutemajärvi as well.

## Skarn or Epigenetic Ironstone-Hosted Gold Mineralization

In Finland, gold occurrences that could be defined as skarn- or epigenetic ironstone-hosted (iron oxide-copper-gold) type have been discovered in the western and southeastern parts of the Central Lapland greenstone belt and in the Peräpohja schist belt (Fig. 1). Gold occurrences in the Kuusamo schist belt also have features in common with both the orogenic and iron oxide-copper-gold type, as recently discussed by Pankka (1997) and Vanhanen (2001). The occurrences in western Lapland (Figs. 3, 9, and 10) most closely resemble skarns, as suggested by Hiltunen (1982).

### *Western Lapland*

Several magnetite orebodies (ironstone) and skarnlike units of diopside-hornblende rock in the Kolari area of the westernmost Central Lapland greenstone belt (Fig. 3) host chalcopyrite-pyrite-pyrrhotite-native gold mineralization. All deposits have a structural control and are located in or close to a fault or shear zone. The ironstone bodies are hosted by a supracrustal sequence containing abundant mafic metavolcanic rocks and marbles, and are close to, or at the contact with, a 1.86 Ga synorogenic monzonite intrusion (Hiltunen,

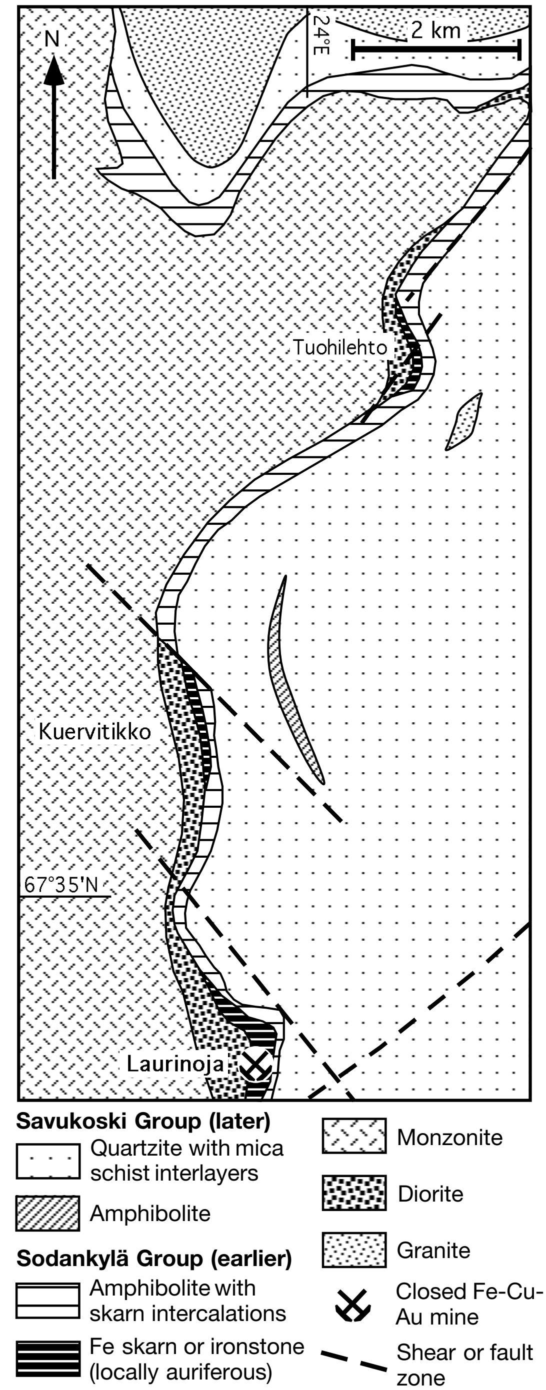


FIG. 9. Geologic map of the area to the north of the Laurinoja Fe-Cu-Au mine in the western part of the Central Lapland greenstone belt. Geology after Hiltunen (1982); stratigraphy after Lehtonen et al. (1998).

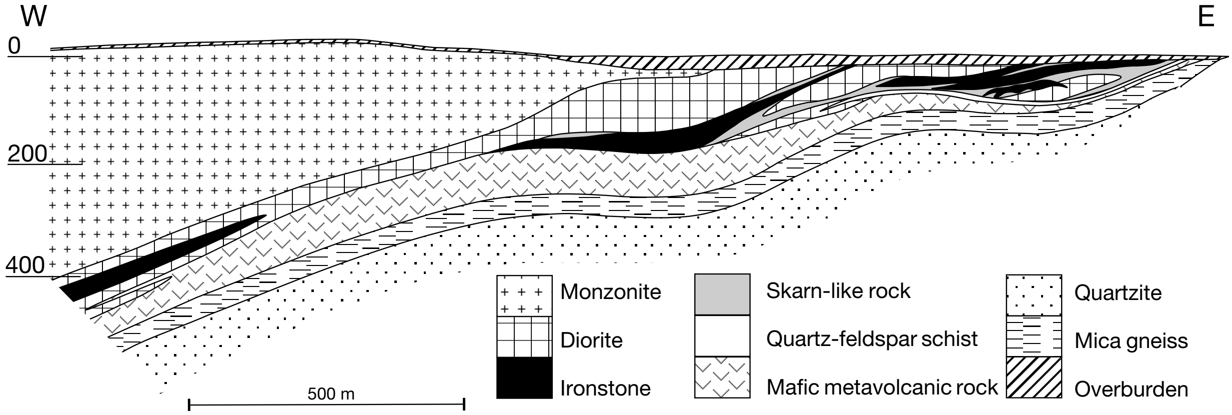


FIG. 10. Section across the Laurinoja deposit, Kolari area, western Central Lapland greenstone belt. Modified from Hiltunen (1982).

1982; Lehtonen et al., 1998). On the other hand, some of the occurrences hosted by skarnlike diopside-hornblende rocks do not show any close spatial association to intrusions. Some of the magnetite bodies have been exploited as iron ores, but gold and copper have been extracted only from the Laurinoja deposit (Figs. 9 and 10; Hiltunen, 1982).

Magnetite contents in the ironstones are typically 20 to 80 percent, with 1 to 5 percent sulfides. Gangue chiefly comprises diopside and hornblende. The main sulfide minerals are chalcopyrite, pyrite, and pyrrhotite, which form disseminations, mm-wide veins, and weak stockworks. Gold is closely associated with sulfides, particularly chalcopyrite, and occurs in native form (Hiltunen, 1982; T. Niiranen, unpub. data, 2003).

Early regional alteration in nearly all rock types in western Lapland includes weak to moderate albitization and scapolitization. The regional alteration is followed by at least two stages of local alteration extending for hundreds of meters to kilometers along strike, and tens to hundreds of meters across the strike of the host rocks. The first stage produced magnetite, diopside, and titanite in the ironstones surrounded by abundant hornblende, diopside, and plagioclase, and minor biotite, garnet, titanite, magnetite, and scapolite. In the second stage, the sulfides and gold, with hornblende and variable but minor amounts of albite, quartz, calcite, biotite, talc, and epidote, overprint the ironstone. The adjacent granitoids also show the effects of hydrothermal alteration, including albite, quartz, hornblende, epidote, biotite, ± pyrite, and chalcopyrite. Elements enriched in the sulfidized ironstones at Kuervitikko and Laurinoja are Ag, Au, Bi, Co, Cu, Fe, Mo, LREE, S, Se, and Te (T. Niiranen, unpub. data, 2003).

The timing of Fe-Cu-Au mineralization in western Lapland is only broadly constrained between 1.86 Ga, which is the age of the youngest intrusive rocks affected by alteration, and 1.80 Ga, which is the age of granitoids that are discordant with respect to regional structural trends (Rastas et al., 2001). However, these latter intrusions are also associated with hydrothermal alteration of country rocks, albeit at a lower metamorphic grade than the magnetite-diopside-titanite skarn association. Typical alteration associated with the monzogranite includes reddened feldspar, actinolite, epidote, and magnetite (P. Sorjonen-Ward, unpub. data, 2003), indicating that at least two hydrothermal events accompanied felsic magmatism in the western part of the Lapland greenstone belt. Both magmatic events are distinct from the first phase of Svecofennian intrusive activity, which is well constrained by U-Pb zircon ages of 1880 Ma from a suite of calc-alkaline plutons and coeval intermediate volcanic rocks (Perttunen and Vaasjoki, 2001; Rastas et al., 2001). These volcanic rocks have been regarded as late to postcollisional with respect to the main phase of deformation in Lapland, and correlated with the Kiruna porphyries in Sweden (Sorjonen-Ward et al., 1997b).

### *Peräpohja schist belt*

In the Peräpohja schist belt, more than 30 individual bodies of ironstone, with sizes ranging from 0.04 to 1.0 Mt, occur within a 2-km-long and 500-m-wide, north-south–trending zone, known collectively as the Vähäjoki Fe-Cu-Co-Au deposit (Fig. 1; E. Korvuo, unpub. report for Lapin Malmi, 1982; Liipo and Laajoki, 1991). The first bodies were discovered by ground magnetic survey in 1943 (Vornanen, 1963), and the area was, at first, only explored for iron. In the early 1980s, other metals were considered, resulting in the discovery of enrichments in gold, cobalt, and copper (Table 1).

The ironstones at Vähäjoki comprise magnetite with a gangue dominated by tremolite-actinolite, cummingtonite, and hornblende (Liipo and Laajoki, 1991). These are hosted by altered dolomitic marble and mafic metavolcanic rocks of the ca. 2.14 to 2.0(?) Ga Tikanmaa Formation (Huhma et al., 1990; Liipo and Laajoki, 1991). Magnetite occurs as a breccia infill, veins, and irregular masses in altered host rocks. The main ore minerals are magnetite, pyrite, chalcopyrite, and cobaltite; ilmenite, haematite, arsenopyrite, sphalerite, galena, mackinawite, linneaite, bornite, marcasite, pyrrhotite, and native gold are present as minor to trace constituents. Native gold occurs with chalcopyrite as inclusions in cobaltite, locally associated with arsenopyrite, and as free grains in gangue (Vornanen, 1963; T. Niiranen, unpub. data, 2003).

In contrast to western Lapland, no regional albitization or scapolitization has been observed; all alteration identified is localized. Two major stages of alteration have been detected at Vähäjoki (T. Niiranen, unpub. data, 2003). During the first stage, hot brines reacted with the host sequence and produced the ironstone bodies with the assemblage magnetite, actinolite, biotite, albite, scapolite, and quartz. This was followed by circulation of low-salinity $H_2O$-$CO_2$ fluids and precipitation of hornblende, quartz, calcite, sulfides, and gold. Arsenic, Au, Co, Cu, Fe, S, and Te are enriched in the deposit.

Alteration and mineralization were probably syn- to peak regional metamorphism. However, the peak metamorphic conditions at Vähäjoki (465° ± 50°C, 2–4 kbars; Liipo and Laajoki, 1991) were higher than elsewhere in the southeast part of the Peräpohja belt. The significance of this is uncertain. There is no direct indication of synmineralization intrusion, but a structural focusing of fluids is evident. Liipo and Laajoki (1991) suggest that the fluid flow was concentrated by a fault zone whose north-south trend is suggested by the array of the ironstone bodies. However, the deposit is also located within in a fold hinge, in proximity to a major east-west–trending fault (V. Perttunen, pers. commun., 2001).

### Intrusion-Related (Nonskarn) Gold Mineralization

A few gold occurrences with similarities to intrusion-hosted stockworks, disseminations of both porphyry and nonporphyry type, and wall rock-hosted breccias, following the classification of Sillitoe (1991), are located in the Raahe-Haapajärvi district of the Svecofennian domain in western Finland and its extension southeastward into central Finland (Fig. 1). Fewer than 10 deposits of this type have been identified (Eilu, 1999), and the following discussion is based primarily on the Kopsa deposit (Figs. 1 and 11), which is the only well-studied example of this group.

The Kopsa deposit is hosted by an I-type, syntectonic, calc-alkaline, tonalite porphyry stock (Fig. 11) and, to a lesser extent, by its sedimentary wall rocks (Gaál and Isohanni, 1979; Gaál, 1990; Nurmi et al., 1991). The Kopsa intrusion is located at the intersection between northwest- and northeast-trending faults and is characterized by sulfide- and gold-bearing quartz-vein stockworks and sulfide dissemination (Gaál and Isohanni, 1979; Weihed and Mäki, 1997). Similar mineralization elsewhere in the region is hosted by supracrustal rocks at a distance of 1 to 2 km from syntectonic intrusions. The gold occurrences in supracrustal rocks are hosted by massive breccias and are structurally controlled as they are close to major northwest-trending fault or shear zones. All deposits are situated within or close to the Raahe-Ladoga Suture zone (Fig. 1).

In all cases, arsenopyrite is the dominant or major ore mineral, together with native gold, chalcopyrite, loellingite, pyrrhotite, and pyrite (Aho, 1975; Gaál and Isohanni, 1979; Eilu, 1999). The mineral assemblage at Kopsa also includes marcasite, sphalerite, molybdenite, cubanite, bornite, stannite, native bismuth, and Bi sulphosalts (Gaál and Isohanni, 1979). All deposits are enriched in Ag, As, Au, Cu, and S; Kopsa also contains B, Bi, Sb, Se, Te, and W (Gaál and Isohanni, 1979; Nurmi et al., 1991), similar to the Au-Cu-Bi-Te-W association of intrusion-related gold deposits (e.g., Sillitoe, 1991; Ulrich et al., 1999).

The host rocks are metamorphosed to lower- to middle-amphibolite facies, but the data available from prospect reports suggest that mineralization was syn- or late tectonic, and there are no indications of metamorphic overprinting.

In all cases where alteration has been closely investigated, K ± B metasomatism is indicated by the formation of K feldspar, biotite, and tourmaline. At Kopsa, the potassic metasomatism is chiefly characterized by K feldspar (Gaál and Isohanni, 1979). Proximal tourmalinization is developed in the adjacent supracrustal rocks in all occurrences (Aho, 1975), and an outer K-enriched zone envelops the B-rich zone.

The lack of correlation between Au and Cu, the enrichment in Ag, As, Au, Bi, Sb, Te, and W, and the local structural control, suggest that the Kopsa deposit may represent porphyry-Cu mineralization that has been overprinted by orogenic gold mineralization. A similar model has been suggested for the Tallberg Cu-Au deposit located in the Skellefte belt, northern Sweden, which is hosted by an 1888

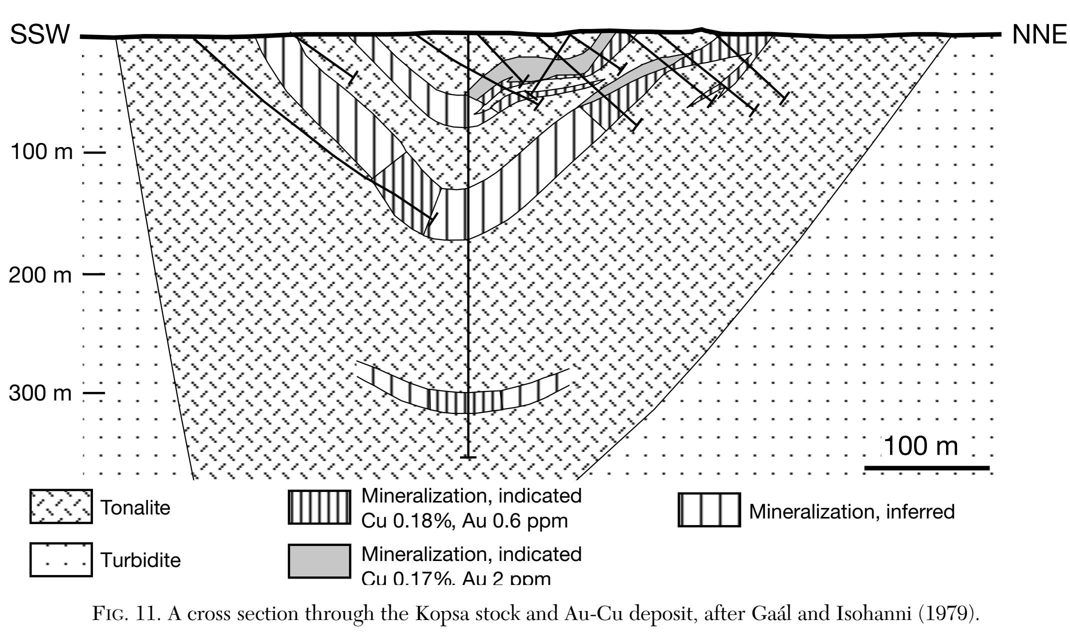


FIG. 11. A cross section through the Kopsa stock and Au-Cu deposit, after Gaál and Isohanni (1979).

Ma, I-type tonalite (Weihed, 1992; Weihed and Fallick, 1994). Overall, the deposits bear a closer resemblance to intrusive-hosted orogenic lode gold deposits, such as Osikonmäki (Savo district) in the Svecofennian domain (Kontoniemi, 1998), and the late Archean Kuittila deposit (Ilomantsi greenstone belt), where Au-mineralized shear zones are clearly discordant across early Mo-W quartz vein networks (Nurmi et al., 1993). The host intrusions typically have magnetically subdued geophysical signatures, and petrographic criteria suggest that they are relatively reduced. However, careful paragenetic studies are required to discriminate between intrusive-hosted orogenic gold deposits and those in which mineralization is directly related to the emplacement of reduced plutons (cf. Thompson et al., 1999).

## Gold in Massive Sulfide Deposits

All Finnish massive sulfide deposits have produced some gold, and the largest producers are listed in Table 8. There is a large variation in host rock type, including ultramafic serpentinites of mantle origin to mafic volcanic rocks, black shales, and still somewhat enigmatic quartz rocks at Outokumpu, as well as felsic to intermediate volcanic rocks and related sedimentary rocks at Pyhäsalmi, Vihanti, and Aijala (Helovuori, 1979; Gaál and Sundblad, 1990). Both ophiolite- and arc-related deposits (Helovuori, 1979; Gaál, 1990; Gaál and Sundblad, 1990; Sorjonen-Ward et al., 1997b) contained significant amounts of Au. The Hammaslahti Cu deposit, hosted by feldspathic turbidites and stratigraphically associated with 2.10 Ga tholeiitic volcanic rocks formed during rifting of the Karelian craton margin, represents a distinctive mineralization style, with elevated Au and Zn, and showing a strong correlation between Cu, Au, and K enrichment, and Na depletion (Loukola-Ruskeeniemi et al., 1991).

Typical gold tenors in all these deposits are below 1 ppm Au. The gold chiefly occurs in association with sulfides both as native gold and in the lattice of the sulfides. Electrum and arsenides, tellurides, Bi minerals, and sulphosalts have been reported, both in the base-metal ore and the wall rocks, associated with gold. At Pyhäsalmi, the grade given in Table 8 refers to the massive sulfide ore, but a higher-grade Au-Ag-As-Pb-Te mineralization is also present locally in the wall rocks, presumably reflecting remobilization of Au and related elements during deformation (Eilu et al., 1988; Mustonen, 1998).

Several features of the Haveri deposit in the Tampere schist belt, notably the geological setting, host rocks, and alteration, indicate a submarine hydrothermal origin (Mäkelä, 1980; Nironen, 1994; Kähkönen and Nironen, 1994). However, correlation between Au and Cu is practically nonexistent, and the gold is related to a distinctly different style of alteration (i.e., structurally controlled biotitization, rather than chloritization typical of VHMS). In the absence of detailed structural studies from Haveri, it is not possible to say whether the deposit has been overprinted by orogenic Au mineralization.

## Paleoplacer Deposits

Paleoplacer gold has been detected in the uppermost, 20- to 2,000-m-thick, molasselike Kumpu Formation of the Central Lapland greenstone belt (Fig. 3). These occurrences are similar to paleoplacer gold elsewhere, and most closely resemble those in Tarkwa, Ghana, which also are Paleoproterozoic in age (Minter, 1991). The Finnish occurrences are hosted by both mono- and polymictic conglomerates deposited in deltaic and fluvial fan environments between 1913 Ma and about 1800 Ma (Härkönen, 1984, 1986). It is noteworthy that the Kumpu Formation is a true red bed sequence, with hematite staining, although locally this has been lost during metamorphic recrystallization. Most of the gold is hosted by the central major unit of the Kumpu Formation, in up to 3-m-thick and 30-m-long conglomerate lenses. Within these lenses, the grade typically varies from 0.1 to 5 ppm Au, but locally reaches 22 ppm (Härkönen, 1984). However, only two cases are known (a cross in Fig. 3) where the Au content exceeds 1 ppm for an interval of more than 1 m in thickness.

Gold in the paleoplacers occurs mainly as free, native, detrital grains with sizes of 0.03 to 0.4 mm, and, in minor amounts, as smaller inclusions in quartz clasts (Härkönen, 1984). Other heavy minerals associated with the gold are magnetite, hematite, uraninite, pyrite, ilmenite, rutile, silver, tourmaline, monazite, titanite, and zircon (Härkönen, 1984). The host rocks are metamorphosed to greenschist facies, and no alteration or significant mobilization of gold has been reported, although the breakdown of hematite during diagenesis or metamorphism is thought to be related to ingress of more reduced fluids.

In the Kumpu Formation, there are no indications of epigenetic gold. It has been suggested that the gold is derived

TABLE 8. Selected Features of Finnish Base-Metal Mines That Have Produced Significant Amounts of Gold

| Mine | Plate tectonic setting | Base-metal association | Production (end of 2001) (Mt) | Average Au grade (ppm) | Total Au produced (kg) | Production history |
|---|---|---|---|---|---|---|
| Keretti (Outokumpu ) | Ophiolite | Cu-Co-Zn | 28.5 | 0.8 | 22,800 | 1913–1988 |
| Vuonos (Outokumpu ) | Ophiolite | Cu-Co-Ni-Zn | 5.89 | 0.1 | 590 | 1972–1981 |
| Pyhäsalmi (Raahe-Ladoga Suture) | Island arc | Cu-Zn | 34.5 | 0.4 | 13,200 | 1962– |
| Vihanti (Raahe-Ladoga Suture) | Island arc | Zn-Cu-Pb | 19 | 0.34 | 6,500 | 1951–1992 |
| Aijala (southwest Finland) | Island arc | Cu-Zn | 1 | 0.7 | 700 | 1948–1960 |
| Metsämonttu (southwest Finland) | Island arc | Zn-Pb | 1.5 | 1.3 | 1,900 | 1951–1974 |
| Haveri (Tampere schist belt) | Marginal basin | Cu | 1.5 | 2.8 | 4,200 | 1942–1962 |

Based on Isokangas (1978), Helovuori (1979), Kontinen (1987), Gaál (1990), Gaál and Sundblad (1990), Puustinen (1991), Kähkönen and Nironen (1994), Nironen (1994), Sorjonen-Ward et al. (1997b), and T. Mäki, pers. commun. (2001); all deposits have a Paleoproterozoic age; note that Au data from two larger mines, the graywacke-hosted Hammaslahti Cu-Zn deposit and Luikonlahti Cu deposit, which is geologically analogous to the Outokumpu deposits, were not available from the underlying greenstones, especially from the numerous orogenic gold deposits (Fig. 3) and small, but equally numerous, massive and disseminated, syngenetic sulfide occurrences (Härkönen, 1984, 1986; Puustinen, 1991). This is reasonable, considering the unconformity between these sediments and the underlying greenstones. However, there is local evidence near the Sirkka Line for the occurrence of late, structurally controlled hydrothermal gold within related sediments, implying either several mineralization events, or a continuum of mineralizing events, during deposition of this late-orogenic cover sequence.

## Placer Deposits

A large number of small placer gold occurrences are known in northern Lapland, in Holocene till, sand, and gravel, chiefly in the valleys of the Ivalonjoki and Lemmenjoki rivers and their tributaries. Despite the numerous occurrences, more than 130 yr of exploitation has only produced about 1,000 to 2,000 kg of gold (Puustinen, 1991). The dominant primary source for the placer gold has been much debated, but is, presumably, the same as for the paleoplacer deposits. In addition, the small, gold-bearing veins in the Archean areas of northern Finland and in the Lapland granulite belt (Fig. 1) may, locally, have made a significant contribution to the placer deposits.

## Summary and Conclusions

Gold deposits in Finland include a wide range of mineralization styles and geological settings. They cover a large time span, beginning from 2.7 Ga, and are present throughout the country in most of the schist belts and other major geological subdomains, in both Archean and Paleoproterozoic settings.

The following styles of gold mineralization are currently recognized: (1) orogenic gold mineralization, (2) metamorphosed epithermal mineralization, (3) skarn- or epigenetic ironstone-hosted mineralization, (4) intrusion-related (nonskarn) deposits hosted by porphyries and brecciated wall rocks, (5) massive sulfide-hosted gold, (6) paleoplacer deposits, and (7) placers. In terms of abundance of deposits identified, the orogenic gold deposits are overwhelmingly dominant, although until recently, most of the gold produced was as a byproduct of processing from Paleoproterozoic basemetal massive sulfide deposits.

Gold mineralization is related to several episodes in the crustal evolution in Finland. During the late Archean, orogenic gold mineralization took place in all greenstone belts at about 2.75 to 2.70 Ga, suggesting a coherent and pervasive tectonic and mineralizing event throughout the craton. During the Proterozoic, the first significant, although low-grade (<1 ppm), concentration of Au occurred in massive sulfide deposits in ophiolite settings (Outokumpu), related to rifting of marginal areas of the Archean craton at about 1.97 to 1.95 Ga. This was followed, between 1.91 and 1.87 Ga, by volcanic-arc magmatism during collisional stages of the Svecofennian orogeny. Syngenetic massive sulfide mineralization (e.g., Pyhäsalmi), with gold at grades of 0.1 to 1.0 ppm, was related to this magmatism in the Raahe-Ladoga Suture (Fig. 1) and southwest Finland. It remains unclear whether syngenetic sulfide mineralization in a marginal basin setting at Haveri, Tampere schist belt, also accumulated gold, or if this deposit was overprinted by later gold. A possible analog of high-sulfidation epithermal gold mineralization also occurs in the Tampere schist belt at Kutemajärvi, related to a transition from calc-alkaline to alkaline magmatism in a possible rifting and subsiding arc setting. In this respect, there are similarities with the Skellefte district of northern Sweden. The epithermal deposits probably escaped erosion due to the fact that the region underwent extension followed by a rapid burial.

In the Svecofennian domain of Finland, the major accretionary stage took place at 1.89 to 1.86 Ga. During that time, intrusion-related (nonskarn) Au-Cu mineralization took place in both syntectonic porphyry stocks and their wall rocks in and close to the Raahe-Ladoga Suture (Fig. 1). Orogenic gold mineralization occurred at, or slightly after, the 1.89 to 1.86 Ga metamorphic peak throughout the domain. A subsequent low-pressure, high-temperature metamorphic event overprinted some of the deposits at around 1.84 to 1.80 Ga, indicating that Svecofennian orogenic gold mineralization predated the latest deformation and metamorphism in the area. A significant proportion of these deposits are hosted by felsic and intermediate supracrustal and intrusive rocks, and the siting of gold partly reflects competency contrasts with the adjacent metasedimentary rocks.

The Lapland domain records a complicated evolution of rifting, magmatism, sedimentation, and collision with various styles of alteration taking place during all major stages of its tectonic evolution. Extensive albitization took place during the early stages of Paleoproterozoic orogenic evolution in both Central Lapland and Kuusamo, and this may have been an important precursor to gold mineralization. Orogenic gold mineralization took place in all major Proterozoic greenstone belts in northern Finland during or after the main compressional stage of the Svecofennian orogeny around 1.89 to 1.86 Ga, roughly at the peak of metamorphism and deformation. Although all rock types of supracrustal and hypabyssal origin may host gold, the most favorable sites are the albitized units close to major shear and fault zones. Skarn or epigenetic ironstone-hosted gold mineralization is also present in northern Finland, in the western part of the Central Lapland greenstone belt, and in the Peräpohja schist belt. These copper-gold occurrences are syntectonic and possibly formed during two distinct episodes, centered around 1.86 and 1.80 Ga. Presently, it appears that there may be a continuum between typical orogenic gold deposits, such as Saattopora, Pahtavaara, and Suurikuusikko, and mineralization similar to the oxide Fe-Cu-Au systems of the Proterozoic of northern Australia. There is, however, a clear need to better constrain the timing of mineralization with respect to deformation and magmatism. Synorogenic deposition of molasselike sediments in Lapland during uplift and intense erosion of surrounding terrain, prior to 1.80 Ga, produced local placer mineralization in the conglomerates of the uppermost formation of the Central Lapland greenstone belt. Gold was derived from both orogenic gold and syngenetic sulfide mineralization in the area.

Most of the features summarized above are common to all orogenic belts. Features related to Precambrian gold mineralization in Finland that are commonly not described elsewhere include the following: (1) the presence of more gold in Proterozoic than in Archean areas (this holds for the entire

Fennoscandian Shield; see also Sundblad, 2003); (2) the common occurrence of orogenic gold in both amphibolite- and greenschist-facies rocks; (3) the early albitization thought to be associated with orogenic gold in northern Finland; (4) the metal association of Au-Cu-Co ± U for many orogenic gold occurrences in Kuusamo; and (5) the preservation of Paleoproterozoic, metamorphosed epithermal gold mineralization.

Based on the compilation of known gold occurrences in Finland, the areas of greatest potential for the discovery of new orogenic gold deposits probably are the Archean greenstone belts in eastern Finland, and the Paleoproterozoic Central Lapland greenstone belt and Kuusamo schist belt. The western parts of the Central Lapland greenstone belt are the most promising for skarn- or epigenetic ironstone-hosted gold. Areas close to the Raahe-Ladoga Suture may be expected to contain other intrusion-related (nonskarn) deposits, and the Tampere schist belt may contain additional epithermal-like gold deposits. It is considered that the greatest potential for a >1-Moz (>30-t) deposit is within the known clusters of deposits in Kuusamo, Ilomantsi, and Central Lapland, where the tectonic evolution, magmatism, deformation, and style of regional alteration are favorable for several different styles of mineralization. Iron-rich rocks (i.e., bif, skarn, and epigenetic ironstones), potential settings for metamorphosed epithermal mineralization, and Archean greenstone belts outside the relatively well known Ilomantsi belt are under explored. The recent discoveries in the poorly exposed Oijärvi greenstone belt, where, prior to 1996, there was no indication of gold mineralization, highlight this potential.

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