CHAPTER

THE SUURIKUUSIKKO GOLD DEPOSIT (KITTILÄ MINE), NORTHERN FINLAND

5.2

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ABSTRACT

Suurikuusikko is a gold deposit in central Finnish Lapland which had a premining gold endowment of 7.9 million ounces. The deposit is hosted by tholeiitic mafic volcanic rocks of the ~2.02 Ga Kittilä group of the Central Lapland Greenstone Belt (CLGB). Gold is refractory occurring in arsenopyrite and pyrite, and mineralization is associated with intense pre-gold albite and syngold carbonate(-sericite) alteration. The host rock sequence is deformed by the subvertical to steeply east-dipping Kiistala shear zone. Numerous ore lenses are distributed along and within this north- to north-northeast-trending structure. Individual ore lenses have experienced multiple phases of deformation and generally have a moderate northerly plunge. Mineralized intervals have been found for more than a 5 km strike length of the host structure, and from surface to a depth of >1.5 kms. Four stages of sulfide formation have been detected at Suurikuusikko. Gold is associated with the second stage of arsenopyrite and pyrite growth. An Re–Os age of 1916 ± 19 Ma has been obtained from gold-bearing arsenopyrite. This suggests that mineralization took place 60–100 Ma after Kittilä group deposition and before the end of collision-related sedimentation in the CLGB. This age for Suurikuusikko is similar to the southwest-directed thrusting event related to the CLGB. Suurikuusikko has nearly all features typical for an orogenic gold deposit. The relatively early apparent timing of this deposit in the local orogenic evolution of the CLGB, albitized host rocks, fine-grained carbon in volcanic host rocks, and dominance of refractory gold are less commonly documented features of orogenic gold deposits, but do not suggest an alternative genetic type for this deposit and are not inconsistent with an orogenic gold system.

Keywords: Suurikuusikko; Kittilä Mine; Central Lapland Greenstone Belt; orogenic gold; refractory gold; arsenopyrite.

INTRODUCTION

Suurikuusikko is by far the largest of the many epigenetic gold (±copper) deposits of the Central Lapland Greenstone Belt (CLGB). It is located about 40 km northeast from the town of Kittilä, in the middle of the CLGB. Nearly all of the CLGB gold occurrences can be classified into the orogenic gold category—the deposit class defined by Böhlke (1982), Groves et al. (1998), and Goldfarb et al. (2001) in which epigenetic gold deposits hosted by orogenic belts and formed by syn- to late-orogenic fluids are called *orogenic*. The gold deposits within the CLGB have a few unusual characteristics. These features include pre-gold mineralization, albitization, and significant enrichment of Cu ± Co ± Ni. Similar features in deposits elsewhere caused Goldfarb et al. (2001) to call such deposits *orogenic gold*

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with *anomalous metal association*. At Suurikuusikko, no other commodities (except the gold), are present, whereas the host rocks do show distinct, pre-gold albitization.

The issues of regional to localized albitization and the polymetallic nature of some of the orogenic gold deposits in Finland is addressed in Subchapter 5.1 (Eilu, 2015). It is sufficient to note here that the Au-Cu ± Ni ± Co occurrences in the CLGB probably do not belong to the iron-oxide–copper–gold category of mineral deposits. Exceptions to this are the few cases in the westernmost part of the region, where iron oxides indeed are part of the mineral assemblage in the ores (Niiranen et al. (2007). These are described in detail in Chapter 6 (Moilanen and Peltonen, 2015).

Exploration in the Suurikuusikko area was initiated by the Geological Survey of Finland (GTK) after visible gold was discovered in a quartz vein in a road cut 4 km south-southwest of Suurikuusikko in 1986. The deposit was discovered in 1987 during diamond drilling by GTK on the deposit's host structure, the Kiistala shear zone (KSZ). Previous reports on the deposit have focused on reporting exploration activities, beneficiation, and giving brief overviews of deposit geology, structure, and ore mineralogy (Aho, 2009; Kojonen and Johanson, 1999; Chernet et al. 2000; Patison et al., 2006, 2007; Saloranta, 2011). In this chapter, we update the previous work with recent, yet unpublished, data from the deposit.

GOLD RESOURCE AND MINE DEVELOPMENT HISTORY

In April 1998, the Suurikuusikko deposit was acquired by Riddarhyttan Resources AB. This company's exploration activities identified gold mineralization over a 5-km strike length of the KSZ, and increased the known gold resource to more than 2 million ounces (Moz). In 2004, Agnico Eagle Mines Limited (AEM) acquired a 14 % ownership interest in Riddarhyttan, and commenced acquisition of the project in 2005.

Commercial gold production began in May 2009 via an open pit operation (Kittilä Mine), with underground production beginning in November 2012. The current (late 2014) predicted life for the Kittilä mining operation is 20 years. Proven and probable gold reserves at the end of 2014 were 4.5 Moz or 28.5 Mt of ore with an average grade of 4.9 g/t Au; with additional resources of 2.6 Moz of gold with an average grade of 3.5 g/t Au (Agnico Eagle Mines Ltd., 2015). In addition, the mine had produced 0.9 Moz of gold (recovery grade at about 90%) by the end of 2014. This makes The Kittilä Mine the largest currently active gold mine in Europe. Table 5.2.1 provides examples of the grade and width of mineralized intervals at Suurikuusikko.

REGIONAL GEOLOGICAL SETTING

Suurikuusikko is hosted by the Paleoproterozoic CLGB (Figs. 5.2.1 and 5.2.2) in northern Finland. The CLGB is part of the Karelian craton, a component of the Fennoscandian Shield. Supracrustal rocks of the CLGB are divided into seven lithostratigraphic groups (Lehtonen et al., 1998; Hanski and Huhma, 2005; Bedrock of Finland–DigiKp, 2014). Felsic volcanic rocks (2.44 Ga) overlying the Archean basement comprise the oldest exposed unit in the eastern and southeastern part of the belt, the Salla group.

The Vuojärvi group quartz-sericite schists and gneisses of uncertain origin represent the oldest lithostratigraphic unit in the southern part. The Salla and Vuojärvi groups are overlain by extensive mafic volcanic rocks of the Kuusamo group. Initial rifting of the Archean basement, and related volcanic activity represented by the Salla and Kuusamo groups, was followed by a more tranquil phase and deposition of a thick sequence of epiclastic sedimentary and minor mafic volcanic rocks, which

Table 5.2.1 Suurikuusikko deposit—examples of gold intercepts from drill core

Zone	Drill hole number	Mineralized section length (m)	Averaged grade of section (g/t Au)
Ketola	02114	6.40	4.20
Ketola	02107	7.00	11.10
Ketola	02107	3.20	7.10
Ketola	02104	10.70	4.00
Etelä	R407	7.00	7.50
Etelä	01802	5.60	8.60
Etelä	02039	8.10	9.50
Main	R473	14.00	10.40
Main	R504	10.80	9.10
Main	00717	14.30	10.60
Main	R478	18.20	5.10
Main	99002	18.20	16.50
Main	R479	26.80	17.30
Main	00730	18.90	9.10
Main	98004	29.60	11.90
Main	00903	46.20	8.90

comprise the Sodankylä group. Outcrop observations and crosscutting relationships indicate that both the Kuusamo and Sodankylä groups were deposited from 2.2–2.44 Ga, and that the latter is younger than the former group. These are overlain by the Savukoski group, a 2.05–2.2 Ga cratonic to cratonic-margin volcanosedimentary sequence of phyllites, graphite- and sulfide-bearing schists, and tholeiitic volcanic rocks, suggesting deepening of the depositional basin.

The uppermost rocks of the Savukoski group consists of komatiitic to picritic volcanic rocks indicating further rifting of the basin. The 2.02 Ga Kittilä group (discussed in more detail later) represents the youngest rifting phase and is bound by tectonic contacts with the older units of the CLGB. The <1.89 Ga Kumpu group, consisting of immature clastic sedimentary rocks and minor felsic to intermediate volcanic rocks, is the youngest unit and was deposited during a collisional tectonic stage. All rocks in the region are metamorphosed; hence, the prefix "meta" is implied but omitted from the names of the rock types in this chapter.

Intrusive rocks of the CLGB consist of 2.44 Ga Koitelainen and 2.05 Ga Kevitsa layered intrusions, 2.2 Ga and 2.1 Ga mafic sills and dikes and 2.05 Ga mafic to felsic dikes (Fig. 5.2.2). These all indicate repeated rifting of the depositional basement (Lehtonen et al. 1998; Rastas et al. 2001; Hanski and Huhma, 2005). The 2.13 Ga Nilipää suite granites in the southern margin of the CLGB indicate that felsic intrusive activity took place during or between the extensional phases. The 1.91–1.86 Ga Haparanda suite calc-alkaline felsic to mafic intrusives and ~1.80 Ga granites represent the syn- and late-collisional intrusive activity in the area, respectively (Lehtonen et al. 1998; Rastas et al. 2001). The post-collisional 1.79–1.77 Ga Nattanen suite granites are the youngest intrusives dated from the region (Heilimo et al., 2009).

The Suurikuusikko deposit is hosted by the Kittilä group rocks, a volcanosedimentary rock package dominated by tholeiitic mafic volcanic rocks (Figs. 5.2.1 and 5.2.3A). The Kittilä group includes four

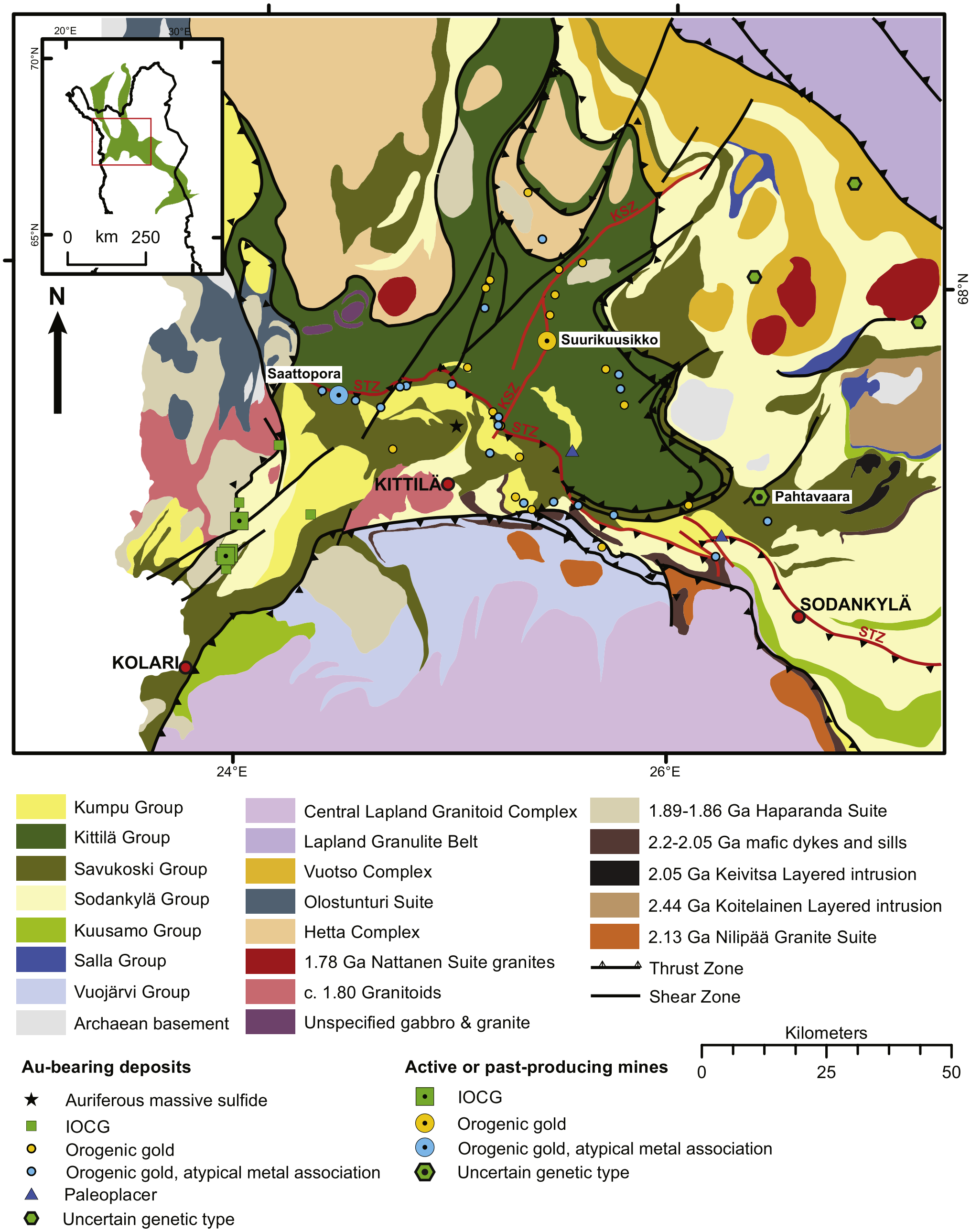

FIGURE 5.2.1 Regional geology map of central Lapland.

Known gold deposits and occurrences, and the location of Kittilä town. KSZ = Kiistala shear zone, STZ = Sirkka thrust zone. Inset: Location of the study area and location and extent of the CLGB (green). Coordinate system in both WGS84, north up.

Source: *Modified after Bedrock of Finland–DigiKp (2014).*

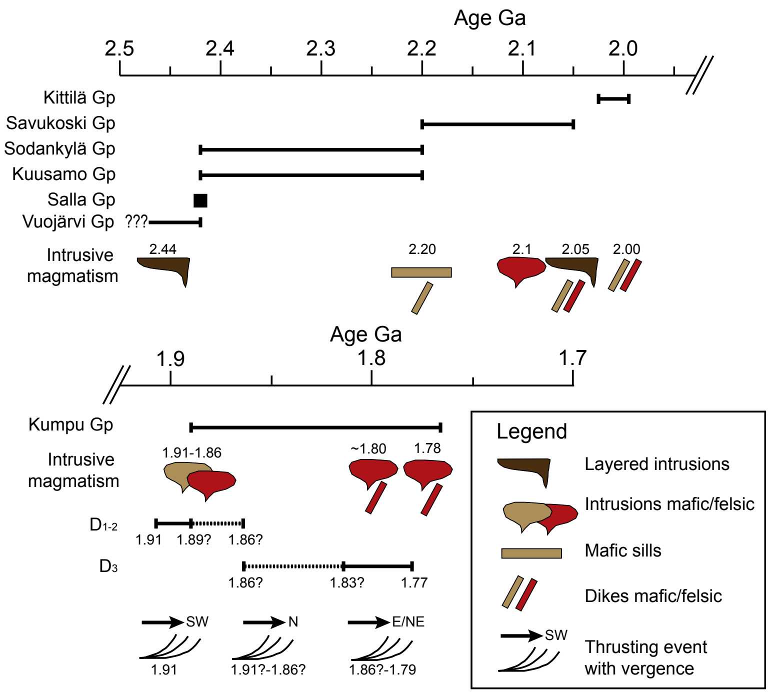

FIGURE 5.2.2 A schematic sequence of the lithostratigraphic groups, intrusive stages, and deformation for the CLGB.

Source: *Based on Lehtonen et al. (1998), Rastas et al. (2001), Hanski and Huhma (2005), Tuisku and Huhma (2006), Hölttä et al. (2007), Niiranen et al. (2007), and Patison (2007).*

formations. Tentatively from oldest to youngest, these are: (1) Kautoselkä formation containing iron-tholeiitic volcanic rocks; (2) Porkonen formation containing oxide and carbonate facies banded iron formation, and iron sulfide-bearing phyllites and schists; (3) Vesmajärvi formation containing magnesium-tholeiitic volcanic rocks; and (4) Pyhäjärvi formation dominated by sedimentary schists (Lehtonen et al., 1998). The regional distribution of each formation shown on published geology maps has been extrapolated from only a few geochemical samples by using the typical magnetic properties of each formation in aeromagnetic data. The Kautoselkä formation is interpreted where mafic rocks have a stronger magnetic response, and the Vesmajärvi formation where the total magnetic field is weaker (Fig. 5.2.4A). Mixed packages of conductive and magnetic rocks are generally assigned to the Porkonen formation (gray areas in Fig. 5.2.4A).

Geochemical heterogeneity among the Kittilä group rocks (for example, mafic rocks with enriched mid-ocean ridge basalt (E-MORB), normal mid-ocean ridge basalt (N-MORB), ocean island basalt (OIB) and island arc tholeiite (IAT) affinities) has been interpreted to indicate that the group is a composite of arc terranes and oceanic plateaus amalgamated during oceanic convergence (Hanski and Huhma, 2005). The Sm–Nd data of the Vesmajärvi formation tholeiites indicate a depleted mantle source and lack of crustal contamination, whereas the slightly negative εNd values of the Kautoselkä formation indicate either a subcontinental lithospheric mantle (SCLM) source or crustal contamination of a depleted mantle source (Hanski and Huhma, 2005). The geochemical signature and isotope data of the Kittilä group tholeiites suggest that it

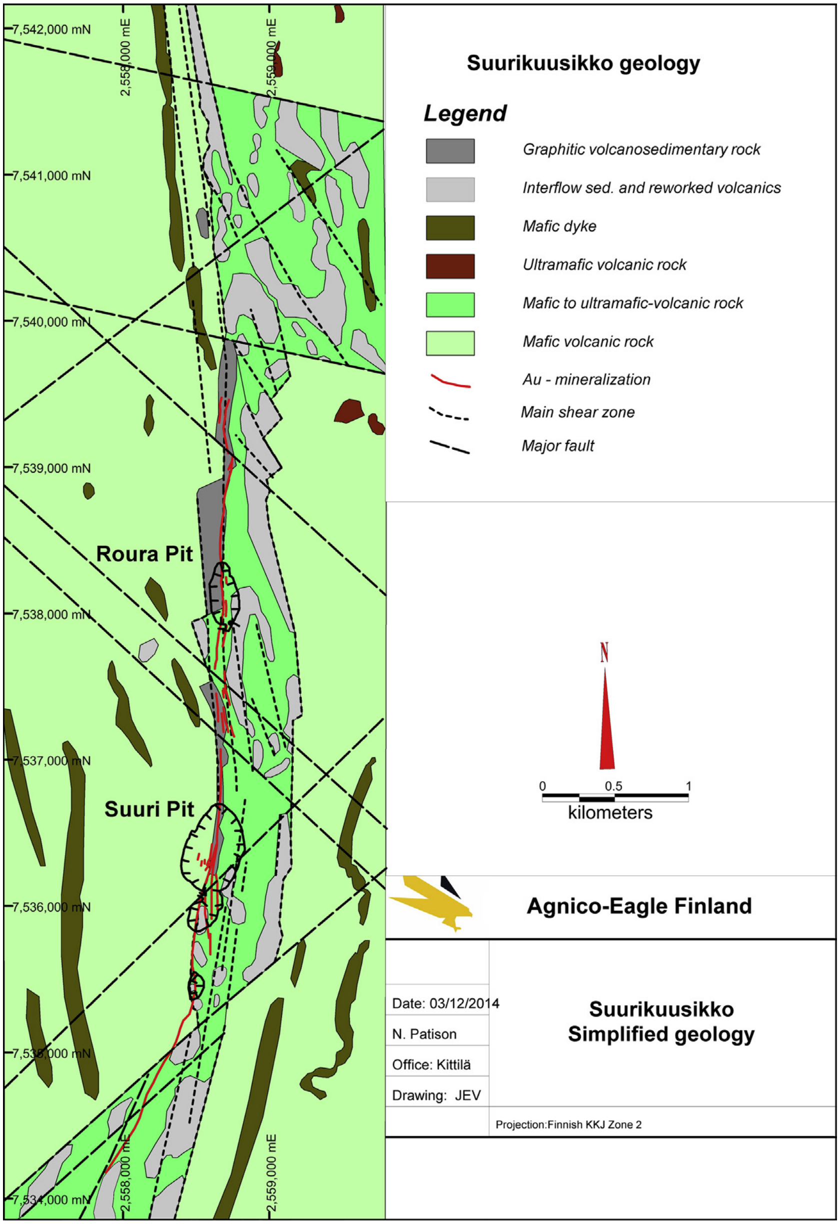

FIGURE 5.2.3 Suurikuusikko trend geology.

Interpreted geology of the Suurikuusikko area with open pit outlines. Coordinate system is Finland KKJ2, values in metres.

may partly represent juvenile oceanic crust. At its current position, the underlying rocks are most likely either Archean, of the surrounding Proterozoic sequences, or both. If the Kittilä group is partly or wholly allochthonous, the proposed tectonic emplacement timing is constrained by the 1.92 Ga Nyssäkoski felsic dike and the 1.91 Ga Ruoppapalo intrusion, both of which intrude the Kittilä group rocks (Hanski et al., 1998). The Kittilä group is also an anomalous area of low-grade (greenschist facies) metamorphism surrounded by higher grade (amphibolite to granulite facies) metamorphic rocks (Hölttä et al., 2007).

Interpretations of reflection seismic data across the CLGB also suggest that geology assigned to the Kittilä group potentially contains a number of distinct crustal blocks (Patison et al., 2006) and, thus, the published extent of this group requires revision. The maximum interpreted thickness of the Kittilä group is about 9 km (Niiranen et al., 2014). Felsic intrusive rocks in the region near Suurikuusikko include the 1.91 Ga Ruoppapalo granodiorite and ~2.02 Ga felsic porphyry dikes throughout the area (Rastas et al., 2001; Hanski and Huhma, 2005).

Multiple extensional events of various timing relative to compressive deformation are inferred due to the presence of extensive mafic dike swarms and layered intrusions (2.44–2.05 Ga intrusions in Figs. 5.2.1 and 5.2.2), but no extensional structures have been mapped in detail. The earliest mapped deformation phases (D1, D2) involve roughly synchronous north- to north-northeast-directed and south- to southwest-directed thrusting at the southern (e.g., Sirkka thrust zone (STZ) in Fig. 5.2.1) and northeastern margins of the CLGB, respectively (Ward et al., 1989). In the northeast, the CLGB is overthrust by the Paleoproterozoic Lapland granulite belt. At its southern margin, the CLGB is overthrusted by volcanosedimentary rocks associated with the Central Lapland Granitoid Complex. The western edge of the CLGB in Finland is interpreted as a cratonic boundary (Berthelsen and Marker, 1986a, 1986b; Lahtinen et al., 2015). All boundaries of the Kittilä group are interpreted as tectonic (Fig. 5.2.1).

Northwest-, north-, and northeast-trending D3 strike-slip shear zones, including the KSZ, cut early folding and thrusting, but may also reflect reactivation of older structures (e.g., transfer faults between the boundary thrusts of the Kittilä group). Post-D3 events are limited to brittle, low-displacement faults. More detailed discussions of regional deformation affecting the CLGB are provided by Gaál et al. (1989), Ward et al. (1989), Sorjonen-Ward (1993), Väisänen et al. (2002), Bergman (2003), Nironen and Mänttäri (2003), Hölttä et al. (2007), and Patison et al. (2007).

Direct age determinations on deformation events are scant. Based on correlations with other areas, potential D1–D2 ages include 1.93–1.91 Ga for southwest-directed thrusting in the northeast (Fig. 5.2.2; Daly et al., 2001; Tuisku and Huhma, 2006); and 1.89–1.87 Ga for north to northeast-directed thrusting (particularly in the southern CLGB; Sorjonen-Ward 1993; Hölttä et al. 2007). Possible D3 deformation ages include 1.89–1.88 Ga, and a minimum age of 1.77 Ga (for an undeformed felsic dike intruding D1 or D2 thrust-related folds within the CLGB; Väisänen 2002). Post-collisional Nattanen-type granites (Fig. 5.2.1) also have an age of 1.79–1.77 Ga (Lehtonen et al. 1998). Peak metamorphic conditions were reached during D1–D2 compressional deformation (Holttä et al. 2007), and a general thermal resetting event is reported for the CLGB in the period 1.79–1.77 Ga (Lahtinen et al. 2005).

GEOLOGY OF THE SUURIKUUSIKKO AREA

Suurikuusikko is located in the central part of the Kittilä group area (Figs. 5.2.1, 5.2.3, 5.2.4), about 15 km east-southeast from the thickest part of the group (Niiranen et al. 2014). Patison (submitted) has produced a bedrock geology model for a 15 × 35 km region including the Suurikuusikko deposit, summaries

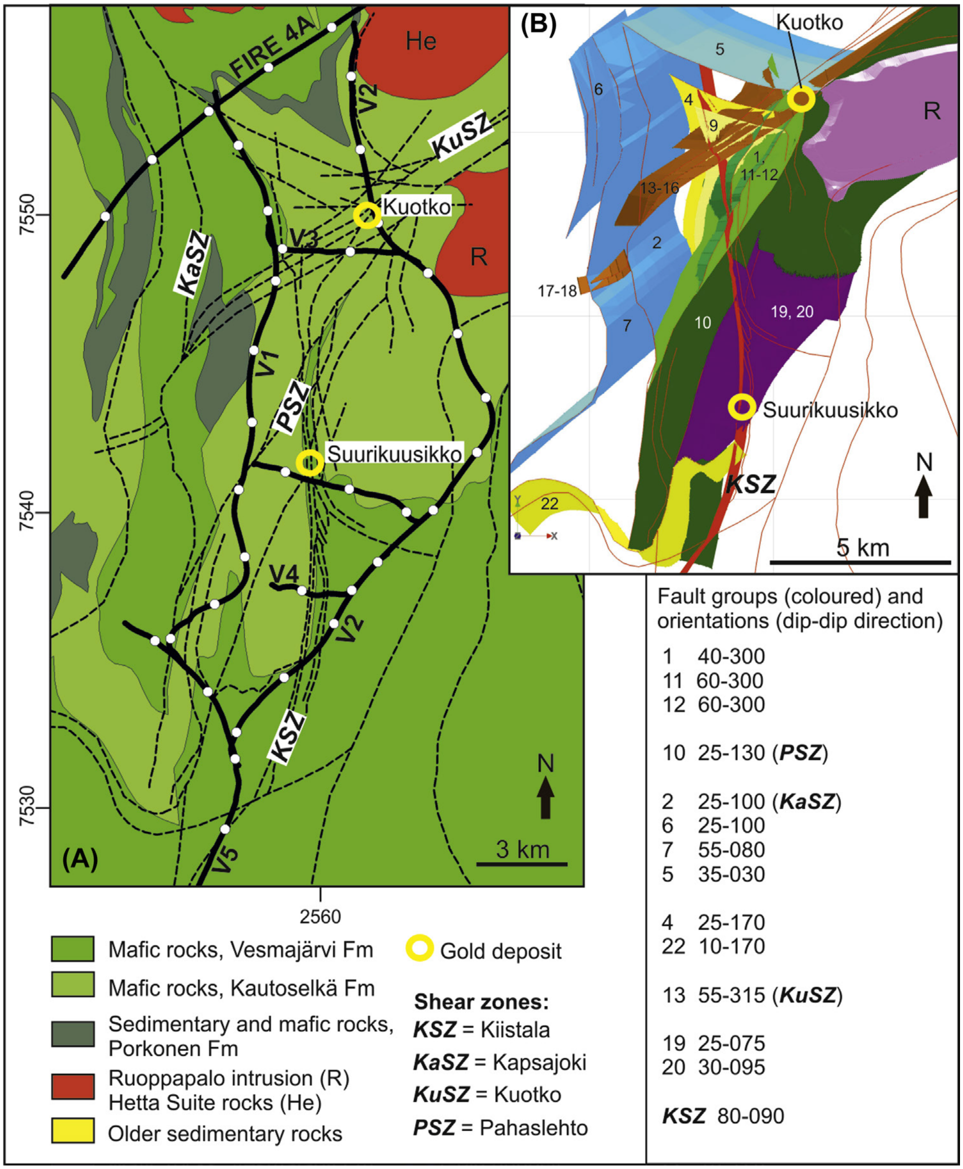

FIGURE 5.2.4 Surface geology of the Suurikuusikko area.

A. Geology map for the Suurikuusikko region. Selected faults are shown as black dashed lines. Thick black lines (V1 to V5) show the high-resolution reflection seismic (HIRE) transects. Transparent labels are seismic line numbers. Labels on white backgrounds are structure names.
B. Modeled faults in the Suurikuusikko region, roughly covering the area of Fig. 5.2.4A. Pink solid (R) is the Ruoppapalo intrusion. Red lines are surface traces of unmodeled faults. Red solid is the Kiistala shear zone (KSZ). Numbers for dip-dip direction are degrees; for example, “40–300” means “40°/300°.” Coordinate system is Finland KKJ2, values in km.

of which are presented here. This model was interpreted from surface geology maps, drilling data, 3D inversion models of magnetic and electromagnetic data, and 2D inversions of magnetotelluric data, and is heavily based on interpretations of high-resolution reflection seismic data collected from an 86.1-km grid over the area extending to a depth of approximately 5 km (line locations shown in Fig. 5.2.4A).

Modeled stratigraphy (rock packages of contrasting density) is shown in Fig. 5.2.5A (blue and purple solids). The interpreted orientation of contacts between rock packages has a low to moderate dip to the northeast. In the east–west sections shown in Fig. 5.2.5A (lines E1 and V4), open folding is interpreted. Similar structures have been mapped immediately adjacent to mineralized zones outside of intensely sheared rock (e.g., Fig. 5.2.5F). Directly beneath the deposit, the modeled bedrock has an antiformal appearance. This may be a thrust-related structure or the result of movements on the Kiistala shear zone (KSZ). The stratigraphic contacts in Fig. 5.2.5A also correlate with modeled faults, interpreted as thrusts with dips of 25° in directions ranging from 075° to 130° (e.g., green Pahaslehto shear zone (PSZ) in Fig. 5.2.4 Patison submitted), complicating the crustal structure in this area prior to the development of the KSZ.

Cross-sections based on drill core data are shown in Figs. 5.2.5C and 5.2.5E. These show similarly oriented bedrock to the model in Fig. 5.2.5A, but also a steepening of dips and a tightening of folding as the KSZ is approached. Cross-section interpretations of drill core data are difficult as the local stratigraphy contains numerous lava flows with ambiguous boundaries, and distinct units that can be used as marker horizons are few. Alteration overprinting provides further complications.

In the cross-sections and in the seismic profile over Suurikuusikko (line V4 in Figs. 5.2.4 and 5.2.5A), the KSZ occurs at an apparent faulted fold hinge. However, this interpretation is not always readily apparent when viewing drill core, and instead different geology is usually mapped on either side of the KSZ. This inconsistency in interpretation might be due to the scales of each interpretation (i.e., single drill holes and mappable exposures vs. 5 km-deep seismic profiles) and/or because of vertical displacement across the KSZ juxtaposing different lithological units.

Local rock types are predominantly thick mafic lava packages (Fig 5.2.4), including pillow lavas. Coarser-grained shallow sills may also occur. Mafic rocks are typically iron tholeiitic in composition (Aho, 2009). In some areas, there is a significant component of mafic volcaniclastic breccias, with little to no reworking during deposition. These breccias are only occasionally polymictic. Primary breccias are in places difficult to recognize due to substantial overprinting by hydrothermal and structural brecciation.

A heterogeneous rock package between lava-dominated domains also occurs. This rock package has been a focus for both deformation and associated alteration. It includes volcaniclastic rock, intermediate to felsic volcanic rocks (andesite flows of Powell, 2001), and carbonaceous ("graphitic") sedimentary intercalations containing chert, argillitic units, and sulfide-rich sedimentary units occurring with mafic volcanic rock. Ultramafic rocks are also present in the more distal parts of the host sequence. The deposit's host structure (KSZ; Figs. 5.2.4, 5.2.5A, and 5.2.5B) mostly follows this heterogeneous rock package. Minor, as yet uneconomic, ore shoots occur on stratigraphic contacts that are adjacent to but at an angle to the KSZ, where elevated gold values are associated with sedimentary and volcaniclastic layers within unmineralized mafic lavas.

The estimated orientation of the KSZ in the deposit area is 80°/090° (dip/dip direction; red plane in Figs. 5.2.5A and 5.2.5C). This is consistent with the orientation mapped for this structure in mine exposures (Figs. 5.2.5B and 5.2.5D) and that interpreted from drill core. The strike of the KSZ changes slightly over its length, but the dip is consistently steep to subvertically eastward. The KSZ has a strike length of at least 25 km (Figs. 5.2.1 and 5.2.4).

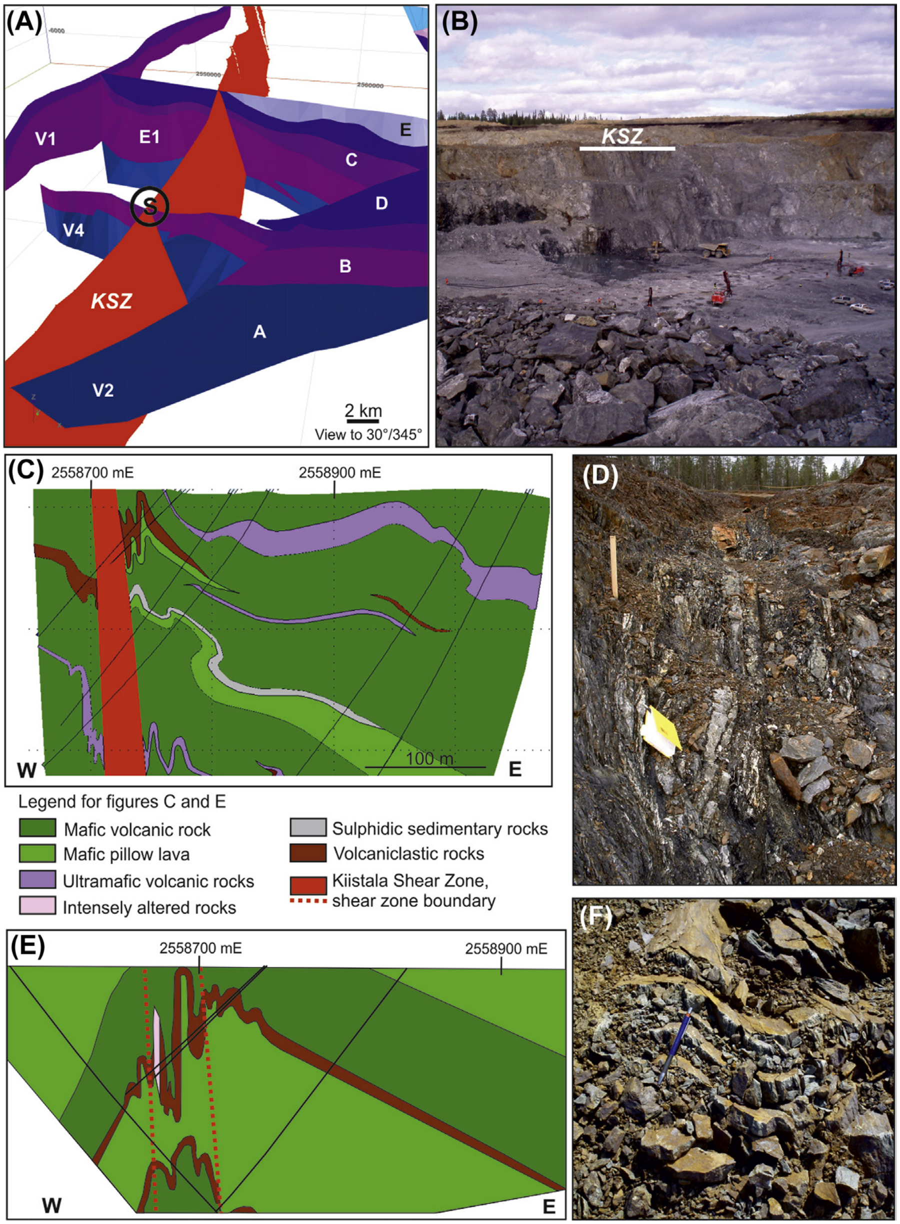

FIGURE 5.2.5 Modelled (A, C, E) and actual (B, D, F) Suurikuusikko geology.

(A) Modeled bedrock layers (blue and purple, labeled A to E) in the Suurikuusikko area, and the Kiistala shear zone (red solid). Suurikuusikko area circled. Interpretation based on HIRE seismic lines E1, V2, and V4. Datum for vertical sections is +250 m and the depth of the interpretation is 2.5 km. The viewing direction for this 3D fence diagram is toward 30°–345° (the plunge and plunge direction of viewing angle).

Known mineralization occurs within north-trending and less frequently northeast-trending (e.g., the Ketola occurrence) shear zone segments. It is a complex structure, recording several phases of movement. A minor degree of west-up movement has occurred, but most deformation has occurred by flattening accompanied by some strike-slip movement. Aeromagnetic images of the KSZ indicate apparent early sinistral strike-slip movement along the zone. Immediately above the widest mineralized zones, late dextral strike-slip movements are recorded on shear planes bounding mineralized zones. An apparent positive correlation exists between points of more intense shearing within the KSZ and the amount of gold present in host rocks.

SUURIKUUSIKKO GOLD DEPOSIT

MINERALIZED ROCK

Mineralized rock at Suurikuusikko has undergone varying degrees of brecciation and veining. Figure 5.2.6 illustrates the typical appearance of the ore. These are altered mafic rocks, probably lava, which show pervasive albite alteration and carbonate-quartz veining. In some areas, brittle deformation has produced breccias Fig. 5.2.6C in which completely fragmented rock has an extensive carbonate-quartz hydrothermal matrix.

Other mineralized rock intervals have a combination of lithologies intermingled by shearing, an example of which is shown in Fig. 5.2.5D; the black material in this picture has a combination of sedimentary and hydrothermally produced or remobilized carbon in a shear-interleaved mix of black schist and volcanosedimentary rock. The pale mineralized rock at this locality may be altered mafic rock, but occasionally it is an altered and mineralized intermediate to felsic rock. Sedimentary units rarely host more than low-grade mineralization, with pyrite. Intensely sheared rock related to mineralization is typically healed (the breccia veins filled mainly by quartz), whereas later shear movements have generated the fractures evident in Fig. 5.2.5D.

ALTERATION

The alteration described next is based on published reports (Härkönen, 1997; Kojonen and Johanson, 1999; Chernet et al., 2000; Patison et al., 2007; Saloranta, 2011; Koppström, 2012) and on findings during ongoing exploration at the mine and its immediate surroundings. Mineral assemblages in the region are typical for greenschist facies rocks. In unaltered mafic rocks, the mineral assemblage is actinolite-chlorite-albite-epidote ± pyrrhotite. Most of the rocks in the hosting shear zone are albitized

◀ (B) Suurikuusikko open pit in August 2009. Darker area is mineralized zone bound by the Kiistala shear zone (KSZ in the photo). Viewing direction approximately north-northeast.
(C) Vertical section geology interpretation based on drill core for section 7539100 mN (= seismic line V4 in Figs. 5.2.4A and 5.2.5A).
(D) Sheared gold-mineralized rock with albitized fragments (pale color) and dark “graphitic” shear planes (location KKJ2 7536,180 mN, 2558,595 mE).
(E) Vertical section geology interpretation based on drill core for section 7539,400 mN (= seismic line E1 in Figs. 5.2.4A and 5.2.5A). The pink polygon, “Intensely altered rocks” indicates area where the original rock types has been so much altered (mostly by albitization) that it is not possible to identify the primary rock type.
(F) Gently north-plunging folds in a chert or an intensely silicified volcanic rock immediately east of sheared ore zones (location KKJ2 7535,935 mN, 2558,635 mE).

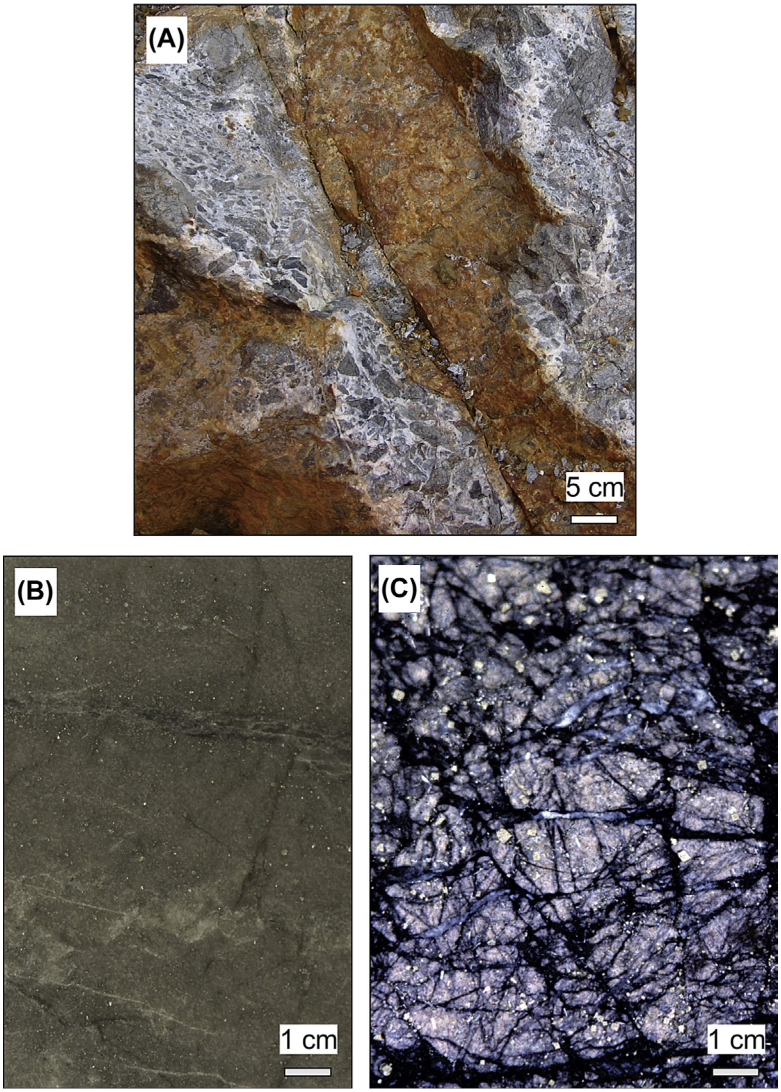

FIGURE 5.2.6 Examples of mineralized rocks.

(A) Pit exposure of hydrothermal breccia with carbonate-quartz veining. Fragments are albitized mafic rock (Rouravaara open pit, 2010).
(B) Bleached, albitized, and veined massive mafic volcanic rock with disseminated arsenopyrite and pyrite.
(C) Sheared, brecciated, and albitized mafic volcanic rock with disseminated arsenopyrite and pyrite, amorphous carbon-carbonate-quartz alteration, and veining.

to a variable degree. Largely, albitization is pervasive in the KSZ and so obvious that mapping albitization is part of core logging routine at the mine.

Albitization is almost always present in the ore, but also in the barren sedimentary and volcanic rocks within the KSZ. This fact and textural relationships in the ore and its wallrocks, such as carbonates replacing all the detected stages of albite porphyroblasts, and ore minerals apparently overprinting albite (Saloranta, 2011), suggest that albitization predated gold mineralization. Intense albitization occurs in both the altered rock itself, replacing other feldspars and mafic silicates, and as albite brecciating micro-veinlets. The amount of albite (up to 82.6 wt%, as calculated from vol.% data achieved by Mineral Liberation Analyzer (MLA) measurements from thin sections) has a strong positive correlation with elevated gold grades (Koppström, 2012). The relationship between albitization and mineralization is further assessed in the "Discussion and summary" section of this chapter.

The alteration halo directly related to mineralization has been divided into three concentric zones: distal, intermediate, and proximal (Koppström, 2012). Of these, the extent of the intermediate zone seems to be most difficult to define, possibly because it is the hardest to recognize in routine core logging. The distal alteration zone is from 100 to more than 300 m wide, extends beyond the KSZ, at least locally, and is characterized by chlorite, rutile ("leucoxene"), minor quartz(?) and calcite replacing amphibole, epidote, and titanite. Calcite also occurs in distal veining (with quartz).

The proximal zone includes all ore and varies in width from the typical 10–50 m to up to 100 m in places. There are also parts of the KSZ with a set of subparallel ore bodies (Fig. 5.2.7) and proximal alteration, with distally altered barren rock between the ore bodies. Proximal alteration and ore gangue (Fig. 5.2.6) include albite, chlorite, muscovite, dolomite, quartz, and lesser amounts of rutile, sericite, amorphous carbon associated with shearing, and relict chlorite and calcite. Dolomite or ankerite veins and hydrothermal breccia matrix characterize the proximal alteration domain, including the ore.

The intermediate alteration zone is characterized by the assemblage albite-calcite-quartz(?)-rutile-pyrite. This assemblage is not visually obvious when compared to assemblages diagnostic for the distal and proximal zones, and during core logging, intermediate alteration might be included either into the proximal or distal alteration zone.

A peculiar feature within the domain of the ore and proximal alteration is the presence of fine-grained reduced carbon species with a graphitic appearance, but having a low degree of crystallization. This mineral is often called"graphite" or "amorphous carbon" at the mine. The relative amount of "graphite" is nowhere large, it occurs everywhere as an accessory mineral, in both the altered rock and in quartz-carbonate veins, but is easy to recognize both in drill core and outcrop. It is clearly of secondary origin, as it occurs not only in lithological units of sedimentary origin, but also in volcanic rocks hosting and enveloping the ore, and in veins.

ORE MINERALOGY

The majority of gold at Suurikuusikko occurs as solid-solution lattice substitutions in arsenopyrite (73.2%) and arsenian pyrite (22.7%) grains; inclusions of native Au and alloys (4.1%) are observed in pyrite and arsenopyrite grains, at grain boundaries and in silicates, and occasionally in association with chalcopyrite (relative amounts defined in mineralogical assessments of the deposit based on drill core samples; Kojonen and Johanson 1999). The composition of gold inclusions includes various alloys with silver and mercury (Chernet et al., 2000). Textures indicate that the Au-rich inclusions and free gold grains are late. They were formed during post-mineralization deformational events, as a product

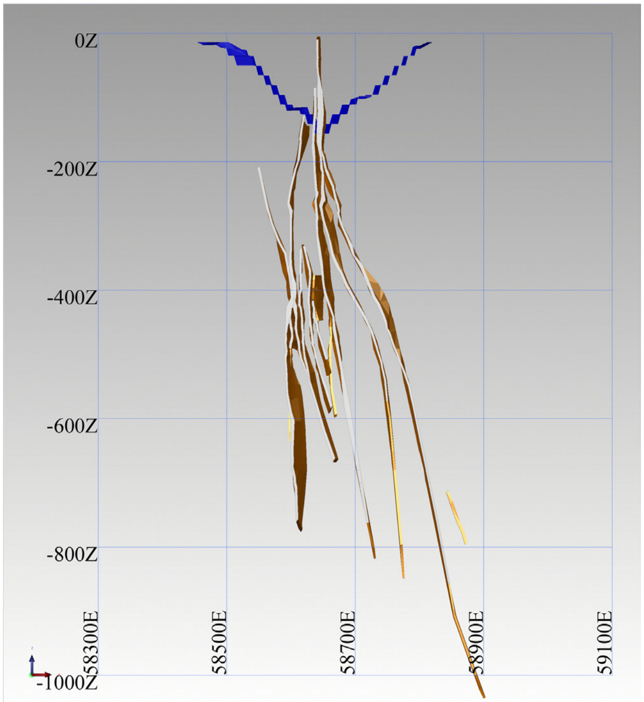

FIGURE 5.2.7 Assay-based modeled east–west section across a set of subparallel ore bodies (brown) at Suurikuusikko.

Outline of the Suuri open pit in this section is marked by blue. View to the north; grid 200 m.

of later-stage alteration or by introduction of late fluids (Koppström, 2012). For the ore-related elements at Suurikuusikko, gold and arsenic exhibit a strong positive correlation, whereas gold and antimony correlate negatively. However, a rare later stage of stibnite veining, which overprints the ore-related sulfides, contains a high gold content.

Pyrite and arsenopyrite commonly form aggregates and intergrowths. Koppström (2012) used electron probe micro-analyzer (EPMA) analysis and laser-ablation inductively-coupled plasma mass spectrometry (LA-ICP-MS) to divide arsenopyrite and pyrite grains into four generations distinguished by textural, compositional, and temporal differences (Figs. 5.2.8A–C). For both minerals, the second generation contains the highest gold content (Fig. 5.2.8B).

The first-generation arsenopyrite (Fig. 5.2.8A) contains inclusions of rutile and other gangue materials, and these arsenopyrites are typically richer in antimony and poorer in arsenic than the average values for all Suurikuusikko arsenopyrites (Härkönen, 1997; Parkkinen, 1997; Kojonen and Johanson, 1999; Chernet et al., 2000; Koppström, 2012). The second arsenopyrite generation mantles the first generation and differs from it by a higher arsenic and a lower antimony content (Fig. 5.2.8A). The third arsenopyrite generation is interpreted as a recrystallization product of the previous generations (Fig. 5.2.8A). The fourth generation is observed only in contact with relatively late quartz-carbonate veins and may be a product of late recrystallization or late fluid introduction events similar to the fourth pyrite generation (Härkönen, 1997; Chernet et al., 2000; Koppström, 2012).

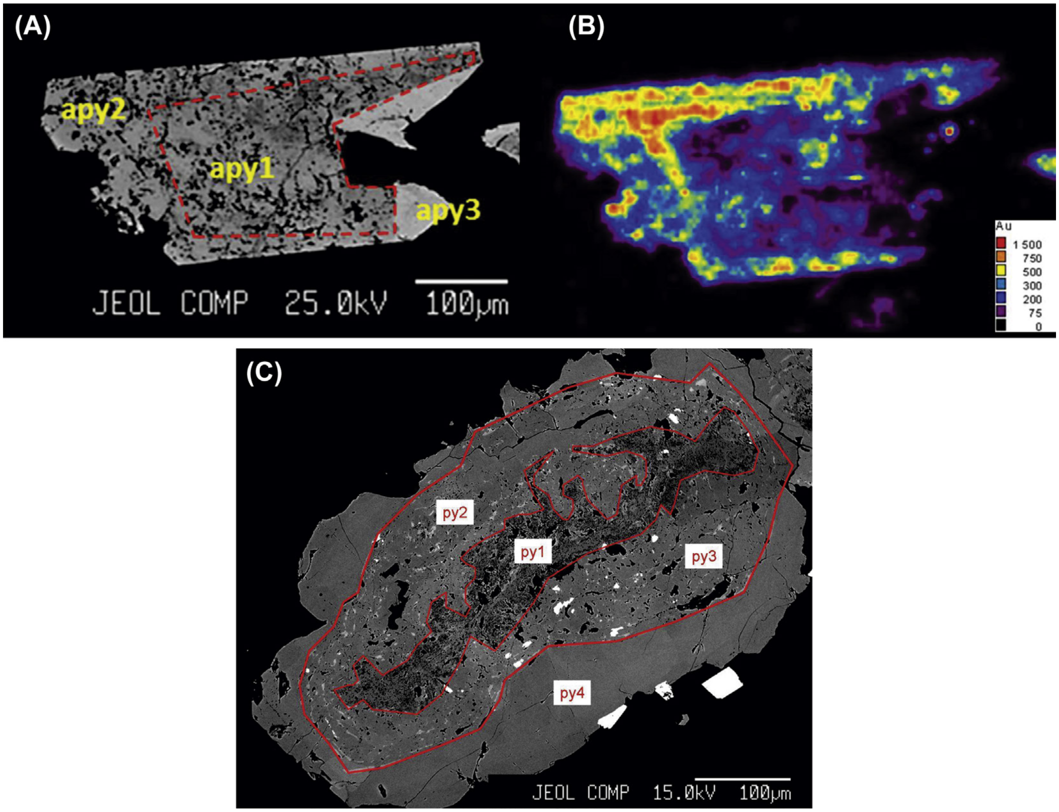

FIGURE 5.2.8 Element distribution maps of an arsenopyrite and a pyrite grain. Growth phases of each grain are labeled.

(A) Back-scatter image of an arsenopyrite grain. The red line shows the border between the first (apy1), the second (apy2), and the third (apy3) generation arsenopyrites.
(B) LA-ICP-MS map of Au distribution in an arsenopyrite grain. The brighter colors represent higher Au concentrations. Note the relation of gold to growth zoning of arsenopyrite. Same scale as in Fig. 5.2.8A. The legend indicates count-detector values representing the relative amount of gold.
(C) Back-scatter image of a zoned pyrite grain that includes four different stages of pyrite formation. The first stage, generation one (py1), is the innermost, porous, and inclusion-rich part of the grain. The remnants of the second generation (py2) are seen as light gray patches within the third generation (py3). The second stage pyrite is defined as the arsenian-generation pyrite. The third generation is the darker gray material inside the py2-py3 area. The fourth generation (py4) forms the outermost gray and only slightly fractured area with almost no inclusions. White inclusions inside the pyrite are mostly antimony minerals and in lesser amounts arsenopyrite.

Source: *After Koppström, 2012*.

Early pyrite grains (py1 in Fig. 5.2.8C) contain inclusions of carbonates, quartz, and rutile. The second pyrite generation (py2 in Fig. 5.2.8C) is arsenian, and has the highest arsenic content of all pyrite generations (Koppström, 2012). The third pyrite generation (py3 in Fig. 5.2.8C) is most likely formed via recrystallization of the second pyrite generation. Inclusions are arsenopyrite (potentially mobilized from py2), antimonides, and gangue minerals. The fourth pyrite generation (py4 in Fig. 5.2.8C) is the least altered. Coarse-grained pyrite of this stage is commonly rimmed by quartz, carbonates, chlorite, and sericite. (Härkönen, 1997; Chernet et al., 2000; Koppström, 2012).

Other ore minerals detected at Suurikuusikko include gersdorffite, chalcopyrite, chalcocite, sphalerite, pyrrhotite, monazite, ullmannite, berthierite, gudmundite, bournonite, galena, jamesonite, native antimony, stibnite, bismuth, bornite, chromite, talnahkite, native gold, gold-silver alloys, and tetrahedrite (Kojonen and Johanson, 1999; Chernet et al., 2000; Aho, 2009). These are present only in trace amounts and are not auriferous except for the native gold and gold-silver alloys. Chalcopyrite, chalcocite, tetrahedrite, and rutile are typical inclusions in pyrite and arsenopyrite.

Abundant, fine-grained carbon with a poorly organized (amorphous) graphitic lattice structure characterizes most of the ore: Gold-bearing sulfides are common on shear planes, stylolithic cleavage, and fractures containing amorphous carbon. Unpublished carbon isotope data (trends in the $\delta^{13}C$ value) suggest that this material is sourced from C-rich sedimentary units within the host sequence.

ORE ZONE GEOMETRY

Modeled ore zones strike north, in some cases northeast, parallel to the local trend of the KSZ (Fig. 5.2.4). The dip of ore bodies is variable. It is generally subvertical and parallel to that of the KSZ (Fig. 5.2.7), but may contain steps with a lower dip angle. The ore bodies have a moderate plunge to the north. The control on the northerly plunge is not completely resolved. Potential causes include the role of intersections between multiple shear planes, and of the intersections of lithological unit contacts and shear planes. The orientation of regional fold axes (similar to axes in Fig. 5.2.5F) may also have a role in determining favorable sites for mineralization during shearing. Sulfides in the ore show evidence for deformation relating to post-mineralization movements on host shear planes. Post-mineralization brittle faults crosscut mineralized zones but are not known to cause significant displacement of ore lenses (Fig. 5.2.4).

AGE OF MINERALIZATION

Rhenium–osmium arsenopyrite geochronology has been used to obtain a direct age of 1916 ± 19 Ma for gold-bearing arsenopyrites at Suurikuusikko (Geospec Consultants Limited, 2008). No age for rocks in the immediately adjacent area has been obtained, but comparing the Re–Os age to the stratigraphic ages quoted, mineralization took place 60–100 Ma after Kittilä group deposition and before the end of collision-related sedimentation in the CLGB (<1.89 Ga). The age for Suurikuusikko is most similar to minor felsic to intermediate intrusive rocks 15–20 km from the deposit: 1919 ± 8 Ma Nyssäkoski porphyry dike (Rastas et al., 2001) and 1914 ± 3 to 1905 ± 5 Ma Ruoppapalo intrusion (Rastas et al., 2001; Ahtonen et al., 2007) that post-date the Kittilä group rocks or (in the case of Ruoppapalo) are early synorogenic in relative age. This age for Suurikuusikko is similar to the southwest-directed thrusting event in the region, based on the suggested age of the overthrusting of the Lapland Granulite Belt, 1.92–1.90 Ga (Tuisku and Huhma, 2006). This thrusting event may have more relevance to mineralization at Suurikuusikko than the not-so-voluminous intrusive activity in the region at that time, as discussed below.

DISCUSSION AND SUMMARY

Most of the characteristics of the Suurikuusikko gold deposit are those typical for an orogenic gold deposit, the deposit class originally suggested by Böhlke (1982), first fully defined by Gebre-Mariam et al. (1995), and further elaborated by Groves et al. (1998) and Goldfarb et al. (2001, 2005). These characteristics include the following:

1. The deposit is hosted by an orogenic belt (a greenstone belt) in rocks metamorphosed under greenschist-facies conditions.
2. Local structures and host rock textures, as well as the arsenopyrite Re–Os age, indicate that the timing of mineralization is during an orogeny.
3. The deposit has a distinct structural control by a long-lived shear zone (KSZ) where the siting, extent, and plunge of individual ore bodies seem largely to be controlled by the structural evolution of the shear zone. Admittedly, there are several structures that have only very recently become obvious, such as most of those shown in Figs. 5.2.3 through 5.2.5, which are yet to be explained and put into the structural evolution sequence of the region. This is an issue of future research at Suurikuusikko.
4. The lithological control appears to be the pre-gold albitized rocks, that is, the locally most competent lithological units.
5. Alteration directly related to gold mineralization has produced a proximal mineral assemblage of albite-muscovite (sericite)-dolomite or ankerite-quartz-rutile-arsenopyrite-pyrite. This mineral assemblage is enveloped by the calcite-albite-chlorite-rutile assemblage with no titanite nor amphibole present even in the distally altered rock. This is diagnostic for an orogenic gold system and reflects a reduced, near-neutral, low-salinity H_2O–CO_2 fluid with H_2S and arsenic as minor constituents, a fluid able to carry and deposit gold under greenschist-facies conditions.
6. The mineralizing fluid probably also contained CH_4, as suggested by the extensively present “graphite” (the amorphous carbon). This reduced carbon may have been sourced from the local graphitic sedimentary units, as is suggested by unpublished carbon isotope data. Another open issue is how did the carbon precipitation affect the gold mineralization process. Did it result in a significant change in redox conditions of the fluid causing S, As, and Au to precipitate? Only careful geochemical modeling may answer these questions. In any case, the close spatial relationship between the “graphite” and auriferous sulfides suggest a close genetic relationship.
7. From the preceding items 4 and 5, we can derive the conclusion that the mineralizing fluid was a typical orogenic fluid, which can be derived from progressive metamorphic devolatilization at depth, typically at the transition from greenschist to amphibolite facies conditions (Goldfarb et al., 2005; Phillips and Powell, 2010). The relatively abundant “graphite” may suggest that the fluid contained more CH_4, and/or was slightly more reducing than the average fluid of an orogenic gold system.
8. The fact that nearly all gold is refractory in arsenopyrite and pyrite suggests that (1) the gold was transported in the mineralizing fluid as both bisulfide and arsenate (or thioarsenate) complexes (Mikucki, 1998; Phillips and Powell, 2010; Williams-Jones and Migdisov, 2014), and (2) reaction between host rock iron and the S and As ligands were among the significant agents (if not the most significant) in gold precipitation (Goldfarb et al., 2005; Phillips and Powell, 2010). Ferrous iron for the sulfidation reactions was readily available, especially from the local tholeiitic basalts.
9. Mass balance has not been evaluated for Suurikuusikko rocks. The existing geochemical raw data indicate that the components enriched during mineralization include, at least, As, Au, CO_2, and

S, whereas there are no indications of base-metal mobility. This fits well with the supposed type of the mineralizing fluid. Only robust mass balance calculations can show how much real Na enrichment is related to the pre-gold albitization, and if any Na, K, or any minor or trace-elements except As, Au, and S were mobile and related to gold mineralization.

A number of features at Suurikuusikko could be seen as unusual for an orogenic gold system, or even suggesting some other genetic type of mineralization. These include refractory gold, albitized host rocks, similar ages for mineralization and local granitoid intrusions, and the possibly early-orogenic timing of mineralization relative to main orogenic events of northern Finland.

The dominance of refractory gold over free gold is uncommon in orogenic gold occurrences in Finland, but is not totally exceptional. A smaller part of gold occurs in pyrite and/or arsenopyrite or löllingite in a large number of gold occurrences and deposits in Finland (Eilu and Pankka, 2009). Globally, refractory gold is not uncommon. A number of small to very large orogenic gold deposits are known to contain significant, or be dominated by, refractory gold in various host rocks of varied mineralization ages. These include the metasedimentary-hosted Obuasi in Ghana and Sukhoi Log in Siberia (Oberthür et al., 1996; Zhang et al., 2008); mafic volcanic-hosted Bulletin in Western Australia and Giant in Yellowknife, Canada (Eilu and Mikucki, 1998; Shelton et al., 2004); the ultramafic-hosted Haimur in Egypt and Jian Cha Ling in China (Emam and Zoheir, 2013; Vielreicher et al., 2003).

Host rocks are intensely albitized at Suurikuusikko. Similar albitization is also present in many barren parts of the KSZ. Textural relationships in the ore and its wallrocks suggest that albitization predated gold mineralization (Saloranta, 2011). Similar relationships are found in the Hanhimaa shear zone 10 km to the west of the KSZ (Saalmann and Niiranen, 2010). These suggests that albitization prepared ground for mineralization by producing the locally most competent rocks and was not part of the gold-mineralizing event. The locally hardest rocks behave in the most brittle manner during deformation, thus creating more open space when the fluid pressure exceeds the lithostatic pressure, hence serving as physical traps for later fluids to deposit silica and ore minerals (Sibson et al., 1988; Weatherley and Henley, 2013).

The CLGB has a long pre-orogenic sedimentary and volcanic depositional history in a rifted intracontinental basin (Hanski and Huhma, 2005). Such an environment is favorable for saline connate fluids to form, with or without evaporates (Yardley and Graham, 2002). These pre-orogenic fluids may have leached and altered the fluid flow channels extensively with albitization, carbonatization, or, at higher temperatures, even scapolitization of any rock type. A similar environment has been suggested for other intracontinental rifted basins of the same age in Finland, Kuusamo, and Peräpohja (Vanhanen, 2001; Kyläkoski, 2012). Saline connate fluids may survive during an orogeny (Yardley and Graham, 2002; Yardley and Cleverley, 2013), causing structurally controlled alteration including albitization during the orogeny.

Albitization has been seen as one of the typical, even diagnostic, features of the iron-oxide–copper–gold (IOCG) class of mineralizing systems (e.g., Oliver et al., 2004; Lopez et al., 2014). Other features regionally typical for the CLGB, and elsewhere connected to the IOCG concept (e.g., Hitzman, 2000; Duncan et al., 2014), include epigenetic copper-gold mineralization, medium- to high-salinity fluids, multistage alteration, and extensive occurrence of scapolite in higher metamorphic grade domains around most of the CLGB.

All of this has been used to argue that many, if not all, of the CLGB polymetallic gold and gold-only deposits could go into the IOCG category (Frietsch et al., 1997). However, with the exception of the extreme western part, no epigenetic hydrothermal iron oxide mineralization, high-salinity oxidizing fluids related to alteration and mineralization, nor metal zoning within a deposit has been detected within the CLGB. All features deviating from the characteristics of the gold-only type of orogenic mineralization within the CLGB can be explained by the Goldfarb et al. (2001) model, which suggests that “where Paleoproterozoic tectonism included deformation of older, intracratonic basins, the resulting ore fluids were anomalously saline and in some cases the orogenic lodes are notably base metal-rich". This resulted in the model of "orogenic gold with anomalous metal association" (Goldfarb et al., 2001). At Suurikuusikko, it is only the albitized rocks that need to be explained as anomalous compared to most deposits of the orogenic gold model.

In the regional geology summary just provided, we mention granitoids with ages close to the arsenopyrite Re–Os age from Suurikuusikko and occurring relatively close to the deposit (Fig. 5.2.9): the 1.92 Ga Nyssäkoski felsic dike and the 1.91 Ga Ruoppapalo granodiorite intrusion (Hanski et al., 1998; Rastas et al., 2001; Ahtonen et al., 2007). This could be taken as an indication of a genetic relationship between granitoid magmatism and gold mineralization. Intrusion-related gold (IRG) or thermal aureole gold (TAG) have been suggested for many regions globally, mainly based on fluid and stable isotope indications, by a close spatial relationship to a granitoid, and in some places by an obvious case of a metamorphosed, low metal grade, porphyry Au(-Cu) occurrence (e.g., Hall et al., 2001; Hart et al., 2002; Duuring et al., 2007; Helt et al., 2014).

The TAGs and IRGs have many features similar to orogenic gold, such as fluid inclusion types, stable isotope ratios, element mobility, and local structural control. However, in most cases the evidence is not conclusive for a genetic relationship to an intrusion, and all features can be explained by the normal orogenic gold model (Goldfarb et al., 2005). Within the CLGB we have not detected any direct diagnostic evidence of intrusion-related mineralization processes such as metal zoning within a deposit or between deposits located concentrically around intrusions, gold mineralization hosted by upper carapaces of granitoids or by a granitoid of any kind, or vertical extensional vein sets (e.g., sheeted veins) within intrusions; post-orogenic gold mineralization, or contemporaneous magmatic Sn or W deposits (cf., Hart et al., 2002; Goldfarb et al., 2005). The IRG concept, as defined by Hart et al. (2002), appears not applicable as, in addition to features listed in above, the CLGB gold deposits (Suurikuusikko included) are clearly not post-orogenic.

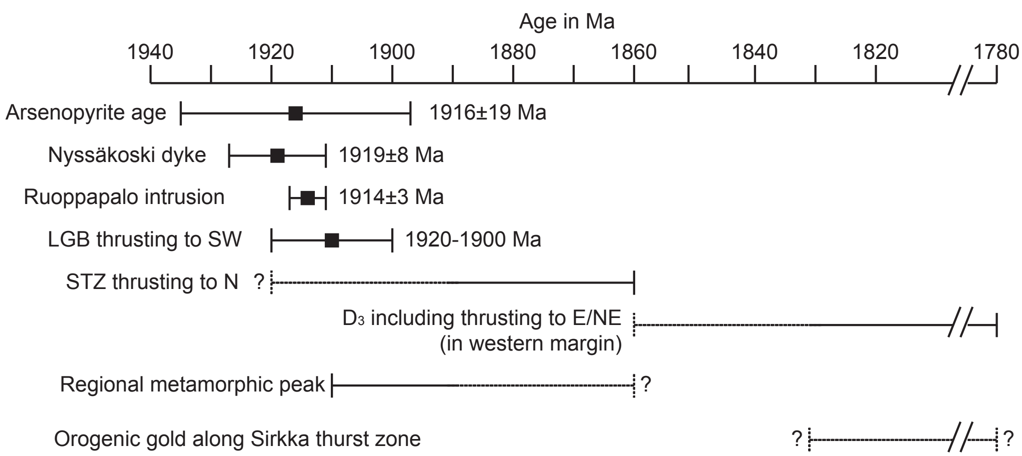

FIGURE 5.2.9 A suggested sequence of events for the CLGB, covering the Paleoproterozoic orogenic events in northern Finland from 1940–1780 Ma, and with a focus on Suurikuusikko and its surroundings.

Thrusting of the Lapland granulite belt (LGB) from the northwest and along the Sirkka thrust zone (STZ) from the south, seem to overlap with mineralization at Suurikuusikko.

Source: *The diagram is chiefly based on data in Hanski et al. (1998), Rastas et al. (2001), Hanski and Huhma (2005), Tuisku and Huhma (2006), Hölttä et al. (2007), Patison (2007), and Niiranen et al. (2014)*.

Four generations of pyrite and arsenopyrite have been detected at Suurikuusikko. Microtexture details suggest that the first two generations may reflect separate stages of sulfidation; that is, two stages when S and As were introduced into the KSZ. Mineral composition data suggest that the second stage sulfidation was the main gold-mineralizing event. On the other hand, the third and fourth generations of pyrite and arsenopyrite appear to indicate stages of local remobilization of S and As, if the textures are correctly interpreted. These later stages might also be those when free gold was formed at Suurikuusikko by remobilization from the arsenopyrite and pyrite lattices. Some gold may also have been introduced by a late external fluid, related to the formation of the rare stibnite veins, which clearly are late in the local paragenetic sequence.

Two to five stages of veining and ore mineral formation have been described from most orogenic and many other types of gold deposits investigated in detail (e.g., Zhang et al., 2008; Helt et al., 2014; Shelton et al., 2004). In practically all cases we know of (except the rare occasions of clear overprint of a syngenetic occurrence by orogenic gold) one hydrothermal stage has introduced most, if not all, of the gold. This seems to be the case also at Suurikuusikko. An open question remains regarding the absolute timing of all the alteration and sulfidation stages.

The arsenopyrite Re–Os age from Suurikuusikko may fit well into the regional orogenic evolution of the CLGB during the Paleoproterozoic, as depicted in Fig. 5.2.9. From the mineral texture details to the larger tectonic scale, it seems gold mineralization took place during the regional metamorphic peak, roughly contemporaneously with minor granitoid intrusions. During that time, the Lapland granulite belt (LGB) was overthrust from the northeast, and the KSZ could then have acted as a transform fault. This early timing would mean that there were two major stages of gold mineralization within the CLGB, an early one shown by Suurikuusikko and a late one indicated by many of the gold occurrences along the Sirkka thrust zone, such as Saattopora (Patison, 2007; Niiranen et al., 2014).

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