PART

GOLD DEPOSITS

5

OVERVIEW ON GOLD DEPOSITS IN FINLAND

5.1

P. Eilu

ABSTRACT

Genetic types of gold deposits identified in Finland include Au-rich volcanogenic massive sulfide (VMS), metamorphosed high-sulfidation epithermal, porphyry gold-copper, orogenic gold, placer, and paleoplacer deposits. There also are gold deposits and occurrences whose genetic type is ambiguous, such as the Au-Co ± Cu occurrences in the Kuusamo schist belt, the Au-U occurrences in the Peräpohja schist belt, and the Pahtavaara gold deposit. In contrast to many other Precambrian shield areas, most of the known gold occurrences and resources in Finland are hosted by Paleoproterozoic sequences. All gold-mineralized environments in Finland, except the possible Archean epithermal deposits and the recent placers, can be related to supercontinent evolution of the region between ~2.75–1.77 Ga. Most of the gold deposits were formed during the main stages of crustal growth globally, at ~2.72–2.64 Ga and 1.91–1.77 Ga, during the Neoarchean and Svecofennian orogenies, respectively.

Keywords: Archean; Paleoproterozoic; Fennoscandian Shield; Finland; orogenic gold; epithermal gold; porphyry gold; supercontinents.

INTRODUCTION

Exploration for gold deposits as major targets began in Finland during the 1980s. Exploration activities soon spread across most of the country, as indicated by the discovery dates of deposits given in Table 5.1.1. Prior to the 1980s, the common perception was that northern Europe lacked major gold deposits.

Mineral Deposits of Finland. http://dx.doi.org/10.1016/B978-0-12-410438-9.00015-7

Table 5.1.1 Gold mines and deposits with a reported resource in Finland

Genetic type, deposit	District[a]	Discovery year	Period of mining	Total size (Mt)	Mined (Mt)	Grade[b]					Reference to remaining resource[d]
						Au	Ag	Co	Cu	Other metals	
Orogenic gold											
Pampalo	Ilomantsi	1990	1996, 2010–	1.85	0.55	4.1					Endomines (2013)
Valkeasuo	Ilomantsi	1992		0.68		3.3					Endomines (2013)
Kuittila	Ilomantsi	1984		0.28		2.58					Damsten (1990)
Rämepuro	Ilomantsi	1984		0.31		2.1					Endomines (2013)
Korvilansuo	Ilomantsi	1986		0.26		2.0					Endomines (2013)
Muurinsuo	Ilomantsi	1987		0.85		1.6					Endomines (2013)
Kuivisto	Ilomantsi	1993		0.18		1.4					Endomines (2013)
Kuikkapuro	Suomus-salmi	1997		0.05		14.6					Heino (2000)
Moukkori	Suomus-salmi	1990		0.02		10.6					Parkkinen (2003)
Pahkalampi	Suomus-salmi	1996		0.25		3.5					Parkkinen (2003)
Pahkosuo	Suomus-salmi	1995		0.10		1.55					Heino (2001)
Syrjälä	Suomus-salmi	1995		0.07		1.55					Heino (2000)
Kutuvuoma	CLGB	1993	1998, 2000	0.07	0.01	6.7					Korkalo (2006)
Suurikuusikko	CLGB	1986	2008–	64.22	4.27	4.14					Agnico-Eagle (2013)
Soretialehto	CLGB	1989		0.01		3.5					Keinänen (1994)
Hirvilavan-maa	CLGB	1986		0.11		2.9					Hulkki and Keinänen (2007)
Kuotko	CLGB	1986		1.82		2.89					Agnico-Eagle (2013)
Vesiperä	R-H	1984		0.3		2.5					Sipilä (1988)
Laivakangas	R-H	1982	2011–2014	26.65	1.53	1.68					GSA Global (2012)
Hirsikangas	R-H	2004		5.68		1.25					GSA Global (2012)

Ängesneva	R-H	1987		3.85		1.19					Belvedere Resources (2010)
Sikakangas	SO	1989		0.17		1.32					Isomaa et al. (2010)
Osikonmäki	SS	1986		4.84		2.0					Belvedere Resources (2011)
Kaape-linkulma	Pirkanmaa	1986		0.16		6.2					Dragon Mining (2009)
Jokisivu	Pirkanmaa	1985	2009–	2.13	0.35	5.2					Dragon Mining (2012a)
Satulinmäki	Häme	1990		0.36		2.34					Kärkkäinen et al. (2006)
Orogenic gold with anomalous metal association											
Kaaresselkä	CLGB	1987		0.3		5					Hulkki and Pulkkinen (2007)
Saattopora	CLGB	1985	1988–1995	2.16	2.16	2.9			0.25		
Kettukuusikko	CLGB	1977		0.44		1.8					Taranis Resources (2011)
Riikonkoski[c]	CLGB	1966		9.56		?			0.45		Yletyinen and Nenonen (1972)
Ängeslampi	R-H	1986		0.27		3.1			0.14		Sipilä (1990)
Pirilä	SS	1983		0.3		6.5	32		0.18	0.76 Pb, 0.11 Zn	Parkkinen (2003)
Kalliosalo	SO	1977		0.3		1	0.7			0.41 Sb	Saltikoff (1980), Tyni (1983)
Sivakkaharju[c]	Kuusamo	1986		0.05		7.5		0.03	0.12		Dragon Mining (2011)
Hangaslampi[c]	Kuusamo	1988		0.40		5.1		0.06	0.1		Dragon Mining (2012b)
Apajalahti[c]	Kuusamo	1970s		0.1		5		0.02	0.05	0.04 W	Lahtinen (1980)
Juomasuo[c]	Kuusamo	1985	1992	1.97	0.018	4.9		0.15	0.03		Dragon Mining (2011)
Pohjasvaara[c]	Kuusamo	1985		0.13		4.0		0.09	0.3		Dragon Mining (2011)
Iso-Rehvi[c]	Kuusamo	1988		0.04		4		0.05	0.1		Vanhanen (1991)
Meurastuk-senaho[c]	Kuusamo	1984		0.89		2.3		0.2	0.1		Dragon Mining (2011)
Säynäjävaara[c]	Kuusamo	1983		0.4		1		0.06	0.02		Pankka and Vanhanen (1992)
Kivimaa[c]	Peräpohja	1965	1969	0.02	0.018	5.3			1.87		

Continued

Table 5.1.1 Gold mines and deposits with a reported resource in Finland—cont'd

Genetic type, deposit	District[a]	Discovery year	Period of mining	Total size (Mt)	Mined (Mt)	Grade[b]					Reference to remaining resource[d]
						Au	Ag	Co	Cu	Other metals	
VMS											
Pahtavaara[c]	CLGB	1985	1996–	7.74	4.98	2.62					Lappland Goldminers (2013a)
Iilijärvi	Uusimaa	1757	1788, 1884	0.05	0.003	4	30		0.6	0.6 Pb, 1.3 Zn	Mäkelä (1989)
Metsämonttu	Uusimaa	1946	1951–1974	1.51	1.51	1.43	25		0.28	0.74 Pb, 3.34 Zn	
Haveri	Tampere	1737	1942–1962	26.3	1.56	1			0.5		Lappland Goldminers (2008)
Outokumpu	Outokumpu	1910	1910–1989	28.5	28.5	0.8	8.9	0.24	3.8	0.12 Ni, 1.07 Zn	
Vihanti	V-P	1946	1954–1992	37.10	27.94	0.44	25		0.48	0.36 Pb, 4 Zn	Outokumpu Oy unpubl. data (1992)
Pyhäsalmi	V-P	1958	1962–	67.38	50.86	0.3	14		0.8	2.2 Zn	Inmet Mining (2013)
Epithermal											
Kutemajärvi	Tampere	1982	1994–	3.19	2.03	5.2					Dragon Mining (2012a)
Kylmäkangas[c]	Oijärvi	1999		1.9		4.11	31				Agnico-Eagle (2013)
Porphyry											
Kopsa	R-H	1939		16.8		0.81	2.2		0.16		Belvedere Resources (2013)
Kedonojan-kulma	Häme	2010		1.8		0.12	11		0.4	0.0018 Mo	Tiainen et al. (2013)
IRG?											
Mäkärärova[c]	N. Finland	1949		0.08		2.1					Nurmi et al. (1991)

Included are those polymetallic deposits where gold potentially is among the main commodities. Also included are the three largest VMS mines (Outokumpu, Pyhäsalmi, Vihanti), as these jointly produced most of the pre-2000 gold in Finland. All deposits (except Pyhäsalmi and Outokumpu) are open at depth, most deposits open also along the strike. Mined tonnages are given as of the end of 2012. Production figures are from the Finnish Mining Registry.

[a]*District names as in Fig. 5.1.2; CLGB = Central Lapland Greenstone Belt, R-H = Raahe-Haapajärvi, SO = Southern Ostrobothnia, SS = Southern Savo, V-P = Vihanti-Pyhäsalmi.*

[b]*Grade in g/t for Au and Ag, other metal grades in percent; ? = poor coverage of data, estimated to range 0.1–5 g/t.*

[c]*Genetic type unclear.*

[d]*No reference: no reported remaining resource.*

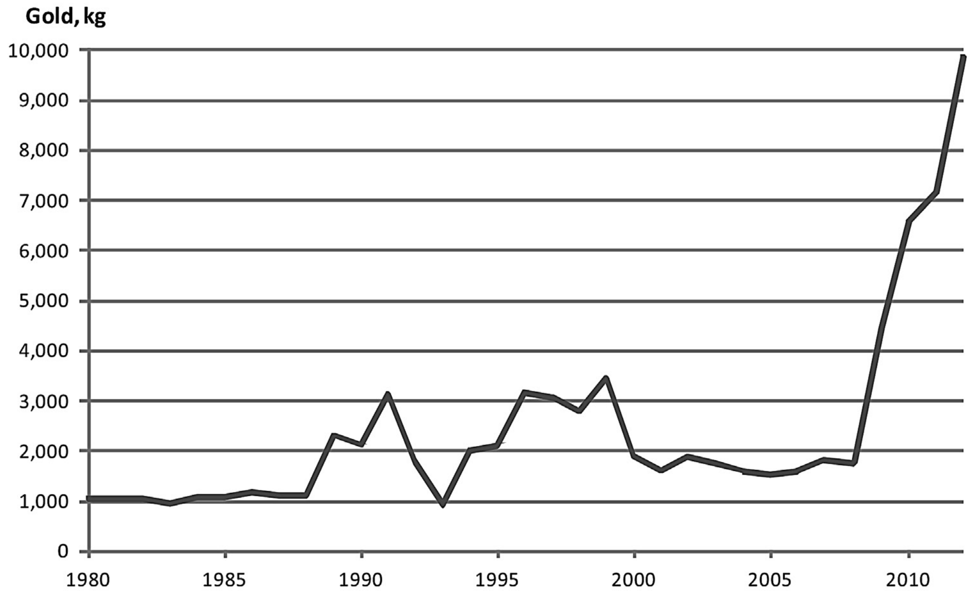

FIGURE 5.1.1

Annual gold production from Finnish mines from 1980 to 2012. Data mainly from Finland's Mining Registry statistics (summarised until 2001 by Puustinen, 2003). The 2012 data is from mining company annual reports. By-product gold from the base metal mines Pyhäsalmi, Vihanti, and Vuonos (Chapter 8) is estimated using the mined ore tonnage, average gold content in the ore and an estimated 80 % recovery grade, except for 1986–2001 where detailed gold production data exists from these mines. No gold grade nor production data exists for the Hammaslahti Cu mine (Urpo Kuronen, pers. comm. 23 Jan 2013) which produced, perhaps, 100–500 kg gold annually during 1973–1986.

The increase in the gold price, major breakthroughs in analytical methods for low-level trace element concentrations, and an improved understanding of the geology and genesis of gold deposits during the 1980s and 1990s helped to generate a much more optimistic exploration environment in Finland. Before commercial production at the Kittilä mine (Suurikuusikko deposit) started in 2009, production of gold had never played a major role in the Finnish mining industry (Puustinen, 1991, 2003). At present (2014), there are five producing gold mines (Table 5.1.1), and Finland has become one of the main gold producers in Europe. However, on a global scale, Finland remains a small player in gold mining; the annual production is close to 10 t (Fig. 5.1.1), representing <0.5 % of global production (USGS, 2012).

There are currently more than 200 drill-indicated gold deposits and occurrences in Finland (Fig. 5.1.2) and new occurrences are discovered every year. About 15–20 companies are currently actively exploring for gold, and more information is flowing in from the earlier discoveries (Eilu and Pankka, 2009; Saalmann and Niiranen, 2010; Grönholm and Kärkkäinen, 2012; Eilu and Niiranen, 2013). Research on various gold deposit types throughout the world continuously improves our ability to explore for these targets and our understanding of the petrogenesis of the deposits. Therefore, many of the Finnish deposits are now assigned to a different genetic type than they were just 10 years ago, the time of publication of the previous in-depth review (Eilu et al., 2003).

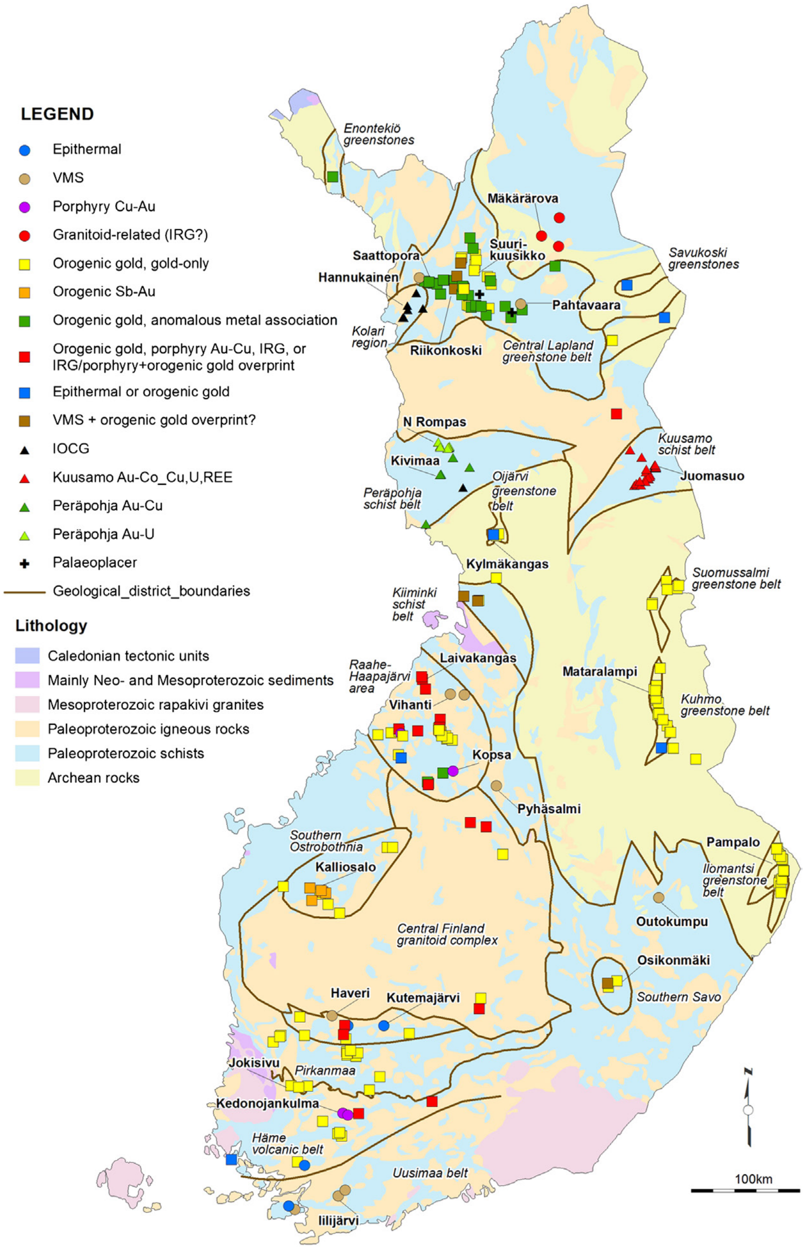

FIGURE 5.1.2

Gold deposits and occurrences in Finland, and the three major VMS-type base metal mines which have produced significant gold (Outokumpu, Pyhäsalmi, Vihanti). The deposit data are based on Eilu and Pankka (2009), Grönholm and Kärkkäinen (2012), Eilu and Niiranen (2013), and on reports referred to in these compilations. Geology is based on the GTK digital bedrock map database as of October 2013. The map is drafted by Kirsti Keskisaari, GTK.

The main aim of this subchapter is to describe the various genetic types of gold deposits in Finland. Several ambiguous cases in which the genetic type is not obvious are also included. All deposit types are described with an emphasis on general and diagnostic features that are characteristic of the Finnish examples. Details of deposits are only given where this serves to illustrate typical features of a certain deposit type. The Suurikuusikko (Kittilä mine) and Pampalo deposits, as well as the gold occurrences in the Rompas area are described in detail in other chapters (i.e., 5.2, 5.3, and 5.4) of this book.

GENETIC TYPES OF GOLD DEPOSITS RECOGNIZED IN FINLAND

Genetic types of gold deposits identified in Finland include Au-rich volcanogenic massive sulfide (VMS), metamorphosed high-sulfidation epithermal, gold-copper porphyry, orogenic gold, placer, and paleoplacer deposits (Fig. 5.1.2). In addition, certain gold occurrences such as Kopsa (Belvedere Resources, 2012) and Kuusamo (Slack et al., 2010) have recently been classified as intrusion-related (IRG) and Blackbird-type deposits. However, conclusive evidence for these models are still lacking. The iron-oxide–copper–gold (IOCG) deposits in the Kolari region and, possibly, in the Peräpohja belt (Fig. 5.1.2) are described in detail in Chapter 6 (Moilanen and Peltonen, 2015) and will not be discussed here. The large variety of deposit types, with the dominance of orogenic gold deposits (Eilu and Pankka, 2009), is typical for Precambrian shield areas and other younger metamorphic terranes (Goldfarb et al., 2005; Groves et al., 2005; Huston et al., 2012).

In general, gold deposits of various types are genetically linked to major tectonic processes such as submarine rifting and volcanism, intracratonic rifting, arc magmatism, arc and microcontinent accretion, continent–continent collision, and multistage regional deformation and metamorphism. It is a function of both geodynamic processes and preservation potential that define which deposit type(s) dominate in a region. Of all the gold deposit types, orogenic gold deposits have the best preservation potential because they form in relatively deep midcrustal regimes, particularly in terranes dominated by greenschist to midamphibolite facies rocks (Goldfarb et al., 2005). This is the case in Finland too, where they are the most common of the gold deposit types (Eilu and Pankka, 2009; Grönholm and Kärkkäinen, 2012): Orogenic gold deposits have been detected in nearly all Finnish greenschist- to amphibolite-facies supracrustal belts, whereas other genetic types are found in only some of the belts and regions in Finland, and in much smaller numbers. Also, gold occurrences are much less abundant both in the high-grade terranes and in regions containing only intrusive rocks.

OROGENIC GOLD DEPOSITS

Epigenetic gold deposits hosted by orogenic belts and formed by syn- to late-orogenic fluids are called *orogenic*. Their characteristics have been summarized by Böhlke (1982), Sibson et al. (1988), Groves et al. (1998), McCuaig and Kerrich (1998), Eilu et al. (1999), Eilu and Groves (2001), Goldfarb et al. (2001, 2005), and Pitcairn et al. (2006). Mineralization typically takes place in accretionary and collisional plate-tectonic settings under compressional to transpressional deformation regimes. The mineralizing agents are low-salinity H_2O-CO_2 fluids containing minor amounts of CH_4, N_2, and H_2S. The fluids carry gold dominantly as bisulfide complexes. The gold is mainly deposited in quartz veins by pressure fluctuations during seismic events and adjacent to veins by reaction between the fluid and the wall rocks. Most of the stable and radiogenic isotope data from ores, as well as trends in gold and associated trace element concentrations in metamorphosed belts, point toward progressive metamorphic dehydration, mostly at midcrustal levels, as being the main process releasing the fluids and metals, with no detectable contributions from local rocks. On the other hand, the data exclude meteoric fluids (modified or not) and fluids derived from local granitoids or the mantle as significant metal sources. The auriferous veins are enveloped by alteration halos characterized by K-mica and CO_2 alteration.

The alteration mineral assemblages reflect the metamorphic grade of the host rocks and ore mineral assemblages, and local structures and textures indicate that mineralization and alteration commonly took place under postpeak metamorphic conditions along the retrograde PT curve. The deposits have a distinct structural control; despite occurring near major crustal structures (first-order faults), they are dominantly hosted by second- to fourth-order faults and shear zones. Deposits may be hosted by any supracrustal rock type within a metamorphic belt, or by intrusions within or adjacent to such a belt. The locally most competent and/or reactive lithological units tend to host most of the ore. Typically, the Au/Ag ratio of the ore is 1–5; elements enriched in the ore and in the alteration halo include As, Au, Bi, K, Rb, Sb, Te, and W; and gold is the sole economic commodity. Although quartz veining is one of the diagnostic features, Si enrichment of the host rocks is rare. Dating of the deposits and their host rocks indicates that mineralization took place significantly after the formation of the host rocks; typically the time gap is 10–100 Ma.

There are about a dozen Archean and 30 Paleoproterozoic orogenic gold deposits in Finland for which both grade and tonnage data are available (Table 5.1.1); their known size varies from 0.04 to 64 Mt and gold grade is 1–15 g/t (FODD, 2013, and references therein). The two largest deposits are Suurikuusikko, with a premining resource of 266 t Au, and Laivakangas with 44 t Au. Half of the orogenic deposits in Finland contain less than 1 t Au. Sufficient resource data to make statistical comparisons with orogenic gold belts elsewhere only exist for the Central Lapland Greenstone Belt (CLGB), the Ilomantsi greenstone belt, and the Raahe-Haapajärvi area (Table 5.1.1, Fig. 5.1.2). Only in the CLGB does the deposit size distribution, with one anomalously large and many smaller deposits, resemble productive parts of greenstone belts elsewhere, such as in Zimbabwe or Western Australia (Hokka, 2011, and references therein). This could mean that (1) large and medium-sized deposits in many regions of Finland remain to be discovered; (2) some of the known deposits are much larger than their presently defined resource; or (3) many of the Finnish gold belts are anomalous in that they lack large gold deposits. Particularly intriguing is the fact that no >1 t gold deposit is known from the Kuhmo and Suomussalmi greenstone belts (KSGB), whereas the geological setting of these belts (i.e., their combined surface area, age, rock types, and metamorphic grade) is very similar to that of the Southern Cross greenstone belt in Western Australia that hosts several >30 t Au deposits and has yielded >300 t Au (Geological Survey of Western Australia, unpublished data, 2013). Another interesting detail is that the grade and tonnage distribution of Finnish orogenic gold deposits is statistically similar to the Paleoproterozoic gold deposits of northern Australia (Eilu et al., 2015). The metal grades and Au/Ag ratios in the Finnish deposits are also similar to those of deposits in other Precambrian and Phanerozoic regions. A number of Finnish orogenic gold deposits contain additional potential economic metals (Co, Cu, Ni, Sb; Table 5.1.1); these are discussed separately in the section 'Orogenic gold deposits with anomalous Ag, Cu, Co, Ni or Sb,' below.

Isotopic age data are available from only a few Finnish orogenic gold occurrences, but the present data and abundant information on structural relationships and mineral textures from the ores and their host rocks clearly suggest that mineralization took place soon after the main regional deformation. Mineralization within the Archean greenstone belts took place close to the D3 or D4 stages of regional deformation, between 2.72 and 2.64 Ga (Sorjonen-Ward, 1993; Rasilainen, 1996), or more probably between 2.68 and 2.64 Ga (Hölttä et al., 2012). This is the time of the global peak of Archean orogenic gold mineralization, of global Neoarchean orogenic activity, and of peak crustal growth (Groves et al., 2005). The second age group of orogenic gold deposits in Finland is related to the Svecofennian composite orogenies, at 1.91–1.77 Ga, coinciding with the second Precambrian global peak of orogenic gold mineralization (Groves et al., 2005). Most of the Paleoproterozoic mineralization probably took place during a continent–continent collision event at 1.84–1.78 Ga, during the regional D3–D4 (or later) stages of deformation (Patison, 2007; Saalmann et al., 2009, 2010; Saalmann and Niiranen, 2010; Eilu et al., 2013). However, some mineralization may be related to the earlier compressional stage representing accretion of igneous arcs and microcontinents at 1.91–1.87 Ga (Mänttäri, 1995; Lahtinen et al., 2012). Unpublished Re-Os isotope data of auriferous arsenopyrite from Suurikuusikko provide support for the earlier, syn-accretionary timing of mineralization (Geospec Consultants Limited, 2008). Indirect structural, textural, and mineral paragenetic evidence from the Häme, southern Savo, and Pirkanmaa belts of southern Finland suggest an ~1.88–1.87 Ga timing for some of the orogenic gold occurrences (e.g., Kontoniemi, 1998).

Some parts of the Archean greenstone belts show an overprint of Svecofennian deformation. There is, however, no recognized Paleoproterozoic gold mineralization event in the Archean rocks in Finland, despite the Proterozoic metamorphic recrystallization and disturbances of isotopic systems (Kontinen et al., 1992; O'Brien et al., 1993; Hölttä et al., 2012). Several generations of Paleoproterozoic dolerites, subsequently metamorphosed at greenschist facies conditions, crosscut the Archean gold ores in the Ilomantsi and KSGB belts, but show no indication of post-Archean gold mineralization (Nurmi et al., 1993; Eilu, 2003).

Two of the Finnish Paleoproterozoic gold deposits (Table 5.1.2), and a small number of occurrences of the same age, but without a publicized resource estimate, are hosted by upper-amphibolite facies rocks (Eilu and Pankka 2009). Orogenic gold mineralization under upper-amphibolite to granulite facies conditions is considered unlikely (e.g., Tomkins and Grundy, 2009). Thus, it seems possible that a few of the Finnish Paleoproterozoic orogenic gold deposits have been metamorphosed, as also suggested by textures present in these occurrences. In both the southern Savo area and the westernmost parts of the Häme belt (Fig. 5.1.2), there are indications of postmineralization metamorphism at upper-amphibolite to lower-granulite facies conditions (Kontoniemi, 1998; Kärkkäinen et al., 2012). Elsewhere within the Svecofennian domain (e.g., in the region to the southwest of the Archean parts of Finland; Fig. 5.1.2), one may also expect some effects of postmineralization metamorphism as the region has experienced not just one, but several spatially overlapping orogenies (Lahtinen et al., 2005, 2012). Such an overlap may result in local (mm to cm scale) remobilization of Au (± As, Bi, Sb, Te) into late fractures, leading to possible misinterpretation of the timing of mineralization. One should also keep in mind that the rather common, late to postorogenic shearing and brittle fracturing may also result in local remobilization of earlier ductile gold grains into new fractures in any orogenic gold occurrence.

All orogenic gold deposits in Finland are structurally controlled. They typically occur within 0.5–3 km from a major, first-order fault, which, in most cases, follows the main strike of the supracrustal belts. The hosting structure is generally a second- or third-order fault or shear zone branching from the major structure. Examples include the faults branching to the northwest and northeast from the main north-trending fault along the KSGB (Luukkonen et al., 2002) and the west-northwest- and west-southwest-trending shear zones associated with the regional northwest-trending shear zone at Jokisivu (Saalmann et al., 2010). All the controlling structures show more than one stage of deformation. The change from earlier high-angle thrusting to later strike-slip movement may be critical for the migration of the mineralizing fluid from the deeper prograde metamorphic source areas, via the main fault, to shallower, retrograde metamorphic crustal levels and to lower-order structures where the fluid would precipitate gold (Sibson et al., 1988; Patison, 2007). The favorable locations of mineralization are those with low or minimum local stress; these include intersections between faults, between a fault and a fold hinge, a slight bend in a fault along a lithological contact, a deviation of the general trend of a fault, or a combination of any of these. The relatively late formation of these structurally favorable sites is one

Table 5.1.2 Ages and regional metamorphic grades of gold deposits and occurrences with a reported resource in Finland

Genetic type, deposit	District[a]	Age (Ga)	Main host rock(s)[b]	Metamorphic grade[e]	Reference
Orogenic gold					
Pampalo	Ilomantsi	2.72–2.65	Intermediate tuffite	Greenschist-amphibolite tr.	Sorjonen-Ward (1993)
Valkeasuo	Ilomantsi	2.72–2.65	Intermediate tuffite	Greenschist-amphibolite tr.	Sorjonen-Ward (1993)
Kuittila	Ilomantsi	2.72–2.65	Tonalite pluton	Greenschist-amphibolite tr.	Sorjonen-Ward (1993)
Rämepuro	Ilomantsi	2.72–2.65	Tonalitic porphyry	Greenschist-amphibolite tr.	Sorjonen-Ward (1993)
Korvilansuo	Ilomantsi	2.72–2.65	Mica schist	Greenschist-amphibolite tr.	Sorjonen-Ward (1993)
Muurinsuo	Ilomantsi	2.72–2.65	Mica schist	Greenschist-amphibolite tr.	Sorjonen-Ward (1993)
Kuivisto	Ilomantsi	2.72–2.65	Intermediate tuffite	Greenschist-amphibolite tr.	Sorjonen-Ward (1993)
Kuikkapuro	Suomussalmi	2.72–2.65	Basalt	Mid amphibolite	Luukkonen et al. (2002)
Moukkori	Suomussalmi	2.72–2.65	Intermediate volcanic rock	Lower amphibolite	Luukkonen et al. (2002)
Pahkalampi	Suomussalmi	2.72–2.65	Amphibolite	Mid amphibolite?	Luukkonen et al. (2002)
Pahkosuo	Suomussalmi	2.72–2.65	Tholeiitic basalt	Mid amphibolite?	Luukkonen et al. (2002)
Syrjälä	Suomussalmi	2.72–2.65	Intermediate volcanic rock	Mid amphibolite	Luukkonen et al. (2002)
Kutuvuoma	CLGB	1.91–1.79	Komatiite, albitized phyllite[c]	Low to mid greenschist	Eilu et al. (2007)
Suurikuusikko	CLGB	1.91–1.79	Tholeiitic basalts, albitized phyllite[c]	Low to mid greenschist	Patison et al. (2013a)
Soretialehto	CLGB	1.91–1.79	Komatiite	Low to mid greenschist	Keinänen (1994)
Hirvilavanmaa	CLGB	1.91–1.79	Komatiite, mafic lava or dolerite	Low to mid greenschist	Hulkki and Keinänen (2007)
Kuotko	CLGB	1.91–1.79	Mafic tholeiites	Low to mid greenschist	Eilu et al. (2007)
Vesiperä	R-H	1.89–1.79	Plagioclase porphyry	Mid amphibolite?	Sipilä (1988)
Laivakangas	R-H	1.89–1.79	Quartz diorite	Mid amphibolite?	Mäkelä (1984)
Hirsikangas	R-H	1.89–1.79	Felsic schist	Mid amphibolite?	Kontoniemi and Mursu (2006)
Ängesneva	R-H	1.89–1.79	Plagioclase porphyry	Upper amphibolite	Nurmi et al. (1991)
Sikakangas	SO	1.89–1.79	Plagioclase porphyry	Mid amphibolite?	Isomaa et al. (2010)
Osikonmäki	SS	1.89–1.79	Tonalite pluton	Upper amphibolite	Kontoniemi (1998)
Kaape-linkulma	Pirkanmaa	1.89–1.79	Quartz diorite	Lower amphibolite	Saalmann et al. (2009)
Jokisivu	Pirkanmaa	1.89–1.79	Mafic volcanic rocks	Mid amphibolite	Saalmann et al. (2010)
Satulinmäki	Häme	1.89–1.79	Felsic to intermedite volcanic rocks	Lower amphibolite	Kärkkäinen et al. (2006)

Orogenic gold with anomalous metal association					
Kaaresselkä	CLGB	1.91–1.79	Albitized phyllite[c]	Upper greenschist	Hulkki and Pulkkinen (2007)
Saattopora	CLGB	1.91–1.79	Albitized phyllite[c]	Low to mid greenschist	Korvuo (1997)
Kettukuusikko	CLGB	1.91–1.79	Komatiite	Low to mid greenschist	Eilu et al. (2007)
Riikonkoski[d]	CLGB	2.1–1.79?	Albitized phyllite[c]	Upper greenschist	Yletyinen and Nenonen (1972)
Ängeslampi	R-H	1.91–1.79	Plagioclase porphyry	Lower amphibolite	Sipilä (1990)
Pirilä	SS	1.91–1.79	Intermediate volcanosedimentary rock	Upper amphibolite	Makkonen and Ekdahl (1988)
Kalliosalo	SO	1.91–1.79	Plagioclase porphyry	Mid amphibolite?	Saltikoff (1980), Appelqvist (1993)
Sivakkaharju[d]	Kuusamo	1.9–1.8?	Albitized sedimentary rocks	Upper greenschist	Vanhanen (2001)
Hangaslampi[d]	Kuusamo	1.9–1.8?	Albitized sedimentary rocks	Upper greenschist	Vanhanen (2001)
Apajalahti[d]	Kuusamo	1.9–1.8?	Sericite quartzite (metasilt?)	Upper greenschist	Vanhanen (2001)
Juomasuo[d]	Kuusamo	1.9–1.8?	Sericite quartzite, basalt	Upper greenschist	Vanhanen (2001)
Pohjasvaara[d]	Kuusamo	1.9–1.8?	Albitized sedimentary rocks	Upper greenschist	Vanhanen (2001)
Iso-Rehvi[d]	Kuusamo	1.9–1.8?	Albitized sedimentary(?) rocks	Upper greenschist	Vanhanen (1991, 2001)
Meurastuk-senaho[d]	Kuusamo	1.9–1.8?	Albitized metasiltstone	Upper greenschist	Vanhanen (2001)
Säynäjävaara[d]	Kuusamo	1.9–1.8?	Sericite schist, mafic volcanic rock	Upper greenschist	Vanhanen (2001)
Kivimaa[d]	Peräpohja	1.9–1.8?	Dolerite	Upper greenschist	Rouhunkoski and Isokangas (1974)
VMS					
Pahtavaara[d]	CLGB	2.10–2.05?	Komatiite	Upper greenschist	Korkiakoski (1992)
Iilijärvi	Uusimaa	1.90–1.89	Felsic volcanic rocks	Lower amphibolite	Mäkelä (1989)
Metsämonttu	Uusimaa	1.90–1.89	Felsic and mafic volcanic rocks	Lower amphibolite	Mäkelä (1989)
Haveri	Tampere	~1.905	Tholeiitic basalt	Lower amphibolite	Eilu (2012)
Epithermal					
Kutemajärvi	Tampere	1.90–1.89	Intermediate volcanic rocks	Lower amphibolite	Poutiainen and Grönholm (1996)
Kylmäkangas[d]	Oijärvi	~2.8?	Quartz-feldspar porphyry	Upper greenschist	Juopperi et al. (2001)

Continued

Table 5.1.2 Ages and regional metamorphic grades of gold deposits and occurrences with a reported resource in Finland—cont'd

Genetic type, deposit	District[a]	Age (Ga)	Main host rock(s)[b]	Metamorphic grade[e]	Reference
Porphyry					
Kopsa	R-H	1.91–1.85	Tonalitic intrusion	Lower amphibolite	Gaal and Isohanni (1979)
Kedonojan-kulma	Häme	1.89–1.88	Tonalitic intrusion	Mid amphibolite	Tiainen et al. (2013)
IRG?					
Mäkärärova[d]	N. Finland	1.9–1.75?	Granitoid gneiss	Upper amphibolite	Härkönen (1987)

Question marks indicate uncertain information.
[a]*District names as in Fig. 5.1.2; CLGB = Central Lapland Greenstone Belt, R-H = Raahe-Haapajärvi, SO = Southern Ostrobothnia, SS = Southern Savo.*
[b]*All hosts are metamorphosed.*
[c]*The "phyllite" includes originally fine-grained rocks from dominantly clastic sedimentary to dominantly volcaniclastic origin, all types commonly with a minor graphite content.*
[d]*Genetic type unclear.*
[e]*"Greenschist-amphibolite tr." = metamorphic grade is close to the transition from greenschist to amphibolite facies.*

of the main indications for the late timing of orogenic gold mineralization, such as along and near the Sirkka thrust zone in the CLGB (Patison, 2007; Saalmann and Niiranen, 2010).

A further important control on gold mineralization is defined by the competency and reactivity of the rock types within an area. Commonly, it is the locally most competent lithological unit that hosts the ore, because such rocks behave in the most brittle manner during deformation, thus creating more open space when the fluid pressure exceeds the lithostatic pressure. If a sudden pressure drop follows, then much of the metal in the fluid will rapidly precipitate; this may be repeated hundreds to thousands of times over a few million years (Sibson et al., 1988; Weatherley and Henley, 2013), forming the common banded ribbon textures of ore-hosting veins at many deposits. Competent hosts may include the most felsic rocks of an area, such as quartz porphyries in pelitic or mafic–ultramafic sequences (Eilu and Ojala, 2007), or even originally ductile rocks that have been hardened by pervasive alteration before mineralization. Ground preparation by premineralization alteration in the CLGB is common within a few kilometers of the Sirkka thrust zone, with intensely albitized and carbonatized volcaniclastic sedimentary (Kaaresselkä, Kutuvuoma, Levijärvi-Loukinen, Saattopora, Sirkka) and carbonatized ± albitized komatiitic units (Hirvilavanmaa, Kutuvuoma, Levijärvi-Loukinen, Soretialehto) (Keinänen, 1994; Korvuo, 1997; Holma and Keinänen, 2007; Hulkki and Keinänen, 2007; Hulkki and Pulkkinen, 2007). Clearly, the Sirkka thrust had been a major fluid conduit before gold mineralization, such that earliest fluid events made the surrounding rocks much more competent. Similar ground preparation has also taken place along some of the north-, northwest-, and northeast-trending faults of the CLGB, such as the Hanhimaa, Kuotko, and Suurikuusikko (Kiistala) faults. One would also expect extensive ground preparation by alteration in other supracrustal sequences with an extensive preorogenic evolution in intracontinental and marginal basin settings, especially in the Kuusamo and Peräpohja belts. This is because such settings potentially provided not just the typical low-salinity metamorphic fluids, but also brines (Yardley and Graham, 2002; Yardley and Cleverley, 2013) that were potentially able to alter the supracrustal sequence before the orogeny.

The rocks that are most reactive relative to the typical orogenic gold fluids are those with the highest Fe/(Fe + Mg) ratio (Phillips, 1986). Together with their enhanced competence, this makes iron-rich tholeiitic units the most prospective ore hosts in many areas of Finland. In places, felsic rocks of favorable Fe/(Fe + Mg) can also be reactive, as can pelitic or volcanogenic sedimentary units that contain reduced carbon (typically graphite). Ores hosted in reactive rocks, such as those at Suurikuusikko, are often called *rock hosted*; that is, most of the gold occurs with disseminated pyrite, pyrrhotite, and/or arsenopyrite in the altered host rock, with much less gold and sulfides occurring in the associated quartz veins.

The ore bodies in orogenic gold deposits typically have a flat lensoid shape. The plunge of the ellipsoid follows the lineation produced by the latest regional deformation in the region. The hosting fault and the ore bodies mostly have a steep to subvertical dip. Shallow-dipping ores also occur, such as at Osikonmäki (Kontoniemi, 1998), but typically form a minor part of a deposit. The ore bodies have lengths from tens of meters to more than 1 km along strike and plunge, and widths of 0.5–10 m. The deposits typically comprise several ore bodies (lodes) along the structure. At the Kittilä mine, the Suurikuusikko deposit and the adjacent ore bodies form a continuum >4 km long, which remains open to the north along the strike. Subparallel lodes may also be present, particularly where the hosting structure is wider than 20 m. Even where an outcropping ore body apparently terminates, additional, blind ore bodies may be present at depth as, for example, at Suurikuusikko, where extensions of the deposit extend beyond 1.5 km depth (Patison et al., 2013a). Most of the orogenic gold deposits in Finland have a reported extent along the strike that is significantly less than 1 km and extend to a maximum depth of 50–200 m. In most cases, however, this limited extent is likely due to limited drilling and exploration, and the deposit is open both along the strike and at depth. For example, this appears to be the case for all deposits in the Neoarchean Ilomantsi greenstone belt (see the Pampalo section, Subchapter 5.3) and at the Paleoproterozoic Jokisivu deposit (Dragon Mining, 2013).

Orogenic gold deposits typically contain 1–5 vol% sulfides and sulfarsenides. Pyrite ± arsenopyrite are dominant in greenschist-facies rocks, whereas pyrrhotite ± löllingite and arsenopyrite characterize deposits in amphibolite facies rocks (Eilu and Pankka, 2009). In the rocks of higher metamorphic grade, any löllingite is typically rimmed by arsenopyrite. Chalcopyrite, sphalerite, and galena are often observed in those parts of the ores that are metamorphosed to the highest grade, but these minerals are of relatively minor abundance, and mass balance evaluations consistently show no significant base metal mobility, although a few notable exceptions are described in the section 'Orogenic gold deposits with anomalous Ag, Cu, Co, Ni or Sb.' Scheelite and Bi-, Sb-, Se-, and Te-bearing minerals have been detected in many occurrences studied by microprobe (e.g., Kontoniemi et al., 1991; Kojonen et al., 1993; Luukkonen, 1994; Kärkkäinen et al., 2006, 2012; Etelämäki, 2007). However, these minerals only occur in minor to trace amounts, quite commonly in volumes equal or less than that of the gold. The main exceptions are the Sb-rich deposits in the Southern Ostrobothnia area, such as the Kalliosalo deposit where native antimony, stibnite, and aurostibite are common (Appelqvist, 1993).

Most of the gold is in its native form, present in fractures within and between the sulfides and the gangue minerals, and in some cases closely associated with Bi-, Sb-, and/or Te-bearing minerals. Gold fineness typically varies between 820 and 950. In a few deposits, including Suurikuusikko, gold is dominantly refractory, situated in the lattice of, or as submicroscopic inclusions in, arsenopyrite and pyrite (Kojonen and Johansson, 1999). In midamphibolite facies and higher-grade rocks, gold may occur as microscopic inclusions in arsenopyrite and as "invisible gold" in löllingite (Etelämäki, 2007). This suggests exsolution of gold from the löllingite lattice during retrograde replacement of löllingite by the arsenopyrite (Neumayr et al., 1993). Another common style of gold occurrence in high-grade rocks comprises composite grains of native gold, and auriferous Te- and Bi-bearing minerals (Kärkkäinen et al., 2012).

The styles of alteration, chemical changes, element enrichments, and the relationship between alteration mineral assemblages and metamorphic grade in the Finnish orogenic gold deposits are similar to those recorded in other parts of the world. Alteration includes sericitization and carbonatization at lower-greenschist to mid-greenschist facies conditions, biotitization and carbonatization at upper-greenschist to lower-amphibolite facies conditions, and biotitization and formation of K feldspar and calc-silicates in rocks of higher metamorphic grades. In addition, host rock sulfidation has taken place under all PT conditions of orogenic gold mineralization. Altered wall rocks may be associated with enrichments of Ag, As, Au, Bi, CO_2, K, Rb, S, Sb, Se, Te, and/or W (e.g., Nurmi et al., 1991; Rasilainen, 1996).

An example of orogenic gold-related alteration and associated chemical changes is provided by the Mataralampi occurrence in the northern part of the Kuhmo greenstone belt, hosted by a competent calc-alkaline quartz-feldspar porphyry (Eilu, 2003; Eilu and Ojala, 2007). Distal alteration is characterized by partial sericitization of biotite, partial to total replacement of titanite by rutile and epidote by calcite + quartz, and hydrothermal pyrite. With increasing degree of alteration and deformation closer to the deposit, muscovite gradually becomes more abundant than biotite and forms continuous, 0.1- to 1-mm-wide shear bands. In addition, calcite, quartz, and rutile gradually replace epidote and titanite, and feldspar phenocrysts are partially replaced by quartz + calcite + muscovite. Proximal alteration, directly adjacent to the auriferous quartz veins, is characterized by pervasive foliation and by the mineral assemblage quartz-albite-muscovite-calcite-rutile-pyrite. All feldspar phenocrysts are replaced by a fine-grained mass of albite + quartz + muscovite ± K-feldspar. The locations of the original quartz phenocrysts are still distinguishable by their sharp boundaries.

Pyrite occurs in disseminated form throughout the alteration halo, but is most abundant in and near quartz veins. Mass balance calculations show that Al, Cr, Ni, P, Ti, and Zr were immobile; Ba, Bi, CO_2, Cu, K, Rb, S, Sb, Te, and W were enriched; and Li, Na, and Sr were depleted throughout the alteration halo. Silver and gold are enriched only within the proximal alteration zone. Mataralampi is anomalous relative to most Finnish deposits because there is no enrichment of As in the former; in veins and in altered wall rock, As concentrations remain at typical background levels of less than 10 ppm. Only 1 km to the east, at the komatiite-hosted Timola occurrence, the As concentrations are as high as 2000 ppm in gold-mineralized zones (Hartikainen, 2001). This difference between two localities probably reflects the effect of host rock reactivity relative to arsenic solubility in the ore fluids: in the ultramafic rocks, As precipitated with gold, whereas in the more oxidized felsic wall rocks, As remained soluble in the gold depositing fluid.

The mineralizing fluid documented in most of the studied Finnish orogenic gold occurrences (see exceptions in the section 'Orogenic gold deposits with anomalous Ag, Cu, Co, Ni or Sb') is typical of this genetic type; it is a low-salinity H_2O-CO_2 fluid with significant H_2S (Kontoniemi, 1998; Poutiainen and Partamies, 2003). In addition to Au, the fluid probably also carried Ag, As, Bi, K, Rb, Se, and Te, as suggested by the ore and gangue mineral assemblages and geochemistry. Stable and radiogenic isotope work carried out on some of the Finnish occurrences (Bornhorst and Wilkin, 1993; Mänttäri, 1995; Kontoniemi, 1998; Hölttä and Karhu, 2001) suggests that the fluids were of similar composition to those in orogenic gold deposits elsewhere. The fluids contained no meteoric or seawater component and were interpreted to be dominantly of crustal origin derived from metamorphic dehydration. They possibly contained minor distal magmatic and/or mantle-derived components, but there are no obvious indications of local sources.

OROGENIC GOLD DEPOSITS WITH ANOMALOUS Ag, Cu, Co, Ni, OR Sb

There are several gold deposits in Finland that resemble typical orogenic gold deposits, but are anomalous because they contain Ag, Cu, Co, Ni, or Sb as potential commodities in addition to gold. These deposits are listed in Tables 5.1.1 and 5.1.2 under the title "Orogenic gold with anomalous metal association". In addition to pyrite, pyrrhotite, and/or arsenopyrite, they may also include significant amounts of chalcopyrite, cobaltite, pentlandite, gersdorffite, and/or stibnite (Vanhanen, 2001; Eilu et al., 2007). Goldfarb et al. (2001) suggest that orogenic gold deposits with an anomalous metal association form where Paleoproterozoic tectonism included deformation of older, intracratonic basins. According to Goldfarb et al., the resulting ore fluids were anomalously saline and in some cases the orogenic lodes are notably base metalrich. They cite examples that include the ore-hosting strata of the Transvaal basin in the Kaapvaal craton of South Africa and the Arunta, Tennant Creek, and Pine Creek inliers of northern Australia.

It is possible that such deposits reflect mobilization of basinal fluids under moderate to high-grade metamorphic conditions (Yardley and Graham, 2002; Yardley and Cleverley, 2013) with the metals possibly (but not necessarily) enriched prior to an orogeny in the fluid source areas by, for example, seafloor hydrothermal and/or diagenetic processes. A similar crustal evolution characterizes the Karelian domain of Finland where supracrustal sequences, possibly including evaporates, formed in intracratonic basins between 2.45 and 1.95 Ga (Perttunen and Vaasjoki, 2001; Rastas et al., 2001; Lahtinen et al., 2005, 2012). They were episodically intruded by magmas, locally resulting in alteration of the supracrustal rocks prior to regional metamorphism. It even seems possible that some (mostly uneconomic), local, base metal ± gold enrichment occurred before the orogeny. The extensive albitization and carbonatization in the Kuusamo, Peräpohja, and Central Lapland belts, and the regional scapolitization in northern Finland and northern Sweden, are the most obvious results of such preorogenic processes (Eilu, 1994; Vanhanen, 2001; Kyläkoski, 2009a, 2009b; Billström et al., 2010).

The issue is further complicated in the CLGB by the presence of multiply deformed, VMS-like, base metal occurrences and the unusual features of the Pahtavaara gold deposit. It remains unsolved how much these early processes affected the availability of gold and other metals now present in the orogenic Au-Cu ± Co, Ni, Sb deposits and occurrences. The geology and petrogenesis of the Pahtavaara gold deposit is discussed in more detail in the section 'Gold-rich VMS deposits'. Whatever the sources of metals and saline fluids, all the mentioned supracrustal sequences experienced multiple deformation, orogenic mineralization, and alteration during 1.91–1.77 Ga (Vanhanen, 2001; Lahtinen et al., 2005; Billström et al., 2010; Lahtinen 2012).

There are more than 20 drilled base metal-rich gold occurrences within the CLGB that can be best classified as base metal-rich orogenic gold deposits (Nurmi et al., 1991; Eilu et al., 2007; Eilu and Pankka, 2009), including the Saattopora deposit where copper was mined along with the gold (Table 5.1.1). In addition to gold, all these occurrences have copper as a potential commodity, and some of those hosted by or near komatiites have significant Ni and Co grades. Other common features include premineralization carbonatization and albitization, and moderate ore fluid salinities of 10–25 % NaCl equivalents. The abundance of Ni- and Co-bearing sulfide minerals in ores in or near the komatiites (e.g., Holma and Keinänen, 2007) suggests a local origin for the base metals. Structural relationships suggest that mineralization mostly took place late during the regional deformation. The Bidjovagge deposit in Norway and the Pahtohavare deposit in Sweden resemble Saattopora and the other Au-Cu occurrences in the CLGB (Eilu et al., 2007; Sandstad, 2012).

The Raahe-Haapajärvi area hosts several Au-Cu occurrences that may best be classified as Cu-rich orogenic gold deposits (Tables 5.1.1 and 5.1.2, and Fig. 5.1.2). Notably, the tectonic setting of this area would not appear to be favorable for the presence of saline metamorphic fluids because there are no indications of intracratonic basins nor evaporates, and the region seems to have undergone relatively rapid accretionary orogenic evolution (Lahtinen et al., 2005). A few Paleoproterozoic porphyry Cu ± Au occurrences, including the Kopsa deposit, have been detected in this area (Gaál and Isohanni, 1979). They are metamorphosed and appear to be overprinted by later orogenic gold mineralization. Such an overprint may explain the Cu-Au association in the region, where early porphyry deposits were tectonically buried and subjected to later mesozonal auriferous hydrothermal activity. In Fig. 5.1.2, such occurrences are included in the category "Orogenic gold, porphyry Au-Cu, IRG, or IRG/porphyry + orogenic gold overprint." Note, however, that not all of the occurrences of the mentioned category show an enrichment in Cu; for example, Laivakangas is a gold-only deposit (Table 5.1.1).

There also exist a few base metal-rich (Cu ± Zn, Ag, Pb) syngenetic VMS and, possibly, SEDEX occurrences that appear to be overprinted by orogenic gold, both within the CLGB (e.g., at Riikonkoski in CLGB) and elsewhere in Finland. These are indicated in Fig. 5.1.2 as "VMS + orogenic gold overprint?" Such overprinting and associated genetic issues are difficult to unravel in multiply deformed and metamorphosed terranes without radiometric dating of the mineralization processes, and thus classification remains far from certain. There are not enough data from any of the deposits marked in Fig. 5.1.2 as possible overprinted syngenetic ores to be sure of their genetic classification. In the past, many Finnish deposits, including those with very little precious metals, have been considered to be products of two different styles of mineralization. For example, the Haveri deposit has been suggested to fall into this "overprint class," but in the section 'Gold-rich VMS deposits', a different interpretation is advanced that solely favors a deformed syngenetic deposit.

KUUSAMO Au-Co ± Cu ± U ± LIGHT RARE EARTH ELEMENTS

The Kuusamo schist belt (KSB) is characterized by Au-Co ± Cu ± U ± LREE mineralization (Pankka, 1992; Pankka and Vanhanen, 1992; Vanhanen 2001). The reported tonnage and Au, Co, and Cu grades of the deposits in the belt show considerable variation (Table 5.1.1). In a few cases, the resource also includes 0.01–0.03 % U and 0.1 % total rare earth elements (REE; Vanhanen, 2001; Dragon Mining, 2013). The main economic interest in the Kuusamo deposits is in Au and Co, whereas Cu and the REE have been regarded as potential by-products and U as a problematic waste product (Dragon Mining, 2013). The available data, mainly from Vanhanen (2001), suggest that most of the reported total REE grades in these occurrences comprise light rare earth elements (LREE). None of the KSB occurrences have so far been proven as economic ores, and only one (Juomasuo) has been test mined, in 1992 when 104 kg gold and 24.7 t cobalt were extracted from 17,635 t of ore (Puustinen, 2003).

The Kuusamo occurrences are hosted by a clastic sedimentary sequence deposited between 2.44 and 2.21 Ga, which also contains basaltic lavas and indications of evaporates (Vanhanen, 2001). The sequence was intruded by basaltic dikes and sills prior to regional deformation. All occurrences have a distinct structural control; most of them are hosted at the intersection of a regional northeast-trending anticline with northwest-trending faults. The largest deposit, Juomasuo, is located in a doubly-plunging part of the northeast-trending anticline.

Alteration in the KSB is extensive and occurred at several stages. The rocks in the belt were affected by three regional alteration events (Pankka, 1992; Pankka and Vanhanen, 1992; Vanhanen, 2001): (1) diagenetic, partial albitization of feldspars and sericitization of clay minerals in all sedimentary units; (2) local, partial to total albitization of clastic sedimentary units and spilitization of volcanic units, either related to the ~2.21 Ga intrusion of the mafic sills and dikes, or during the early stages of subsequent orogenic evolution; and (3) overprinting of the early spilitization and albitization by much more extensive albite and scapolite alteration and local carbonatization. The intensity of the last alteration varied from weak (<10 vol% albite) to strong, locally resulting in almost pure albite rocks (99 vol% albite, with traces of carbonate, rutile, and quartz).

Syndiagenetic, alkaline, oxidizing fluid activity has also been proposed for a clastic sedimentary sequence, 2.3–2.1 Ga in age, located in a rifted craton margin setting a few hundred km to the south of Kuusamo (Lahtinen et al., 2013). Such fluids can aggressively alter the rocks with which they interact, as indicated by the disturbed REE patterns in the area (Lahtinen et al., 2013). In addition to the regional alteration, local alteration surrounding the metallic mineralization in the KSB includes carbonatization, sericitization, biotitization, and sulfidation. The deposits are enriched in As, Au, Bi, Co, CO_2, Cu, K, LREE, Mo, Rb, S, Se, Te, U, and W. Somewhat less enriched are Fe, heavy REE (HREE), Mn, Mo, Ni, Pb, and Th, and the Au/Ag ratio is consistently higher than 1 (Pankka, 1992; Vanhanen, 2001). The main ore minerals in the KSB deposits are pyrite, pyrrhotite, cobaltite, cobaltian pentlandite, and chalcopyrite. Native gold occurs in free form within gangue and also associated with Bi- and Te-bearing minerals that are present as inclusions and in fractures in pyrite, pyrrhotite, cobaltite, and uraninite (Pankka, 1992; Vanhanen, 2001).

The metallic occurrences in the KSB have been historically classified into various deposit classes, including orogenic gold deposits with atypical metal associations, iron-oxide–copper–gold deposits, Blackbird-type deposits, and syngenetic deposits (e.g., Pankka, 1992; Pankka and Vanhanen, 1992; Vanhanen, 2001; D.I. Groves, personal communication, 2006; Slack et al., 2010; Slack, 2012). No similar deposits have yet been discovered elsewhere in Finland; therefore, they are classified as “Kuusamo-type” deposits in Fig. 5.1.2. However, as most of the available evidence suggests a late-orogenic timing of mineralization, they are included into the class of "Orogenic gold with anomalous metal association" in Tables 5.1.1 and 5.1.2. The timing of mineralization in the KSB seems to be consistent with both the orogenic gold and Blackbird-type deposit models. Alteration style, metal association, and the nature of the mineralizing fluid(s) fit best with the Blackbird-type model. The nature of the mineralizing fluid(s), the metal association, and the rift–shelf setting are consistent with features of a Blackbird-type model, or an orogenic gold deposit model with an atypical metal association. Structural control and gold fineness are not uncharacteristic of any of the proposed models. Most of the data suggest that the KSB deposits are epigenetic, and that premetamorphic alteration prepared the ground by hardening soft rocks and rendering them competent, and providing brines to transport the metals. Overall, the deposit characteristics are most consistent with the orogenic gold model, although with an atypical metal combination.

PERÄPOHJA Au-Cu AND Au-U

Two types of gold occurrences have been discovered in the Peräpohja schist belt (PSB). One occurs as Au- and Cu-rich quartz vein deposits hosted by 2.3–2.1 Ga metadolerites and their immediate clastic metasedimentary and mafic metavolcanic wall rocks (Rouhunkoski and Isokangas, 1974; Perttunen and Vaasjoki, 2001; Eilu et al., 2007). The second type includes nuggety gold ± uraninite in multiply veined and altered supracrustal rocks of probably both clastic sedimentary and volcanic origin (Nebocat, 2012). Both types are listed under "Orogenic gold with anomalous metal association" in Tables 5.1.1 and 5.1.2, although not enough is known to be sure of the genetic type(s) of these clearly epigenetic occurrences.

The Au-Cu deposit type could be regarded as orogenic gold, but again with an atypical metal association. The PSB occurrences, such as the Kivimaa deposit (Rouhunkoski and Isokangas, 1974), share many features with orogenic gold deposits. The occurrences are epigenetic, hosted by competent lithologies, and brittle to brittle-ductile in structural style. The gold is hosted in quartz veins and their immediate wall rocks associated with sulfides and silicate gangue; the alteration halo, typical of orogenic gold systems in upper-greenschist facies rocks, includes proximal biotite-calcite ± sulfides and distal biotite zones (Eilu et al., 2007). The Au-Cu metal association fits well with an intracratonic rift basin environment that contains evaporates, is filled by clastic sedimentary and mafic volcanic rocks, is intruded by mafic dikes and sills, and has a 570 Ma evolutionary history (~2.45–1.88 Ga) before regional deformation and metamorphism (Perttunen and Vaasjoki, 2001; Kyläkoski, 2009a, 2009b). This environment could produce fluids with uncommonly high salinities that are able to leach, transport, and deposit gold and copper during orogeny (Goldfarb et al., 2001). However, other models have also been suggested for these PSB deposits, such as distal mineralization in red bed copper systems (Kyläkoski, 2009b).

The Au ± U type of mineralization is even more difficult to classify. The discovery of these occurrences was made as recently as 2010, in the Rompas area, in the northwestern part of the PSB (Nebocat, 2012). The host rocks, possibly 2.3–1.95 Ga in age, are so intensely and extensively altered that their primary character is often impossible to define in outcrop or in core logging, and so not much is yet known of them. Thus, the deposits are termed Peräpohja-type Au-U (Fig. 5.1.2). More information about the Rompas occurrences is presented in Subchapter 6.1.

GOLD-RICH VOLCANOGENIC MASSIVE SULFIDE DEPOSITS

In some VMS deposits and prospects in Finland, Au grades are sufficiently high (up to 4 g/t; Table 5.1.1) to be considered a major commodity. Some of the deposits could be originally gold-poor, base-metal occurrences that were overprinted by orogenic gold mineralization, as mentioned previously (the section 'Orogenic gold deposits with anomalous Ag, Cu, Co, Ni or Sb'), but others are clearly Au-rich VMS deposits. Examples of the latter occur in many VMS belts in Finland, and include the Iilijärvi Au-Ag-Cu-Zn-Pb, Haveri Au-Cu, and Pahtavaara Au deposits.

The Iilijärvi deposit has a style of alteration that indicates strongly acidic conditions of mineralization, which characterize high-sulfidation epithermal ores (Hedenquist et al., 1996), but other features, such as a submarine setting and the presence of adjacent VMS deposits, clearly indicate that they are seafloor VMS deposits (Mäkelä, 1989). None of the Iilijärvi-style occurrences have produced any ore to date; Iilijärvi itself was test mined in the eighteenth and nineteenth centuries (Table 5.1.1). The 1.90–1.89 Ga host rocks have been altered to Si-Al rich rocks, which were metamorphosed to a mineral assemblage of quartz + Al silicates, the latter being typically andalusite ± sericite. The host rocks can comprise any lithological unit of the local supracrustal sequence, but most commonly are felsic to intermediate volcanic rocks (Mäkelä, 1989). The Au/Ag ratio is generally <1, and typically about 0.1. The metal grades are 1–10 g/t Au, 10–100 g/t Ag, and 0.1–5 % for Cu, Zn, and Pb.

The Haveri Au-Cu deposit is located in the western part of the Paleoproterozoic Tampere schist belt (TSB) in southwest Finland. During 1942–1962, 1.559 Mt of ore was mined at grades of 2.85 g/t Au and 0.39 % Cu (Puustinen, 2003). Recent exploration has produced an inferred resource of 24.7 Mt at 0.89 g/t Au (Lappland Goldminers, 2008). Kähkönen and Nironen (1994), Eilu (2012), and Ruotoistenmäki (2012) have described the deposit as chiefly hosted by massive and pillowed, mafic tholeiitic lavas that are ~1.905 Ga in age and formed in a back-arc setting. Lithological, structural, geochemical, and mineralogical evidence from ore and alteration assemblages support a VMS deposit model. There appears to be no support for an IOCG model (c.f., Strauss, 2004), and only minor support for an orogenic gold overprint on a Cu-only VMS deposit.

The submarine hydrothermal system is thought to have initially produced chlorite- and albite-rich domains that were metamorphosed to amphibole- and plagioclase-dominated assemblages, respectively. Most of the sulfides and gold, which were partially remobilized during deformation, and the locally abundant magnetite, can also be shown to have been originally deposited in a submarine hydrothermal system. The Haveri deposit is dominated by a subseafloor stringer-style mineralization common to the lower parts of VMS deposits (e.g., Poulsen and Hannington, 1996; Schardt et al., 2001), although significantly affected by multistage deformation and regional metamorphism.

The Pahtavaara gold-only deposit near Sodankylä, CLGB, is hosted by pillowed and massive komatiitic volcanic rocks of possibly 2.10–2.05 Ga in age. The deposit is genetically problematic and has commonly been grouped into the orogenic gold category (e.g., Korkiakoski, 1992). It comprises a swarm of subparallel lodes with nearly all gold disseminated in free native form. The deposit has many of the alteration features of lower-amphibolite facies orogenic gold deposits and an obvious structural control. Lodes are folded and plunge steeply to the west or west-southwest. However, there also are a number of unusual features, as summarized by Patison et al. (2013b). There is a tremolite-quartz-barite-dolomite-magnetite-biotite-pyrite-gold mineral association and a very high fineness (>995) of gold. The geometry of high-gold-grade (10–20 g/t) quartz-barite lenses and amphibole-dominated ore bodies relative to biotite-rich alteration zones is also atypical of orogenic gold deposits, as are the $\delta^{13}C$ values of carbonate alteration minerals.

Pahtavaara could be interpreted as a metamorphosed seafloor hydrothermal system with ore lenses being either carbonate- and barite-bearing cherts or quartz-carbonate-barite veins. The gold may have been introduced later, but its small grain size, textural position (nearly all occurs as free native grains with silicates instead of sulfides), and high fineness point to a prepeak metamorphic genesis. In addition, the interpreted ore zone geometry is compatible with folding of a syngenetic alteration domain, remobilization of gold, and the formation of ore-hosting later veins in fractures in folds or in shear zones. In 2012, ore bodies were discovered that had a style of mineralization different from that mined previously. These recent discoveries have abundant sulfides and significant copper in addition to gold (Lappland Goldminers, 2013b). How these discoveries fit into the picture of syn- or epigenetic mineralization is yet to be explained.

EPITHERMAL GOLD DEPOSITS

Epithermal gold deposits (e.g., Hedenquist et al., 1996; Simmons et al., 2005) form in subaerial (above 2 km depth) magmatic hydrothermal systems. They occur most commonly 50–700 m below the water table, in zones of fluid upflow, and typically form at temperatures of 160–270 °C, although in some examples as high as 350 °C. The tectonic setting is most consistently one of convergent plate margins, commonly in association with magmatism in a back-arc rift. The deposits are controlled by early faults in areas of local extension. Epithermal deposits have probably formed since the onset of plate-tectonic processes on Earth. For example, epithermal gold has been identified in two localities of Archean rocks in Western Australia (Huston et al., 2001; McFarlane et al., 2007). On the other hand, the near-surface subaerial ore formation in a rapidly uplifting arc setting suggest a poor preservation potential. Thus the vast majority of mined epithermal deposits occur in late Mesozoic to Cainozoic rocks. Significant pre-Mesozoic epithermal gold deposits have probably only been preserved where the ores were quickly buried under younger supracrustal sequences and, thus, were protected from being eroded (Dube et al., 1998). Another problem with correctly classifying epithermal deposits in Precambrian terranes is that, with any superimposed regional metamorphism and deformation, many diagnostic, delicate features are destroyed beyond recognition. Thus, the emphasis that follows is on those indicators of epithermal gold deposits that have the best preservation potential.

Epithermal deposits can be subdivided into low-, medium- and high-sulfidation subclasses (LS, IS and HS, respectively) according to their sulfidation state reflecting the ambient pH and f_S of the system (Hedenquist et al., 1996; Simmons et al., 2005). The most intense and distinct alteration is produced in an HS setting, where fluid pH may range from <2 in the core to near neutral in the most distal parts of the hydrothermal system. This results in the following alteration zoning from the distal parts to the core, independent of primary host lithology: propylitic → argillic → advanced argillic → vuggy silica. The mineral assemblages produced are: chlorite ± illite, epidote + remains of primary silicates → illite or smectite + remains of primary silicates → alunite + chalcedony ± kaolinite ± pyrophyllite → chalcedony ± quartz, respectively. The ore is mainly hosted by the vuggy silica rock and, in a number of cases, also by the advanced argillic alteration zone. The main ore minerals are gold, electrum, pyrite, and/or other high-sulfur sulfides, such as enargite, luzonite, covelline, and fahlore. The Au/Ag ratio can vary from <0.01–10; the large Cainozoic HS gold deposits typically have more gold than silver. The chemical composition of the rock reflects the style of alteration. The vuggy silica rock typically contains 95–99.9 wt% SiO_2, with the remainder of the rock characterized by minerals of the least-mobile elements, such as Ti-bearing phases, and ore minerals. In the advanced argillic zone, SiO_2 and Al_2O_3 form as much as 99 wt% of the rock. During alteration, all Na, K, Ca, Mn, and Mg, and nearly all Fe, are removed; some Fe may be fixed into the ore minerals. No mafic silicates, muscovite, feldspars, or carbonates remain in the advanced argillic or the vuggy silica zones.

The most intense alteration and related chemical changes of the HS systems can be recognized even with a significant regional metamorphism and deformation, possibly even in granulite-facies rocks (Hallberg, 1994; Dube et al., 1998). In such settings, one may see an epigenetic quartz rock enveloped by quartz-Al silicate rock, both potentially hosting the ore. For example, at Enåsen, Sweden, the host to the ore is a topaz-bearing quartz-sillimanite gneiss having (SiO_2 + Al_2O_3) > 85 wt% and (Na_2O + K_2O + CaO + MgO) < 1.5 wt% (Hallberg, 1994).

In Finland, the most probable HS epithermal gold deposit is Kutemajärvi in the TSB (Fig. 5.1.2). The features described in the following for Kutemajärvi are summarized form Luukkonen (1994), Poutiainen and Grönholm (1996), and Talikka and Mänttäri (2005). The TSB formed in a volcanic-arc setting with extensive calc-alkaline to alkaline magmatism and rapid orogenic evolution of magmatism related to accretion of the Tampere arc to a microcontinent in the north. The Kutemajärvi deposit is hosted by altered intermediate volcanic rocks and comprises several pipe-like, vertical ore bodies 2- to 20-m across and hundreds of meters long; the two main ore bodies are open at a depth of 700 and 1000 m, respectively (Dragon Mining, 2013). The ore bodies are hosted by quartz-andalusite-pyrophyllite rock (SiO_2 80–90 wt%), with minor to trace amounts of topaz, fluorite, lazulite, kaolinite, rutile, apatite, tellurides, and gold. Sulfides, mainly pyrite, are more common in the alteration halo than in the ore. Proximal alteration enveloping the ore is characterized by the assemblage andalusite-pyrophyllite-quartz, whereas the distally altered rock contains the propylitic assemblage quartz-muscovite-chlorite-pyrite-rutile ± chalcopyrite.

The unaltered host rock shows an assemblage of quartz-biotite-plagioclase ± K feldspar, hornblende, epidote, and magnetite. This probably represents the primary sequence from the most proximal, originally vuggy quartz rock with some kaolinite or pyrophyllite, through the advanced argillic kaolinite-alunite-quartz, and to the distal propylitic zone, all metamorphosed under lower-amphibolite facies conditions. It is distinctly similar to that described at the Hope Brook gold deposit in Newfoundland, Canada (Dube et al., 1998). No carbonatization, potassic or sodic alteration, nor auriferous quartz veining have been identified at Kutemajärvi. It is essentially a gold-only deposit with average grades of 5–12 g/t Au, a Au/Ag ratio of 2–10, and Au/Te < 1 (Luukkonen, 1994). Other elements enriched in the ore include As, Bi, F, Sb, Se, and Si, whereas Ba, Ca, Co, Cu, Fe, K, Mn, Mg, Ni, Rb, and Sr are relatively depleted. The presence of F-rich minerals suggests a significant magmatic component in the fluid, typical of a high-sulfidation epithermal environment. The source for the heat and the acidic fluids could be the hypabyssal Pukala porphyry intrusion located <500 m to the north of the deposit.

There are several other Au ± Ag–base-metal occurrences in Finland that may also belong to the epithermal class, and there is a group of less certain deposits for which not enough conclusive data are available (Eilu and Pankka, 2009). These are indicated as “Epithermal” and “Epithermal or orogenic,” respectively, in Fig. 5.1.2. For example, the Järvenpää Au-Ag-base metal occurrence and the Stenmo Au occurrence in the Tampere and Uusimaa belts, respectively, are classified here as epithermal. The best example of the less-certain cases is Kylmäkangas, in the Archean Oijärvi greenstone belt (Table 5.1.1), where the host to the ore is, possibly, a quartz rock whereas the local quartz veins are barren (Juopperi et al., 2001).

PORPHYRY COPPER-GOLD AND INTRUSION-RELATED GOLD

Porphyry-type deposits form in geological settings similar to those of epithermal deposits. The main difference with regard to preservation potential is that the former form at deeper levels of the crust, between 1–5 km below the surface (e.g., John et al., 2010; Sillitoe, 2010), hence their slightly better preservation. Nevertheless, compared to many other tectonic environments, arcs offer relatively poor preservation potential, as indicated by the paucity of Precambrian porphyry deposits. In Finland and Sweden, several porphyry-style Cu-Au occurrences are known from the Paleoproterozoic Svecofennian domain, including the very large Aitik deposit in northern Sweden, which has been in production since 1968 and has a current mineral reserve of 702 Mt at 0.14 g/t Au, 1.6 g/t Ag, 0.25 % Cu, and 0.003 % Mo (Bejgarn et al., 2011; Wanhainen et al., 2012; FODD, 2013).

In Finland, the best known probable porphyry Cu-Au deposits are Kopsa and Kedonojankulma in west and southwest Finland, respectively (Table 5.1.1; Fig. 5.1.2). Both are hosted by I-type, calc-alkaline, composite, porphyritic intrusions of dominantly tonalitic composition, formed within an active igneous arc probably during periods of terrane accretion, and overprinted by regional deformation and amphibolite-facies metamorphism. They show multistage veining predating regional deformation; typical porphyry-style potassic, sericitic, and propylitic alteration, and silicification; and ore minerals occurring both in veins and as dissemination. Kedonojankulma also shows metal zoning typical of porphyry deposits, with Cu-Au-Ag-As-Mo in the core, Mo and Cu in quartz veins outside of the core, and Zn-Cu-Ag in the outermost zone. The host intrusion at Kopsa is located at the intersection of major early(?) faults, also a typical feature for porphyry Cu-Au systems.

Because Precambrian porphyry Cu-Au deposits commonly occur in metamorphic terranes, it is conceivable that they are porphyry Cu deposits overprinted by orogenic gold or other mineralizing processes (Wanhainen et al., 2012). However, no clear evidence has been found in the Finnish deposits for such overprinting. Common deformation-related late structures host some mineralization, but textures seem to suggest localized remobilization of porphyry gold, rather than much later overprinting mineralization.

It has recently been suggested that the Kopsa deposit may be an intrusion-related gold deposit (IRG; Belvedere Resources, 2012), probably because the gold grade is low (0.8 g/t), the mineralization is synchronous with emplacement of the host granitoid, there is some shearing in the ore, and the deposit is hosted by a granitoid in an orogenic belt. Economic intrusion-related gold deposits are globally relatively rare (Lang and Baker, 2001; Goldfarb et al., 2005; Groves et al., 2005, 2009). It is unclear if such occurrences exist at all in Finland. For example, the diagnostic criteria of (1) tectonic setting well inboard of convergent plate boundaries in deformed shelf sequences; (2) regional association with W or Sn ores and reduced (Cu-poor) magmas; (3) postorogenic timing; and (4) metal zoning from Au-Bi-Te ± W, Mo, As, in sheeted veins in the source intrusion cupola, to hornfels-hosted Au-As ± W, Sn, Sb (within 2–3 km outside of the intrusion), and distal, low-temperature Au-As-Sb-Hg ± Ag, Pb, Zn, and Ag-Pb-Zn (Lang and Baker, 2001; Goldfarb et al., 2005; Groves et al., 2009) are missing for the gold occurrences in the Svecofennian domain of Finland. In addition, the following features, suggested to be typical for IRGs (e.g., Lang and Baker, 2001), are not diagnostic, as all these also characterize many orogenic gold systems: (1) anomalous concentrations of Bi, Te, and W; (2) low-salinity H_2O-CO_2 fluids; (3) postpeak metamorphic, but still synorogenic timing; (4) shallow ore formation; and (5) spatial association with reduced granitoids (Goldfarb et al., 2005).

Some of the criteria that are diagnostic for the IRGs possibly apply to some deposits in northern Finland. For example, this area contains deformed shelf sequences that are characteristic of IRG deposits. Along the southwest margin of the Lapland granulite belt, there are several unusual gold occurrences whose age is late relative to the ductile deformation stages of the Paleoproterozoic orogeny (Mäkärärova, and others). It is only these occurrences that are marked as "Granitoid-related (IRG?)" in Fig. 5.1.2.

Although these do not resemble the Fort Knox deposit (Alaska, U.S.A.), the only economic example of the IRG class, they may well be postorogenic because they are located close to postorogenic granitoids, and they have metal associations (Au-Fe-Ba) and ore and gangue minerals (baryte–hematite ± pyrite ± chalcopyrite) not typical of orogenic gold (Härkönen, 1987). In any case, exploration geologists should be aware that orogenic gold and porphyry Cu-Au deposits are major global gold producers, whereas the IRG occurrences are not. Many deposits around the world that have been suggested by some workers to fall into the IRG category (e.g., Pogo in Alaska, Donlin Creek in Yukon, Linglong in China, Muruntau in Uzbekistan, Vasilikovskoye in Russia, Jilau in Tajikistan, Kidston in Australia) are not IRGs, but orogenic gold or porphyry-related deposits (Groves et al., 2009; R. Goldfarb, personal communication 2013).

PALEOPLACER AND PLACER GOLD

Paleoplacer gold occurrences have been identified in the uppermost Kumpu group of the CLGB. No resource has been published about them, hence they do not appear in Tables 5.1.1 and 5.1.2. These occurrences resemble paleoplacer gold deposits elsewhere, most notably those at Tarkwa, Ghana, which also are Paleoproterozoic in age (Minter, 1991). The Finnish occurrences are hosted by both monomictic and polymictic conglomerates deposited in deltaic and fluvial fan environments after ~1.873 Ma and probably before 1.77 Ga (Härkönen, 1984; Rastas et al., 2001). Most of the gold is hosted by conglomerate lenses that are as much as 30–60 m in thickness. Within these lenses, the grade typically varies from 0.1–5 g/t Au, but locally reaches 22 g/t (Härkönen, 1984). However, only two cases are known (Fig. 5.1.2) where the Au content exceeds 1 g/t for an interval of more than 1 m in thickness. Gold in the Kumpu paleoplacers occurs mainly as free, native, detrital grains with diameters of between 0.03 and 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).

A large number of small placer gold occurrences are known from northern Lapland, in Pleistocene to Holocene regolith, till, sand, and gravel. Despite the numerous occurrences, more than 140 years of artisanal exploitation has officially produced less than 2000 kg of gold (Puustinen, 1991; Finnish Mining Registry data). The metal endowment of these occurrences is difficult to estimate; grades commonly are below 1 g/m^3, but in the best pay streaks may reach several tens g/m^3 (A. Peronius, personal communication 2013). In any case, all presently available information suggests meager possibilities for profitable industrial-scale gold production from these occurrences. On the other hand, these occurrences remain a potentially useful tool in exploration for hard-rock gold deposits in parts of northern Finland, as they indicate areas of primary gold mineralization in the region.

SUMMARY: GOLD MINERALIZATION IN FINLAND AND ITS RELATIONSHIP TO SUPERCONTINENT EVOLUTION

Finland contains a large number of Au deposits and occurrences, due in large part to the diversity of tectonic processes that affected the region (Table 5.1.3, Figs. 5.1.3 and 5.1.4). The oldest gold deposits in Finland may be epithermal, as suggested by indications from the Oijärvi greenstone belt. Subsequently, orogenic gold mineralization took place from 2.72–2.64 Ga in probably all Archean greenstone belts and was related to the collisional processes during the assembly of the Neoarchean

Table 5.1.3 Gold mineralization events in Finland and their possible relationship to supercontinent evolution stages (Lahtinen, 2012; Lahtinen et al., 2012)

Metallogenic event	Metal association[a]	Deposit type[b]	Geological domains[b]
Kenorland assembly			
2.8–2.72 Ga Igneous arcs?	Au-Ag	Epithermal?	Oijärvi?
2.72–2.64 Ga Continent–continent collision	Au	Orogenic gold	All Archean greenstone belts
Paleoproterozoic rifting stages of the Archean continents: Kenorland breakup			
2.45 Ga Failed rifting	–	No Au mineralization	
2.2–2.0 Ga Intracontinental rifting	Au + base metals?	Metal enrichment in red bed and VMS systems?; ground preparation by alteration?	CLGB?, Kuusamo?, Peräpohja?
2.1–1.95 Ga Ocean opening	Au	Au-rich VMS?	CLGB (Pahtavaara)?
Paleoproterozoic igneous arcs and accretion: pre-Columbia arcs to Columbia initial assembly			
1.91–1.90 Ga Igneous arcs	Au-Cu	Au-rich VMS	Tampere
1.91–1.90 Ga Igneous arc and microcontinent accretion	Au	Orogenic gold?	CLGB (Suurikuusikko)?
1.89–1.88 Ga Igneous arcs	Au, Au-Cu	Au-rich VMS, epithermal, porphyry	Uusimaa, Häme, Tampere, Raahe-Haapajärvi
1.885–1.875 Ga Igneous arc and microcontinent accretion	Au, Au-Cu ± Ni, Co?	Orogenic gold, orogenic gold with anomalous metal association?	Häme?, Southern Savo?, Raahe-Haapajärvi? Kuusamo?, CLGB?, Peräpohja?
Paleoproterozoic collisional: Columbia assembly			
1.84–1.79 Ga Continent–continent collision	Au, Au-Cu ± Ni, Co?, Fe-Cu-Au	Orogenic gold, orogenic gold with anomalous metal association?	Häme, Southern Savo?, Raahe-Haapajärvi?, Kuusamo?, CLGB?, Peräpohja?
1.79–1.77 Ga Late collision	Au?	IRG?	North of the CLGB?

Supercontinent stages are according to Mertanen and Pesonen (2012). Geological domains are named as in Fig. 5.1.2. Timing overlap of metallogenic events is due to different processes simultaneously taking place in difference parts of the region. For the Paleoproterozoic evolution, see also Figs. 5.1.3 and 5.1.4.

[a]Main auriferous metal association.

[b]Uncertain timings of mineralization and uncertain genetic types are indicated by the question mark. The problematic genetic types include the Archean epithermal, 2.1–1.95 Ga Au-rich VMS, and the IRG type. The rest are timing issues: For example, the anomalous metal association of orogenic gold mineralization took place at 1.89–1.88 or 1.84–1.79 Ga or during both time intervals within the CLGB, Kuusamo, and Peräpohja. Orogenic gold in the Häme and Pirkanmaa belts may have taken place both during the 1.885–1.875 Ga and 1.84–1.79 Ga orogenic peaks.

supercontinent Kenorland. The episodic disintegration of Kenorland from 2.45 or 2.2 to 1.95 Ga (Mertanen and Pesonen, 2012), first with formation of intracontinental basins hosting red beds and evaporates and later with ocean opening (pink in Fig. 5.1.3), provided a setting for multiple hydrothermal systems that may have enriched gold and other metals in the supracrustal sequences and, during the oceanic stages, possibly formed Au-rich deposits such as Pahtavaara in submarine VMS-like settings.

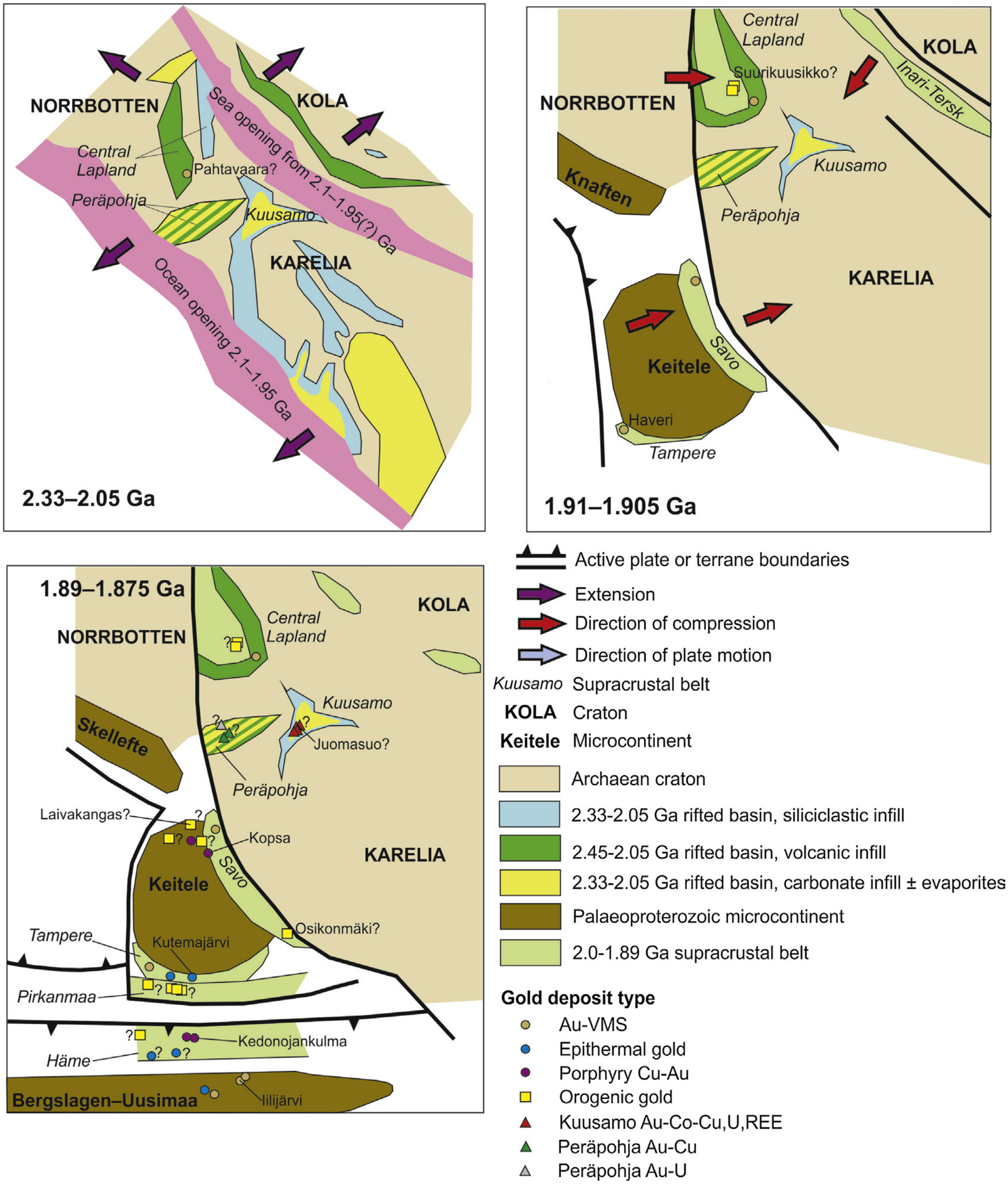

FIGURE 5.1.3

General tectonic setting of Fennoscandia and gold mineralisation in Finland from ca. 2.33 to 1.875 Ga. Only the episodes directly related to gold mineralisation are shown. Based on Lahtinen et al. (2005, 2013), Eilu and Pankka (2009), Grönholm and Kärkkäinen (2012), and Mertanen and Pesonen (2012). The question mark in the maps indicates cases whose timing is uncertain; this uncertainty is most prominent for the deposits in northern Finland.

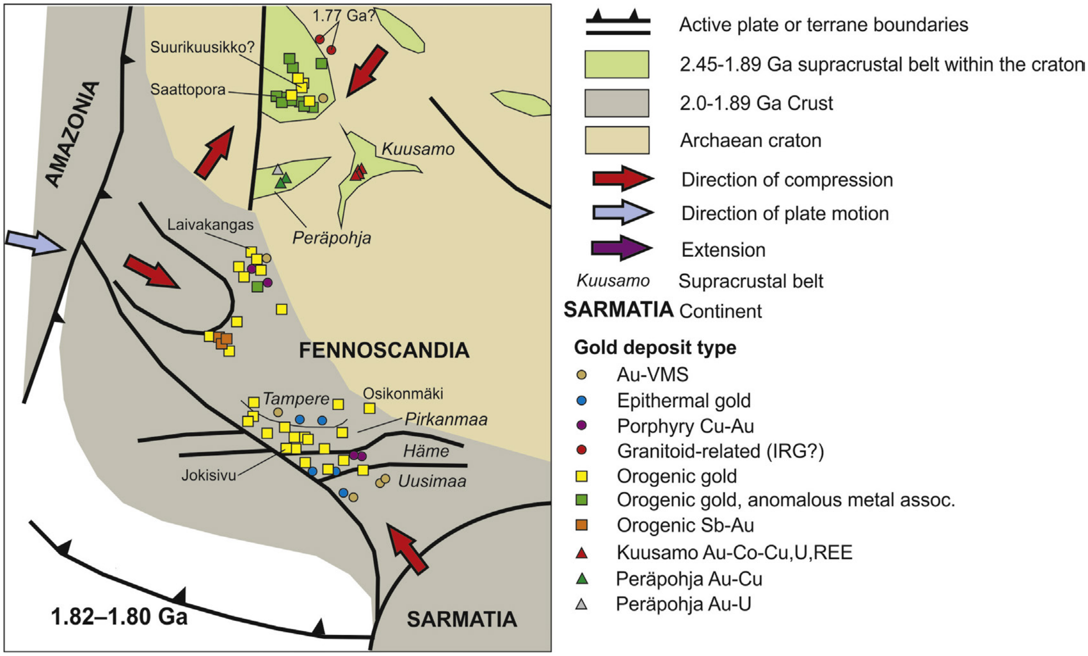

FIGURE 5.1.4

Tectonic setting of Fennoscandia and gold mineralisation in Finland during the latter, continent-continent collisional stage of the Svecofennian orogeny, 1.82–1.80 Ga. Also the location of the possibly 1.77 Ga, IRG-related(?), gold occurrences in northern Finland is indicated. Based on Lahtinen et al. (2005, 2013), Eilu and Pankka (2009), Grönholm and Kärkkäinen (2012), and Mertanen and Pesonen (2012). The question mark indicates cases whose timing is unclear.

Extensive albitization and carbonatization prepared the ground for later mineralizing processes in the intracontinental basins of the CLGB and the Kuusamo and Peräpohja belts. Essential in this ground preparation was the hardening of soft rocks, which later behaved as competent lithological units providing structurally and lithologically controlled locations for the orogenic fluids to deposit the metals.

The onset of the Svecofennian orogeny and assembly of the Columbia supercontinent resulted in multiple gold-mineralization processes (Table 5.1.3). The VMS deposits were related to back-arc basins that were common from 1.93–1.89 Ga. At least one of these, at Haveri, produced a gold-rich seafloor deposit at ~1.905 Ga in the Tampere belt, and several others in the western Uusimaa belt at 1.90–1.89 Ga. At the same time, terrane accretion was taking place in the north, possibly producing the first orogenic gold deposits in the CLGB (Suurikuusikko). Both the Paleoproterozoic deposits and the older Archean deposits may be the sources of gold in the CLGB paleoplacers. Evolution of igneous arcs at 1.89–1.88 Ga introduced epithermal gold (Tampere and Uusimaa belts) and porphyry copper-gold (Raahe-Haapajärvi region and Häme belt) within central and southern Finland. The arcs and juvenile microcontinents amalgamated with each other and with the Archean cratons from 1.89 Ga onward. This may have resulted in extensive orogenic gold mineralization across Finland in 1.885–1.875 Ga and possibly constituted a further gold source for the paleoplacers of the CLGB. The second major stage of Columbia assembly, with continent–continent collision between Fennoscandia, Sarmatia (in the southeast), and Amazonia (in the west), was at 1.84–1.77 Ga. Collision resulted in the formation of orogenic gold deposits in southern Finland and, possibly, IRG mineralization in northernmost Finland in the final stages of the orogeny.

The orogenic gold deposits of anomalous metal association of the CLGB, and the Kuusamo Au-Co ± Cu deposits, can be seen as products of a combination of both preorogenic and synorogenic to late-orogenic processes. They required a sequence of tectonic events related to supercontinent breakup followed by supercontinent assembly, including the following elements: (1) formation of intracontinental rifts, with clastic ± evaporitic sedimentation (serving as fluid ± metal sources), and intracratonic igneous activity (providing heat ± metals) during breakup; (2) ascent of diagenetic and basinal brines, which caused extensive albitization and possibly preenrichment of metals; and (3) formation of orogenic gold deposits involving both early brines and metamorphic fluids during the Svecofennian orogeny and Columbia assembly. The Peräpohja Au-Cu and Au ± U occurrences probably also relate to the evolution of the Paleoproterozoic intracratonic basin and subsequent orogenesis, but the details of this relationship are yet to be unraveled.

ACKNOWLEDGMENTS

Sincere thanks to Rich Goldfarb for a critical and comprehensive review of this contribution. Wolfgang Maier and Eero Hanski are thanked for reviewing the text. Kirsti Keskisaari, at GTK, drew Fig. 5.1.2.

REFERENCES

Agnico-Eagle, 2013. Deposit Reserves and Resources. Accessed online at www.agnicoeagle.com/en/Operations/Reserves-and-Resources/Pages/default.aspx.

Appelqvist, H., 1993. Ore mineralogy in the Proterozoic Kalliosalo gold occurrence, western Finland, with preliminary data on an unspecified mineral, Ag3Au3Sb10S10. Geological Survey of Finland. Special Paper 18, 37–44.

Bejgarn, T., Årebäck, H., Weihed, P., Nylander, J., 2011. Geology, petrology and alteration geochemistry of the Palaeoproterozoic intrusive hosted Älgträsk Au deposit, northern Sweden. Geological Society of London Special Publications 350, 105–132.

Belvedere Resources, 2010. Media release 2 June 2010. Accessed online at http://www.belvedere-resources.com/belvedere-announces-indicated-resource-estimate-for-the-k1angesneva-occurrence-on-the-kiimala-gold-property/.

Belvedere Resources, 2011. Media release 11 October 2011. Accessed online at http://www.belvedere-resources.com/belvedere-significantly-increases-gold-resources-on-their-osikonmaki-prospect-in-finland/.

Belvedere Resources, 2012. Media Release 18 January 2012. Accessed online at http://www.belvedere-resources.com/further-high-grade-gold-drill-results-and-commencement-of-bulk-metallurgical-testing-at-kopsa-finland/.

Belvedere Resources, 2013. Media Release 2 October 2013. Accessed online at http://www.belvedere-resources.com/assets/news02oct2013final.pdf.

Billström, K., Eilu, P., Martinsson, O., et al., 2010. IOCG and related mineral deposits of the northern Fennoscandian Shield. In: Advances in the Understanding of IOCG deposits. In: Porter, T. (Ed.), Hydrothermal Iron Oxide-Copper-Gold & Related Deposits: A Global Perspective, vol. 4. PGC Publishing, Adelaide, pp. 367–400.

Böhlke, J.K., 1982. Orogenic (metamorphic-hosted) gold-quartz veins. U.S. Geological Survey Open-File Report 82–795, 70–76.

Bornhorst, T.J., Wilkin, R.T., 1993. Fluid inclusion data for selected quartz from gold prospects in the late Archaean Hattu schist belt, Ilomantsi, eastern Finland. Geological Survey of Finland. Special Paper 17, 317–322.

Damsten, M., 1990. Tutkimustyöselostus Ilomantsin kunnassa valtausalueella Kuittila 1 3, kaiv. rek. n:ot 3808 ja 3956, suoritetuista malmitutkimuksista. Geological Survey of Finland, Report M06/4244/ 90/1/10. p. 8. (in Finnish).

Dragon Mining, 2009. Annual Report 2008. Dragon Mining Limited, Perth. p. 104. Accessed online at http://www.dragon-mining.com.au/sites/default/files/2008_-_full.pdf.

Dragon Mining, 2011. Media release 3 November 2011. Accessed online at http://www.dragon-mining.com.au/sites/default/files/2011-11-03_juomasuo_resource_update_v2.pdf.

Dragon Mining, 2012a. Media release 31 January 2012. Accessed online at http://www.dragon-mining.com.au/sites/default/files/2012-01-31_december_2012_quarterly_report.pdf.

Dragon Mining, 2012b. Media release 19 June 2012. Accessed online at http://www.dragon-mining.com.au/sites/default/files/2012-06-19__hangaslampi_resource_update_v2.pdf.

Dragon Mining, 2013. Annual Report 2012. Dragon Mining Limited, Perth. p. 100. Accessed online at http://www.dragon-mining.com.au/sites/default/files/2013-03-27_dra_annualreport_2012.pdf.

Dube, B., Dunning, G., Lauziere, K., 1998. Geology of the Hope Brook mine, Newfoundland, Canada: a preserved Late Proterozoic high-sulphidation epithermal gold deposit and its implications for exploration. Economic Geology 93, 405–436.

Eilu, P., 1994. Hydrothermal alteration in volcano sedimentary rocks in the Central Lapland greenstone belt, Finland. Geological Survey of Finland, Bulletin 374, 145.

Eilu, P., 2003. Primary and alteration geochemistry at Härmänkylä (Mataralampi), Kuhmo greenstone belt, eastern Finland. Geological Survey of Finland, Report CM19/4412/2003/4/10, p. 34.

Eilu, P., 2012. Haveri copper-gold deposit: genetic considerations. Geological Survey of Finland. Special Paper 52, 255–266.

Eilu, P., Groves, D.I., 2001. Geology, geochemistry and primary geochemical dispersion haloes of Archaean orogenic gold deposits in the Yilgarn Craton: the preweathering scenario. Geochemistry: Exploration, Environment. Analysis 1, 183–200.

Eilu, P., Niiranen, T. (Eds.), 2013. Gold deposits in northern Finland. Excursion guidebook FIN1. 12th SGA Biennial Meeting, August 12–15. Geological Survey of Sweden, Uppsala, p. 56.

Eilu, P., Ojala, V.J., 2007. Mass balance and geochemical anomalies related to the Mataralampi orogenic gold occurrence, Archaean Kuhmo greenstone belt, eastern Finland. Proceedings of the 23rd International Applied Geochemistry Symposium, Oviedo, Spain, June 14–19. Extended abstracts. University of Oviedo. 64–76.

Eilu, P., Pankka, H., 2009. FINGOLD—A public database on gold deposits in Finland. Version 1.0. Geological Survey of Finland. Digital data product 4. Optical disc (CDROM).

Eilu, P., Mathison, C.I., Groves, D.I., Allardyce, W., 1999. Atlas of Alteration Assemblages, Styles and Zoning in Orogenic Lode-Gold Deposits in a Variety of Host Rock and Metamorphic Settings. Geology and Geophysics Department (Centre for Strategic Mineral Deposits) & UWA Extension. The University of Western Australia. Publication 30, p. 64.

Eilu, P., Niiranen, T., Lauri, L., 2013. Geological and tectonic evolution of the northern part of the Fennoscandian shield. Excursion guidebook FIN1. Proceedings of the 12th SGA Biennial Meeting, August 12–15. Geological Survey of Sweden, Uppsala, pp. 8–21.

Eilu, P., Pankka, H., Keinänen, V., et al., 2007. Characteristics of gold mineralisation in the greenstone belts of northern Finland. Geological Survey of Finland, Special Paper 44, 57–106.

Eilu, P., Rasilainen, K., Halkoaho, T., Huovinen, I., Karkkainen, N., Kontoniemi, O., Lepisto, K., Niiranen, T. & Sorjonen-Ward, P. 2015. Quantitative assessment of undiscovered resources in orogenic gold deposits in Finland. Geological Survey of Finland, Report of Investigation 216. p. 318.

Eilu, P., Sorjonen-Ward, P., Nurmi, P., Niiranen, T., 2003. Review of gold mineralisation in Finland. Economic Geology 98, 1329–1353.

Endomines, 2013. Media release 18 March 2013. Accessed online at http://www.endomines.com/index.php/release/?releaseID=1274530.

Etelämäki, T., 2007. Tammelan Riukan Au-mineralisaatio. M.Sc. thesis, Department of Geology, University of Helsinki, p. 97 (in Finnish).
FODD, 2013. Fennoscandian Ore Deposit Database. Accessed online at http://en.gtk.fi/informationservices/databases/fodd/index.html.
Gaal, G., Isohanni, M., 1979. Characteristics of igneous intrusions and various wall rocks in some Precambrian porphyry copper-molybdenum deposits in Pohjanmaa, Finland. Economic Geology 74, 1198–1210.
Geospec Consultants Limited, 2008. Re-Os Analyses, Arsenopyrite Geochronology for Geological Survey of Finland. Analytical Report No 2.
Goldfarb, R.J., Baker, T., Dube, B., et al., 2005. Distribution, character, and genesis of gold deposits in metamorphic terranes. Economic Geology 100, 407–450.
Goldfarb, R.J., Groves, D.I., Gardoll, S., 2001. Orogenic gold and geologic time: a global synthesis. Ore Geology Reviews 18, 1–75.
Grönholm, S., Kärkkäinen, N. (Eds.), 2012. Gold in Southern Finland: Results of GTK studies 1998–2011. Geological Survey of Finland. Special Paper 52, p. 276.
Groves, D.I., Bierlein, F.P., Goldfarb, R.J., 2009. Some irks with IRGS and snags with TAGs. In: Williams, P.J., et al. (Eds.), Smart Science for Exploration and Mining. Proceedings of the 10th Biennial SGA Meeting, Townsville, Australia, 17–20.8.2009. EGRU. James Cook University, Townsville, pp. 356–358.
Groves, D.I., Goldfarb, R.J., Gebre-Mariam, M., et al., 1998. Orogenic gold deposits: A proposed classification in the context of their crustal distribution and relationship to other gold deposit types. Ore Geology Reviews 13, 7–27.
Groves, D.I., Condie, K.C., Goldfarb, R.J., et al., 2005. Secular changes in global tectonic processes and their influence on the temporal distribution of gold-bearing mineral deposits. Economic Geology 100, 203–224.
GSA Global, 2012. Summary report—mineral resource and ore reserve update. Laiva gold deposit. 7 December. GSA Global, Perth, p. 23.
Hallberg, A., 1994. The Enåsen gold deposit, central Sweden. 1. A Palaeoproterozoic high-sulphidation epithermal gold mineralization. Mineralium Deposita 29, 150–162.
Härkönen, I., 1984. The gold bearing conglomerates of Kaarestunturi, Central Finnish Lapland. In: Foster, R.P. (Ed.), Gold ‘82; the Geology, Geochemistry and Genesis of Gold Deposits. Geological Society of Zimbabwe. Special Publication 1, 239–247.
Härkönen, I., 1987. Kultatutkimukset Mäkärärovan alueella Sodankylässä vuosina 1980–1985. Geological Survey of Finland, Report M19/3724/-87/1/10, p. 18 (in Finnish).
Hartikainen, A., 2001. A research report of studies concerning the claim of Timola 1 (register number of claim 5451/1), located in the village of Härmänkylä, Kuhmo, eastern Finland. Geological Survey of Finland, Report M06/4412/2001/1/10, p. 10.
Hedenquist, J.W., Izawa, E., Arribas, A., White, N.C., 1996. Epithermal gold deposits: Styles, characteristics, and exploration. Resource Geology Special Publication 1, 16.
Heino, T., 2000. Mineral Resource Assessment of the Kuikkapuro 1 (mine reg. N:o 6748/1), Kuikkapuro 2 (N:o 6841/1), Kuikkapuro 3 (N:o 6880/1), Kuikkapuro 4 (N:o 6880/2) and Kuikkapuro 5 (N:o 6912/1) gold mineralizations. Geological Survey of Finland Report CM06/4511/2000/1, p. 22.
Heino, T., 2001. Mineral Resource Assessment of the Pahkosuo gold mineralization, claims Pahkosuo (mine reg. N:o 5621/1), Pahkosuo 2 (N:o 6272/1), Pahkosuo 3 (N:o 6272/2) and Pahkosuo 4 (N:o 6410/1). Geological Survey of Finland, Report M19/4513/2001/1, p. 3.
Hokka, J., 2011. Malmiesiintymämalli Suomen orogeenisille kultaesiintymille. M.Sc. thesis. Department of Geology, University of Helsinki. p. 62 (in Finnish).
Holma, M., Keinänen, V., 2007. The Levijärvi-Loukinen gold occurrence: An example of orogenic gold mineralisation with atypical metal association. Geological Survey of Finland, Special Paper 44, 163–184.
Hölttä, P., Karhu, J., 2001. Oxygen and carbon isotope compositions of carbonates in the alteration zones of orogenic gold deposits in central Finnish Lapland. Geological Survey of Finland, Special Paper 31, 25–29.
Hölttä, P., Heilimo, E., Huhma, H., et al., 2012. The Archaean of the Karelia Province in Finland. Geological Survey of Finland, Special Paper 54, 21–73.

Hulkki, H., Keinänen, V., 2007. The alteration and fluid inclusion characteristics of the Hirvilavanmaa gold deposit, Central Lapland Greenstone Belt, Finland. Geological Survey of Finland, Special Paper 44, 135–151.

Hulkki, H., Pulkkinen, E., 2007. Exploration history of the Kaaresselkä gold-copper occurrence, Central Lapland. Geological Survey of Finland, Special Paper 44, 155–164.

Huston, D., Blewett, R.S., Champion, D.C., 2012. Australia through time: a summary of its tectonic and metallogenic evolution. Episodes 35, 23–43.

Huston, D.L., Blewett, R.S., Sweetapple, M., et al., 2001. Metallogenesis of the north Pilbara granite–greenstones, Western Australia—a field guide. Western Australia Geological Survey, Record 2001/11, p. 87.

Inmet Mining, 2013. Media release February 13, 2013. Accessed online at http://ir.inmetmining.com/Files/ac/acc06f0d-b2db-474b-97b4-89243c3d46d2.pdf.

Isomaa, J., Koistinen, E., Kärkkäinen, N., 2010. Sikakangas gold prospect at Seinäjoki, Western Finland. Geological Survey of Finland, Report M19/2222/2010/55, p. 37.

John, D.A., Ayuso, R.A., Barton, M.D., et al., 2010. Porphyry copper deposit model, chap. B of Mineral deposit models for resource assessment. U.S. Geological Survey Scientific Investigations Report 2010-5070-B, p. 169.

Juopperi, H., Karvinen, A., Rossi, S., 2001. The Oijärvi gold prospects in Northern Finland. Summary. Geological Survey of Finland, Report CM06/3521/2000/1, p. 12.

Kähkönen, Y., Nironen, M., 1994. Supracrustal rocks around the Paleoproterozoic Haveri Au-Cu deposit, southern Finland: evolution from a spreading center to a volcanic arc environment. Geological Survey of Finland, Special Paper 19, 141–159.

Kärkkäinen, N., Jokinen, T., Koistinen, E., 2006. Satulinmäki gold prospect at Somero, SW Finland. Geological Survey of Finland, Report M19/2024/2006/1/10, p. 55.

Kärkkäinen, N., Lahtinen, R., Pakkanen, L., 2012. Discovery and mineralogy of gold occurrence at Velkua, Southwestern Finland. Geological Survey of Finland, Special Paper 52, 115–130.

Keinänen, V., 1994. Shear zone-related Soretialehto gold occurrence in green carbonate rocks in the Central Lapland Greenstone Belt. Kittilä, Finnish Lapland. 21:a Nordiska Geologiska Vintermötet, Luleå. Abstracts, p. 99.

Kojonen, K., Johansson, B., 1999. Determination of refractory gold distribution by microanalysis, diagnostic leaching, and image analysis. Mineralogy and Petrology 67, 1–19.

Kojonen, K., Johansson, B., O'Brien, H.E., Pakkanen, L., 1993. Mineralogy of gold occurrences in the late Archaean Hattu schist belt, Ilomantsi, eastern Finland. Geological Survey of Finland, Special Paper 17, 233–271.

Kontinen, A., Paavola, J., Lukkarinen, H., 1992. K-Ar ages of hornblende and biotite from Late Archaean rocks of eastern Finland – interpretation and discussion of tectonic implications. Geological Survey of Finland, Bulletin 365, 31.

Kontoniemi, O., 1998. Geological setting and characteristics of the Palaeoproterozoic tonalite-hosted Osikonmäki gold deposit, southeastern Finland. Geological Survey of Finland, Special Paper 25, 39–80.

Kontoniemi, O., Mursu, J., 2006. Hirsikangas gold prospect in Himanka, western Finland. Claim areas Hirsi 1 and 2 (7847/1 and 8036/1). Geological Survey of Finland, Report M19/2413/2006/1/10, p. 32.

Kontoniemi, O., Johanson, B., Kojonen, K., Pakkanen, L., 1991. Ore mineralogy of the Osikonmäki gold deposit, Rantasalmi, southeastern Finland. Geological Survey of Finland, Special Paper 12, 81–89.

Korkalo, T., 2006. Gold and copper deposits in Central Lapland, northern Finland, with special reference to their exploration and exploitation. Acta Univ. Oulensis. A Scientiae Rerum Naturalium 461, p. 122.

Korkiakoski, E., 1992. Geology and geochemistry of the metakomatiite hosted Pahtavaara gold deposit in Sodankylä, northern Finland, with emphasis on hydrothermal alteration. Geological Survey of Finland, Bulletin 360, 96.

Korvuo, E., 1997. The Saattopora gold ore and the Pahtavuoma Cu-Zn-U occurrences in the Kittilä region, northern Finland. Geological Survey of Finland, Guide 43, 21–25.

Kyläkoski, M., 2009a. Basin scale alteration features and their implications for ore formation in the Palaeoproterozoic Peräpohja schist belt, Northwestern Finland. In: Smart Science for Exploration and Mining: Proceedings of the 10th Biennial SGA Meeting, Townsville, Australia, August 17–20. James Cook University, Townsville, pp. 457–459.

Kyläkoski, M., 2009b. Varhaisproterotsooista laakiobasalttikerrostumaa edustavan Jouttiaavan muodostuman nikkeli-, kupari- ja platinaryhmäpotentiaali. Phil Lic thesis. Department of Geology, University of Oulu, p. 209 (in Finnish).

Lahtinen, J., 1980. Väliraportti Au-mineralisaatiosta. Outokumpu Oy Malminetsintä, Report 001/4522/JJL/80, p. 13 (in Finnish).

Lahtinen, R., 2012. Main geological features of Fennoscandia. Geological Survey of Finland, Special Paper 53, 13–18.

Lahtinen, R., Hallberg, A., Korsakova, M., et al., 2012. Main metallogenic events in Fennoscandia. Geological Survey of Finland, Special Paper 53, 397–401.

Lahtinen, R., Huhma, H., Lahaye, Y., et al., 2013. Long-lived LREE mobility in the cratonic, rift and foredeep to foreland sedimentary cover margin of the Karelia Province. Lithos 175–176, 86–103.

Lahtinen, R., Korja, A., Nironen, M., 2005. Palaeoproterozoic tectonic evolution of the Fennoscandian Shield. In: Lehtinen, M., Nurmi, P.A., Rämö, O.T. (Eds.), Precambrian Geology of Finland—Key to the Evolution of the Fennoscandian Shield. Developments in Precambrian Geology 14. Elsevier, Amsterdam, pp. 418–532.

Lang, J.R., Baker, T., 2001. Intrusion-related gold systems: the present level of understanding. Mineralium Deposita 36, 477–489.

Lappland Goldminers, 2008. Haveri project, Finland. Accessed online at http://www.lapplandgoldminers.com/system/visa.asp?HID=1345&FID=1154&HSID=25481&ActMenu=25557&ActSubMenu=25578&ActSubSubMenu=25632.

Lappland Goldminers, 2013a. Mineral Resources at 1st January 2013. Accessed online at http://www.lappland-goldminers.com/system/visa.asp?HID=1345&FID=1154&HSID=25479&ActMenu=25538&ActSubMenu=25542.

Lappland Goldminers, 2013b. Media release in 15 November 2013 Available online at http://mb.cision.com/Main/8073/9499979/184669.pdf.

Luukkonen, A., 1994. Main geochemical features, metallogeny and hydrothermal alteration phenomena of certain gold and gold-tin-tungsten prospects in southern Finland. Geological Survey of Finland, Bulletin 377, 153.

Luukkonen, E., Halkoaho, T., Hartikainen, A., et al., 2002. Itä-Suomen arkeeiset alueet -hankkeen (12201 ja 2105000) toiminta vuosina 1992–2001 Suomussalmen, Hyrynsalmen, Kuhmon, Nurmeksen, Rautavaaran, Valtimon, Lieksan, Ilomantsin, Kiihtelysvaaran, Enon, Kontiolahden, Tohmajärven ja Tuupovaaran alueella. Geological Survey Finland, Report M19/4513/2002/1, p. 265 (in Finnish).

Mäkelä, M. 1984. Raahen Laivakankaan kvartsi-arseenikiisukultaesiintymä. M.Sc. thesis. University of Turku, p. 105 (in Finnish).

Mäkelä, U., 1989. Geological and geochemical environments of Precambrian sulphide deposits in southwestern Finland. Annales Academiae Scientiarum Fennicae. Series A. III. Geologica-Geographica 151, 102.

Makkonen, H., Ekdahl, E., 1988. Petrology and structure of the early Proterozoic Pirilä gold deposit in southeastern Finland. Bulletin of the Geological Society of Finland 60, 55–66.

Mänttäri, I., 1995. Lead isotope characteristics of epigenetic gold mineralization in the Palaeoproterozoic Lapland greenstone belt, northern Finland. Geological Survey of Finland, Bulletin 381, 70.

McCuaig, T.C., Kerrich, R., 1998. P-T-t-deformation-fluid characteristics of lode gold deposits: evidence from alteration systematics. Ore Geology Reviews 12, 381–453.

McFarlane, C.R.M., Mavrogenes, J.A., Tomkins, A.G., 2007. Recognizing hydrothermal alteration through a granulite facies metamorphic overprint at the Challenger Au deposit, South Australia. Chemical Geology 243, 64–89.

Mertanen, S., Pesonen, L.J., 2012. Paleo-Mesoproterozoic assemblages of continents: paleomagnetic evidence for near Equatorial supercontinents. Lecture Notes in Earth System Sciences 137. Springer, Berlin. pp. 11–35.

Minter, W.E.L., 1991. Ancient placer deposits. In: Foster, R.P. (Ed.), Gold Metallurgy and Exploration. Blackie and Sons Ltd., Glasgow, pp. 283–308.

Moilanen, M., Peltonen, P., 2015. Hannukainen Fe-Cu-Au deposit, western Finnish Lapland: Deposit model updated. In: Maier, W.D., O'Brien, H.,, Lahtinen, R. (Ed.), Mineral Deposits of Finland. Elsevier, Amsterdam. pp. 485–504.

Nebocat, J., 2012. Progress report on the geology, mineralization and exploration activities on the Rompas gold-uranium property, Southern Lapland, Finland. Resources Ltd. PGS Pacific Geological Services, p. 58.

Neumayr, P., Cabri, L.J., Groves, D.I., et al., 1993. The mineralogical distribution of gold and relative timing of gold mineralization in two Archean settings of high metamorphic grade in Australia. Canadian Mineralogist 31, 711–725.

Nurmi, P., Lestinen, P., Niskavaara, H., 1991. Geochemical characteristics of mesothermal gold deposits in the Fennoscandian Shield, and a comparison with selected Canadian and Australian deposits. Geological Survey of Finland, Bulletin 351, 101.

Nurmi, P.A., Sorjonen-Ward, P., Damsten, M., 1993. Geological setting, characteristics, and exploration history of mesothermal gold occurrences in the late Archaean Hattu schist belt, Ilomantsi, eastern Finland. Geological Survey of Finland, Special Paper 17, 193–231.

O'Brien, H.E., Nurmi, P.A., Karhu, J.A., 1993. Oxygen, hydrogen, and strontium isotopic compositions of gold mineralization in the late Archean Hattu schist belt, eastern Finland. Geological Survey of Finland, Special Paper 17, 291–306.

Pankka, H., 1992. Geology and mineralogy of Au-Co-U deposits in the Proterozoic Kuusamo volcanosedimentary belt, northeastern Finland. Ph.D. dissertation. Geology, Michigan Technological University, p. 233.

Pankka, H.S., Vanhanen, E.J., 1992. Early Proterozoic Au-Co-U mineralization in the Kuusamo district, northeastern Finland. Precambrian Research 58, 387–400.

Parkkinen, J., 2003. Update of Quality Control of Mineral Resource Estimate, 2003. Geological Survey of Finland, Report CM19/2332/2003/1/10.

Patison, N.J., 2007. Structural controls on gold mineralisation in the Central Lapland Greenstone Belt. Geological Survey of Finland, Special Paper 44, 105–122.

Patison, N., Ojala, J., Eilu, P., Niiranen, T., 2013a. Kittilä gold mine (Suurikuusikko deposit). Excursion guidebook FIN1. Proceedings of the 12th SGA Biennial Meeting, August 12–15. Geological Survey of Sweden, Uppsala, pp. 31–42.

Patison, N., Eilu, P., Niiranen, T., Ojala, J., 2013b. Pahtavaara gold mine. Excursion guidebook FIN1. Proceedings of the 12th SGA Biennial Meeting, August 12–15. Geological Survey of Sweden, Uppsala. pp. 24–28.

Perttunen, V., Vaasjoki, M., 2001. U-Pb geochronology of the Peräpohja schist belt, northwestern Finland. Geological Survey of Finland, Special Paper 33, 45–84.

Phillips, G.N., 1986. Geology and alteration in the Golden Mile. Kalgoorlie Economic Geology 81, 779–808.

Pitcairn, I.K., Teagle, D.A.H., Craw, D., et al., 2006. Sources of metals and fluids in orogenic gold deposits: insights from the Otago and Alpine Schists, New Zealand. Economic Geology 101, 1525–1546.

Poulsen, K.H., Hannington, M.D., 1996. Volcanic-associated massive sulphide gold. In: Eckstrand, O.R., Sinclair, W.D., Thorpe, R.I. (Eds.). Geology of Canadian Mineral Deposit Types. Geological Survey of Canada, 8. Geology of Canada, pp. 183–196.

Poutiainen, M., Grönholm, P., 1996. Hydrothermal fluid evolution of the Palaeoproterozoic Kutemajärvi gold telluride deposit, Southwest Finland. Economic Geology 91, 1335–1353.

Poutiainen, M., Partamies, S., 2003. Fluid inclusion characteristics of auriferous quartz veins in Archean and Paleoproterozoic greenstone belts of eastern and southern Finland. Economic Geology 98, 1355–1369.

Puustinen, K., 1991. Gold deposits of Finland: Journal of Geochemical Exploration 39, 255–272.

Puustinen, K., 2003. Suomen kaivosteollisuus ja mineraalisten raaka-aineiden tuotanto vuosina 1530–2001, historiallinen katsaus erityisesti tuotantolukujen valossa. Geological Survey of Finland, Report M10.1/2003/3, p. 578 (in Finnish).

Rasilainen, K., 1996. Geochemical alteration of gold occurrences in the late Archean Hattu schist belt, Ilomantsi, eastern Finland. Geological Survey of Finland, Bulletin 388, 80.

Rasilainen K., Eilu P., Halkoaho T., et al. in press. Quantitative assessment of undiscovered resources in orogenic gold deposits in Finland. Geological Survey of Finland, Report of Investigation.

Rastas, P., Huhma, H., Hanski, E., et al., 2001. U–Pb isotopic studies on the Kittilä greenstone area, Central Lapland, Finland. Geological Survey of Finland, Special Paper 33, 95–141.

Ruotoistenmäki, T., 2012. Local- and regional-scale geophysical characteristics of the Haveri mine. Geological Survey of Finland, Special Paper 52, 245–254.

Rouhunkoski, P., Isokangas, P., 1974. The copper-gold vein deposit of Kivimaa at Tervola, N-Finland. Bulletin of the Geological Society of Finland 46, 29–35.

Saalmann, K., Niiranen, T., 2010. Hydrothermal alteration and structural control on gold deposition in the Hanhimaa shear zone and western part of the Sirkka Line. Geological Survey of Finland, Report M19/2741/2010/58, p. 30.

Saalmann, K., Mänttäri, I., Ruffet, G., Whitehouse, M.J., 2009. Age and tectonic framework of structurally controlled Palaeoproterozoic gold mineralization in the Häme belt of southern Finland. Precambrian Research 174, 53–77.

Saalmann, K., Mänttäri, I., Peltonen, P., et al., 2010. Geochronology and structural relationships of mesothermal gold mineralization in the Palaeoproterozoic Jokisivu prospect, southern Finland. Geological Magazine 147, 551–569.

Saltikoff, B., 1980. Nurmon Kalliosalon antimoniesiintymän malmimäärä. Geological Survey of Finland, Report M19/2222/-80/2/10, p. 4 (in Finnish).

Sandstad, J.S., 2012. Kautokeino Au-Cu. Geological Survey of Finland. Special Paper 53, 116–118.

Schardt, C., Cooke, D.R., Gemmell, J.B., Large, R.R., 2001. Geochemical modeling of the zoned footwall alteration pipe, Hellyer volcanic-hosted massive sulfide deposit, Western Tasmania, Australia. Economic Geology 96, 1037–1054.

Sibson, R.H., Robert, F., Poulsen, H., 1988. High-angle reverse faults, fluid-pressure cycling, and mesothermal gold-quartz deposits. Geology 16, 551–555.

Sillitoe, R.S., 2010. Porphyry copper systems. Economic Geology 105, 3–41.

Simmons, S.F., White, N.C., John, D.A., 2005. Geological characteristics of epithermal precious and base metal deposits. Society of Economic Geologists. Economic Geology 100th Anniversary Volume 485–522.

Sipilä, E., 1988. Kultatutkimukset Haapaveden Vesiperällä ja sen ympäristössä 1985–1988. Geological Survey of Finland, Report M19/2433/-88/1/10, p. 4 (in Finnish).

Sipilä, E., 1990. Kultamineralisaatioiden tutkimuksista valtausalueilla Kiimala 1 ja 2 Haapavedellä 1988–1989. Geological Survey of Finland, Report M19/2433/-90/3/10, p. 22 (in Finnish).

Slack, J.F., 2012. Strata-bound Fe-Co-Cu-Au-Bi-Y-REE deposits of the Idaho cobalt belt: multistage hydrothermal mineralization in a magmatic-related iron oxide-copper-gold system. Economic Geology 107, 1089–1113.

Slack, J.F., Causey, J.D., Eppinger, R.G., et al., 2010. Co-Cu-Au deposits in metasedimentary rocks. A preliminary report. U.S. Geological Survey Open-File Report 2010–1212, 13. Available online at http://pubs.usgs.gov/of/2010/1212.

Sorjonen-Ward, P., 1993. An overview of structural evolution and lithic units within and intruding the late Archaean Hattu schist belt, Ilomantsi, eastern Finland. Geological Survey of Finland, Special Paper 17, 9–102.

Strauss, T.A.L., 2004. The geology of the Proterozoic Haveri Au-Cu deposit, southern Finland. Ph.D. thesis, Rhodes University.

Talikka, M., Mänttäri, I., 2005. Pukala intrusion, its age and connection to hydrothermal alteration in Orivesi, southwestern Finland. Bulletin of the Geological Society of Finland 77, 165–180.

Taranis Resources, 2011. Media release 12 October. Accessed online at http://www.taranis.us/News_Releases/Taranis_10_12_2011nr.pdf.

Tiainen, M., Molnar, F., Koistinen, E., 2013. The Cu-Mo-Au mineralization of the Paleoproterozoic Kedonojankulma intrusion, Häme belt, southern Finland. In: Johnsson, et al. (Eds.), Mineral Deposit Research for a High-Tech World. Proceedings of the 12th Biennial SGA Meeting, August 12–15, Uppsala, pp. 892– 895, Sweden.

Tomkins, A.G., Grundy, C., 2009. Upper temperature limits of orogenic gold deposit formation: Constraints from the granulite-hosted Griffin's Find deposit, Yilgarn Craton. Economic Geology 104, 669–685.

Tyni, M., 1983. Nurmon Kalliosalon antimoni-kultaesiintymän malmiarvio. Myllykoski Oy. report (in Finnish).

USGS, 2012. Mineral commodity summaries 2012. U.S. Geological Survey. p. 198. Accessed online at http://minerals.usgs.gov/minerals/pubs/mcs/2012/mcs2012.pdf.

Vanhanen, E., 1991. Tutkimustyöselostus Kuusamossa valtausalueella Iso-Rehvi 1, kaiv. rek. n:o 4442, malmitutkimuksista vuosina 1988–1989. Geological Survey of Finland, Report M06/4611/-91/1/10, p. 4 (in Finnish).

Vanhanen, E., 2001. Geology, mineralogy and geochemistry of the Fe-Co-Au-(U) deposits in the Paleoproterozoic Kuusamo schist belt, northeastern Finland. Geological Survey of Finland, Bulletin 399, 229.

Wanhainen, C., Broman, C., Martinsson, O., Magnor, B., 2012. Modification of a Palaeoproterozoic porphyry-like system: integration of structural, geochemical, petrographic, and fluid inclusion data from the Aitik Cu-Au-Ag deposit, northern Sweden. Ore Geology Reviews 48, 306–331.
Weatherley, D.K., Henley, R.W., 2013. Flash vaporization during earthquakes evidenced by gold deposits. Nature Geoscience 6, 294–298.
Yardley, B.W.D., Cleverley, J.S., 2013. The role of metamorphic fluids in the formation of ore deposits. Geological Society, London. Special Publications 393, doi:10.1144/SP393.5.
Yardley, B.W.D., Graham, J.T., 2002. The origins of salinity in metamorphic fluids. Geofluids 2, 249–256.
Yletyinen, V., Nenonen, E., 1972. Selostus malmitutkimuksista Kittilän Riikonkoskella vuosina 1969–1972. Geological Survey of Finland, Report M19/2734/72/1/10, p. 32 (in Finnish).