CHAPTER

5.3

EXPLORATION TARGETING AND GEOLOGICAL CONTEXT OF GOLD MINERALIZATION IN THE NEOARCHEAN ILOMANTSI GREENSTONE BELT IN EASTERN FINLAND

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ABSTRACT

The Hattu schist belt in easternmost Finland has been systematically explored for gold over several decades and the Pampalo mine commenced operations during the latter half of 2010. Here we document the exploration history of this region, which represents the first Archean gold province to be exploited in Fennoscandia. This review focuses on exploration strategies as well as geological characterization of gold occurrences and deposits, with particular emphasis on till geochemical exploration, which proved particularly effective, and the structural controls on mineralization.

The Hattu schist belt supracrustal sequence is notable for the relative abundance of felsic volcanic and epiclastic deposits. Isotopic data indicate that deposition, deformation, and granitoid intrusion were very closely related in time, the ages of the earliest supracrustal units, at 2.75 Ga, effectively overlapping with those of syntectonic granitoids. All exposed contacts between the Hattu schist belt and these granitoids are intrusive, or else tectonically modified, and hence the granitoids cannot represent depositional basement to the greenstone belt. In spite of locally intense and complex deformation, the Hattu schist belt has retained a high degree of stratigraphical coherence, which has enabled the overall topology of lithic units and structures to be further clarified.

Mineralization does not appear to occur preferentially in any particular lithology, although lithological transitions may be favored, due to associated chemical and rheological gradients. Pervasive fluid flow is, however, also indicated by broad, highly deformed alteration zones and disseminated rather than vein-style mineralization at some prospects. Alteration characteristics of gold mineralization throughout the Hattu schist belt gold occurrences are broadly similar, if less intense than the hydration, carbonation, and potassic alteration generally reported for Archean lode gold deposits. The albite-carbonate alteration mineralogy so characteristic of gold deposits in Archean mafic and ultramafic provinces is far from ubiquitous in the Hattu schist belt, although it is well developed at the largest known deposit, at Pampalo. Instead, chlorite, muscovite, and tourmaline dominate alteration parageneses in mineralized metasediments. Native gold is fine grained (mostly $<15\ \mu m$) and occurs largely in free-milling form between silicate grains, associated with pyrite, pyrrhotite, and minor arsenopyrite and rutile; it is typically intergrown with Bi, Pb, Ag, Fe, and Au tellurides and native bismuth.

Gold mineralization at most prospects is geochemically distinctive, with notable enrichments of Te, B, Bi (and locally Mo and W), compared to many other Archean gold provinces, reflected in the abundance of tourmaline, tellurides and locally, scheelite. The syntectonic Kuittila tonalite contains an early molybdenite-scheelite vein system overprinted by sheared biotite-muscovite-calcite-scheelite-pyrite-gold veins and demonstrates the syntectonic

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timing of mineralization. Extensive alteration of granites and country rocks in the northern part of the schist belt is typified by microcline-muscovite-pyrite alteration and is perhaps more reminiscent of epithermal systems. Therefore, it is possible that gold mineralization in the Hattu schist belt does record some kind of interaction between magmatic and metamorphic influences during a continuum of arc-related and orogenic tectonic processes. These issues are the subject of ongoing investigations, to be reported elsewhere.

The structural architecture of the Hattu schist belt is characterized by upward-facing, generally steeply dipping structures, and it is possible to establish a close, sequential relationship between tightening of folds, attenuation of fold limbs, development of shear zones with strike-slip displacements, and the propagation of new folds due to strain incompatibilities between shear zones. Structural controls on alteration and mineralization are a consequence of strain partitioning due to rheological contrasts between rock units and interaction with large scale structures. This is most apparent in the distribution of disseminated mineralization in the hanging wall above the western margin of the Kuittila tonalite and in the location of the Pampalo gold deposit within the backrotated toe of a strike slip duplex, recording a progressive transition from contractional to oblique extensional behavior. Numerical simulations of regional structural patterns with FLAC3D™ have been performed to assess the importance of variations in far-field stress configuration in controlling rock failure and localizing mineralization, in particular addressing the issue of whether the inferred kinematics represent a local response to orthogonal shortening and compression, rather than deformation within a regional strike-slip regime. Results indicate that northwest–southeast directed deformation favors simultaneous failure and dilation in both the northeast-trending Pampalo zone and northwest-trending Kuittila zone, which can be attributed to their somewhat anomalous orientations and attitudes. Ongoing research involves assessment of results of modeling against field-based geometric and kinematic constraints, to better understand and predict structural controls on mineralization.

Keywords: gold; Archean; greenstone belt; Pampalo; till geochemistry; pathfinder elements; deformation; numerical modeling.

INTRODUCTION

Neoarchean crustal growth and reworking were closely associated with the formation of a significant proportion of known and mined gold deposits, most notably in the Witwatersrand Basin of the Kaapvaal craton in southern Africa, the Abitibi subprovince of the Superior craton in Canada, and the Eastern Goldfields terrane of the Yilgarn craton in Western Australia. However, although Archean rocks in the Fennoscandian Shield are distributed over an area comparable to that of the Yilgarn craton, there is so far little indication that gold resources might be comparable. Whether this is a fundamental issue of gold endowment, relating to essential differences in subcontinental lithospheric characteristics and Neoarchean orogenic processes, remains to be seen. Here we review the exploration history and geological context of mineralization for the only Archean greenstone belt in Fennoscandia where gold is currently being mined, namely the Hattu schist belt in the Ilomantsi district in eastern Finland. Our purpose is to both document the nature of mineralization, comparing and contrasting with Archean gold deposits elsewhere, and to demonstrate the exploration targeting approaches that have been most useful; this approach also reflects the interaction between data collection and mapping, and our evolving understanding of the key features relating to mineralization. For this reason, particular emphasis is given to till geochemical exploration, which was critical in appreciating the potential of the region and in identifying prospective targets, and to structural geometry, as during the course of investigations, the importance of structural controls on mineralization became more apparent.

GEOLOGIC OUTLINE OF THE HATTU SCHIST BELT

In recent reviews of the Archean of Fennoscandia, the terms *Ilomantsi terrane* (Sorjonen-Ward and Luukkonen, 2005) and *Ilomantsi* (Hölttä et al., 2012) have been used to refer to the greenstone belts and surrounding granitoids at the western edge of the Neoarchean Karelian craton in southeastern Finland (Fig. 5.3.1). The Ilomantsi complex includes the Ilomantsi greenstone belt, which consists of a western branch, known as the Kovero belt, and an eastern segment, which has been informally referred to as the Hattu schist belt (Nurmi et al., 1993; Sorjonen-Ward, 1993a).

The Kovero belt contains a greater proportion of mafic and ultramafic rocks than the Hattu belt, which is dominated by feldspathic epiclastic sediments and felsic volcanics, with sporadic magnetite banded iron formation (BIF) and mafic and ultramafic volcanic units (Nurmi et al., 1993; Sorjonen-Ward, 1993a). The Kovero belt also contains older rock units than the Hattu belt (Huhma et al., 2012) and consists of two bifurcating northwest- and northeast-trending branches (Fig. 5.3.2), which appear

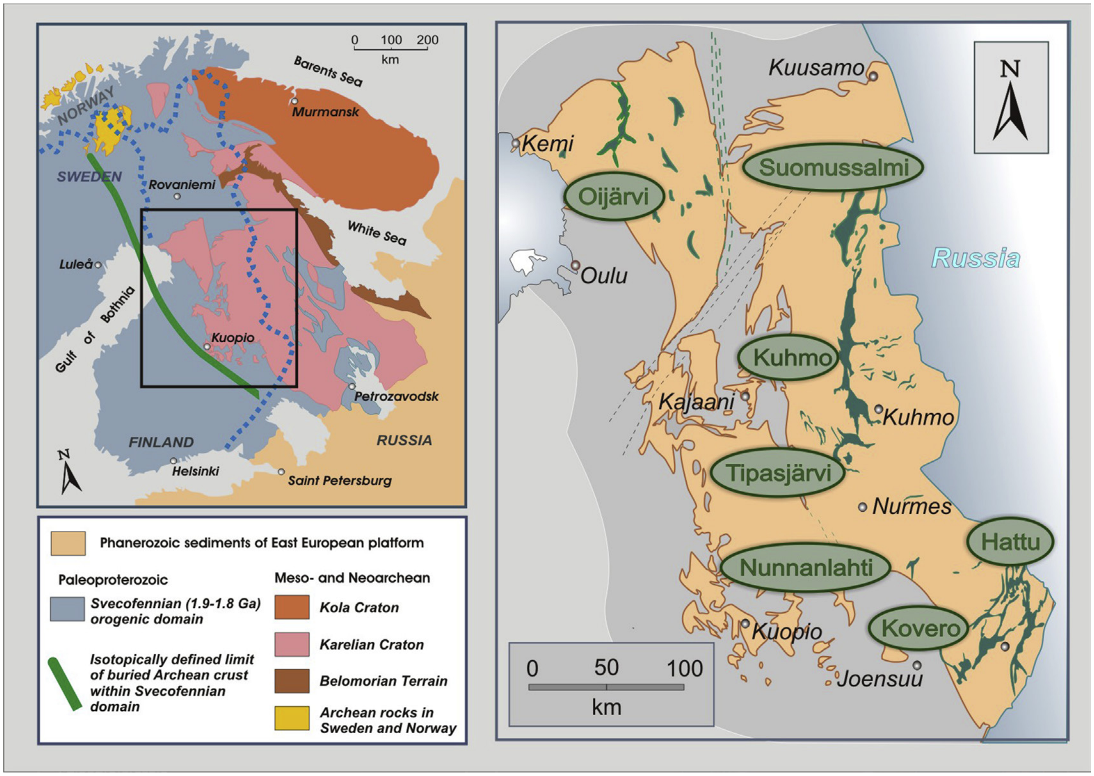


FIGURE 5.3.1 Context of Hattu schist belt within Fennoscandian Shield.

Left: Principal Archean crustal domains and significant boundaries, in part defined isotopically. The Kola and Karelian cratons are separated by the Belomorian terrane, which records both Neoarchean and Paleoproterozoic orogenic events. Black rectangle indicates location of diagram on right panel. *Right:* The extent of the Karelian craton in Finland and the principal greenstone belts.

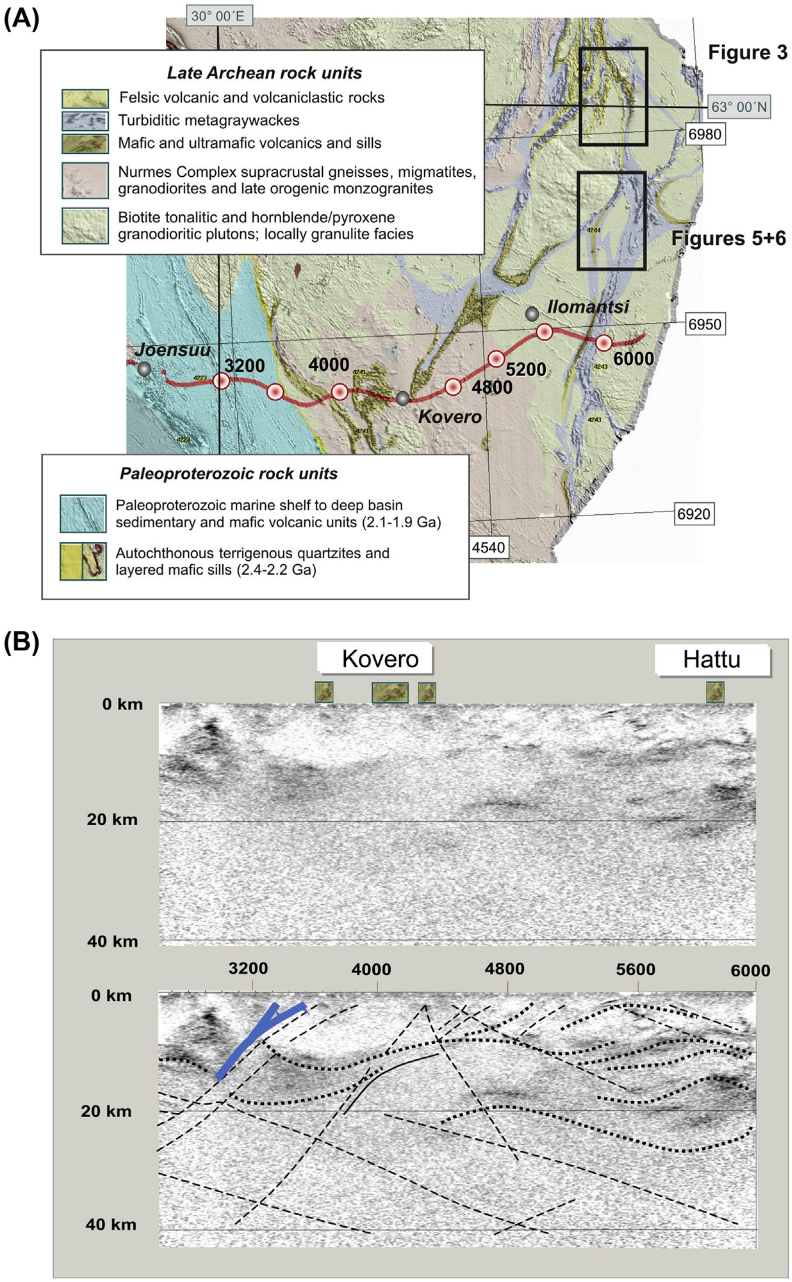


FIGURE 5.3.2 Geological extent and depth expression of the Hattu schist belt.

(A) Simplified regional geology superimposed on total magnetic intensity across the Archean–Proterozoic boundary zone, showing the Hattu schist belt and location of the FIRE 3A seismic profile. Black rectangles indicate location of figures. (B) Crustal seismic reflection profile, to a depth of 40 km, across the area shown in (A), from Sorjonen-Ward (2006). Note prominent subhorizontal reflectivity down to 20 km depth, but surface trace of greenstone belts do not seem to be discernible in the image. West-dipping heavy blue line marks position of Proterozoic boundary.

favorable for orogenic Au mineralization in terms of structural architecture and metamorphic grade (cf. Goldfarb et al., 2001). However, while reconnaissance till geochemical surveys by the Geological Survey of Finland (GTK) indicated anomalous Au, particularly in the southwestern part of the area (Fig. 5.3.4), subsequent studies and outcrop investigations have shown very little evidence for structurally constrained hydrothermal alteration or anomalous concentrations of gold or associated pathfinder elements.

In contrast, the Hattu belt is known to be prospective for gold and has been mapped systematically, such that the overall structural architecture and lithostratigraphic units are well defined, providing a framework for exploration and interpretation of controls on mineralization (Sorjonen-Ward, 1993a,b). The Hattu schist belt supracrustal sequence consists predominantly of felsic pyroclastic and epiclastic deposits with laterally persistent but minor tholeiitic intercalations, and some komatiites in the upper part of the succession. This lithostratigraphical interpretation is considered robust, being well constrained in the area west of the Pampalo Gold Mine (Fig. 5.3.3). Isotopic constraints indicate that the supracrustal rock units were deposited and erupted during a brief time around 2.76–2.75 Ga and was intruded by felsic to intermediate granitoids and porphyries with ages from 2.75–2.72 Ga (Vaasjoki et al. 1993, Sorjonen-Ward and Luukkonen 2005; Huhma et al., 2012).

The greenstone sequence thus represents one of the youngest Archean supracrustal units in the Fennoscandian Shield, and was deformed and metamorphosed simultaneously with and shortly after sediment deposition. Microstructural studies documenting dynamic recrystallization and peak metamorphic assemblages overprinting alteration, in combination with titanite and monazite ages from some granitoids, intersecting concordia at 2.70 Ga, have been used to infer a minimum age constraint on the timing of gold mineralization (Sorjonen-Ward, 1993a; Vaasjoki et al., 1993).

In spite of locally intense and complex deformation, the Hattu schist belt has retained a high degree of stratigraphical coherence, which has enabled formal lithostratigraphic units to be defined. It has also been possible to interpret lateral facies variations as delineating two distinct and partially overlapping felsic volcanic complexes, with associated subvolcanic intrusions, developed within sporadically emergent but generally turbidite-dominated basins (Sorjonen-Ward, 1993a). Tholeiitic basalt flows and a single clastic-textured komatiite unit, exhibiting autoclastic brecciation as well as massive textures, punctuate the stratigraphic sequence and form useful marker horizons, enabling the structural geometry to be further clarified.

An abundance of depositional younging criteria in the metasediments indicate that the major folds in the greenstone belt are upward facing, militating against interpretations invoking large-scale early recumbent folding. No evidence of unconformities or any kind of depositional substrate to the Hattu schist belt has been found, although progradation of the turbidites and volcaniclastic deposits of the Hattu supersequence, over a mafic volcanic substrate, has been deduced, based on lithofacies transitions observed in the easternmost part of the schist belt (Sorjonen-Ward, 1993a).

A full description of lithostratigraphic units and the basis for subdivision is beyond the scope or purpose of this review, but an important key to understanding the geological context and structural controls on gold mineralization derives from mapping and geophysical interpretation of the area west of the Pampalo Gold Mine, summarized earlier in Fig. 5.3.3. Recognition of the regional scale, northerly plunging Pihlajavaara anticline allows an eastward younging stratigraphical series to be defined, from the Sivakkojoki formation in the core of the anticline through the Tiittalanvaara formation to the Pampalo formation, which is the lithological host to the Pampalo ore. The Poikopää formation is lithologically diverse, with abundant epiclastic feldspar-phyric sediments with local evidence for

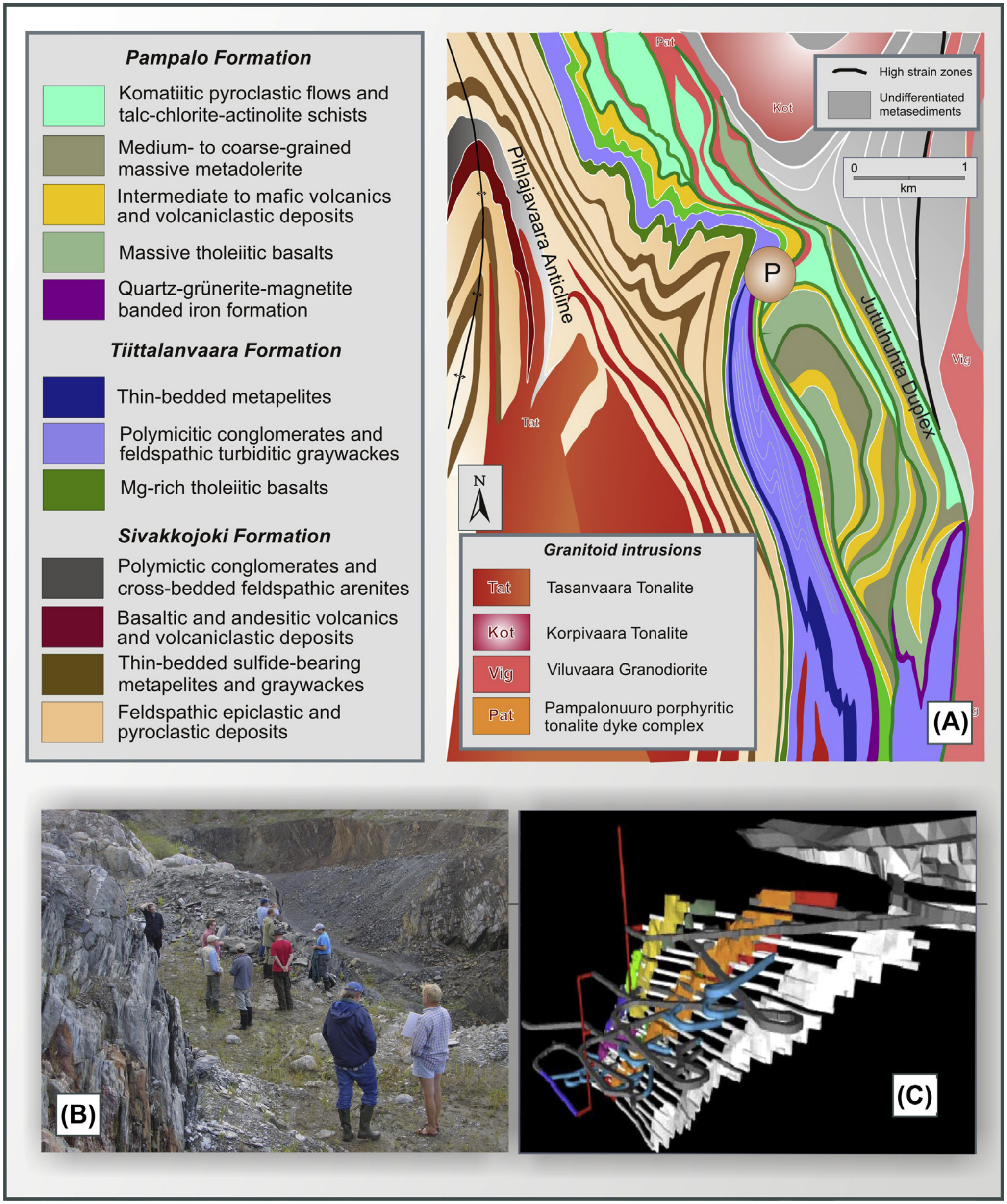


FIGURE 5.3.3 Lithostratigraphic setting of the Pampalo gold deposit.

(A) Simplified geology of the Pampalo zone, indicating the position of the Pampalo ore body at the toe of the Juttuhuhta strike-slip duplex. (B) View southward over open pit prior to construction of processing plant by Endomines Oy. Foreground comprises talc-chlorite schists intruded by porphyritic tonalite dikes; far side of pit consists of metabasalt defining footwall to the main lodes. (C) Northward view of model of the three main north-northeast–plunging ore lodes at Pampalo, showing decline and stopes to a depth of nearly 400 m.

shallow-water reworking, as well as evidence for eruptive deposits, including some basaltic flows. The overall thickness of this sequence, accounting for strain, could exceed several kilometers.

The Tiittalanvaara formation records a transition through coarse-clastic deposits, including well-sorted polymictic conglomerates to finer-grained turbidites, punctuated by coarser debric flows and culminating in banded iron formation, transitional to the overlying basalts, autoclastic komatiites, and felsic to intermediate volcanics of the Pampalo formation. The Pampalo formation appears to record a brief if diverse phase of volcanism, apparently, but not conclusively, overlain by a rather monotonous sequence of metasediments with only sporadic basaltic intercalations (Sorjonen-Ward, 1993a,b).

Published U-Pb zircon ages of the supracrustal rock units range from 2754 ± 6 Ga, for an intermediate hyaloclastic to peperitic unit, at one of the lowest stratigraphic levels, within the Poikopää formation, to 2726 ± 15 Ma for porphyry clasts in a conglomerate higher up in the sequence, within the Tiittalanvaara formation (Vaasjoki et al., 1993). These ages overlap statistically with those for surrounding syntectonic granitoids (2757 ± 4 to 2725 ± 6 Ma) which intrude the belt (Vaasjoki et al., 1993). Although this indicates rapid crustal evolution, there is increasing evidence of heterogeneous and xenocrystic zircon populations, suggesting the presence of an older crustal component in detrital sediments, even if most of the Hattu schist belt sediments represent reworking of penecontemporaneous volcanogenic deposits.

Isotopic data from plutonic zircons also indicate the presence of older crustal material in the source regions of some granitoids, with SIMS zircon studies on the Silvevaara granodiorite and associated porphyritic dike swarms having revealed inheritance from a protolith up to 3.1–3.3 Ga in age (Sorjonen-Ward and Claoué-Long, 1993; Heilimo et al, 2011; Huhma et al., 2012). Anatexis of older continental crust is also evident from some highly evolved, peraluminous granitoids, including tourmaline-muscovite leucogranites, which appear to be analogous to S-type granitoids in Phanerozoic collisional belts (Sorjonen-Ward, 1993a; O'Brien et al., 1993). Titanite and monazite ages with concordia intercepts in the range 2710–2696 are considered to provide a minimum age estimate of crustal metamorphism and reworking (Vaasjoki et al., 1993), which correlates broadly with the widespread deposition of graywackes that were rapidly converted to migmatites and paragneisses throughout the Archean of eastern Finland (Käpyaho et al., 2007; Kontinen et al., 2007).

EXPLORATION TECHNIQUES AND HISTORY

By the late 1970s, airborne and ground geophysical surveys (Airo, 2005) and till geochemical mapping had become well-established and were being routinely used in Finland, in exploration programs managed by both the Geological Survey of Finland and Outokumpu Oy, which at that time was the dominant exploration and mining company operating in the country. Exploration was focused primarily on base metals, particularly nickel, copper, and zinc, which had led to some investigations in the Kovero domain of the Ilomantsi greenstone belt (Kurki, 1980; Hartikainen and Salminen, 1982; Salminen and Hartikainen, 1985; Männikkö et al., 1987). In addition, a comprehensive review of iron ore resources in Finland included a provisional assessment of magnetite in banded iron formations in the Hattu schist belt (Lehto and Niiniskorpi, 1977; Hugg and Heiskanen, 1983).

However, the global resurgence in gold exploration and mining in the early 1980s also awakened a general awareness of the potential for gold discoveries in the Paleoproterozoic and Archean terrane in Finland (Nurmi et al., 1993; Eilu, 2007). Thus, the initial stimulus for gold exploration in the Hattu schist belt was in 1982, when anomalous arsenic values were recognized in till geochemical data, acquired during the GTK regional geochemical mapping program (Hartikainen and Salminen, 1982). Based on the known association between arsenic and gold from studies in Canada, follow-up heavy mineral studies were undertaken in 1983, but concentrates were found to contain scheelite rather than gold. Subsequent comprehensive analysis of till samples revealed coincident anomalies in W and Mo over an area of some 20 km^2, instigating a more detailed sampling survey (16 samples/km^2). Encouraged by the results, several exploration trenches were excavated in the Kuittila area, in the southern part of the Hattu schist belt, during the northern summer of 1984, confirming the presence of scheelite and molybdenite within quartz vein networks in tonalite. Additional sampling and analysis of altered and pyritic quartz veins from the trenches also revealed the presence of anomalous gold, while elevated Au concentrations were simultaneously reported from further regional till surveys (Hartikainen and Damstn, 1991; Salminen and Hartikainen, 1985, 1986).

Therefore, a comprehensive exploration program was established by GTK in 1985, with the twin aims of assessing the gold potential of the Hattu schist belt while systematically evaluating optimal sampling and analytical techniques that might also be applied to exploration elsewhere (Hartikainen and Damstén, 1991). Geochemical mapping was supplemented by bedrock lithogeochemical analysis, from outcrop and drill core, ground geophysical surveys, and detailed outcrop mapping to define structural architecture and the nature of lithostratigraphic units (Fig. 5.3.3). Results of these investigations were subsequently published in the Geological Survey of Finland Special Paper series (Nurmi et al., 1993; Sorjonen-Ward, 1993a,b).

Meanwhile, Outokumpu Oy had also independently become interested in assessing gold potential in Finland and began a comprehensive program of assaying archived sulfide-bearing samples. One such sample, from a solitary, small riverbank exposure in the midst of an extensive swamp, just a couple of kilometers south of the village of Hattuvaara, had originally been submitted by an amateur prospector, Timo Poikonen, in 1970. Upon analysis, this sample was found to contain a remarkable 93 ppm Au and 75 ppm Ag (Pekkarinen, 1988; Ojala et al., 1990). Outokumpu Oy, operating at that time as Outokumpu Finnmines Ltd., therefore commenced exploration in 1985, and excavations around the discovery outcrop and the first analyses across the contact zone between metagraywackes and tourmaline-sericitic altered porphyritic tonalite also yielded an average Au grade of 6.7 ppm. Ground magnetic and electromagnetic surveys assisted in tracing this critical contact zone over a strike length of nearly a kilometer, with subsequent induced polarization surveys being the most useful in delineating areas characterized by disseminated sulfides (Pekkarinen, 1988; Ojala et al., 1990). This occurrence was initially known as Hattuvaara, but was later named Rämepuro, after the stream containing the discovery outcrop.

By 1994, on completion of an additional sampling and drilling survey by GTK in the northern parts of the Hattu schist belt (Heino et al., 1995; Hartikainen and Niskanen, 1995), bedrock mineralization had been confirmed along nearly 40 km of strike length. After submission of GTK technical reports to the then Ministry of Trade and Industry, the subsequent tendering process resulted in the southern part of the belt and the Pampalo concession being granted to Outokumpu Mining Oy, which also still held the Rämepuro lease. The area from Pampalo northward was awarded to the junior company Endomines Oy in 1996. Outokumpu Mining carried out regional exploration further south, as far as Mutalahti near the Russian border, but focused on Pampalo, conducting beneficiation tests and opening a small production pit in 1996, and commencing selective underground mining in 1999. A total of 114,372 tons of ore was transported to Outokumpu Oy's processing facilities at Pyhäsalmi and Vammala, yielding 1755 kg gold at an average grade of 15.3 ppm.

With a major shift in corporate policy, Outokumpu relinquished its exploration and mining activities in the region in 2003, selling its assets to Polar Mining Oy, the Finnish subsidiary of Australia's Dragon

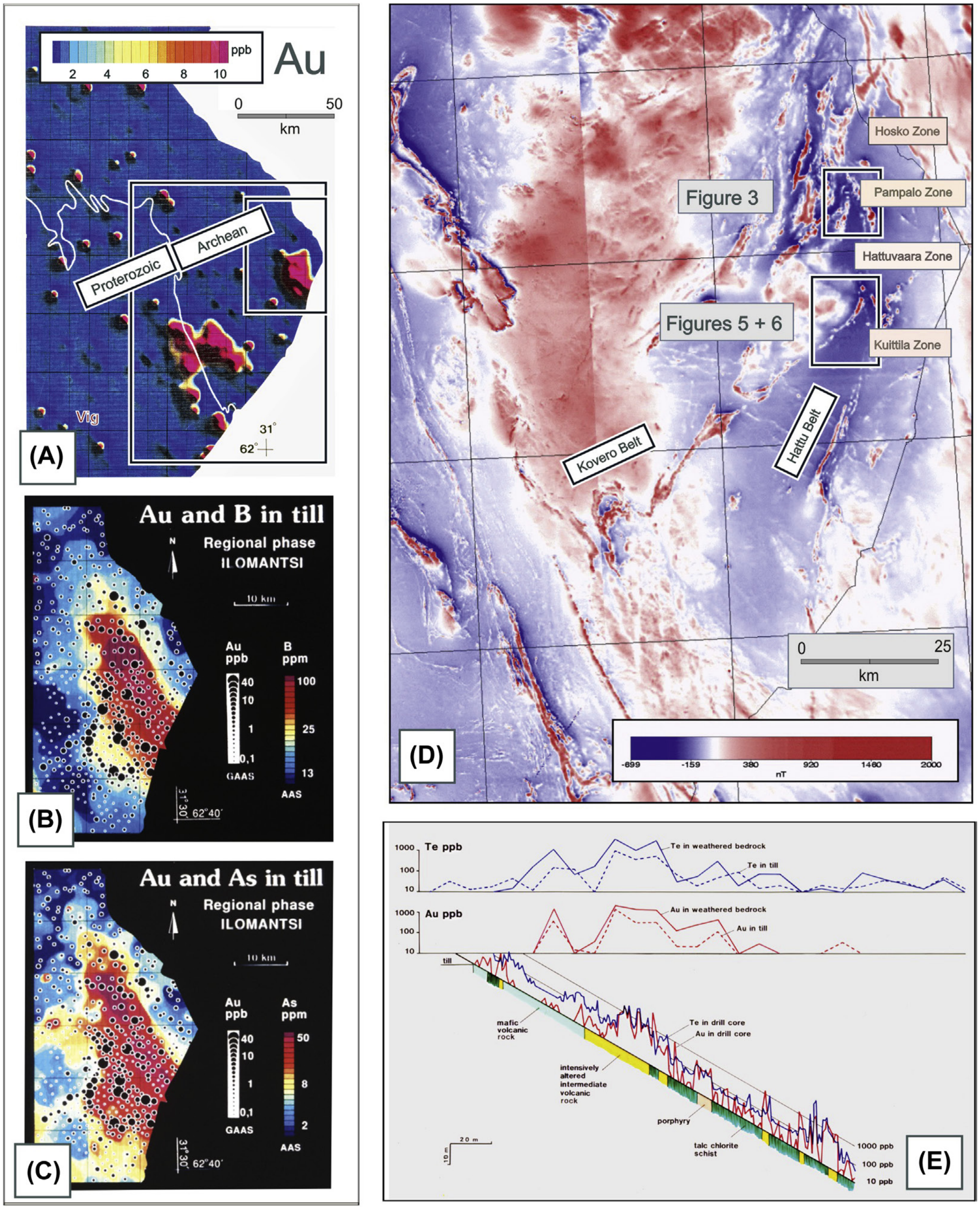


FIGURE 5.3.4 Regional geophysical signatures of rock units in the Hattu schist belt and till geochemical expressions of gold distribution.

(A) Regional survey data (1 sample/4 km^2) shows a distinct anomaly coincident with Hattu schist belt, but also with the Kovero belt, and straddling the Archean–Proterozoic boundary; the latter anomalies are not yet satisfactorily explained. Larger black rectangle indicates area of geophysical image in (D); smaller rectangle shows area illustrated in (B) and (C). (B) Distribution of Au and B in till; compare with (C) which shows Au and As; both As and B defined large anomaly field coincident with that of Au in (A). (D) Total magnetic intensity image of area shown in (A); broad geometry of greenstone belt is evident but correlation between magnetic and regional Au geochemical anomalies is weak, or misleading. (E) Example of close correlation between till anomalies for Te and Au, also demonstrating coincidence with bedrock mineralization and, thus, applicability as a targeting tool in exploration.

Source: *From* Hartikainen and Nurmi (1993).

Mining NL. In October 2006, all of the mining licenses and claims held by Polar Mining, as well as all exploration results from the southern part of Hattu schist belt, together with the Pampalo deposit, were transferred to Endomines Oy. Underground mining commenced at the Pampalo deposit in early 2011, with crushing and flotation processing onsite; at the time of writing, additional ore was being supplied by expansion of the open pit at Pampalo, and the commencement of mining at Rämepuro. Exploration in the near-mine environment and throughout the Hattu belt is continuing, and a list of resource and reserve estimates is summarized in Table 5.3.1.

TILL GEOCHEMISTRY AS AN EXPLORATION AND TARGETING TECHNIQUE

Geochemical surveying by the Geological Survey of Finland was initially undertaken at reconnaissance scale (on average, 1 composite sample/16 km^2) for the Karelian region as a whole, and then regionally over the Hattu schist belt (during 1976, with composite samples comprising 10 successive samples taken at 100-m intervals), and finally in selected areas on a regular grid with a sampling density of 16 samples/km^2. Anomalous areas were then sampled along profiles with a sampling density of 100–400 analyses per km^2. Particular efforts were made to sample the till directly overlying the bedrock interface, on the assumption that dispersion of material over distances greater than several hundred meters would generally lead to dilution below detection limits for gold and critical pathfinder elements. Accordingly, the presence of anomalous metal values in the analyzed <0.06 mm fraction could be inferred to indicate proximity to mineralized bedrock. In most cases, rock chips were also obtained from the bedrock surface and a strong correlation with till analytical data was observed (Fig. 5.3.4(E)).

This approach was used to select and guide drilling targets and proved successful: more than half of the mineralized bedrock occurrences delineated and confirmed during the years 1985–1994 were identified in this way (Nurmi et al., 1993; Heino et al., 1995). The effectiveness of this technique in the Hattu schist belt is also in part due to the Quaternary glacial and postglacial sedimentary history, in that much of the area is covered by a single, relatively thin till sequence, commonly only 5 m in thickness (Nenonen and Huhta, 1993). An average depth to bedrock of about 5 m also facilitated rapid and comprehensive sampling, while reliable analysis and data reduction was ensured by the ability to obtain accurate measurements of elements, down to detection limits of 0.1 ppb for Au and 1 ppb for Te, using a combination of graphite furnace and atomic absorption spectrometry (GAAS), as described by Hartikainen and Nurmi (1993).

It seems remarkable that insights into the nature and distribution of mineralizing processes are discernible in the till geochemical data, in the form of distinct elemental associations of anomaly patterns (Fig. 5.3.3 and later in Fig. 5.3.6). Multivariate statistical analysis of these associations of anomalous elements enabled several factors to be identified that proved useful in target selection and in interpretation and also correlated with pathfinder element associations identified in lithogeochemical data from drill core (Hartikainen and Nurmi, 1993; Rasilainen et al., 1993; Rasilainen, 1996). Together with detailed mineralogical and microprobe analyses (Kojonen et al., 1993), these studies also confirmed a close association between gold and a variable range of trace elements, notably Te, Bi, Ag, As, W, B, and Mo, while altered rocks enclosing mineralization are characterized by additions of volatiles and K, and removal of Na (see Fig. 5.3.7 later).

Fig. 5.3.4(A) shows regional scale data for Au, while Figs. 5.3.4(B) and (C) illustrate the most significant features of regional-scale (1 sample/4 km^2) till geochemical surveys over the Hattu schist

Table 5.3.1 Gold deposits with reserve or resource estimates from the Hattu schist belt

Name	*X*-coordinate	*Y*-coordinate	Class	Tonnage (Mt)	Grade (Au, g/t)	Contained metal (Au, t)	Reference
Hosko	710900	7001000	Proven reserves	0.048	7.9	0.380	Heino et al., (1995); Parkkinen (2003); Geoconsulting Parkkinen cited in Endomines Oy Ab (2014)
Hosko	710900	7001000	Probable reserves	0.049	5.5	0.271	Heino et al., (1995); Parkkinen (2003); Geoconsulting Parkkinen cited in Endomines Oy Ab (2014)
Hosko	710900	7001000	Indicated resources	0.604	1.5	1.160	Heino et al., (1995); Parkkinen (2001, 2003); Geoconsulting Parkkinen cited in Endomines Oy Ab (2014)
Hosko	710900	7001000	Inferred resources	0.153	1.4	0.220	Heino et al., (1995); Parkkinen (2003); Geoconsulting Parkkinen cited in Endomines Oy Ab (2014)
Pampalo	715900	6991250	Stockpile	0.006	2.1	0.013	Geoconsulting Parkkinen cited in Endomines Oy Ab (2014)
Pampalo	715900	6991250	Proven reserves	0.230	3.0	0.690	Geoconsulting Parkkinen cited in Endomines Oy Ab AB (2014)
Pampalo	715900	6991250	Probable reserves	0.108	2.4	0.260	Geoconsulting Parkkinen cited in Endomines Oy Ab AB (2014)
Pampalo	715900	6991250	Pillars	0.021	2.0	0.043	Geoconsulting Parkkinen cited in Endomines Oy Ab AB (2014)
Pampalo	715900	6991250	Inferred resources	0.634	2.0	1.249	Geoconsulting Parkkinen in Endomines Oy Ab AB (2014)
Pampalo East	716150	6991200	Probable reserves	0.140	1.3	0.181	JV Kaivossuunnittelu Oy (2012) cited in Endomines Oy Ab (2014)
Pampalo East	716150	6991200	Inferred resources	0.195	1.2	0.234	Outotec (2012) cited in Endomines Oy Ab (2014)
Rämepuro	716700	6981200	Probable reserves	0.169	2.1	0.358	Pekkarinen (1988); Geoconsulting Parkkinen cited in Endomines Oy Ab (2014)
Rämepuro	716700	6981200	Inferred resources	0.136	2.3	0.309	Pekkarinen (1988); Geoconsulting Parkkinen cited in Endomines Oy Ab (2014)

Source: *Compiled from published reports and press releases by Endomines Oy.*

belt; visual comparison reveals that at this scale, arsenic and boron anomalies are more or less congruent, and a positive correlation between them is evident, irrespective of whether they are genetically related or of independent origin. Similar patterns are evident in Fig. 5.3.7 from which it may be deduced that enrichments in some elements, for example Bi and As, do not spatially correlate with anomalies in Mo and W. Tungsten anomalies are somewhat independent from gold, apart from the discrete anomaly in the Kuittila area in the southeastern part of the images. Moreover, although scheelite is abundant and closely associated with gold at the Pampalo mine, this association is not seen in the regional sampling data. This high degree of correlation was also observed in detailed studies and is also reflected in the abundance of tourmaline veins and disseminations in altered and mineralized bedrock outcrops. Tellurium was found to be a very reliable proxy for gold (Figs. 5.3.3(E) and 5.3.6(A)) because background concentrations are somewhat higher, while telluride phases typically occur as fine-grained minerals and alloys, intimately associated with gold. In contrast, gold may be present as isolated large grains that, through the so-called nugget effect, can skew and obscure interpretation of data. It was also noted that Te was sometimes highly abundant in sulfide-bearing zones that lacked evidence of anomalous Au; such zones were also easily discriminated on the basis of elevated chalcophile element concentrations.

The principal element associations identified in multivariate analysis of till and bedrock data (Hartikainen and Nurmi, 1993; Rasilainen et al., 1993) proved relevant both as pathfinders in exploration and in considering mineralizing processes. Factor analyses of chemical data from till and gold occurrences were found to be characterized by several distinct element enrichment assemblages, notably Au-Te-Bi-Ag, Mo-W-CO_2, and Cu-S. The Mo-W-CO_2 assemblage is typically allied to vein networks in Kuittila suite plutons, predating the main stage of mineralization, but other enrichment associations are more independent of host rock lithology (cf. Fig. 5.3.7). Prominent regional As and B anomalies are evident, but this correlation often breaks down at deposit scale, and while tourmaline is usually present, gold is mostly as tellurides or free grains between silicates or within pyrite; a notable exception to this is the turbidite-hosted Hosko prospect where arsenopyrite is closely associated with gold.

DESCRIPTIVE CHARACTERISTICS OF MINERAL DEPOSITS

Bedrock drilling, mostly on the basis of till geochemical anomalies (Hartikainen and Nurmi, 1993; Nurmi et al., 1993), has confirmed the presence of gold in almost all rock types, indicating that mechanical and compositional contrasts within and between rock units have been influential in localizing fluid-rock interaction and mineralization. Hydrothermal alteration occurs within well-defined domains but differs in some respects from typical Archean orogenic Au deposits in that there is evidence for superimposition on early, perhaps volcanic-related alteration (Rasilainen et al., 1993; Sorjonen-Ward, 1993a; Rasilainen, 1996). This is particularly evident in the northernmost part of the belt, where extensive potassic alteration has affected turbiditic sediments and volcaniclastic deposits, as well as some granitic rocks interpreted as subvolcanic intrusions. At present there is no conclusive evidence that gold would have been introduced by synvolcanic epithermal or porphyry-type mineralizing events, since early sericite-microcline alteration assemblages appear to have been deformed and foliated prior to vein-hosted gold mineralization and associated alteration.

Another distinctive feature of gold mineralization in the Hattu schist belt is the abundance of scheelite and molybdenite, tourmaline, and numerous minerals containing bismuth and tellurium

(Kojonen et al., 1993), particularly within and proximal to mineralization in granitoids. This is suggestive of the possible involvement of synorogenic magmatic fluids, consistent with, but not proven by, the results of isotopic studies (Vaasjoki et al., 1993; Stein et al., 1998; Molnar et al., 2013), and is reminiscent of the class of intrusive-hosted gold deposits. On the other hand, combined paragenetic and structural studies of mineralized veins within the Kuittila tonalite indicate that auriferous shear zones and veins, with characteristic sericite-biotite-carbonate alteration, were superimposed on an earlier set of veins containing molybdenite and scheelite (Nurmi et al., 1993; Sorjonen-Ward, 1993a).

A further connection with a specific association of granitoids is also intriguing and might indicate a larger-scale geodynamic link between orogenic processes and gold mineralization. Granitoids intruding and surrounding the Hattu schist belt fall into distinct categories on the basis of field relationships and composition, with ages from 2757 ± 4–2725 ± 6 Ma (Vaasjoki et al., 1993). The Kuittila suite forms a distinct group of small, elongate plutons aligned within the structural trend of the schist belt and which appear to have been constructed by coalescing steeply dipping *en echelon* sheets intruded during highly partitioned transpressive deformation. Compositions range from biotite tonalite to trondhjemite; hornblende is absent and inclusions are very rare, while associated plagioclase-phyric porphyry dikes indicate that differences in chemistry result in progressive fractionation with retention of plagioclase earlier and deeper.

U-Pb zircon studies, Sm–Nd model ages, and Re–Os studies on molybdenite indicate a short crustal residence time for the protoliths to these rocks. Recent and more detailed studies of the petrogenesis of these plutons reveal a sanukitoid affinity and show that they are characteristic of the earliest stages of convergent deformation in the Karelian craton, between 2.74 and 2.71 Ga in age, potentially representing hybridization of magmas derived from mantle affected by subduction-derived fluids (Halla, 2005; Lobach-Zhuchenko et al., 2005; Heilimo et al., 2010). While a spatial association between these types of intrusions and the prospective terrane in the Ilomantsi complex is discernible, it is not yet clear whether they have general potential as regional exploration indicators. The fact that the Ilomantsi sanukitoids appear to have intrusive ages some 10–20 Ma older than similar rocks in the eastern part of the Karelian craton has been considered puzzling and anomalous, and therefore of interest with regard to the coupling of geodynamic processes and gold potential. However, until the precise timing of mineralization is established, either closer to 2740 Ma and the emplacement of the Kuittila suite of sanukitoids, or later, more related to the 2700 crustal reworking and migmatization event, the potential significance of this remains purely speculative.

The issue of timing is also inherently more problematic in the Hattu schist belt for two reasons. First, the evidence of porphyroblast growth and dynamic recrystallization of altered and mineralized assemblages indicated that the thermal metamorphic peak postdated gold mineralization, which was inferred as late Archean, on the basis of cooling ages from monazite and titanite in several granitoids intruding the Hattu schist belt (Vaasjoki et al., 1993). This inference was at variance with the postpeak timing generally advocated for gold mineralization in the Yilgarn craton at that time, although recognition of synmetamorphic mineralization in amphibolites facies domains was emerging, ultimately leading to the metamorphic continuum model (Groves, 1993). Moreover, a Paleoproterozoic thermal event, albeit with low strain, was clearly superimposed on the Hattu schist belt; resetting of Archean biotite, or growth of new biotite at around 1800 Ma is recorded in K–Ar data (Kontinen et al., 1992), while Rb–Sr and O data from tourmaline, quartz, and mica in mineralized zones also show the effects of Proterozoic disturbance (O'Brien et al., 1993).

Halla and Heilimo (2009) further demonstrated regional-scale Paleoproterozoic Pb isotopic disturbance in K-feldspar phenocrysts in granitoids, including those adjacent to the Hattu schist belt. Moreover, the proximity to metamorphosed and deformed Proterozoic quartzites that unconformably overlie Archean basement, some 50 km to the west and 30 km to the east of the Hattu schist belt, as well as the recrystallization of mineral assemblages in Paleoproterozoic mafic dikes, demonstrates that temperatures had attained greenschist facies conditions between 1.9 and 1.8 Ga, as a consequence of Svecofennian orogenic deformation. However, the lack of significant deformatione of Paleoproterozoic mafic dikes, being restricted to brittle-ductile strain at the dike margins, combined with microstructural studies of recrystallization, provides strong evidence against significant remobilization or introduction of gold during Paleoproterozoic time (Sorjonen-Ward, 1993a).

DESCRIPTIONS OF INDIVIDUAL GOLD OCCURRENCES

Based on distribution of mineralization and anomalies, and geological and structural features, it has proven useful to consider the Hattu schist belt in terms of four distinct mineralized segments or anomalous zones, each of which contains one or more gold deposits (where estimates of resources or reserves have been attempted) or occurrences (where drilling or outcrop sampling has identified the presence of anomalous gold). From south to north these are, respectively, the Kuittila, Hattuvaara, Pampalo, and Hosko anomaly zones (Figs. 5.3.2 and 5.3.8 later). Detailed descriptions of structural architecture of these zones and the structural setting and alteration, mineralogy, and of gold occurrences are reported in Sorjonen-Ward (1993a) and Nurmi et al. (1993). Table 5.3.1 summarizes the gold occurrences and deposits at the time of writing. The following summaries are intended to provide an overview and background for considering the overall structural controls on mineralization and the application of numerical modeling to exploration targeting.

KUITTILA ZONE

The Kuittila zone is centered on and surrounds the small, elongate pluton known as the Kuittila tonalite (Figs. 5.3.4 and 5.3.5). It was named after the location of the first exploration trenches where exposed quartz-vein networks and sericitic and carbonated shear zones containing pyrite and gold (in addition to scheelite and molybdenite) were found. Till geochemical studies subsequently indicated the presence of anomalous gold with metasedimentary rocks along the western margin of the Kuittila tonalite, but not along the eastern side, which might have been expected if gold were exclusively sourced from the tonalite itself (Figs. 5.3.4(A) and 5.3.6). However, the eastern margin of the tonalite intrusion is poorly exposed, and while no evidence for alteration has been found in outcrop, it has not yet been rigorously assessed by till geochemical or geophysical surveying. Despite this lack of information, there are still several geological features that suggest that mineralization may be asymmetrically distributed, preferentially along the western margin. The Kuittila zone is readily delineated on the basis of till geochemical anomalies (Figs. 5.3.3(A) and 5.3.6), in particular those due to Au, Te, Na, and loss of ignition, the last two reflecting the intensity of hydrothermal processes in the metasedimentary country rocks (Hartikainen and Nurmi, 1993).

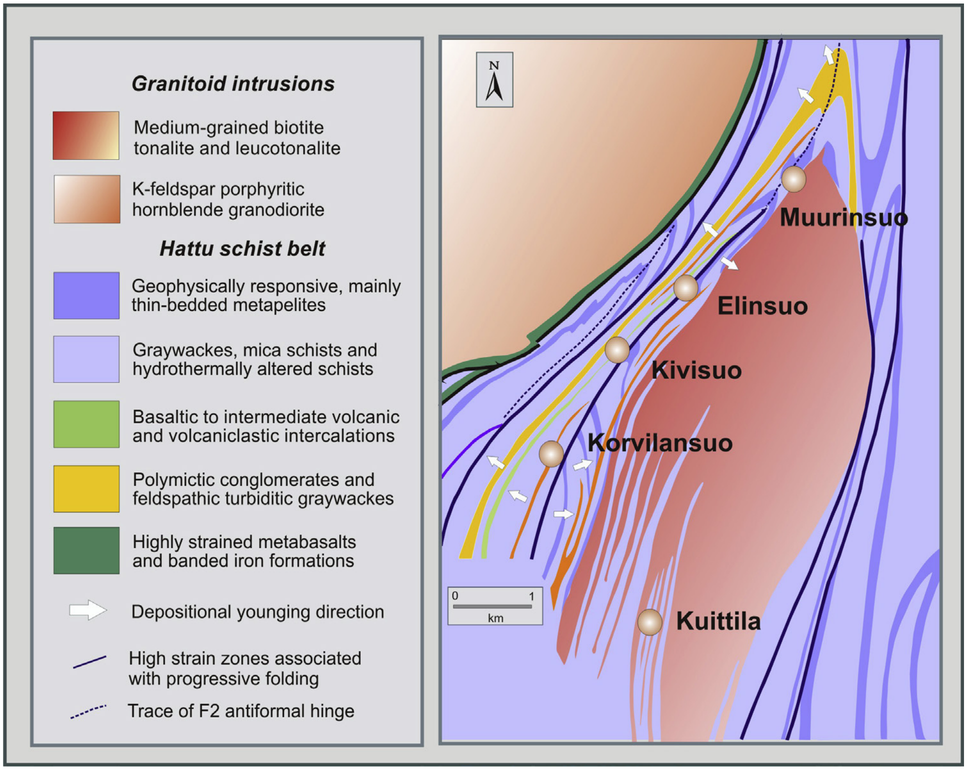


FIGURE 5.3.5 Essential geological features of the Kuittila zone, showing location of gold occurrences several hundred meters from the contact with the Kuittila tonalite.

Note alternation of screens of metasediment and tonalitic dikes between Kuittila and Korvilansuo, constrained by outcrop mapping, drill core, and till–bedrock interface sampling. Note also oblique transaction of fold hinges along the western margin of Kuittila tonalite between Korvilansuo and Muurinsuo, from which close interaction between emplacement and deformation is deduced.

Detailed ground geophysical surveys cover the entire Kuittila zone but gold mineralization is not directly evident, neither can the metasediments and tonalite be distinguished from one another geophysically (Figs. 5.3.5, 5.3.6), except to a limited extent in the induced polarization (IP) survey data. This is because the Kuittila tonalite is a weakly magnetic ilmenite-series granitoid, and the low abundances of sulfides and oxide minerals result in generally weak IP responses, whereas fine-grained pyrrhotite disseminations in mica schists commonly generate distinct IP anomalies.

Mineralization in metasedimentary rocks in the Kuittila zone

The Kuittila zone was further subdivided by Nurmi et al. (1993) into a southerly subzone, where the contact with the Kuittila tonalite and foliation and lithic layering in metasediments trends almost north–south, and a northern subzone, where the contact is northeast-trending (Figs. 5.3.4(B) and 5.3.5). The southern subzone contains the Kuittila deposit, which is the only example of gold

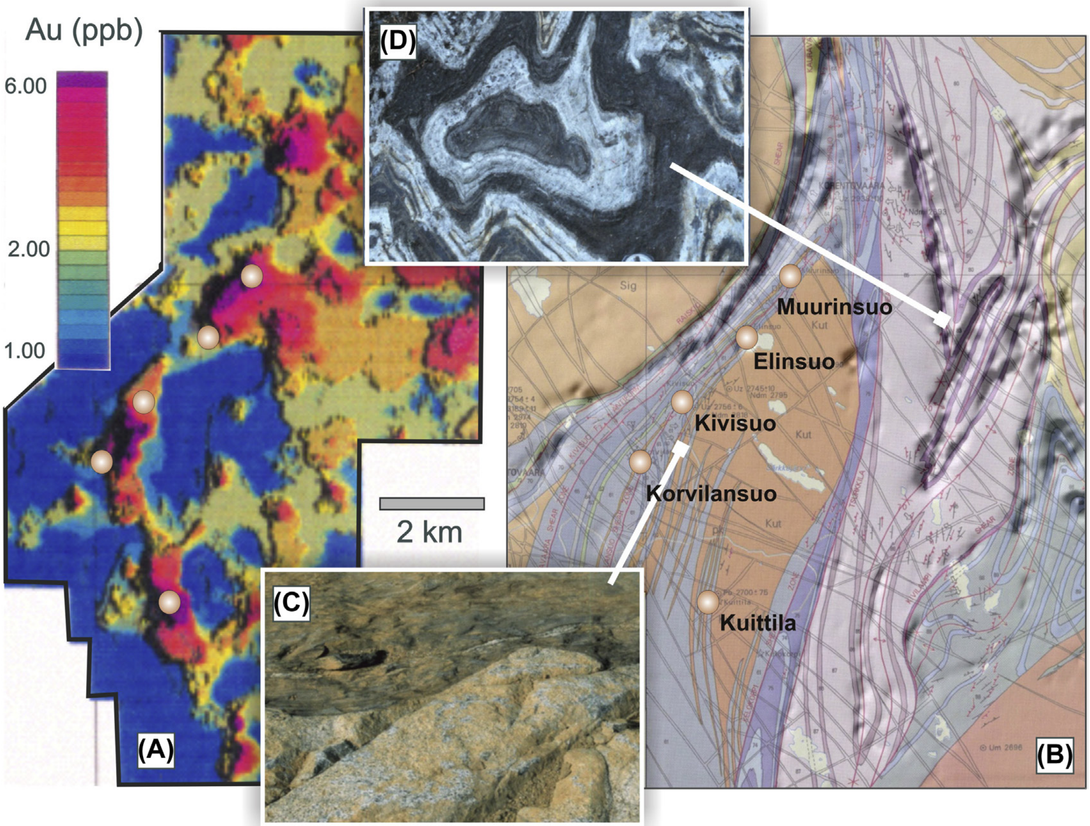


FIGURE 5.3.6 Geochemical anomalies and Kuittila zone geology.

Gold occurrences and deposits are indicated by golden dots. (A) Gold concentrations in till at detailed sampling scale, from Hartiakinen and Nurmi (1993). Compare the distribution of the most intense Au anomalies, which define an arcuate zone surrounding the Kuittila tonalite, with the geological map in (B). (C) Ductile strain at contact of Kuittila tonalite and metasediments; no indication of alteration or mineralization at the contact. Note also the lack of magnetic anomalies along the western margin of the Kuittila tonalite. (D) Refold interference pattern in banded iron formation resembles map of Australia. Note correlation with prominent magnetic anomalies in (B).

mineralization known within the main body of the pluton, and the Kelokorpi occurrence, which comprises diverse rock types dominated by mica schists and metagraywackes variably altered to sericite- or biotite-dominated schists and intercalated with sporadic greenish chloritic schists and strongly recrystallized porphyritic tonalite dykes. Tourmaline is abundant in mineralized zones, which are characterized by weak, yet pervasive, sulfide disseminations containing pyrrhotite, sphalerite, and chalcopyrite. Additional phases include arsenopyrite, molybdenite, tellurides and argentopentlandite, and rare native gold (Kojonen et al., 1993).

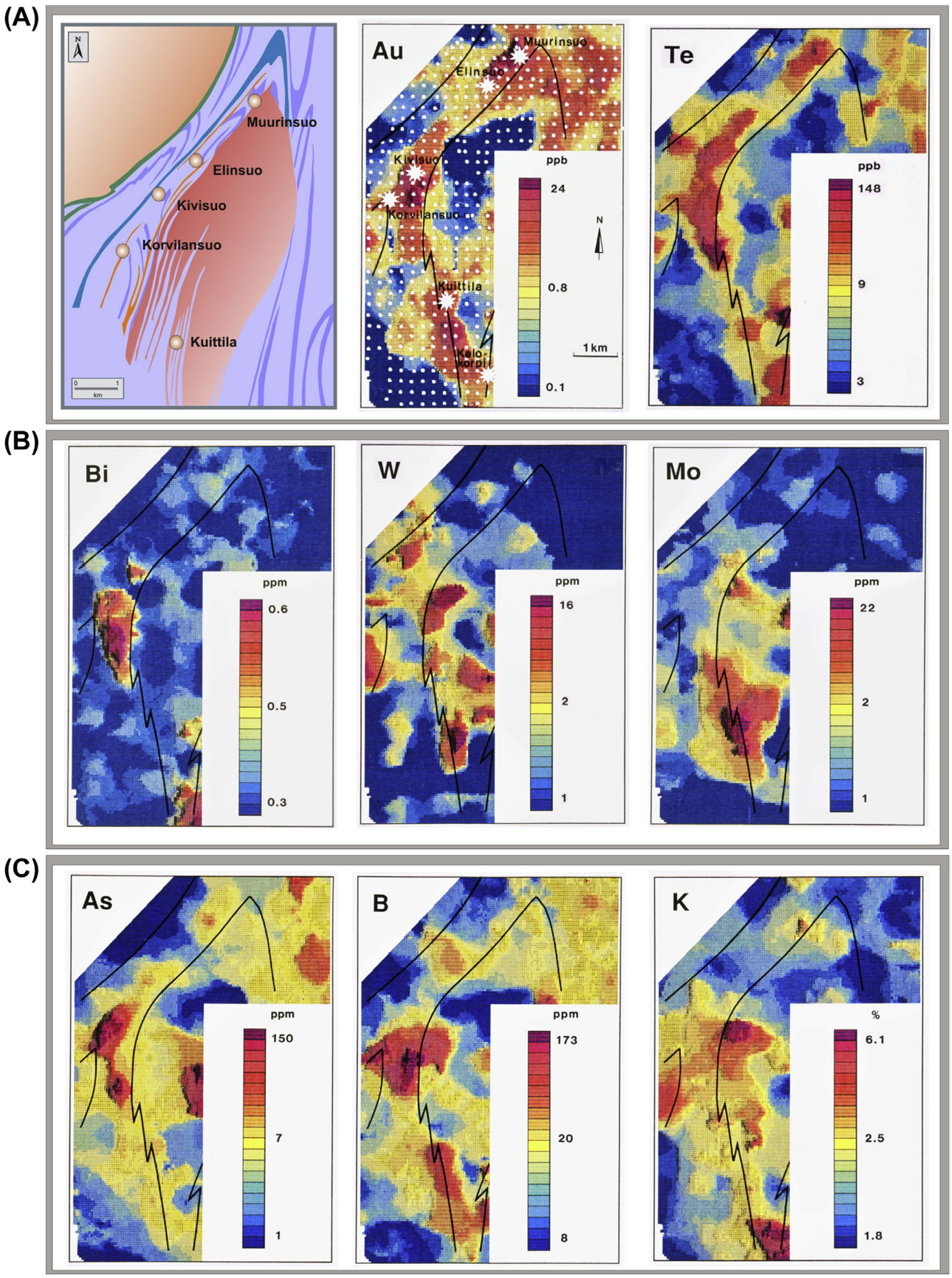


FIGURE 5.3.7 Till geochemical maps for selected elements in the Kuittila zone.

(A) Simplified geology surrounding the Kuittila tonalite, Au distribution and sampling grid, and Te anomalies, which correspond closely with Au. (B) The congruence of Mo and W anomalies and their location within the Kuittila tonalite, contrasting with the Bi anomaly centered on the Korvilansuo area outside the pluton; this not only indicates the precision of till anomalies with respect to bedrock mineralization but is also consistent with the existence of independent enrichment processes for Bi and Mo. (C) The similarity between As and Bi in (B), the intensity of tourmaline in the Korvilansuo area, and the possibility that K alteration in the margin of the Kuittila tonalite was associated with Mo and W enrichment.

Source: *From Hartikainen and Nurmi (1993).*

The Kelokorpi occurrence is, thus, similar in character to the mineralization found within the northern subzone, which specifically includes the Korvilansuo, Kivisuo, and Muurinsuo deposits, and the Elinsuo occurrence, which may be contiguous with Muurinsuo. These were discovered, drilled, and documented during the GTK research program (Nurmi et al., 1993) but Korvilansuo and Muurinsuo have been drilled more recently since acquisition by Endomines Oy, with further clarification of mineral resources and some preliminary reserve estimates (see Table 5.3.1).

The prospectivity of the Korvilansuo and Kivisuo areas was apparent after the earliest detailed till geochemical surveys (Hartikainen and Nurmi, 1993) and confirmed when arsenopyrite-bearing bedrock samples assaying 4–8 ppm Au were recovered from an exploration pit excavated over a conspicuous anomaly at Kivisuo. Shallow drilling was also undertaken along several east–west traverses across the schist belt. Mineralized lithologies consisted mostly of sheared, silicified, and partly tourmalinized porphyry dikes and tourmaline-bearing mica schists showing chlorite-sericite alteration. Despite alteration, poor exposure, and locally high strain (Figs. 5.3.5(B) and (C)), primary depositional grading has been recognized in some graywacke units, in outcrop and in drill core. In combination with foliation-lithology, asymmetry and truncations of geophysical anomalies have enabled the structural architecture to be defined with some degree of confidence. The mineralized zone coincides with an area where foliation and lithic layering dips are less steep than in most of the Hattu schist belt, between 55 and 70°, and fold axes plunge moderately northward throughout the zone. Several antiformal and synformal pairs have been delineated, truncated by, or transposed into oblique high-strain zones that are discernible through excision of lithostratigraphic marker horizons (Fig. 5.3.6). Sorjonen-Ward (1993a) interpreted this geometry in relation to emplacement of the Kuittila tonalite during progressive deformation.

A distinctive feature at Korvilansuo is the presence of tonalitic dikes that show intensive silicification and replacement by tourmaline, while highly strained, locally ultramylonitic metasediments can contain gold either as sporadic disseminations or within tourmaline-quartz vein arrays assaying up to 10–15 ppm Au. It is likely that tourmaline was introduced in two stages, the first being related to alteration of the tonalite, while the later stage involved vein-type alteration associated with gold deposition. Korvilansuo exemplifies the distinctive ore mineral parageneses of the Hattu schist belt; sulfides include pyrrhotite, chalcopyrite, and pyrite with minor arsenopyrite, galena, and sphalerite, while fine-grained native gold is commonly associated with Au-Ag-Bi-Pb tellurides and native bismuth.

The metasediments at Kivisuo and Korvilansuo commonly contain sericitic pseudomorphs after andalusite porphyroblasts and microstructural studies indicate that they overprint early foliation and, in some places, sulfide minerals, suggesting that dynamic recrystallization under peak metamorphic conditions postdated hydrothermal alteration. Kyanite has also been observed and may indicate that mineral assemblage has in fact recrystallized later, in response to the Paleoproterozoic thermal event, as discussed earlier.

Mineralization at Muurinsuo and Elinsuo was initially revealed by prominent anomalies in Au and Te and less distinct As, loss on ignition (LOI), and negative Na anomalies, which led to delineation of a continuous northeast-trending anomaly zone within the schist belt, located about 200 m from the northwestern contact of the Kuittila tonalite (Figs. 5.3.5 and 5.3.6). As at Kivisuo and Korvilansuo, the host rocks are intensely foliated mica schists with graywacke and mafic tuffitic interbeds, invariably altered to sericite and sericite-chlorite schists. Pyritic dissemination is typical in quartz-and plagioclase-phyric tonalitic porphyry dikes, which are abundant, particularly in the southwestern part of the deposit. The mineralization is situated near the hinge zone of the Muurinsuo F2 antiform (Fig. 5.3.6), but the discontinuous nature of mineralization, at least with the presently available drilling density, favours interpretation as a number of separate lenses that could well be elongated parallel to the dominant shape fabric lineation, which in this region plunges at 60–70 degrees towards the north-northeast. Mineralization is disseminated and invariably hosted by altered mica schists, mafic volcanics, and porphyry dikes. Gold again occurs in association with Bi, Au, and Ag tellurides, with minor arsenopyrite, chalcopyrite, pentlandite, and galena (Kojonen et al., 1993).

Mineralization in the Kuittila tonalite

The Kuittila tonalite is typically medium-grained and equigranular, with randomly oriented subhedral plagioclase grains and oriented aggregates of fine-grained biotite; hornblende is absent and K-feldspar is uncommon. Mafic enclaves are sporadically present, with irregular shapes attesting to low strain during crystallization, consistent with interpretations from quartz vein networks. Alteration of the tonalite does not invariably correlate with increasing strain intensity, although the most highly mineralized zones are intensely sericitized, with complete destruction of plagioclase and biotite, and intensely deformed. In drill core, it is evident that the tonalite commonly has a sheared and bleached appearance over distances of several meters around the quartz lodes, reflected in a mineral assemblage containing quartz, albite, sericite, calcite, K-feldspar, biotite, and epidote; where alteration is most intense, quartz, sericite, and carbonate dominate. This visible alteration correlates with a lithogeochemical anomaly surrounding the deposit, with distinct enrichments in Mo, W, CO_2, Cu, S, Rb, K, and Si and loss on ignition, indicative hydration, carbonation, and potassic alteration; conversely, Na and Sr are depleted in comparison with unmineralized parts of the pluton (Nurmi et al., 1993). Native gold occurs principally as inclusions or intergrowths with pyrite in association with sporadic tellurides (Kojonen et al., 1993).

The overall form of the Kuittila tonalite is an asymmetric lenticular, elongate pluton with dips of about 60°E to the west, below the schist belt, on its western margin, whereas the eastern contact is evidently subvertical. The pluton is compositionally zoned, with a distinctly more leucocratic trondhjemitic central phase, compared to the generally medium-grained biotite tonalite comprising the bulk of the pluton. The western margin is also characterized by porphyritic dikes with euhedral plagioclase and in places, quartz phenocrysts. Although mutual intrusive relationships between the porphyry dikes and the main tonalite phase have not been demonstrated in outcrop, nor in drill core. They are however, very similar chemically, with a notable exception being positive Eu-anomalies in dikes contrasting with the negative anomaly in the main tonalite intrusion (O'Brien et al., 1993), which may be attributed to the abundance and retention, or accumulation of, plagioclase phenocrysts in the dikes.

Drilling within and adjacent to the southwestern margin of the pluton, between the Korvilansuo and Kuittila deposits, revealed alternating screens of metasediments between tonalitic dikes (Figs. 5.3.4(B) and 5.3.5). Together with structural interpretations of folding and shearing in the country rocks, this permits an interpretation for construction of the Kuittila tonalite by successive emplacement and coalescence of dikes during progressive deformation. A plausible scenario for explaining the present geometry is that the intrusion represents a releasing bend within an extensive north–south trending deformation zone. Observations of quartz vein networks at several locations within the pluton are of relatively uniform orientation and, though recrystallized, are not highly strained, implying that the present pluton shape is original, and not a product of post-emplacement shearing (Sorjonen-Ward, 1993a).

Following the discovery of mineralization in the metasediments that structurally overlie the steep, westward-dipping tonalite contact, it was also natural to consider whether the mineralization could have been associated with magmatic to hydrothermal fluid infiltration in the hanging wall of the cooling pluton. Alternatively, the mechanical contrast between the pluton and the country rock could have induced strain partitioning, with gold mineralization occurring in brittle-ductile fault meshes in the more homogenous tonalite, contrasting with pervasive alteration along shear zones in the more anisotropic sediments. The role of plutons as mechanically rigid bodies that locally influence rock permeability and fluid flow, rather than primary sources of heat and metals, has been controversial and continues to be debated for many orogenic gold systems (Goldfarb et al., 2001).

Three groups of observations favor the former interpretation in the case of the Kuittila tonalite. First, structural relationships with respect to folding in the country rocks favor emplacement in the ductile regime under greenschist to amphibolites facies conditions, rather than at high crustal levels in which a porphyry or epithermal magmatic to hydrothermal regime could have been established. Second, at the Kuittila deposit, the alteration and deformation zones associated with gold mineralization characterized by intense veining, silicification, and sericitization have been superimposed upon northwest to west-northwest trending subvertical quartz vein networks containing molybdenum and scheelite; this indicates that gold was introduced in zones of structurally enhanced permeability after solidification of the pluton. This suggests that after cooling sufficiently to deform by brittle failure, the pluton was subjected to only small amounts of regionally homogenous strain.

Microstructural observations of recrystallization within and at the margins of molybdenite-scheelite-bearing quartz veins also indicate that penetrative foliation developed in the tonalite after, if not during, vein development (Sorjonen-Ward, 1993a). Third, while the zones of pervasive alteration and mineralization associated with the Korvilansuo, Kivisuo, and Muurinsuo deposits trend subparallel to the margin with the Kuittila tonalite, they are nevertheless located several hundred meters from the contact; if the regional permeability structure had been conducive to the pluton generating convective cells with discharge and infiltration zones, more evidence of alteration immediately adjacent to, and within the margin of, the pluton would surely be expected.

While it is plausible that the same structural zones that facilitated emplacement of the Kuittila tonalite were active in transferring and circulating hydrothermal fluids, the role of the pluton as a thermal driver can further be disputed by considering that if it were emplaced into country rocks at greenschist facies conditions, then the thermal gradient generated across the contact would have been rather modest, and even more so if the emplacement occurred in the form of successive sheet-like bodies.

HATTUVAARA ZONE

The Hattuvaara zone is simply defined as the predominantly north-trending segment of the schist belt, passing through the village of Hattuvaara, from the northern end of the Kuittila zone to the Pampalo zone (refer to Figs. 5.3.2 and 5.3.8 later). The schist belt in this area is in places less than a kilometer in width, and consists of highly strained and tightly folded epiclastic metagraywackes, although north of Hattuvaara, there is a transition to mafic rock units of the Pampalo formation, exposed in the core of a tight northerly plunging F2 synform (Sorjonen-Ward, 1993a,b). Southward of Hattuvaara, in the vicinity of the Rämepuro deposit, it appears that the limbs of the synform are attenuated and transposed, perhaps accompanied by major shear displacement. Apart from several till anomalies and isolated mineralized glacial boulders found along the zone (Nurmi et al., 1993), Rämepuro is the only known gold deposit; following extensive evaluation and feasibility tests and environmental permitting, mining commenced at Rämepuro in 2014.

As described earlier, the discovery of Rämepuro was due to analysis—after a delay of more than a decade—of a chalcopyrite-bearing sample collected by a local prospector in 1970. When Outokumpu Finnmines Oy commenced geophysical surveys and a drilling program was initiated in 1985, a small exploration pit excavated around the discovery outcrop revealed a shear zone some 10-m wide at the boundary between a porphyritic tonalite dike and metasediments, which assayed about 7 ppm Au. In contrast to mineralization within the Kuittila zone, it was found that the mineralized shear zone at Rämepuro generated a distinct IP anomaly, 20–30 m in width and several hundreds of meters in length. Conversely, Rämepuro is one of the few gold occurrences in the Hattu schist belt that is not associated with significant till anomaly patterns on geochemical maps, even at a sampling density of 16 samples/km^2 (Hartikainen and Nurmi, 1993; Hartikainen and Niskanen, 2001). This is perhaps surprising as drilling by Outokumpu during the 1985–1987 campaign (Pekkarinen, 1988) and more recently by Endomines Oy Ab (2014) confirms that the bedrock surface is mineralized along strike over a distance of at least 500 m.

The Rämepuro deposit is located at the boundary between two different supracrustal rock units, where a porphyritic tonalite dike up to 30 m in thickness has intruded along the contact. The sequence to the west of the dike consists predominantly of well-preserved graywackes with some polymictic conglomeratic intercalations (Endomines Oy Ab, 2014; Ojala et al., 1990; Pekkarinen, 1988; Sorjonen-Ward, 1993a). On the eastern side of the dike, more homogenous, fine-grained intermediate biotite-plagioclase-quartz schists prevail, with local banded iron formation horizons; protoliths may have been of intermediate pyroclastic origin (Ojala et al., 1990) but their affinities with rocks elsewhere in the schist belt are unclear.

Gold at Rämepuro is typically found with dynamically recrystallized and strained quartz-tourmaline-sulfide veins within the intensely deformed tonalite dike and adjacent metagraywackes, indicating that mineralization accompanied, or more probably post-dated, dike emplacement. Silicate alteration assemblages comprise quartz, sericite, biotite, albite, chlorite, and tourmaline. Native gold is fine-grained, occurs interstitially between quartz and tourmaline grains and intergrown with pyrite and pyrrhotite, and shows a broad spatial correlation with chalcopyrite and sphalerite; metallic bismuth and hedleyite are also characteristic (Kojonen et al., 1993).

PAMPALO ZONE

The Pampalo zone has more of a northwesterly trend than the Hattuvaara zone to the south and Hosko zone to the north and northeast (Figs. 5.3.2 and 5.3.7); this change in structural geometry between the Pampalo and Hosko zones is attributed to strain partitioning and accommodation of deformation within a shear system, which has had a complex history. Geometrically, however, the system is relatively simple, if viewed essentially as a progressively evolving regional-scale antiformal and synformal fold pair subjected to oblique sinistral transpression (Sorjonen-Ward, 1993a). As can be seen from Fig. 5.3.3, the Pihlajavaara anticline, with well-constrained younging determinations, lies to the west of the Pampalo zone and provides a key to both stratigraphic and structural interpretation. The plunge of this anticline and subsidiary minor folds varies in the range of 40–70° toward the north in the southern part of the area, which is typical for much of the Hattu schist belt, but becomes progressively gentler in the northern part of the zone, with southerly plunges and lineations being characteristic of the boundary between the Pampalo and Hosko zones. This geometrical pattern can be explained by transpressive shear, resulting in asymmetric doubly plunging dome and basin folds in the adjacent Hosko zone, while within the Pampalo zone, discrete shear zones appear to have excised some of the stratigraphic sequence along the eastern limb of the Pihlajavaara anticline.

In the southern part of the Pampalo zone, the boundary with the Hattuvaara zone is somewhat arbitrary, but the structural architecture can be interpreted in terms of tightening of the regional synform complementary to the Pihlajavaara anticline, which is again supported by abundant depositional younging criteria (Sorjonen-Ward, 1993a,b). In this area, plunges are steep toward the north and the resultant geometry is explained as a consequence of variations in response to different rock types to deformation, in particular the presence of the largest occurrence of mafic and ultramafic rocks observed in the schist belt. These rocks are assigned to the Pampalo formation which, as indicated in Fig. 5.3.3, is the uppermost stratigraphical unit recognized in the northern part of the Hattu schist belt, overlying conglomerates and graywackes of the Tiittalanvaara formation and including, at the base, a banded iron formation unit (Sorjonen-Ward, 1993a,b).

The anomalous thickness of the Pampalo formation in this area is interpreted as a strike-slip duplex formed by oblique shearing along the steeply dipping eastern limb of the Pihlajavaara anticline, resulting in imbrication of mafic units of the Pampalo formation by detachment along the anisotropic banded iron formation, which separates the Pampalo formation from the underlying sediments of the Tiittalanvaara formation (Fig. 5.3.3(A)). Although further resolution of details is still desirable, this interpretation satisfies the first-order geometrical and structural constraints based on field mapping and interpretation of geophysical imagery. For a detailed description and analysis of the Juttuhuhta duplex and its relationship to gold mineralization, the reader is referred to Nurmi et al. (1993) and Sorjonen-Ward (1993a).

The prospective part of the Pampalo zone appears to be 1–2 km wide and is distinctive in that ultramafic rocks are exposed over much of its length, so that regionally, the zone coincides with prominent Ni and As geochemical anomalies in till; although the latter element is also commonly associated with Au, arsenopyrite has also been found in hydrothermally altered mafic sediments that are devoid of gold, and which are more likely to represent subseafloor alteration processes. Several additional gold occurrences have been delineated in proximity to the Pampalo deposit, namely Pampalo Northwest and Pampalo East, and bedrock mineralization was also demonstrated in an outcrop several kilometers along the strike from Pampalo, at Korpilampi, adjacent to the Korpivaara tonalite (Nurmi et al., 1993).

In the northern part of the Pampalo zone, till anomalies have also been drilled and bedrock mineralization has subsequently been confirmed in extensively sericitized feldspathic wackes or pyroclastic deposits, with delineation of the Kuivisto and Kuivisto East occurrences as steeply dipping mineralized zones concordant with respect to enclosing lithological units (Heino et al., 1995). This sericitic alteration demonstrably predated intensive foliation development and may also be related to subvolcanic alteration processes, demanding careful paragenetic studies in distinguishing this from later structurally controlled alteration related to gold mineralization.

The Korpilampi occurrence, between Kuivisto and Pampalo, was perhaps the most accessible and obvious target in the entire region, being one of the few road cuttings in the area. The exposure comprised talc-chlorite schists and ultramafic rocks intruded by pegmatites with extensive tourmaline alteration and with abundant sulfides. Potassic alteration is also indicated by biotite replacement of talc-chlorite assemblages (Nurmi et al., 1993). Mineralized pegmatite veins contained erratic anomalous gold, with arsenopyrite and pyrite, as well as bismuth minerals, pyrrhotite, marcasite, sphalerite, and chalcopyrite (Kojonen et al., 1993), but drilling failed to intersect significant mineralization. Nevertheless, the area is of potential interest given the presence of till geochemical anomalies on both sides of the outcrop and the general lithological similarities with those at Pampalo, which remains, at the time of writing, the most significant deposit in the Pampalo zone.

Pampalo Gold Mine

Attention was first drawn to the region surrounding the Pampalo deposit on the basis of prospective analogy; the Pampalo zone is the only part of the Hattu schist belt where mafic lithologies are relatively abundant, as in many gold districts, but more importantly, the distinctive and deviant structural geometry appeared, by analogy with structurally controlled gold deposits elsewhere, to be favorable for mineralization (Sorjonen-Ward, 1993a; Nurmi et al., 1993). It was therefore fortuitous indeed that a structurally anomalous outcrop in this area, trending almost orthogonally with respect to the main shear system, was found to contain visible gold. In addition, it was realized that distinct and prominent till geochemical anomalies had been recorded from several profiles that terminated some distance to the west of the outcrop (Hartikainen and Nurmi, 1993). The first exploratory drilling across the area in 1990 consisted of three holes, the second of which yielded ore grade intersections (17 ppm over 7 m and 3.3 ppm over 12.6 m), indicating that the discovery outcrop was situated at the eastern edge of the main ore zone, in an area that is now known and mined as the Pampalo East deposit. Three *en echelon* elongate or lenticular ore zones, plunging moderately at 40–50°E to the north-northeast, were defined after the earliest phase of drilling and this interpretation has been subsequently confirmed and formed the basis for mine planning (Fig. 5.3.3(C)).

A critical and significant feature of the Pampalo deposit is its structural setting, having a northerly to northeasterly trend, which is highly discordant to the overall northwesterly trend of the Pampalo zone. This can be explained by sinistral transpressive folding within the Pampalo zone, even though the larger scale map geometry gives the impression that the Pampalo zone represents a sinistral dilational jog or left-stepping releasing bend architecture between the northerly trending Hattuvaara and Hosko zones. In contrast, the transpressive, contractional interpretation places the Pampalo deposit within the toe of the oblique sinistral, Juttuhuhta duplex and would seem to imply, if not require, progressive changes in relative strain rate along the bounding shear zones (Sorjonen-Ward, 1993a). A detailed assessment and understanding of the evolution of these structures is important in developing structurally oriented exploration strategies, as it is critical to establish whether *en echelon* mineralization zones are present elsewhere, oriented within the axial planes of these transpressive folds, rather than parallel to the main northwest-trending Pampalo zone shear system.

Porphyritic dikes, including those at the discovery outcrop, are tightly folded with the country rocks, as well as being mineralized so that the relationships between deformation, magmatic events, and mineralization share much in common with the Kuittila zone. Indeed, there is an evident mirror symmetry when comparing the relationship between the Tasanvaara tonalite and Pampalo zone with the Kuittila tonalite and the Kuittila zone, the former having a northeasterly trend and latter a northwesterly trend. An important difference, however, which may be of significance in assessing the possible role of granitoids in mineralization, is that the Tasanvaara tonalite is situated further away from the mineralized zone. On the other hand, the enveloping surface to the Pampalo shear system and associated porphyry dikes are effectively dipping moderately eastward beneath the contact with the Korpivaara tonalite.

The Pampalo deposit is hosted by a diverse range of rock types, with a reasonably well-defined stratigraphy based on correlation with surrounding areas (Fig. 5.3.3(A)). The eastward younging transition from turbiditic graywackes and conglomerates of the Tiittalanvaara formation to banded iron formations marking the base of the Pampalo formation is well-documented from drilling, and this has also been taken as the likely floor thrust to the Juttuhuhta duplex (Sorjonen-Ward, 1993a). The internal lithological subdivisions recognized within this latter formation include massive basalts and dolerites, separated by a distinctive intermediate to mafic clastic unit which appears to be the most favorable host rock for mineralization. Although younging criteria are lacking, the uppermost part of the Pampalo formation comprises bimodal felsic and ultramafic units, the latter having been altered to talc-chlorite-carbonate schist in the eastern part of the deposit; the ultramafic rocks are not mineralized, but folded and boudinaged porphyry dikes contain gold. Distinct vitreous felsic units, which may have been rhyolitic flows or subvolcanic, are extensively albitized with abundant tourmaline and are pervasively mineralized, forming one of the main rock types mined in the Pampalo East deposit.

The nature of structural control and the timing of introduction of gold, the possible role of magmatic as well as metamorphic fluids, and the extent of recrystallization and remobilization at the Pampalo deposit are not yet adequately understood. Visible gold occurs within narrow anastomozing mylonitic seams that show evidence for both brittle and ductile behavior, in equilibrium with biotite and in some cases actinolite, but it is not clear if this represents the remobilization of earlier mineralization, or actually represents the main stage of mineralization. Resolution of these issues is an important matter for exploration if, for example, it were shown that gold was locally remobilized into the northeasterly trending shear zones during folding, having originally been introduced within the main northwest-trending shear system, or was actually introduced within an axial planar orientation during the later folding event.

Gold tends to be disseminated, with sulfides, within the altered clastic unit, or in dynamically recrystallized veins and fractures in porphyritic dikes, indicative of contrasting mechanical behavior for the two rock types. In general, discrete mineralized quartz veins arrays are rare, suggesting that wall-rock sulfidation has been a more significant process than fluid mixing or phase separation.

The main sulfide mineral phases accompanying gold at Pampalo are pyrite, with pyrrhotite, chalcopyrite, pyrrhotite, galena, and sphalerite. As elsewhere, bismuth and Pb-, Ag-, and Au-tellurides are characteristic (Kojonen et al., 1993). Scheelite is remarkably common within the ore and a useful qualitative indicator of proximity to mineralization underground and in drill core. Gold tends to occur as free grains, fracture fillings in hydrothermally altered mineral grains, such as microcline, or as inclusions in pyrite; this has proven very favorable for beneficiation with efficient recovery by gravitational and flotation processes.

HOSKO ZONE

This zone represents the northeastern part of the Hattu schist belt, and is distinctive in terms of the asymmetric doubly plunging folds and the extensive seritic alteration of epiclastic or pyroclastic deposits, which evidently predates regional foliation development, and is therefore likely a product of submarine volcanic-related hydrothermal processes. Despite the extensive alteration, primary depositional units and clastic features are commonly preserved, facilitating mapping of structural features and outlining the dome and basin topology. The Kartitsa granite also displays dynamically recrystallized to quartz-muscovite-microcline assemblages, and, locally, fluorite, implying that it may be a subvolcanic intrusion, with later sulfide-bearing vein systems superimposed (Sorjonen-Ward, 1993a). Accordingly, in assessing gold potential, careful microstructural studies are necessary to discriminate between early synvolcanic and later structurally controlled synmetamorphic alteration assemblages.

Detailed till geochemical data are available for the southern part of the zone (Hartikainen and Nurmi, 1993; Hartikainen and Niskanen, 2001) and on the basis of till anomalies in the Valkeasuo area, the Hosko deposit was identified and bulk samples (760 kg) were collected from a test pit by Endomines Oy in 1999 for beneficiation tests. Recovery up to 90% was obtained; however, the ore mineral assemblage at Hosko differs somewhat from other mineralization in the Hattu schist belt in that it is more refractory, with abundant arsenopyrite. Metamorphic grade, however, is not higher than at other deposits, and the host rocks are thin- to thick-bedded turbidites with dark pelitic intercalations, and show varying degrees of sericitic alteration. Tourmaline is ubiquitous in mineralized veins, and is also texturally replacive in the pelitic layers, which also typically contain abundant laminated mineralized quartz-tourmaline-pyrite-arsenopyrite carbonate veins. In addition to arsenopyrite, pyrrhotite, marcasite, and scheelite are present (Heino et al., 1995; Käpyaho et al., 2013).

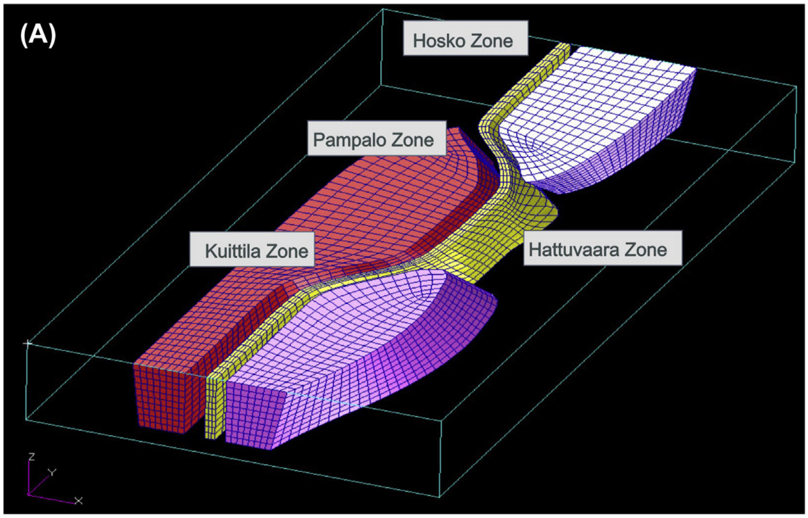
Mineralization has been delineated over about 600 m of strike length, and varies from 2–15 m in width, with sporadic drill hole intersections yielding exceptionally high Au abundances. Variations in grain size and the erratic distribution of mineralization have also made resource estimation more difficult. The mineralized zone corresponds to a distinct IP anomaly, which can be traced southward from Hosko for several kilometers toward the Kuivisto deposit in the Pampalo zone, but the presence of mineralization along the entire strike length has yet to be confirmed.

STRUCTURAL ANALYSIS AND EXPLORATION TARGETING—NUMERICAL SIMULATION OF FAVORABLE STRUCTURAL ARCHITECTURE AND CONTROLS ON MINERALIZATION

Orogenic gold deposits characteristically show strong structural control, or are at least associated with networks of crustal scale and subsidiary shear zones (Goldfarb et al, 2001). As described earlier, gold mineralization in the Hattu schist belt also displays distinct structural controls, although the orientation and intensity of hosting structures varies from place to place. It is therefore natural to consider whether some structural features can be identified that would provide insights into the distribution of mineralization and perhaps prove to be of predictive value.

Structurally enhanced permeability during orogenic deformation is widely invoked and accepted as a critical factor in the formation of lode gold deposits, driven by feedback between rock material properties and structural architecture, fluid pressure, and orientation of far-field stresses (Cox et al., 2001; Ord and Oliver, 1997; Sibson, 2001). In recent decades, numerical simulations of mechanical processes and coupled fluid–rock interaction have been used to analyze and predict structural controls on gold mineralization at various scales (Schaubs and Zhao, 2002; Sorjonen-Ward et al., 2002; Zhang et al., 2013). Therefore, we decided to perform some numerical simulations of deformation relevant to the known structural geometry and rock types present in the Hattu schist belt.

Because mineralization is known to occur within tonalities, as at Kuittila, as well as in enclosing metasediments, or in high-strain zones near the contact between plutonic and supracrustal rocks, a useful model should be capable of discriminating between at least these three rock categories. We therefore developed some 3D models based on a highly simplified emulation of the geometry of rock units in the Hattu schist belt (Fig. 5.3.8(A)). Although simple, the mesh does incorporate several fundamental geological features, namely the less steep northwesterly and northeasterly dips of respective enveloping surfaces in the Kuittila and Pampalo zones. Moreover, because mineralization occurs in various structural orientations, it was considered necessary to test the influence of systematic variations in stress fields as well as mechanical contrasts in rock units. This allows the testing of various hypotheses, for example, whether results would suggest that structures having different orientations could be equally and effectively permeable under the same stress regime, or whether mineralization in different orientations represents superimposed or unrelated events.



Rock Unit	Density	Young's modulus	Poisson's ratio	Cohesion	Tensile strength	Friction angle	Dilation angle	Porosity	Permeability
Shear Zone	2500	4e10	0.2	5e6	0.5e6	15	3	0.1	1e-15 m2
Metasediments	2650	5e10	0.25	1e7	1e6	30	3	0.1	5e-17 m2
Granitoids	2650	6e10	0.25	3e7	3e6	35	3	0.1	1e-17 m2

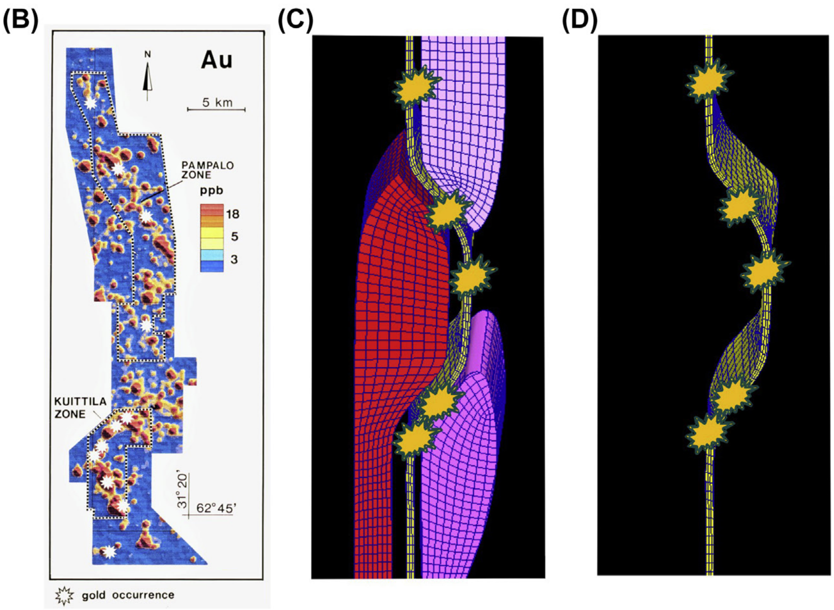


FIGURE 5.3.8 Mesh geometry, material properties, and boundary conditions of FLAC3D™ model.

(A) 3D perspective of model mesh, representing three domains simulating stiff plutonic intrusions in a uniform anisotropic matrix, apart from a simulated shear zone transecting the model from north to south. A significant element of the model is the northeast dip of the northwest-trending Pampalo zone and conversely, the northwest dip of the northeast-trending Kuittila zone. Mesh simulates a volume of rock 40 km (north–south) × 20 km (east–west) × 5 km. Simulations are based on Mohr–Coulomb rheology with and fluid coupling according to Darcy's law, with pore fluid pressure sublithostatic. (B) Gold anomaly distribution along the Hattu schist belt, from Hartikainen and Nurmi (1993), to illustrate the complexity of patterning represented by the simplified meshes in (C) and (D).

The simulations were performed with the finite element code FLAC3D, which was originally developed for engineering applications by the Itasca Consulting Group (Itasca, 2006). FLAC3D allows simulation of fluid flow patterns in deforming rock masses and has been widely applied to the study of structurally controlled hydrothermal processes. The material properties assigned to the rock units in the numerical simulations are based on the interpreted relative strength of the rocks and, in the absence of properties derived via geotechnical testing of the actual rocks, average representative values were obtained from literature sources (Lama and Vutukuri, 1978). The granitoid rocks were interpreted to be the most competent, and were therefore assigned mechanical strength properties higher than those of the metasediments.

Shear zones, because of their pronounced anisotropy, were interpreted to be much weaker than the granitoids, and metasediments and properties were assigned accordingly. Shear zones were interpreted to be fluid pathways and therefore the permeability assigned to them is much higher than in the granitoids and metasediments. It should also be noted that these are bulk properties averaged over time, which is considered a reasonable approximation for an active shear zone subject to episodic overpressuring and failure (cf. Cox et al., 2001; Sibson, 2001). Testing the sensitivities of these parameters was beyond the scope of this study. Nevertheless, comparison of variations and contrasts between model results, for example, where stress vectors vary but material properties and duration of run are held constant, can provide valid insights, irrespective of the absolute precision of model parameters.

In FLAC3D, fluid flow is predominantly governed by permeability and, as such, this parameter is used to differentiate the flow conduit (shear zone) and less permeable host rocks. This qualitatively reflects field observations, for example, the tendency for dispersed hydrothermal alteration throughout the Korvilansuo-Kivisuo-Elinsuo-Muurinsuo deposits in metasediments parallel to the contact with the less mineralized Kuittila tonalite pluton. Porosity only plays a minor role in flow in crystalline bedrock and accordingly is not linked to permeability here, due to the complexity of the relationship between these two parameters, in particular, the degree of pore space connectivity. Uniform porosity was, therefore, used in the models to highlight the importance of permeability.

When a FLAC3D model mesh is subjected to simulated stresses, elements that fail according to Mohr–Coulomb rheology undergo positive or negative dilation, which is linked to changes in permeability, which in turn affects fluid pressure and flow vectors. In this way, the simulation reflects episodic failure and fluid transport in natural deformation zones. As the model simulation progresses, we observe where volumetric or shear strain dilation is greatest, as a proxy for rock masses that are favorable for failure and fluid-rock interaction, and by inference, for hydrothermal mineralization.

The aim of these simulations was to test whether we could predict, or at least understand, the distribution of gold mineralization (Fig. 5.3.8(B) through (D)), by comparing results of modeling with known gold occurrences (Schaubs et al., 2012). The ability to test model predictions by validation against available field data, or by seeking new information in the field, is one of the main reasons for modeling, and also requires that the model and its boundary conditions are carefully designed.

Accordingly, we may define three types of model scenarios, in which the model geometry and material properties remain uniform, but principal stress orientations are varied, to establish:

- Whether the known geometry and orientation could be explained by a single far-field stress configuration.
- Whether rotation of the structures with respect to an external reference frame during progressive deformation led to preferential activation of some orientations.
- Whether the different orientations represented discrete superimposed processes.

The first two cases assume that mineralization was essentially coeval and, by implication, derived from a favorable set of circumstances with respect to metal supply, transport efficiency, and precipitation mechanisms in permeable structures. The third case, if shown to be feasible, or even necessary, would then provide further stimulus for seeking evidence for overprinting of structural fabrics and modification or remobilization of mineral assemblages; recall that isotopic evidence for recrystallization and local remobilization at the Pampalo deposit was indicated by Vaasjoki et al. (1993) and substantiated by Molnar et al. (2013).

In these models, we were particularly interested in the orientation of maximum compressive stresses that would allow the formation of veins and shear zones in the observed orientations (Fig. 5.3.9(A)). This was done by systematically and incrementally varying stress directions across the models, using 15° increments. Results were then compared with known distribution of high-strain zones and gold-bearing structures. In all simulations, the same initial state was chosen for model mesh and material properties.

Results for some of the simulations are presented in Fig. 5.3.9(B), which illustrates cumulative volumetric strain increment as the model mesh is subject to shortening, with varying principal stress directions. The most interesting conclusion, or speculation, that can be made from these results is that the northeast-dipping orientation of the Pampalo zone is shown to be most favorable for tectonic activation and dilation in many different stress configurations. By implication, such areas may be the loci of repeated mineralizing events and therefore have cumulative potential for greater endowment. However, it may seem counterintuitive that west-northwest to east-southeast to northwest-southeast directed maximum compressive stress orientations that are subparallel to the Pampalo zone show less of a tendency for dilation, while the Kuittila zone volume strain is conversely greater.

Although sensitivity to changes in mechanical properties should ideally be tested as well, it is nevertheless noteworthy that when the maximum principal stress orientation is centered around north-northwest to south-southeast, dilation is significant in both the Pampalo and Kuittila zones. There is, however, no known reason why we should expect mineralization to have occurred simultaneously along the entire schist belt, rather than forming from discrete events in isolated short-lived hydrothermal cells. We may further speculate that the structural significance of both of these zones lies in their deviation from vertical orientation (Fig. 5.3.8(A) and (D)), which should favor the formation of oblique gently dipping or plunging structures, with opportunities for both reverse-sense and strike-slip components oblique to the main shear zone trends. Under this stress configuration, dilation within north to south shear zones, with generally steep plunges would be anticipated, as indeed is the case for mineralization in the Hosko zone and within the Hattuvaara zone at Rämepuro.

Some concluding points illustrating the interaction between model results and field verification include the evidence for a zone of dilation propagating from the Pampalo zone toward the northeast, around the southern margin of the Korpivaara tonalite, for maximum stress orientations between north-northwest to south-southeast and north-northeast to south-southwest. Another rather unexpected zone of dilation is present to the east of the Kuittila tonalite, where the maximum compressive stress is oriented east to west. Assessment of such potential targets can be made with reference to till geochemical surveys and structural analysis in outcrop, to confirm or refute predictions. For example, although there are no bedrock exposures in the area to the east of the Kuittila tonalite, making structural analysis difficult, Figs. 5.3.4(A) and 5.3.8(B) both indicate at least some anomalous Au in till. Conversely, regional scale till geochemical anomalies are somewhat more erratic in the area northeast of Pampalo, but there are reasonable constraints on structure and rock type due to better bedrock exposure (Sorjonen-Ward, 1993b). Finally, it should be noted that favorable structural architecture alone need not imply high proespectivity, if there were no associated processes generating fluids of appropriate composition during a deformation event.

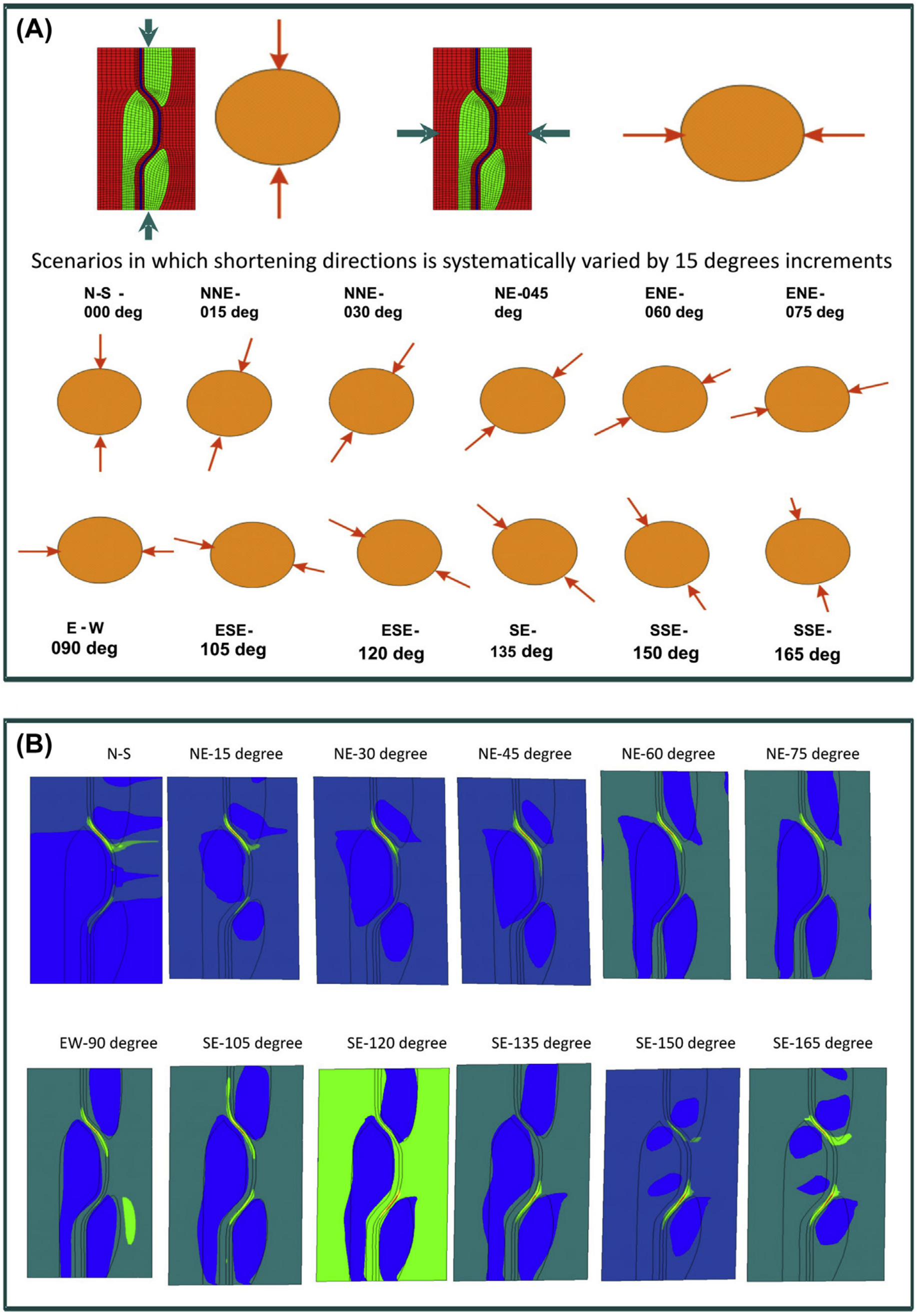


FIGURE 5.3.9 FLAC3D simulations of varying stress field orientation.

(A) Illustration of systematic variation of principal stress orientations, or velocity conditions imposed on model, by 15° increments. (B) Results of shortening simulations showing contours of volumetric strain in plan-view, on a section plane 500 m below top surface of model. Blue shades correspond to negative volume strain, with volume reduction in the range of 2–3%, while yellow to red colors indicate positive volume strain or dilation, with values ranging from 3–8% and indicate sites of preferential rock failure and fluid infiltration. The Pampalo zone is dilatational under most stress configurations, whereas dilation occurs simultaneously in the Pampalo and Kuittila zones when principal compressive stress is between northwest to-southeast and north to south.

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