CHAPTER

KOMATIITE-HOSTED NI-CU-PGE DEPOSITS IN FINLAND

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ABSTRACT

Eight economically promising komatiite-hosted sulfide deposits have so far been found in eastern and northern Finland. They are related both to Archean (Tainiovaara, Hietaharju, Peura-aho, Vaara, Ruossakero, and Sarvisoaivi) and Paleoproterozoic (Hotinvaara and Lomalampi) komatiitic to komatiitic basalt magmatism. The deposits are mostly associated with the Al-undepleted komatiite type (AUK) (Al_2O_3/TiO_2 = 15-20), but Ti-depleted komatiites ($Al_2O_3/TiO_2 > \sim 20$) are predominant in the Hotinvaara, Ruossakero, and Sarvisoaivi areas. Disseminated Fe-Ni-Cu sulfides (commonly <5 wt% S) and minor massive sulfide accumulations as well as remobilized massive veins are associated with thick, MgO-rich and Cr-poor metacumulates. In some cases, sulfide mineralization is partly hosted in associated schist, as in the Peura-aho deposit. Most of the deposits were modified by postmagmatic processes to various degrees, resulting in a notable increase in metal contents of the sulfide fraction in some of the deposits, notably the Vaara deposit.

The deposits are divided into two main groups based on their metal content: (1) deposits that are enriched in PGE (Pd + Pt > 500 ppb) and Cu (Ni/Cu < 13) (Vaara, Hietaharju, Peura-aho, and Lomalampi), and (2) deposits that are enriched in Ni (Ni/Cu > 15) and have low PGE contents (Sarvisoaivi, Ruossakero, and Hotinvaara). The Tainiovaara deposit has an intermediate composition between these two groups. Lomalampi is a unique deposit, because it has relatively high levels of PGE compared to base metals (i.e., it is a PGE-(Ni-Cu) deposit)—and a Pt/Pd ratio of around 2, as opposed to most other komatiite-hosted Ni-Cu-(PGE) deposits globally that have Pt/Pd around unity. The Lomalampi deposit contains isotopically heavy sulfur with $\delta^{34}S$ of +10 to +15‰, which is consistent with the presence of a large proportion of crustal sulfur in this deposit. Most of the Finnish Ni-Cu-(PGE) deposits have $\delta^{34}S$ close to the mantle range (±2 per mil). Multiple isotope analyses of the Archean Vaara and Hietaharju deposits have revealed a considerable mass-independent fractionation of sulfur isotopes in both the ores and their country rocks, demonstrating a significant role of external sulfur assimilation in ore formation. Although no significant economic deposits have so far been found, the number of known mineralizations and the high PGE contents in some of them indicate that komatiites in Finland still provide potential targets for future exploration work.

Keywords: Komatiites; komatiite-hosted Ni-Cu-PGE deposits; PGE; sulfides; sulfur isotopes; alteration; greenstone belt; Suomussalmi greenstone belt; Central Lapland Greenstone Belt; Finland.

INTRODUCTION

Recognition of primary, high-temperature ultramafic lavas, called komatiites, in the late 1960s (Viljoen and Viljoen, 1982) started a new era of nickel exploration. In favorable environments and under appropriate dynamic physical conditions, ultramafic lavas can generate profitable nickel-copper sulfide deposits (e.g., Naldrett, 1966; Woodall and Travis, 1970; Ross and Hopkins, 1975). In 2006,

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approximately 18% of global nickel sulfide reserves were estimated to be associated with komatiites (Hronsky and Schodde, 2006). The komatiitic ultramafic lavas and komatiitic basalts and, in particular, associated olivine-rich cumulates in lava channels are potential host rocks for nickel deposits. In addition, sills and feeder dikes related to komatiitic magmatism are also potential environments for Ni-Cu-PGE ores.

Two main types of nickel deposits occur in komatiitic systems. Type I consists of accumulations of massive and/or matrix ore at the base of komatiitic lava channels. The nickel grades in massive sulfide ores vary between 2 and 20 wt%. Type II is characterized by sulfide disseminations within, rather than at the base of, the lava channel cumulates. In this deposit type, the whole-rock Ni contents are generally less than 1 wt%. Komatiite-related nickel deposits can be transitional between these two end-member types and deposits containing both types of mineralization have been described. In some of the deposits, the metals have been mobilized during postmagmatic tectono-metamorphic processes (type IV–V) (e.g., Lesher and Keays, 2002; Lesher and Barnes, 2009).

In Finland, no significant economic komatiite-hosted Ni-Cu-PGE deposits have been discovered yet. The small Tainiovaara deposit is the only one that has so far been mined, in 1989. Nevertheless, several small, low-grade sulfide deposits occur in Archean and Paleoproterozoic greenstone belts in eastern and northern Finland (Fig. 3.2.1 and Table 3.2.1).

NATURE OF KOMATIITE-HOSTED NI-CU-PGE DEPOSITS

Most komatiitic magmas are thought to have resulted from an extensive degree of partial melting of depleted mantle peridotite (e.g., Herzberg, 1992). As a consequence of the high degree of melting (>30%), these magmas are sulfur-undersaturated after segregation from their mantle source and carry elevated contents of chalcophile elements (Ni, Cu, and PGE). Critical factors controlling the genesis of magmatic Ni-Cu-PGE deposits include the formation of an immiscible sulfide liquid during magma ascent through the Earth's crust or after its eruption on the Earth's surface. To achieve high Ni tenors, the separation of the immiscible sulfide liquid has to take place before a significant amount of mafic silicates, particularly olivine, has crystallized from the magma. Additionally, because komatiitic magmas are commonly strongly S-undersaturated when emplaced in the upper crust, it is generally believed that the generation of Ni sulfide ores requires addition of external S to the magma.

This explains why Ni-Cu-PGE deposits are usually found in dynamic magma channel environments where thermo-mechanical erosion of the host rocks is believed to have been most efficient (e.g., Lesher and Groves, 1986; Keays, 1995; Lesher and Arndt, 1995; Lesher et al., 2001; Sproule et al., 2005; Barnes, 2007; Arndt et al., 2008). A dynamic magma environment also allows the segregated sulfides to be equilibrated with a large amount of silicate magma (cf. Campbell and Naldrett, 1979), thereby efficiently sequestering chalcophile metals from the magma. Recent studies of Bekker et al. (2009), Fiorentini et al. (2012a, b), and Konnunaho et al. (2013) have shown that coupled $\delta^{34}S$ and $\delta^{33}S$ measurements provide a powerful tool to constrain sulfur sources for Archean komatiite-hosted Ni-Cu deposits even in situations where $\delta^{34}S$ values are nondiagnostic.

The concentration of chalcophile elements in mineralized and unmineralized komatiitic rocks can be affected by primary magmatic processes (e.g., degree of mantle melting, composition of mantle, varying R factor, crustal contamination) and/or secondary processes. In general, the chalcophile

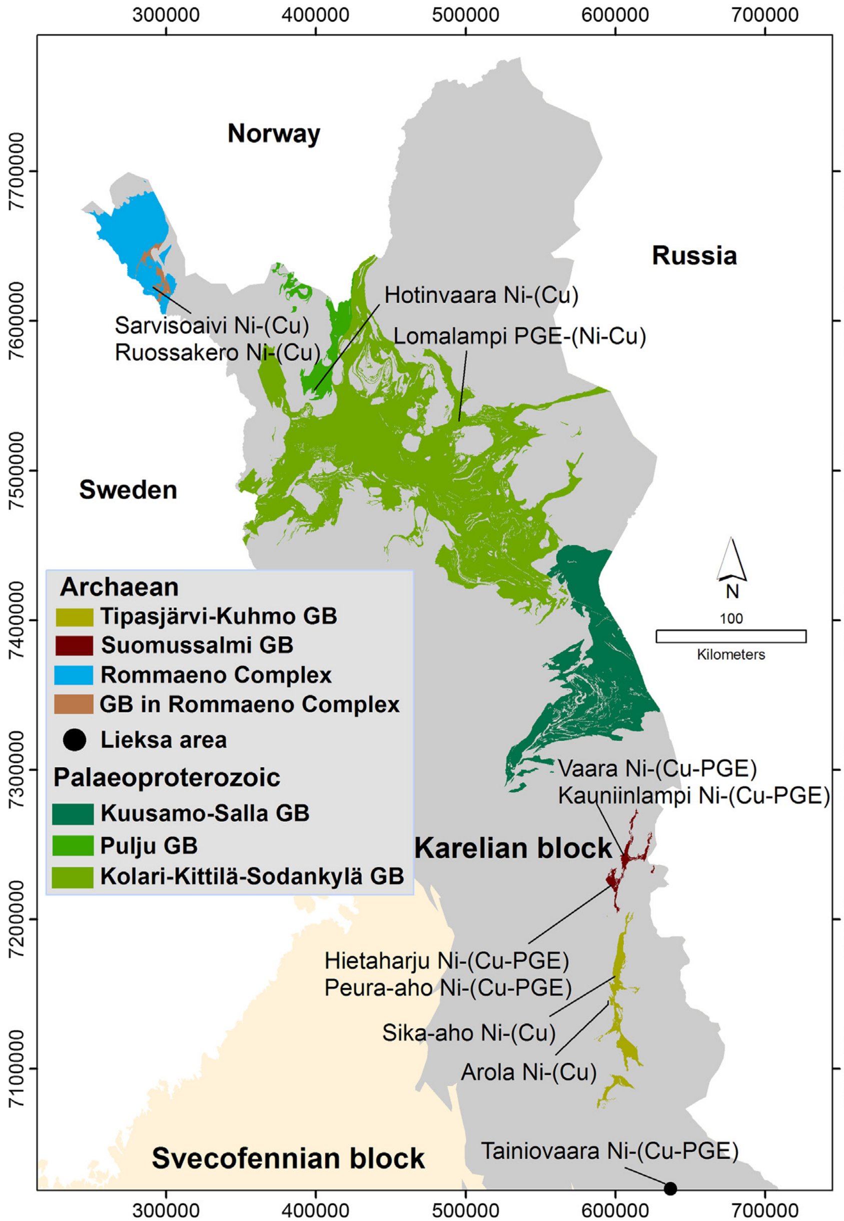

FIGURE 3.2.1 Archaean and Paleoproterozoic greenstone belts (GB) in northern and eastern Finland and associated komatiite-hosted Ni-Cu-PGE mineralizations.

Table 3.2.1 Classification of Finnish komatiite hosted Ni-Cu-PGE deposits (GB = greenstonen belt, AUK = aluminum undepleted komatiite, CLGB = Central Lapland greenstone belt)

						Mineralisation type			Ratios			
Deposit name	**Area**	**Age**	**Magma Type**	**Host rock**	**Deposit type**	**I**	**II**	**IV**	**Al/Ti**	**Ni/Cu**	**Pt/Pd**	**Pd/Ir**
Vaara	Suomussalmi GB	Archaean	AUK	oOC to oMC	Ni-(Cu-PGE)		x		19	13	0.4	28
Hietaharju	Suomussalmi GB	Archaean	AUK	oOC to oMC	Ni-(Cu-PGE)	(x)	x		15	4	0.5	22
Peura-aho	Suomussalmi GB	Archaean	AUK	oOC to oMC (+ surrounding schists)	Ni-(Cu-PGE)	(x)	x	x	15	3	0.5	14
Tainiovaara	Ultramafic body within Archean basement	Archaean	AUK	oMC	Ni-(Cu-PGE)	(x)	x		23	19	0.4	10
Lomalampi	Kolari-Kittilä-Sodankylä GB (CLGB)	Palaeoproterozoic	AUK	oOC to oMC	PGE-(Ni-Cu)		x		15	4	2	15
Hotinvaara	Pulju GB (CLGB)	Palaeoproterozoic	AUK	oMC to oAC	Ni-(Cu)	(x)	x	(x)	34	36	0.6	10
Ruossakero	Rommaeno Complex	Archaean	Ti-depleted	oMC to oAC	Ni-(Cu)		x		46	55	0.4	15
Sarvisoaivi	Rommaeno Complex	Archaean	Ti-depleted	oMC to oAC	Ni-(Cu)		x		37	15	0.2	47

oOC = olivine orthocumulate
oMC = olivine mesocumulate
oAC = olivine adcumulate
Deposit type ( ) = by product
Mineralisation type ( ) = minor type

element concentrations in the sulfide fraction vary from area to area and deposit to deposit, although they are commonly higher in disseminated ores than in massive ores (Lesher and Barnes, 2008; Fiorentini et al., 2010); it seems that disseminated sulfide deposits were formed at higher R factors than massive sulfide deposits (e.g., Lesher and Barnes, 2008). After crystallization, magmatic sulfides may become further enriched in precious metals if the host igneous body is subjected to strong hydrothermal alteration (e.g., oxidation, serpentinization, carbonatization, or desulfurization) or supergene alteration. This concerns particularly disseminated deposits, which may become markedly upgraded in their metal tenors (e.g., Stone et al., 2004; Barnes et al., 2009; Lesher and Barnes, 2009; Konnunaho et al., 2013). Secondary enrichment can explain the notable PGE (Pd + Pt) enrichment in some deposits in Finland. On the other hand, high metal tenors could also be due to PGE-rich mantle sources. There are still many open questions related to the noncoherent behavior of PGE in komatiites, for example, the origin of the different Pt/Pd in mineralized and unmineralized komatiites. In komatiite-hosted Ni-Cu-PGE deposits, Pd is commonly enriched over Pt by a factor of around 1.5–2, whereas most unmineralized komatiites show Pt/Pd close to unity (Lesher and Keays, 2002; Fiorentini et al., 2010). Barnes et al. (2012) discussed potential explanations for the high Pd/Pt in ores and concluded that this can be a primary magmatic signal in addition to postmagmatic alteration.

LOCATION AND CLASSIFICATION OF KOMATIITE-HOSTED NI-CU-(PGE) DEPOSITS IN FINLAND

Komatiite-hosted Ni-Cu-PGE deposits are found both in Archean and Paleoproterozoic greenstone belts in Finland (Fig. 3.2.1 and Table 3.2.1). In this chapter we will first describe several Archean deposits, including three major deposits within the Kuhmo-Suomussalmi greenstone belt (Vaara, Hietaharju, and Peura-aho), the Tainiovaara deposit located in a greenstone relict in eastern Finland, and the Ruossakero and Sarvisoaivi deposits in the Enontekiö-Käsivarsi area of northwestern Finland. In addition, some smaller Archean showings are also mentioned. This will be followed by a description of two notable Paleoproterozoic deposits, namely the Hotinvaara and Lomalampi deposits in the Central Lapland Greenstone Belt.

The Finnish Ni-Cu-PGE deposits belong mainly to the type II (disseminated type) of deposits, but some deposits belong to the type I (massive type) and type IV (hydrothermally, metamorphically mobilized type) deposits (Table 3.2.1) (cf. Barnes, 2006; Lesher and Barnes, 2009). Some deposits represent a mixture of types II, I and/or IV. All eight main deposits are associated with the MgO-rich and Cr-poor cumulate portion of komatiitic or komatiitic basalt units and they mostly consist of disseminated sulfides (e.g., Vaara, Lomalampi, and Ruossakero) and minor massive to semimassive sulfides (e.g., Tainiovaara, Hietaharju, and Peura-aho). Some of the deposits were modified by postmagmatic processes to various degrees (e.g., Vaara). In some deposits, Ni-Cu sulfides may be partly associated with the country rocks, including the Peura-aho deposit and the Sika-aho and Arola showings (Fig. 3.2.1).

In terms of their PGE content, the Finnish deposits can be divided into PGE-enriched and PGE-poor types. They have been classified as Ni-(Cu-PGE) and Ni-(Cu) deposits in this work, respectively. The PGE-enriched deposits are found in both age groups and are either S-poor (e.g., Lomalampi) or S-rich (e.g., Hietaharju and Peura-aho). The PGE-enriched deposits also tend to be enriched in Cu compared to the PGE-poor deposits (e.g., Sarvisoaivi, Ruossakero, and Hotinvaara).

NI-CU-PGE DEPOSITS OF THE SUOMUSSALMI GREENSTONE BELT

GEOLOGICAL SETTING

The Archean Suomussalmi greenstone belt represents the northernmost segment of the ~220-km-long and 10-km-wide, north–south trending Kuhmo-Suomussalmi greenstone belt complex (Fig. 3.2.1). A recent review of the complex was published by Papunen et al. (2009). The whole belt is characterized by the presence of komatiitic volcanic rocks, which show in some places well-preserved primary volcanic structures (Hanski, 1980; Tourpin et al., 1991; Gruau et al., 1992; Maier et al., 2013).

In the Suomussalmi belt, four lithostratigraphic formations have been defined. From the oldest to the youngest, these include the Luoma, Mesa-aho, Tervonen, Saarikylä, and Huutoniemi formations. The Luoma formation consists predominantly of andesitic to dacitic volcanic rocks, but also includes mafic and felsic volcanic rocks, quartz porphyry dikes, and banded amphibolites (Papunen et al., 2009). The U-Pb zircon data show that the age of the felsic volcanic rocks of the Luoma formation is ~2.95 Ga (Huhma et al., 2012). Most of the greenstone belt consists of tholeiitic basalts with Banded Iron Formation (BIF) interlayers belonging to the Tervonen formation. Stratigraphically above the Tervonen formation is the Saarikylä formation, which contains felsic metavolcanic rocks and graphitic black schists overlain by Cr-rich basalts and komatiitic rocks. The latter formation includes komatiitic olivine and olivine-pyroxene cumulates and lava flows, and komatiitic basalts (Halkoaho et al., 2000a,b; Luukkonen et al., 2002; Papunen et al., 2009).

The Vaara, Kauniinlampi, Hietaharju, and Peura-aho Ni-(Cu-PGE) deposits occur in this formation. The uppermost part of the stratigraphic sequence comprises felsic to intermediate metavolcanic rocks and graphite-bearing metasediments of the Huutoniemi formation. A felsic volcanic rock from the eastern branch, correlative with the Huutoniemi formation, has given a U-Pb zircon age of ~2.82 Ga (Huhma et al., 2012). From this, it can be concluded that the geochronological resolution currently available does not provide tight constraints on the depositional ages of the Mesa-aho, Tervonen, Saarikylä, and Huutoniemi formations. In analogy with other komatiitic rocks of the Tipasjärvi-Kuhmo-Suomussalmi greenstone complex, the komatiite-bearing Saarikylä formation is thought to have been formed at ~2.82 Ga (cf. Huhma et al., 2012).

GEOLOGY AND KOMATIITES OF THE VAARA REGION

The Vaara extrusive body is one of five ultramafic lenses that form a 15-km-long, north–south trending chain of bodies in the Saarikylä area, easily recognizable on magnetic maps. On the surface, the Vaara ultramafic lens is approximately 1 km long and 400 m wide. It is truncated by numerous northwest–southeast trending faults and is folded in a complicated manner (Konnunaho et al., 2013, see their Fig. 2). According to the current geological interpretation (Luukkonen et al., 2002; Papunen et al., 2009), the direction of the stratigraphic top is to the east. In the immediate footwall of the Vaara body there are phyllites, black schists, and sulfide-bearing sericite schists, likely belonging to the Mesa-aho formation (Luukkonen et al., 2002). Further to the west, felsic volcanic rocks of the Luoma formation occur. Due to folding, there also are felsic volcanic rocks intervened with cumulate rocks in the Vaara area, and these could be part of the Saarikylä formation. The phyllite-black schist association to the east of the Vaara body belongs to the Huutoniemi formation. The tholeiitic basalts on the southern and northern flanks of the Vaara body are assigned to the Tervonen formation (Konnunaho et al., 2013, see their Fig. 2).

At Vaara and elsewhere in the Tipasjärvi-Kuhmo-Suomussalmi greenstone belt complex, the komatiitic lavas have been pervasively metamorphosed to (1) tremolite-chlorite (± serpentine, talc, carbonate, albite) rocks, representing metamorphosed massive flow lobes and/or upper parts (A zone) of differentiated komatiite lava flows, and (2) serpentinites (±talc, tremolite, carbonate, chlorite) representing metamorphosed massive lava flows and/or lower olivine cumulate zones (B zone) of differentiated lava flows. At Vaara, serpentinites are more abundant than tremolite-chlorite rocks. Commonly, tremolite-chlorite rocks change gradually to serpentinites, representing a transition from the A to B zone in the layered lava flows.

Although the rocks in the Vaara area have been metamorphosed at upper greenschist to middle amphibolite facies conditions and have undergone pervasive alteration, primary igneous textures can still be recognized in places, particularly among olivine cumulates. Magmatic silicates are totally altered, but chrome spinel is locally well preserved. In the northern part of the Vaara ultramafic lens, some thin lava flows altered to tremolite-chlorite rocks still preserve randomly oriented spinifex textures. Olivine cumulates are mainly homogenous, massive, and fine- to medium-grained rocks. The primary textures in these rocks include: (1) unimodal polyhedral cumulate textures, (2) bimodal polyhedral cumulate textures (equant olivine grains together with scattered olivine plates), and (3) harrisitic textures. Accessory opaque minerals include chromite, magnetite, ilmenite, and Fe-Ni-Cu sulfides.

VAARA NI-(CU-PGE) DEPOSIT

The Vaara Ni-(Cu-PGE) deposit was discovered in 1998 by the Geological Survey of Finland (GTK). The deposit is composed exclusively of disseminated Fe-Ni-Cu sulfides that are hosted by komatiitic olivine cumulates (Figs. 3.2.2, 3.2.3, Table 3.2.1). It belongs to the type II komatiitic deposits (i.e., stratabound internal), comprising disseminated sulfides mainly in the central part of olivine cumulate bodies. The deposit is north–south trending and has been delineated by drilling for a strike length of ~450 m and to a depth of 50–180 m below the surface (Halkoaho et al., 2000a). The deposit consists of three separate mineralized sulfide horizons (Figs. 3.2.2. and 3.2.3), the thickness of which varies from ~2–3 m (at the northernmost end) to ~50 m (at the southernmost end). As shown by the drillcore profile in Fig. 3.2.3, the mineralization is associated with relatively Cr-poor olivine cumulates. The indicated reserves of the deposit are 2.62 Mt of ore at 0.49 wt% Ni, 0.04 wt% Cu, 0.01 wt% Co, 0.28 ppm Pd, and 0.11 ppm Pt (Altona Mining, 2012).

Disseminated sulfides (Ø 0.1 to 1 mm) occur mainly in the interstitial space between former olivine crystals, and the original shapes of the sulfide blebs are well preserved. Of the sulfide minerals, millerite (50–75 vol%), pyrite (15–35 vol%), and chalcopyrite (~10 vol%) are the most abundant. Ni-rich pentlandite (41 wt% Ni) and violarite (38 wt% Ni) are less abundant, but can be locally important (Fig. 3.2.4 (A)) (Halkoaho et al., 2000a; Konnunaho et al., 2013). The volume of magnetite within sulfide blebs varies from 40–80 vol%. The quantity of magnetite at Vaara is higher than in most other komatiite-related Ni-Cu deposits (e.g., Heath et al., 2001). However, millerite-pyrite-magnetite blebs similar to those occurring at Vaara, with the magnetite content reaching up to 50 vol%, have been described from disseminated ores in the Otter Shoot and Black Swan deposits in Western Australia (Keele and Nickel, 1974; Barnes et al., 2009). Extensive replacement of interstitial sulfides by magnetite (Fig. 3.2.4(A)) and the presence of millerite- and violarite-bearing, pyrrhotite-free sulfide assemblages indicate postmagmatic, low-temperature hydrothermal oxidation of the primary magmatic pyrrhotite-pentlandite-chalcopyrite assemblages and associated sulfur loss. This process has led to a significant upgrading of the original metal tenors of the Vaara deposit (Konnunaho et al., 2013).

Platinum-group and tellurium minerals are mainly associated with Ni-bearing sulfides, chalcopyrite, and pyrrhotite, and occur as small grains (<10 μm) inside or at the edge of sulfide grains. In some

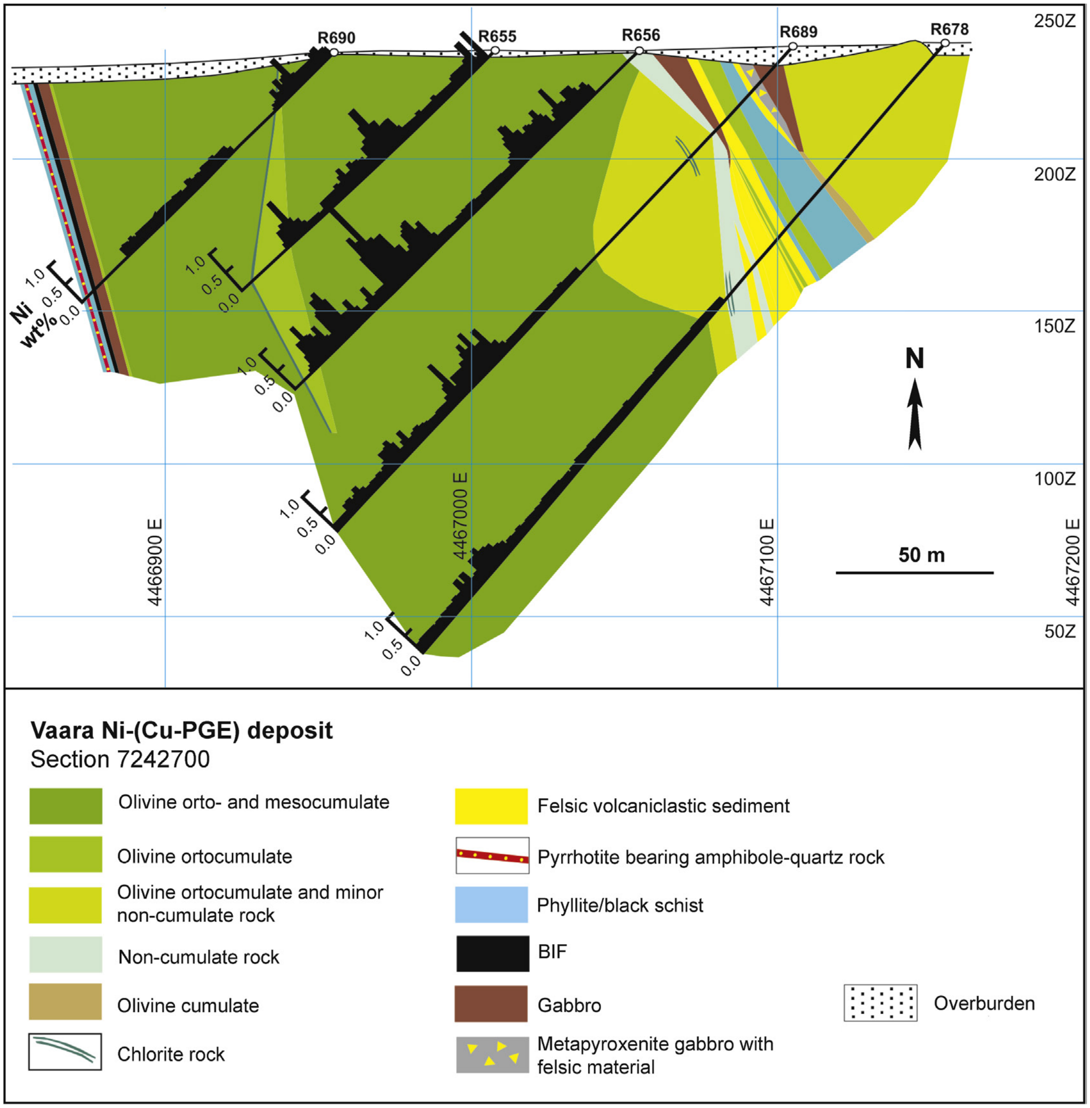

FIGURE 3.2.2 Vertical section of the Vaara ultramafic body, showing variation of whole-rock nickel content in a drilling profile.

Source: *Modified after Luukkonen et al. (2002) and Konnunaho et al. (2013).*

cases, PGE and tellurium minerals have also been found within silicates (notably serpentinized olivine) and oxides (ilmenite and chromite). The most common Pt-bearing mineral is sperrylite $PtAs_2$. Several different Pd-bearing minerals have also been identified (Konnunaho et al., 2013).

During the exploration within the area, GTK also found two small Ni-(Cu-PGE) occurrences called Kauniinlampi North and Kauniinlampi South (Fig. 3.2.1). These occurrences are associated

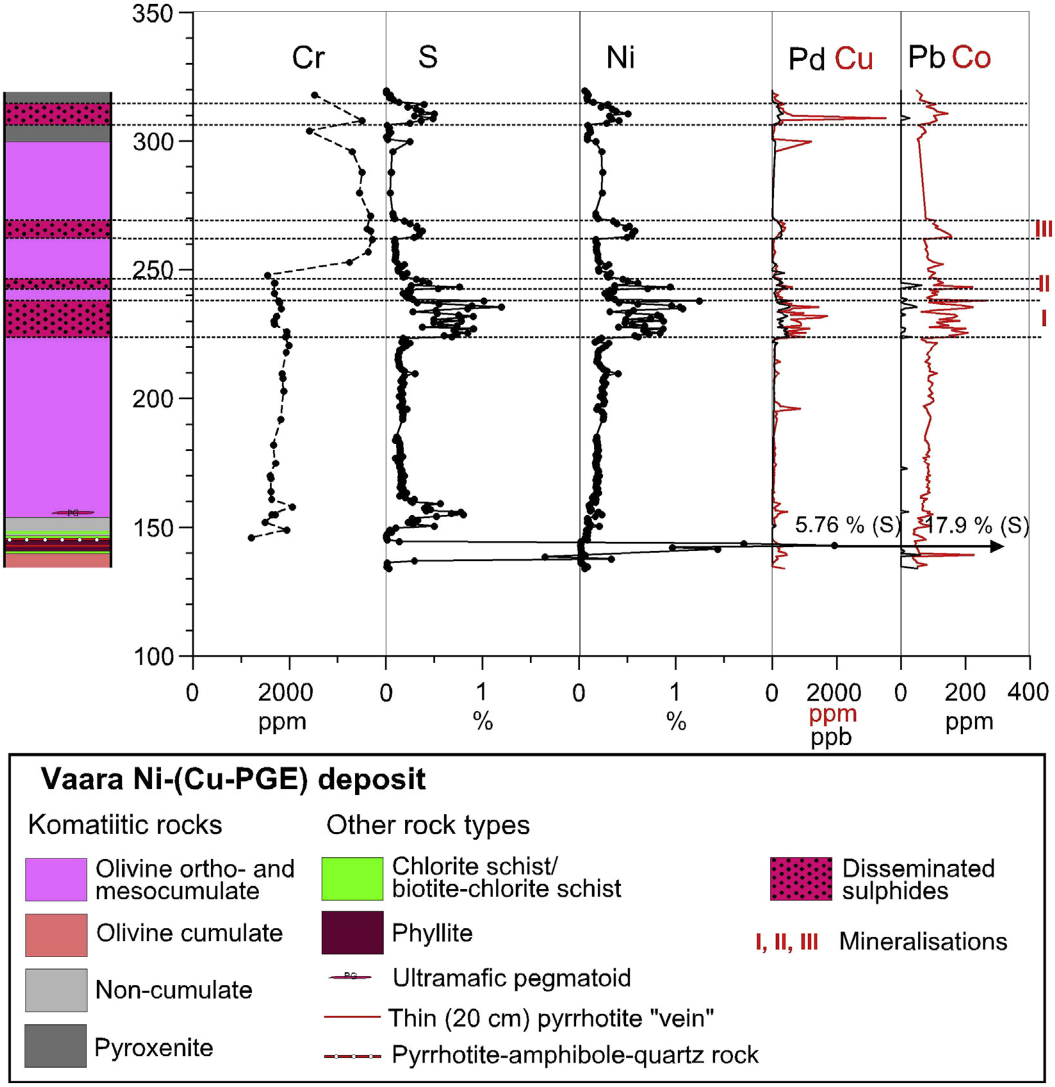

FIGURE 3.2.3 Variation in Cr, S, and chalcophile element concentrations across the Vaara deposit.

Source: *Modified after Luukkonen et al. (2002) and Konnunaho et al. (2013).*

with the Kauniinlampi cumulate body in the Saarikylä area (a few kilometers north of the Vaara cumulate body), which is cut by a shear zone. PGE-enriched sulfides have been remobilized into this zone at Kauniinlampi North. Kauniinlampi South consists of Ni-poor disseminated iron sulfides in the cumulate body. These two occurrences are not economically important, but they provide further evidence for operation of ore-forming processes in the Saarikylä area (Halkoaho et al., 2000a).

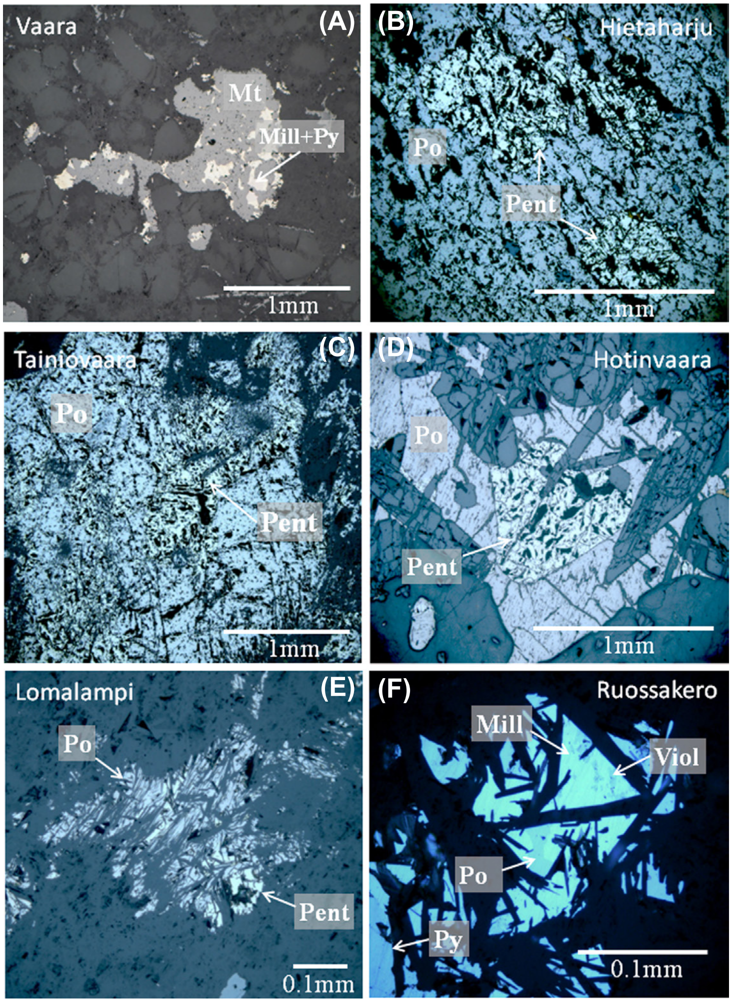

FIGURE 3.2.4 Photomicrographs in reflected light of sulfide aggregates in olivine cumulates from (A) Vaara (disseminated sulfide-magnetite aggregates), (B) Hietaharju (massive sulfides), (C) Tainiovaara (massive sulfides), (D) Hotinvaara (coarse grained sulfide blebs), (E) Lomalampi (disseminated sulfides), and (F) Ruossakero (disseminated sulfides).

Note the extensive replacement of sulfides by magnetite in the Vaara deposit. Abbreviations: Py = pyrite, Mill = millerite, Viol = violarite, Pent = pentlandite, Po = pyrrhotite, Mt = magnetite

GEOLOGY AND KOMATIITES OF THE HIETAHARJU AND PEURA-AHO AREAS

The komatiite-hosted Ni-Cu-PGE sulfide deposits of Peura-aho and Hietaharju are located in the Kiannanniemi area (Fig. 3.2.1 and Table 3.2.1), approximately 13 and 18 km southwest of the Vaara deposit, respectively. The Ni-Cu-PGE deposits occur in metamorphosed olivine-pyroxene cumulates of komatiitic basalt and surrounding schists belonging to the Saarikylä formation. The lithological unit containing felsic and mafic metavolcanic rocks, komatiitic basalts, and interbedded sulfur-bearing metasedimentary rocks (phyllites, black schists, and felsic schists) ranges from 100–150 m in thickness. Komatiitic lava flows and related olivine cumulates also occur in the Kiannanniemi area.

Fine- to medium-grained tremolite-chlorite-(±serpentine) rocks represent komatiitic noncumulates to orthocumulates or pyroxenitic cumulate portions. Komatiitic basalts are mainly massive hornblende-plagioclase rocks. Primary flow structures have been almost completely obliterated, but some well-preserved pillow and variolitic structures were found in outcrops of komatiitic basalts. Komatiitic olivine-pyroxene cumulates were metamorphosed to fine- to medium-grained serpentine-talc-carbonate-chlorite rocks. Talc-carbonate rocks (i.e., soapstones) are common, especially in the Hietaharju area. In some cases, cumulate textures occur in less altered and sheared orthocumulates and pyroxenites.

HIETAHARJU NI-(CU-PGE) DEPOSIT

The Hietaharju Ni-Cu-PGE deposit was found in the early 1960s by Outokumpu Oy. The deposit is mainly composed of disseminated Fe-Ni-Cu sulfides, but massive to semimassive veins and lenses as well as breccias are also present. The deposit is hosted by olivine-pyroxene cumulates of komatiitic basalts (Fig. 3.2.5). It belongs to the type II komatiitic deposits (i.e., stratabound internal), comprising disseminated sulfides mainly in the central part of olivine cumulate bodies. However, Hietaharju also contains some features of type I komatiitic deposits (Lesher and Keays, 2002) (Table 3.2.1). The host unit is approximately 100 m thick and 1 km long. The deposit is north–south trending and has a strike length of ~200 m, a width of 50 m, and a depth of at least 200 m (GTK Mineral Deposit Database, 2014). The deposit consists of several subparallel mineralized horizons or lenses (Fig. 3.2.5) whose thicknesses vary from ~0.5–10 m. The estimated reserves of the Hietaharju deposit are 0.85 Mt of ore at 0.85 wt% Ni, 0.44 wt% Cu, 0.06 wt% Co, 1.25 ppm Pd, and 0.53 ppm Pt (Altona Mining, 2012).

Pyrrhotite, pentlandite, and chalcopyrite are the most abundant sulfide minerals at Hietaharju. Based on Kojonen (1981) and Kurki and Papunen (1985), the ores can be divided into three main types: (1) finely disseminated sulfides and thin veinlets, (2) massive (Fig. 3.2.4(B)), granular sulfides, and (3) brecciated sulfides. Small amounts of sphalerite, cubanite, and mackinawite occur as inclusions in chalcophyrite and pyrite. Marcasite and violarite are common alteration phases. Arsenides (e.g., gersdorffite and cobaltite) are associated with disseminated sulfides in talc-carbonate rocks, and gersdorffite occurs as one of the main ore minerals in the most intensively carbonated parts of the deposit (Kojonen, 1981; Halkoaho and Papunen, 1998).

Gold, tellurides (i.e., Pd- and Bi-bearing tellurides), sperrylite, and other PGMs (platinum group minerals) occur mainly as inclusions in other ore minerals, but they are also found within silicates and oxides. The oxide minerals magnetite, ilmenite, and zoned chromite are common in all rock types, occurring as fine disseminations through the ultramafic body. All ore types contain disseminated magnetite, but in contrast to the Vaara deposit, sulfide replacement by magnetite is rare (Figs. 3.2.4(A,B)). Pyrrhotite, pentlandite, and chalcopyrite represent the primary magmatic sulfide assemblage, which was modified by postmagmatic processes (e.g., formation of Ni-Co arsenides). Massive and brecciated sulfides are probably the result of postmagmatic sulfide mobilization, but some massive lenses at the contact between the ultramafic body and metasedimentary rocks could represent reworked primary massive sulfide accumulations. Having relatively high Pd and Pt concentrations, the Hietaharju deposit belongs to the PGE-rich group of the komatiite-hosted Ni-Cu-PGE deposits in Finland (refer to Table 3.2.1).

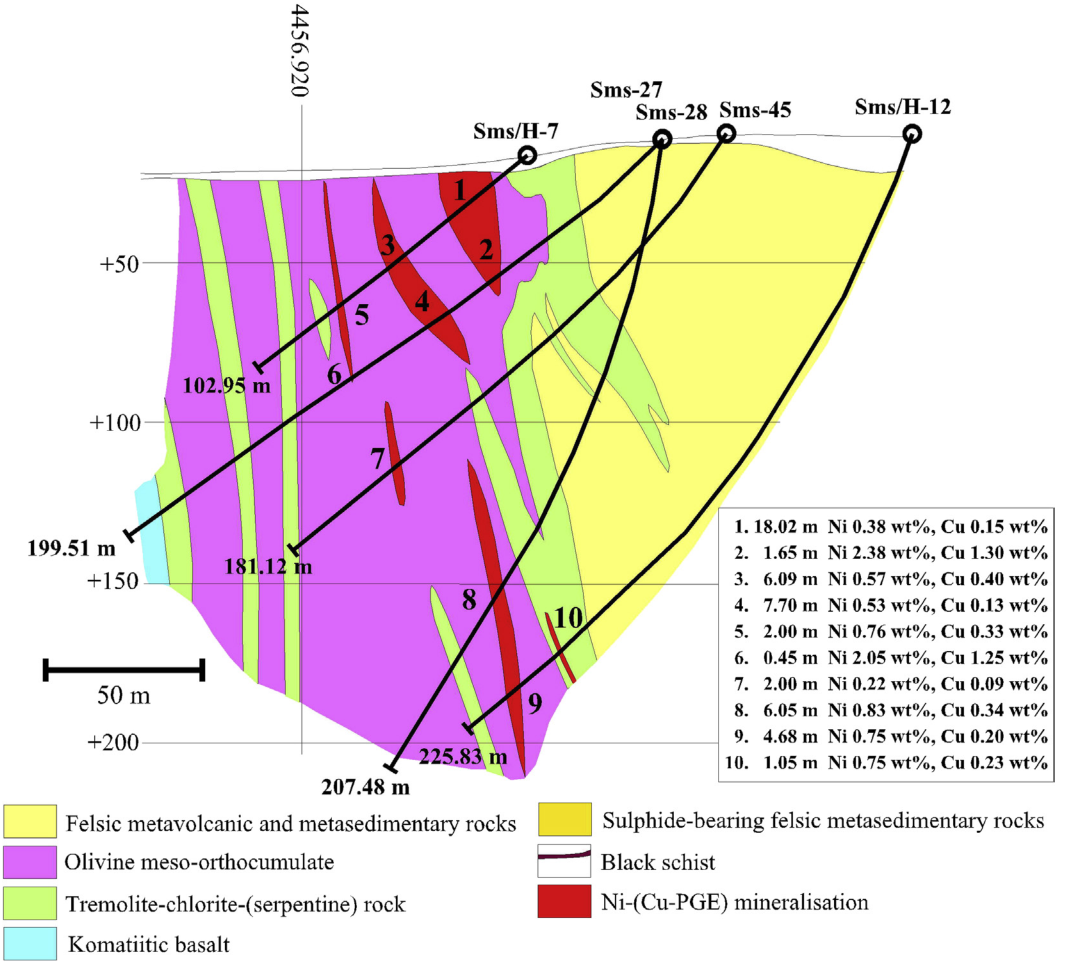

FIGURE 3.2.5 Vertical section of the Hietaharju nickel deposit showing locations of drillcores and their Ni and Cu contents.

Source: *Modified after Kojonen (1981) and Kurki and Papunen (1985). The table shows core lengths and average Ni and Cu contents of intersected sulfide-bearing zones.*

PEURA-AHO NI-(CU-PGE) DEPOSIT

The Peura-aho Ni-Cu-PGE deposit was found during the same exploration activities as the Hietaharju deposit. The Peura-aho area is characterized by an anticlinal structure with the fold axis dipping 65–70° to the east (Kojonen 1981; Kurki and Papunen, 1985) (Fig. 3.2.6). The Peura-aho Ni-Cu-PGE deposit consists of five sulfide-bearing lenses (A–E), whose length varies from ~30–250 m and thickness from ~3–10 m (Kojonen, 1981; Kurki and Papunen, 1985) (Fig. 3.2.6). The ore deposit is approximately 200 m long and 50 m wide on the surface and extends to a depth of at least 150 m (GTK Mineral Deposit Database, 2014). The main mineralized lenses are termed the A and B mineralizations. The disseminated Fe-Ni-Cu sulfides of mineralization A are located in the central part of an olivine ortho- to

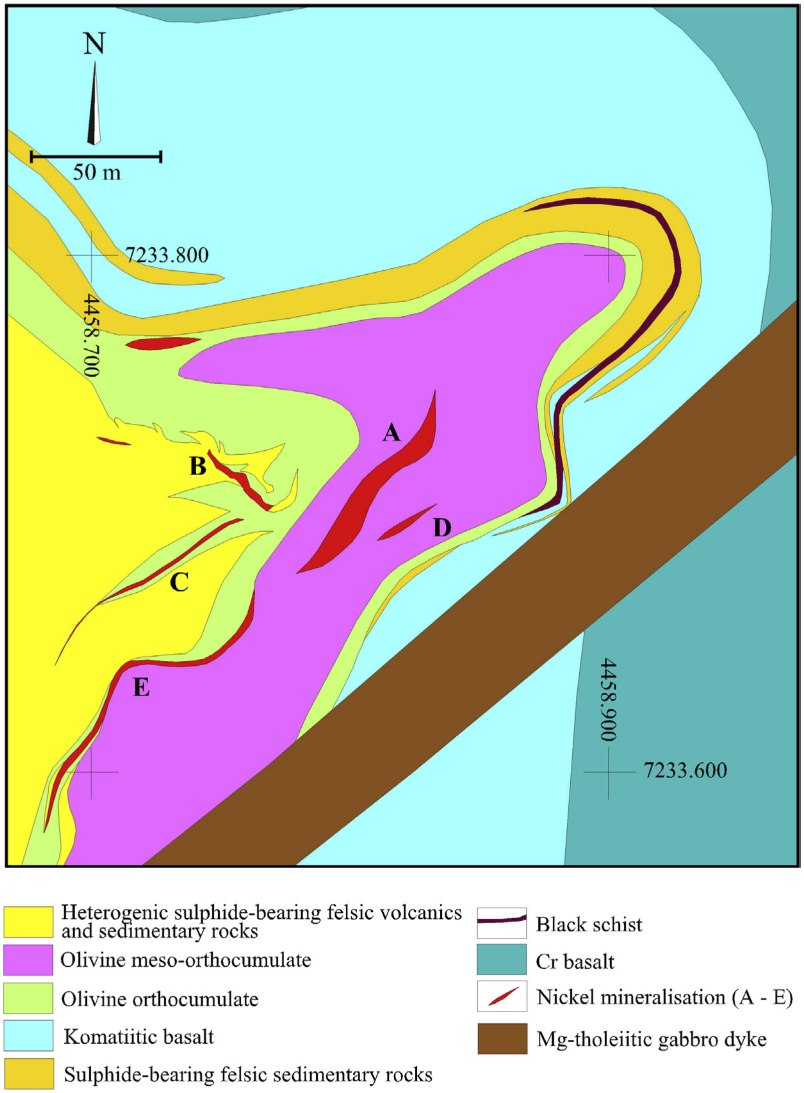

FIGURE 3.2.6 Geological map of the Peura-aho area.

Source: *Modified after Kojonen (1981) and Kurki and Papunen (1985).*

mesocumulate body (serpentinite), whereas massive sulfides of mineralization B are associated with tremolite-chlorite-(± serpentine) rocks, chlorite schists, and/or felsic metavolcanic/metasedimentary rocks. The sulfide disseminations in mineralizations C, D, and E are relatively weak. The disseminated sulfides in the C mineralization occur in tremolite-chlorite-(±serpentine) rocks stratigraphically below the serpentinite lens. Mineralization D occurs in the middle part of the small serpentinite lens and mineralization E in the basal part of a small serpentinite lens between the serpentinite and tremolite-chlorite-(±serpentine) rock or quartz-feldspar schist (Fig. 3.2.6). Mineralizations A, C, D, and E belong to the type II komatiitic deposit, whereas mineralization B represents the type IV (Lesher and Keays, 2002) (Table 3.2.1). The indicated resources of the Peura-aho deposit are 0.40 Mt at 0.63 wt% Ni, 0.29 wt% Cu, 0.04 wt% Co, 0.28 ppm Pt, and 0.62 ppm Pd (Altona Mining, 2012).

According to Kojonen (1981), the massive Ni-Cu-PGE mineralization (B in Fig. 3.2.6) consists mostly of pyrrhotite, pyrite, violarite, and chalcopyrite. Pyrite is euhedral or subhedral and contains marcasite, pyrrhotite, chalcopyrite, and magnetite inclusions. Chalcopyrite is often twinned and consists of lamellae. Pentlandite has mainly been altered to violarite. The disseminated and vein-style Ni-Cu-PGE mineralizations (A, C, D, and E in Fig. 3.2.6) consist mainly of pyrrhotite, pentlandite, and chalcopyrite. The oxides include zoned chromite, fine-grained magnetite, ilmenite, and hematite. Marcasite, mackinawite, and sphalerite are minor phases. Marcasite and violarite are common weathering products of sulfides. Platinum-group minerals are associated mainly with sulfides, analogous to the Hietaharju deposit.

The origin of the sulfides can largely be explained by alteration of primary pyrrhotite, pentlandite, and chalcopyrite. Violarite is a common alteration product of pentlandite. According to Kojonen (1981), it formed at a low temperature through weathering processes. Kojonen (1981) divided the pyrite in the Peura-aho mineralization into three generations: (1) Co-bearing euhedral pyrite in the disseminated A mineralization, (2) Ni-bearing euhedral pyrite in the massive B mineralization, and (3) secondary pyrite formed through weathering of pyrrhotite. The Co-bearing pyrite might be a high temperature mineral. The Ni-bearing pyrite is associated with sulfurization of Fe and Ni released during serpentinization. The secondary pyrite is normally intergrown with marcasite, which formed through weathering of pyrrhotite (Kojonen, 1981). The main difference between the Peura-aho and Hietaharju Ni-(Cu-PGE) mineralizations is that, in the latter, the talc-carbonate rocks contain Ni-Co arsenides. According to Kojonen (1981), this suggests introduction of arsenic by alteration fluids. Massive sulfide mineralizations probably formed as a result of postmagmatic sulfide mobilization, but some massive lenses could represent reworked primary massive sulfide accumulations, analogous to the Hietaharju deposit. Similarly to the Hietaharju deposit, the Peura-aho deposit belongs to the PGE- and Cu-enriched group of the komatiite-hosted Ni-Cu-PGE deposits in Finland (Table 3.2.1).

THE TAINIOVAARA NI-CU-PGE DEPOSIT, EASTERN FINLAND

The Tainiovaara deposit is located ~7 km northeast of the town of Lieksa. A small Archean serpentinite body and associated amphibolites form a greenstone belt relict within Archean tonalite gneisses of the Lieksa complex (GTK, DigiKP, 2014) (Figs. 3.2.1 and 3.2.7). An approximately 180-m-long and 80-m-wide serpentinite lens dips 70° to the west, with its longitudinal axis plunging approximately 35° to the northwest (Pekkarinen, 1980; Vanne, 1981) (Fig. 3.2.7). The Tainiovaara deposit occurs in the central part of the serpentinite lens, consisting mainly of altered olivine mesocumulates (Fig. 3.2.7). During the exploration activities by GTK, several other similar serpentinite bodies were found in the area (Halkoaho and Niskanen, 2004).

The Tainiovaara deposit is approximately 130 m long and 25 m wide and extends to a depth of at least 50 m (Vanne, 1981). It consists mainly of disseminated sulfides (type II komatiitic deposit), but there are also small massive to semimassive and net-textured sulfide accumulations (type I) at the bottom of the serpentinite lens (Vanne, 1981; Papunen, 1989) (Fig. 3.2.7). The major ore minerals are pyrrhotite and pentlandite, and chalcopyrite and pyrite form minor phases. Magnetite, zoned chromite, and ilmenite occur in disseminated form throughout the ore body. The main gangue minerals are serpentine, talc, chlorite, carbonate, and tremolite.

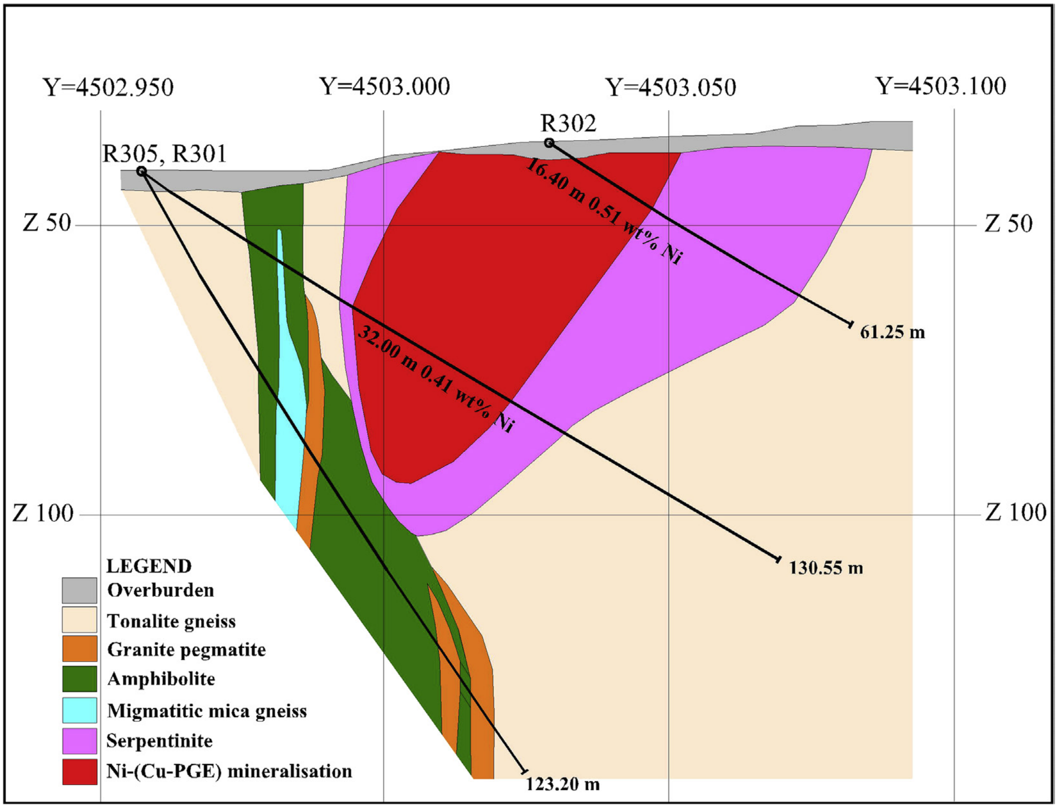

FIGURE 3.2.7 Vertical section of the Tainiovaara nickel deposit, showing locations of drillcores and their Ni content.

Source: *Modified after unpublished figure prepared by L. Pekkarinen.*

The estimated resources of the Tainiovaara deposit are 0.45 Mt at 0.5 wt% Ni, 0.03 wt% Cu, and 0.01 wt% Co (Vanne, 1981). The deposit was mined in 1989 by Outokumpu Oy. The total production was approximately 20,000 t at 1.4 wt% Ni and 0.12 wt% Cu (Puustinen et al., 1995). The deposit still contains 0.43 Mt of unexploited nickel ore. The Tainiovaara deposit is clearly magmatic in origin, as indicated by the magmatic sulfide assemblages, but was modified by postmagmatic processes. This is indicated by minor to moderate sulfide replacement by magnetite, especially in disseminated ore (Fig. 3.2.4(C)). The deposit is enriched in Cu and PGE, but not as much as some of the other Finnish PGE-enriched deposits (e.g., Hietaharju, Peura-aho, Lomalampi, and Vaara) (Table 3.2.1).

NI-CU-PGE DEPOSITS OF THE CENTRAL LAPLAND GREENSTONE BELT

GENERAL GEOLOGICAL SETTING

The Paleoproterozoic Central Lapland Greenstone Belt (CLGB) is one of the largest greenstone belts in the Fennoscandian Shield. The CLGB is generally subdivided into three subdomains (Fig. 3.2.1): (1) Pulju belt, (2) Kolari-Kittilä-Sodankylä belt, and (3) Kuusamo-Salla belt. The volcanic-sedimentary sequence of the CLGB is assigned to seven lithostratigraphic groups deposited on the Archean basement. From the oldest to the youngest these are: (1) Salla, (2) Vuojärvi, (3) Kuusamo, (4) Sodankylä, (5) Savukoski, (6) Kittilä, and (7) Kumpu. These groups have been subdivided into several formations by Lehtonen et al. (1998), Hanski et al. (2011), and Hanski and Huhma (2005). The oldest metavolcanic rocks (Salla group) erupted ~2.45 Ga ago, whereas the youngest metasedimentary rocks of the Kumpu group are younger than ~1.88 Ga (Hanski and Huhma, 2005); thus the geological evolution of the sequence spanned more than 0.5 Ga. The komatiite-bearing Savukoski group has yielded a Sm-Nd age of ~2.06 Ga (Hanski et al., 2011). For a more comprehensive description of the CLGB, the reader is referred to Lehtonen et al. (1998), Hanski et al (2011), and Hanski and Huhma (2005).

THE PULJU BELT

The Paleoproterozoic supracrustal rocks of the Pulju belt cover an area of 10 × 20 km in the northwestern part of the CLGB. The belt can be traced into Norway where it joins the Karasjok greenstone belt (Barnes and Often, 1990) (Fig. 3.2.1). In its lower part, the Pulju belt consists of a metasedimentary unit (quartzites and biotite-hornblende gneisses) and minor mafic metavolcanic rocks (Sietkuoja formation) of the Sodankylä group. The metavolcanic and metasedimentary units in the middle part (Mertavaara formation) of the sequence are associated with komatiitic rocks of the Savukoski group. MgO-rich olivine cumulates are rare in the CLGC, but in the Pulju belt, they are common. These cumulate bodies host the Hotinvaara Ni-(Cu) deposit and some other minor Ni-(Cu) showings. Sulfur-rich metasedimentary rocks (metacherts and calc-silicate rocks) and felsic metavolcanic rocks are among the lithological components of the Mertavaara formation. Komatiites are interbedded with sulfide-bearing metasedimentary rocks and metavolcanic rocks. The metasedimentary unit (paraschists with graphite-bearing interlayers) of the Vittaselkä formation (Savukoski group) forms the uppermost part of the stratigraphical succession in the Pulju belt (Inkinen et al., 1984; Papunen, 1998; DigiKp, 2014) (Figs. 3.2.8 and 3.2.9).

The komatiitic rocks of the Pulju belt were subdivided into two groups (Papunen, 1998): (1) nondifferentiated komatiitic lava flows (i.e., tremolite-chlorite rocks) without significant cumulate portions, and (2) differentiated komatiitic lava flows with extensive cumulate bodies (i.e., tremolite-chlorite-serpentine rocks to serpentinites and olivine rocks). Nondifferentiated komatiitic lava flows occur as independent layers together with mafic metavolcanic rocks of the Mertavaara formation. These rocks are characterized by well-preserved primary structures including volcanic breccias, pillows, and tuffogenic layering. They have been correlated with similar komatiites in the Sattasvaara formation of the Savukoski group (Lehtonen et al., 1998) and the Karasjok greenstone belt (Barnes and Often, 1990). Deviating from the stratigraphic position of the nondifferentiated lava flows, differentiated komatiitic lava flows occur in association with S-bearing metasediments and calc-silicate rocks occurring in the lower parts of the Mertavaara formation. Differentiated lava flows are typically coarse-grained and less foliated than nondifferentiated lava flows. Primary magmatic textures have not been recognized in differentiated lava flows. The gradual change from tremolite-chlorite-serpentine rocks to pure serpentinites indicates internal differentiation of flow units into A and B zones. In some places, tremolite-chlorite rocks occur as interbeds within sulfide-bearing metasediments and irregular masses within cumulates (Papunen, 1998).

Komatiites and associated supracrustal rocks were folded and sheared in at least four deformation phases and affected by hydrothermal alteration in several stages (Papunen, 1998). Relicts of an olivine spinifex texture were discovered in one drillcore in the Hotinvaara area (Papunen, 1998). The olivine

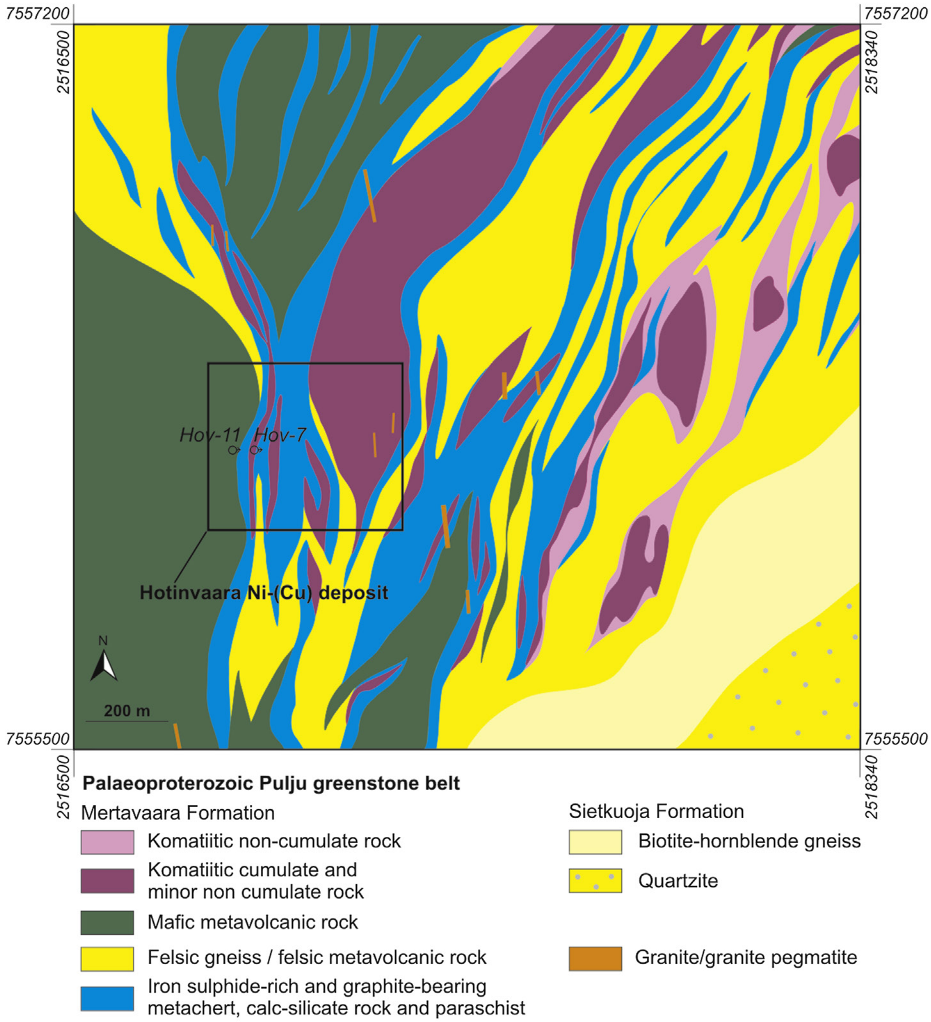

FIGURE 3.2.8 Geological map of the Hotinvaara area and location of the drilling profiles shown in Fig. 3.2.9.

Source: *Modified after Inkinen et al. (1984)*.

cumulates are very heterogeneous, medium- to coarse-grained rocks, in which primary magmatic minerals and textures are not preserved. The cumulate portion consists of various serpentine-chlorite-tremolite rocks (±carbonate-talc) to almost pure olivine rocks (i.e., metadunites and metaperidotites). The metaperidotites contain metamorphic olivine, phlogopite, and pyroxenes. Accessory opaque minerals include chromite, magnetite, ilmenite, and Fe-Ni-Cu sulfides. Some chromite grains with an irregular form and without typical magnetite rims are also interpreted to be of metamorphic origin. Magnetite occurs as a fine-grained dissemination and dust, or forms crosscutting veinlets. Some magnetite was produced by oxidation of sulfides (Papunen, 1998).

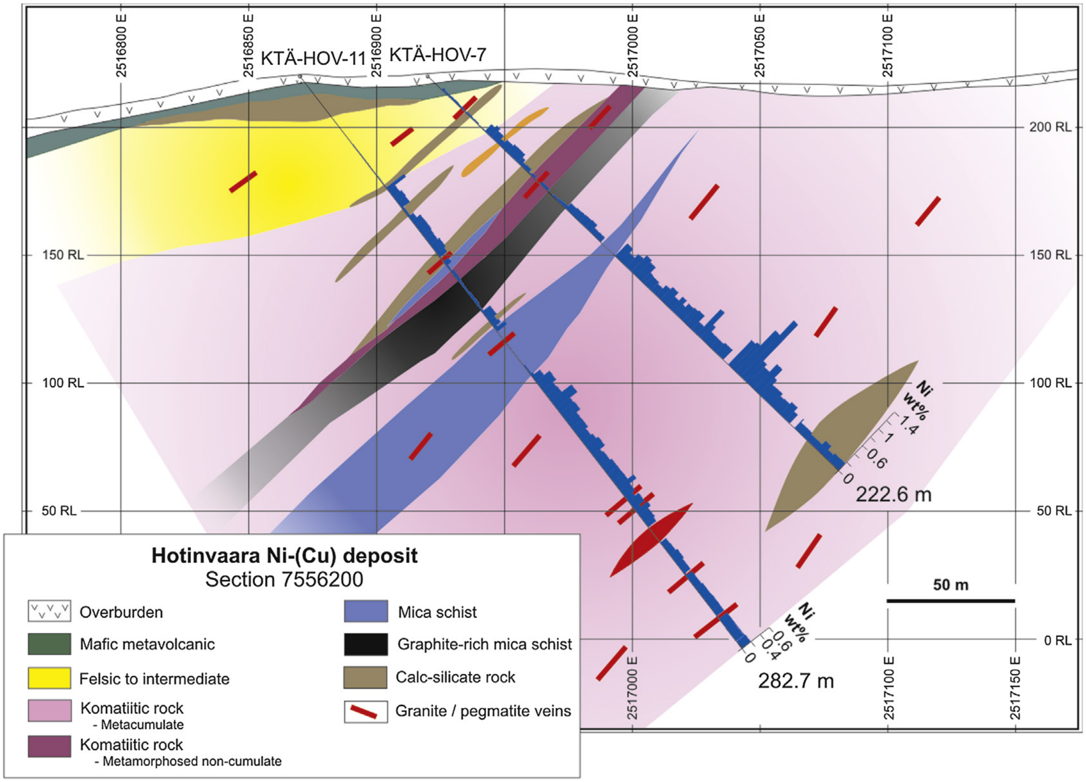

FIGURE 3.2.9 Vertical section of the Hotinvaara ultramafic body, showing locations of drillcores and their Ni content (see Fig. 3.2.8 for the location of the section).

HOTINVAARA NI-(CU) DEPOSIT

The Hotinvaara Ni-(Cu) mineralization was discovered as a result of exploration carried out by Outokumpu Oy in the early 1980s (Inkinen et al., 1984). Exploration activities of the company were mainly focused on an approximately 6-km-long and 1.3-km-wide zone in the Hotinvaara and Mertavaara areas where the komatiitic cumulates are most abundant. There are also other Ni-(Cu) occurrences (e.g., Mertavaara and Siettelöjoki) in the Pulju belt, but they are economically insignificant (Inkinen et al., 1984).

The Hotinvaara deposit is composed mainly of disseminated Fe-Ni-Cu sulfides and belongs to the type II komatiitic mineralization, but massive to semimassive sulfides (type I) have also been found in some drillcores. The Ni-(Cu) mineralization is hosted by strongly metamorphosed komatiitic olivine cumulates associated with differentiated komatiitic lava flows (Figs. 3.2.8, 3.2.9, and Table 3.2.1). In places, Ni-bearing iron sulfides associated with surrounding schists represent the type IV mineralization. The olivine cumulate body that hosts the mineralization is approximately 1.6 km × 1 km in size. Ni-(Cu) mineralization is roughly north–east trending and has been followed by drilling in a zone i.e., ~200 m long along strike, ~200 m wide, and ~200 m deep below the surface. The disseminated mineralization occurs in several subzones without any sharp contacts (Fig. 3.2.9). Massive to semimassive sulfides occur at the basal contact of the cumulate pile or close to the contact between the cumulates and intervening sediments. The preliminary feasibility study of the Hotinvaara deposit performed by Outokumpu Oy indicated Ni resources of 0.3 Mt ore at 0.66 wt% Ni (Inkinen et al., 1984).

Hexagonal pyrrhotite and pentlandite are the most abundant sulfide minerals at Hotinvaara. Pyrrhotite occurs as coarse and roundish grains or as a fine-grained dissemination. Monoclinic pyrrhotite occurs at the margins of, and in cracks within, hexagonal pyrrhotite grains. Pentlandite is associated with pyrrhotite and often occurs as individual coarse grains or as fine-grained dissemination and flames within pyrrhotite. Some of the sulfides, especially coarse-grained pentlandite and pyrrhotite, were formed by recrystallization of primary sulfides. Chalcopyrite, mackinawite, gersdorffite, troilite, and vallerite are accessory sulfides, and most of the Ni-rich sulfides are alteration products of pentlandite. Molybdenite and sphalerite have also been identified in mineralized samples (Sotka, 1984, 1986).

The chalcopyrite-poor and pyrrhotite-pentlandite-rich sulfide assemblage of the Hotinvaara mineralization is mainly a result of hydrothermal alteration, metamorphic recrystallization, and postmagmatic oxidation. Some disseminated and massive sulfides might be magmatic in origin (Papunen, 1998), but this question has not been investigated sufficiently. Only minor sulfide replacement by magnetite occurs in the Hotinvaara deposit (Fig. 3.2.4(D)). Platinum-group minerals have not been observed. Measured PGE abundances are very low and hence the deposit belongs to the PGE-poor group of the komatiite-hosted Ni-Cu-PGE deposits in Finland (Table 3.2.1).

GEOLOGICAL SETTING OF THE LOMALAMPI AREA

The Lomalampi deposit is located in the northern part of the Kittilä-Sodankylä belt (Fig. 3.2.1). In the Lomalampi area, the bedrock is mostly composed of metasedimentary rocks belonging to the Matarakoski formation (Savukoski group) and various types of ultramafic (komatiitic to komatiitic basalts) volcanic and cumulate rocks of the Peurasuvanto formation (Savukoski group). Minor olivine cumulates are associated with thin (~5–10 m thick) volcanic flows, but mostly they occur as sheet-like cumulate bodies up to several tens of meters in thickness that can be traced for 500–1500 m along strike.

KOMATIITES OF THE LOMALAMPI AREA

Based on drillcore data, komatiitic volcanic rocks are widespread in the Lomalampi area. Most common are fragmental rocks (hyaloclastites, tuffs, breccias) and relatively thin (3–10 m) flows. Macroscopically, they are mostly fine-grained, massive rocks composed of amphibole and chlorite with biotite present in more strongly altered rocks. Hyaloclastites and some other fragmental komatiites have preserved their original textures, but generally, primary textures of the volcanic rocks are destroyed or obscured by alteration and shearing.

Four significant massive komatiitic cumulate bodies occur in the Lomalampi area. The rocks are composed of serpentine-chlorite ± talc ± amphibole, with locally developed talc ± carbonate rocks. Original cumulus olivine is replaced by serpentine, while the interstitial material was altered to chlorite ± amphibole. Based on locally well-preserved textures, the cumulate rocks were originally olivine orthocumulates, which locally grade into mesocumulates. Olivine pseudomorphs show rounded to elongate habits with the average grain size varying between 0.5 and 1.0 mm. Poikilitic textures are locally preserved where original pyroxene oikocrysts are replaced by amphibole, and olivine inclusions by serpentine.

LOMALAMPI PGE-(NI-CU) DEPOSIT

The Lomalampi PGE-Ni-Cu deposit was discovered in 2004 by the Geological Survey of Finland. It is composed mainly of disseminated sulfides and classified as a type II komatiitic deposit (i.e., stratabound internal). Geochemically, it is an unusual type of mineralization, being enriched in Pt and Pd but containing relatively low concentrations of base metals (Ni, Cu, Co) (Table 3.2.1). The mineralization is hosted by a 30–65-m-thick, northeast–southwest trending olivine cumulate body, and it has been traced by drilling for ~550 m along the strike and to a maximum depth of 130 m. The deposit typically consists of one to three, several-meter-thick zones with 0.5–2.0 ppm Pt + Pd within a wider zone (up to 40 m) of weakly mineralized rock (0.1–0.5 ppm Pt + Pd) (Figs. 3.2.10 and 3.2.11) (Törmänen et al., 2010; Törmänen et al., *in preparation*). The mineralized zone usually occurs in the lower or middle part of the host cumulate, but it can also occur at the upper contact of the cumulate (Figs. 3.2.10 and 3.2.11). The preliminary mineral resource estimate published by GTK contains (at 0.3 ppm Pt cutoff) 1.05 Mt at 0.21 wt% Ni (including some silicate bound Ni), 0.078 wt% Cu, 0.42 ppm Pt, 0.19 ppm Pd, and 0.1 ppm Au (Koistinen and Heikura, 2010; Törmänen et al., 2010).

Disseminated sulfides occur as lobate to irregular grains and grain aggregates <0.1–0.5 mm in size, located in the interstitial space between altered olivine grains. In more sulfide-rich samples, recrystallized sulfide blebs can be up to 5 mm in size. Pyrrhotite is by far the most abundant sulfide phase, whereas pentlandite and chalcopyrite are subordinate (Fig. 3.2.4(E)). Arsenic-bearing samples contain

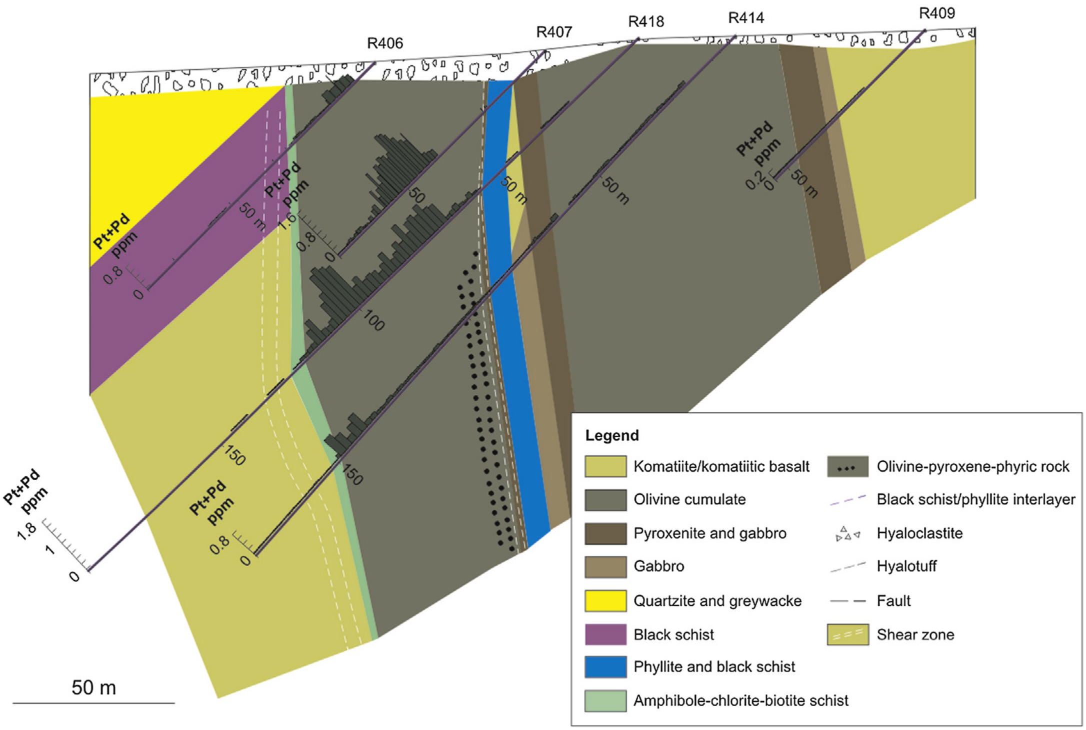

FIGURE 3.2.10 Vertical section of the Lomalampi deposit showing the mineralized and barren cumulate bodies and Pt + Pd contents in drillcores.

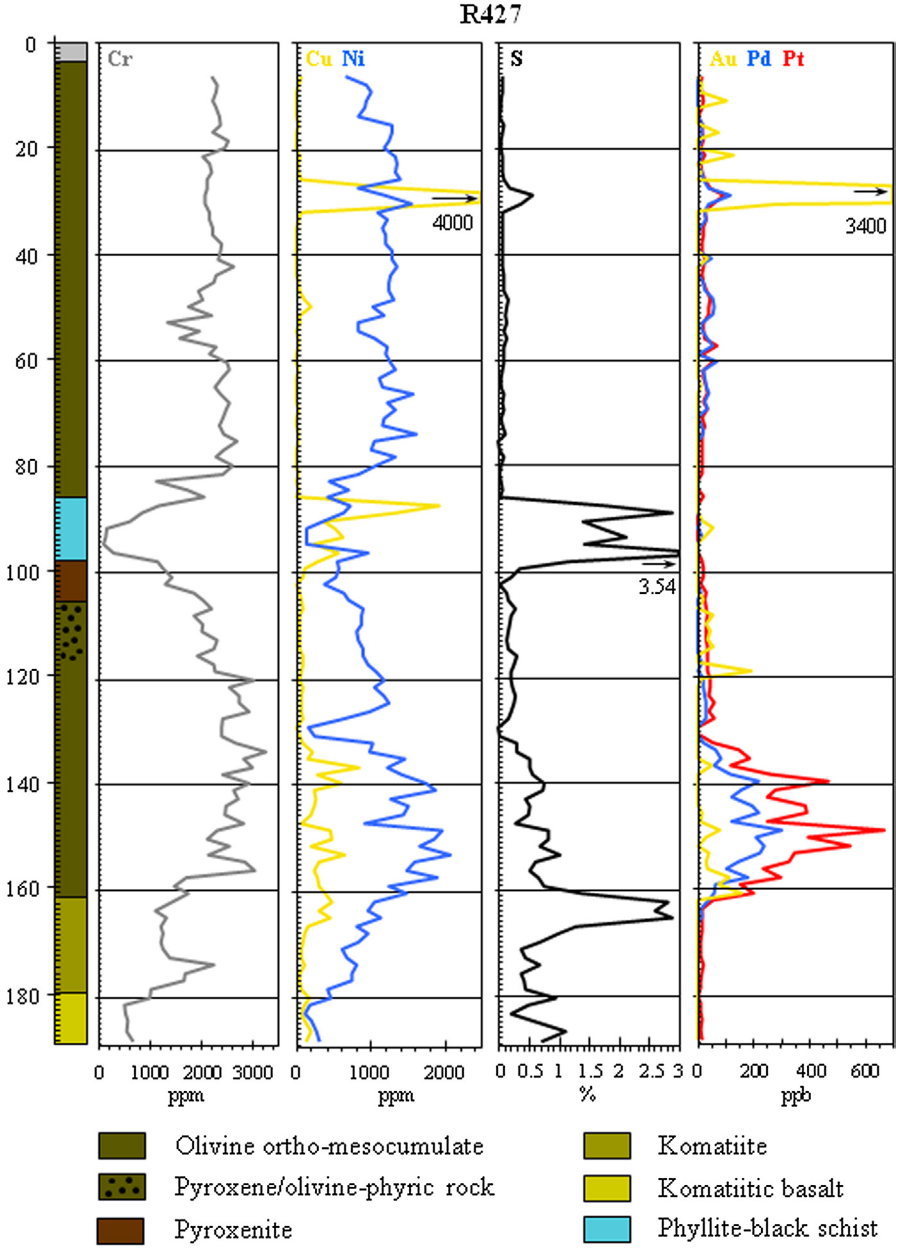

FIGURE 3.2.11 Variation of Cr, Ni, Cu, S, Au, Pd, and Pt contents across the barren and mineralized cumulate bodies in drillcore R427 from the Lomalampi deposit.

some sulfarsenides and nickeline grains. Other trace phases include pyrite, millerite, sphalerite, galena, and molybdenite.

Platinum-group minerals occur as small (<10 μm) grains associated with secondary silicates, base metal sulfides (mostly pyrrhotite and pentlandite), MeAsS-MeAs phases, oxides (magnetite, chromite), and carbonates. The only significant Pt-bearing phase is sperrylite, which occurs mostly with silicates (80%), and in lesser amounts in sulfides (8%) and oxides (8%). Palladium occurs as Pd- and Bi-bearing melonite—$(Ni, Pd)(Te, Bi)_2$—and as two unnamed Pd-Ni-Te-Sb ± Bi phases. The main host phases for Pd-minerals are silicates (~50%) and sulfides (39%), but the situation varies greatly between individual samples; the percentage of Pd-phases hosted by sulfides varies from 18–72 (Törmänen et al., *in preparation*).

The Lomalampi deposit belongs to the PGE-rich group of komatiite-hosted Ni-Cu-PGE deposit in Finland (i.e., it is a PGE-(Ni-Cu) deposit) (Table 3.2.1). It is magmatic in origin, but the high PGE content coupled with the low Ni-Cu-Co content is an unusual feature for komatiite-hosted Ni-Cu-PGE deposits worldwide.

NI-(CU) DEPOSITS OF THE ENONTEKIÖ-KÄSIVARSI AREA

The Archean Ropi terrane (referred to as Rommaeno complex) is located in the northwestern corner of Finland (Fig. 3.2.1) and northern Sweden. Reviews of the general geology of the area have been published by Bergman et al. (2001) and Sorjonen-Ward and Luukkonen (2005). The terrane is separated from the Karelian domain by the Karesuando-Arjeblog deformation zone and several Svecofennian granitoids (Bergman et al., 2001; Sorjonen-Ward and Luukkonen, 2005). On the western side, it is covered by the Caledonides. The Ropi terrane consists mainly of Archean supracrustal rocks surrounded by gneissose granitoids. Bodies of Archean felsic intrusive rocks also occur in the area (Bergman et al., 2001). Archean rocks are locally covered unconformably by Paleoproterozoic supracrustal rocks (e.g., Lätäseno group). The unconformity between the Archean and Paleoproterozoic rocks served as a zone where 2.5–2.4 Ga mafic intrusions (e.g., Tsohkoaivi and Kelottijärvi intrusions) were injected. The Archean supracrustal belts are characterized by the presence of komatiitic rocks, but so far only few studies of the Archean rocks from the area have been published (e.g., Heggie et al., 2013).

In recent geological interpretations by the Geological Survey of Finland (DigiKP, 2014), the Archean Rommaeno complex was divided into four formations (from oldest to youngest): Vuoskujoki, Ruossakero, Aatsakuru, and Pailuajärvi. These formations consist of metasedimentary and metavolcanic schists and belong to the Ropi group. The Vuoskujoki formation consists predominantly of sulfide-bearing, felsic to intermediate metatuffs with a U-Pb zircon age of ~2.93 Ga (in the felsic rocks) (GTK, unpublished data). This age is close to the U-Pb zircon age (2.95 Ga) of felsic metavolcanites from the Luoma formation in the Suomussalmi greenstone belt (Huhma et al., 2012). The Ruossakero formation consists of mafic and ultramafic metavolcanic rocks (komatiites) with BIF interlayers in the former (Fig. 3.2.12). It includes thick komatiitic olivine and olivine-pyroxene cumulates and thin lava flows, and minor amounts of komatiitic basalts. The Ruossakero and Sarvisoaivi Ni-(Cu) deposits occur within this formation.

The Aatsakuru formation consists of reworked sulfide-bearing felsic to intermediate metavolcanic rocks. U-Pb zircon data show that the age of these rocks is ~2.76 Ga (GTK, unpublished data). The uppermost part of the stratigraphic sequence comprises metasedimentary rocks such as sericite and fuchsite quartzites, and conglomerates of the Pailuajärvi formation. There is probably a hiatus between the Ruossakero and Aatsakuru formations.

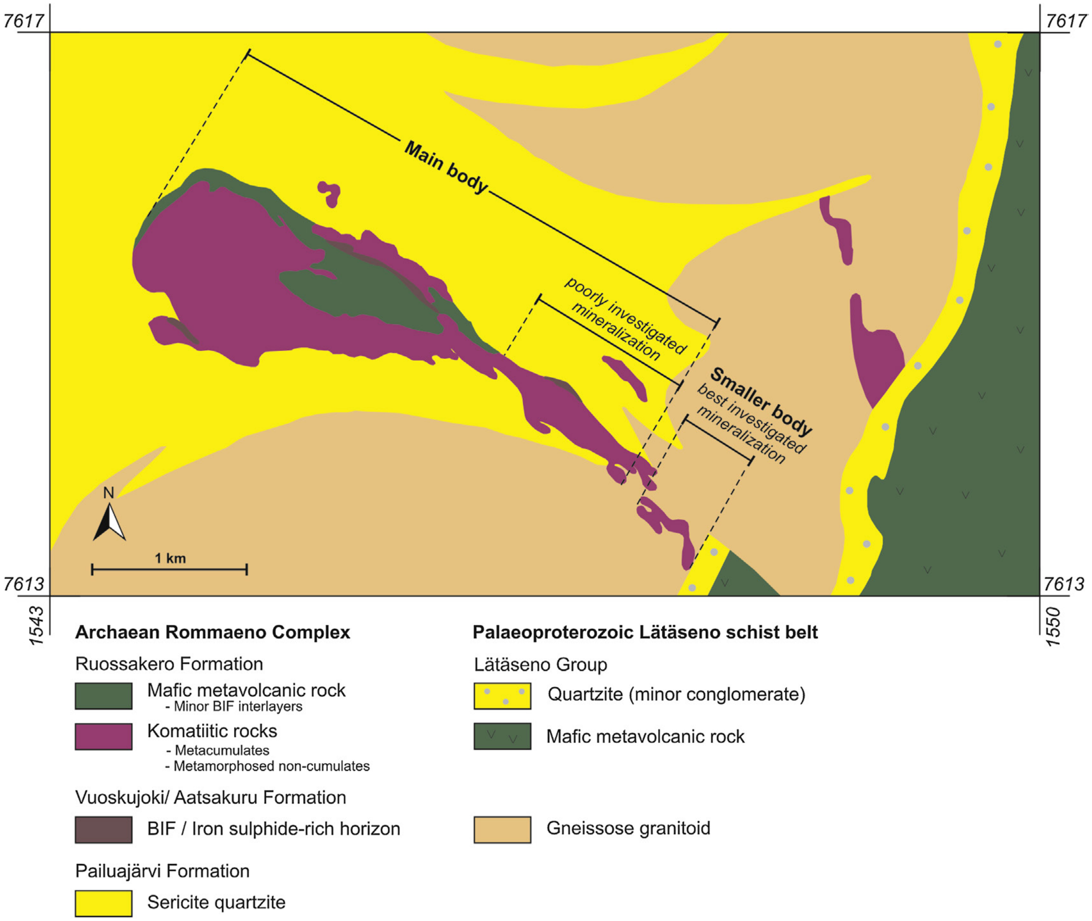

FIGURE 3.2.12 Geological map of the Ruossakero area.

Source: *Modified after Isomaa (1988)*.

GEOLOGY AND KOMATIITES OF THE RUOSSAKERO AND SARVISOAIVI AREAS

The Ruossakero komatiitic body is one of the largest ultramafic lenses in the Archean Rommaeno complex (Figs.3.2.1 and 3.2.12). On the surface, the lens is ~7 km long and 500 m to 3 km wide. The whole ultramafic body and adjacent supracrustal rocks are folded in a complicated manner and there is a major shear zone at the northern contact of the ultramafic body. Isomaa (1988) divided the lens into two parts: (1) the main body and (2) the smaller body. According to the geological interpretation of the area, the main body is surrounded by Archean metasedimentary and metavolcanic rocks and the smaller body is located within Archean granitoids close to the contact of the Paleoproterozoic Lätäseno schist belt. The mafic metavolcanic rocks of the Ruossakero formation are associated with the Ruossakero main body and these include sulfide-bearing schist layers, which might be equivalents to the BIF interlayers or sulfide-bearing volcanic rocks of the Vuoskujoki or Aatsakuru formations. Minor amounts of

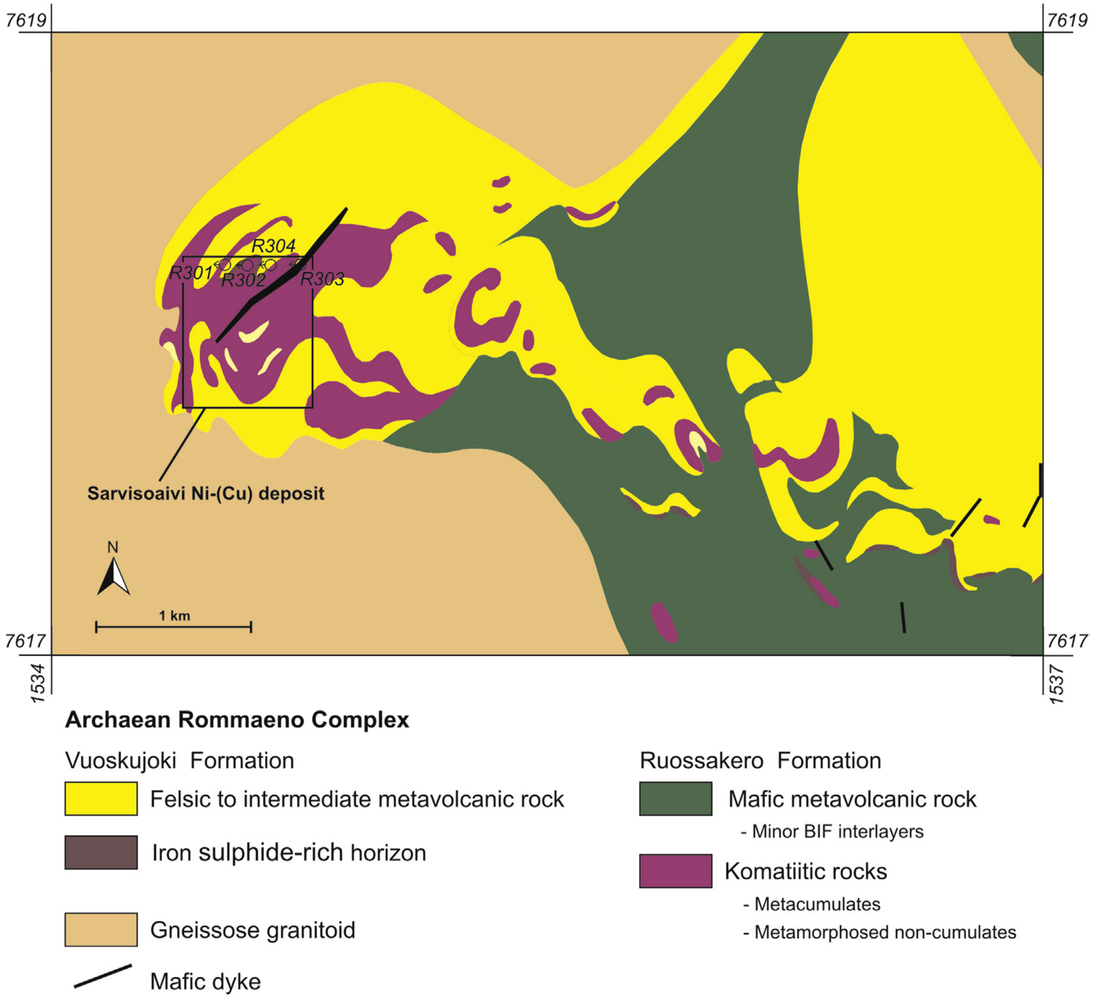

FIGURE 3.2.13 Geological map of the Sarvisoaivi area and location of the drilling profiles shown in Fig. 3.2.14.

Source: *Modified after Isomaa (1982).*

komatiitic lavas (tremolite-chlorite rocks) are also associated with the Ruossakero main and smaller cumulate bodies.

The Sarvisoaivi komatiitic body is located ~9 km west of the Ruossakero komatiitic body in the western corner of the Archean greenstone belt within the Rommaeno complex (Figs. 3.2.1 and 3.2.13). Komatiitic bodies in the Sarvisoaivi area can be divided into the main mineralized body and smaller unmineralized bodies on the eastern side of the main body (Fig. 3.2.13). The main body is complexly folded and cut by several shear zones (Isomaa, 1982).

The Sarvisoaivi komatiitic bodies are surrounded by Archean felsic to intermediate metavolcanic rocks of the Vuoskujoki formation and mafic metavolcanic rocks of the Ruossakero formation.

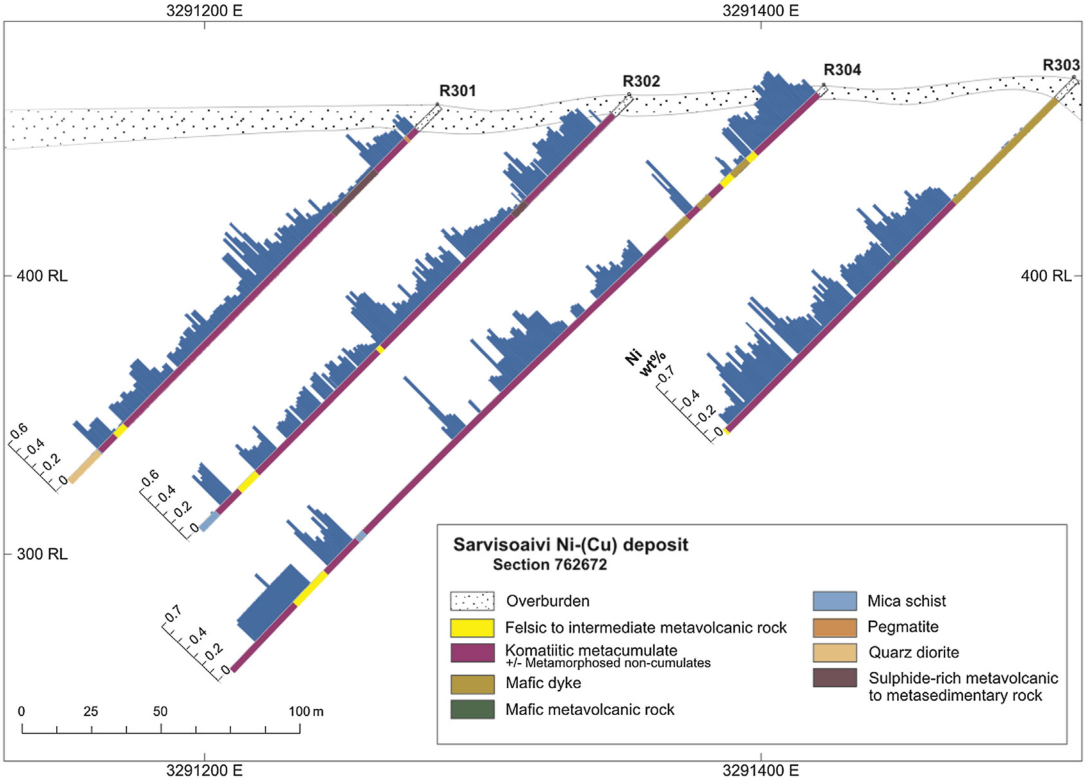

FIGURE 3.2.14 Vertical section of the Sarvisoaivi ultramafic body showing whole-rock Ni contents in drillcores (see Fig. 3.2.13 for the location of the section).

The metavolcanic rocks of the Vuoskujoki formation are rich in iron sulfides. Minor amounts of metasedimentary rocks (e.g., quartzites) of the Pailuajärvi formation also occur in the area. Thin zones of tremolite-chlorite rock are associated with the Sarvisoaivi ultramafic bodies. In the eastern part of the Sarvisoaivi area, they also occur as small lenses within metavolcanic and metasedimentary rocks (Fig. 3.2.13).

In the Ruossakero and Sarvisoaivi areas, komatiitic rocks consist of homogenous, massive, and medium- to coarse-grained metamorphosed peridotites and dunites, as well as minor pyroxenites within dunites. The rocks were metamorphosed at amphibolite facies conditions, and the primary silicates have been replaced mainly by serpentine as well as chlorite, amphibole, talc, and carbonate. They commonly contain olivine and pyroxene of metamorphic origin. Despite the pervasive alteration, primary cumulus textures can still be recognized locally in ultramafic cumulates. Some ultramafic cumulates display a serpentine- and talc-pseudomorphed texture that resembles a spinifex texture, but it is metamorphic in origin. Snoken and Calk (1978) have called this kind of texture *jackstraw texture*.

The presence of metamorphic olivine and pyroxene is a characteristic feature in the Sarvisoaivi and Ruossakero cumulates. Large olivine grains are often zoned (Isomaa, 1982). In some places,

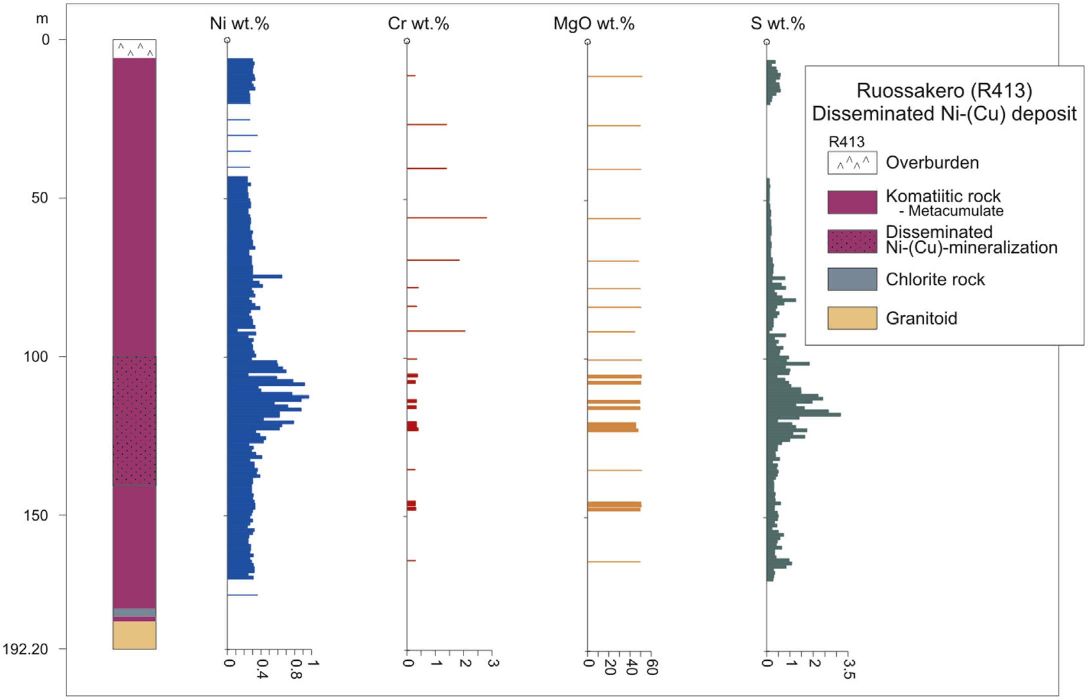

FIGURE 3.2.15 Variation of Ni, Cr, MgO, and S across the Ruossakero mineralized cumulate body in drillcore R413.

metamorphic pyroxene occurs as large (Ø >1 cm) grains poikilitically enclosing metamorphic olivine and other metamorphic silicates. Accessory opaque minerals include chromite, magnetite, ilmenite, and Fe-Ni-Cu sulfides. Thin zones of tremolite-chlorite rock are associated with the contact zone of the Ruossakero and Sarvisoaivi ultramafic bodies. In the Sarvisoaivi area, they also occur as small lenses within metavolcanic rocks. The komatiites that represent noncumulates contain variable proportions of amphibole (tremolite), chlorite, serpentine, and metamorphic olivine.

RUOSSAKERO AND SARVISOAIVI NI-(CU) DEPOSITS

The Sarvisoaivi deposit was discovered during a drilling program of the Geological Survey of Finland in 1978 and the Ruossakero deposit was discovered in 1980. Both deposits are composed of disseminated Fe-Ni-Cu sulfides hosted by metamorphosed Cr-poor komatiitic olivine cumulates (Figs. 3.2.14 and 3.2.15). The deposits belong to the type II komatiitic mineralization of Lesher and Keays (2002) (i.e., stratabound internal), comprising disseminated sulfides mainly in the central part of an olivine cumulate body (Figs. 3.2.14 and 3.2.15). Disseminated sulfide mineralization has been found in several distinct subzones in both deposits (Korhonen, 1981; Isomaa, 1982, 1986, 1988).

At Ruossakero, the smaller komatiitic body hosts the most thoroughly investigated mineralization. It is roughly west–east trending, extending for ~340 m along the strike. It is 100 m wide and 50–100 m

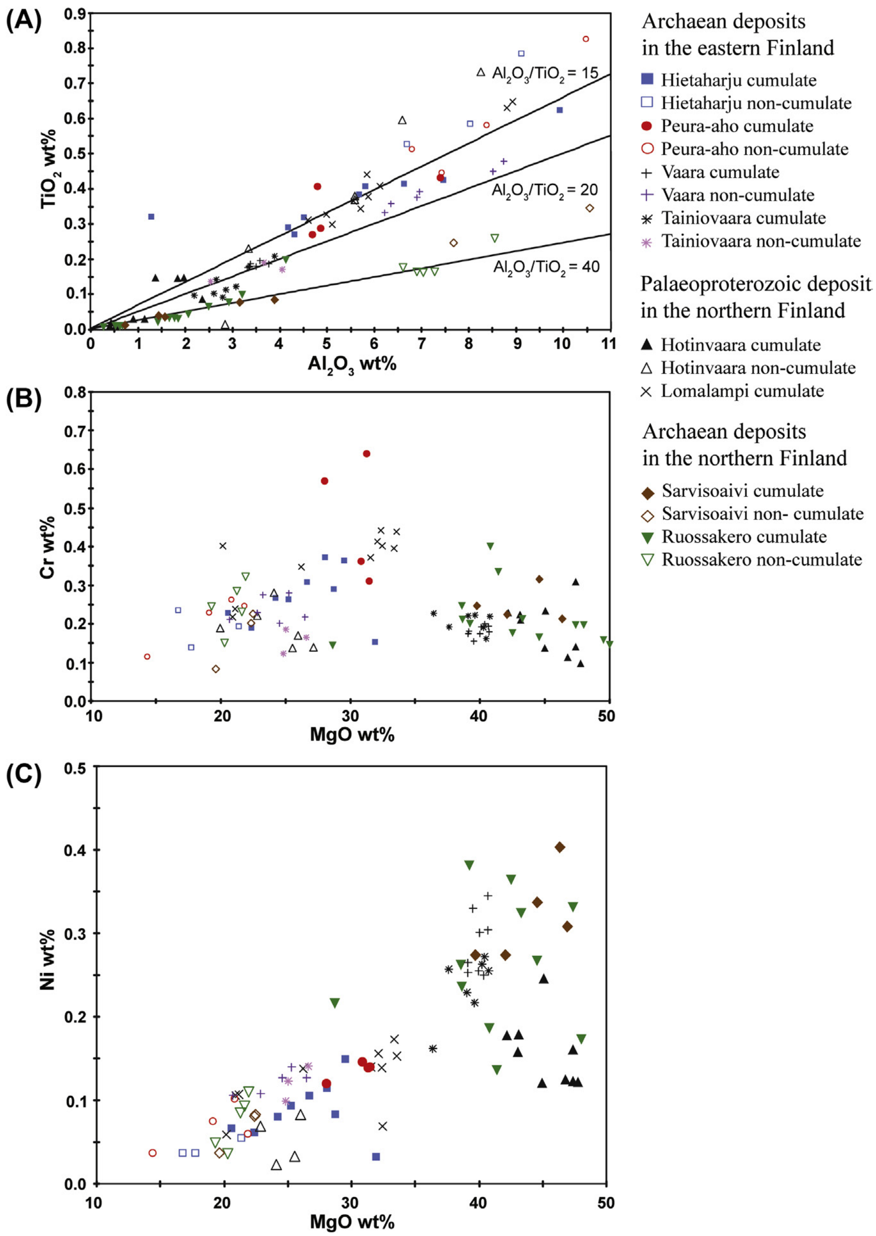

FIGURE 3.2.16 Variation diagrams for (A) TiO_2 versus Al_2O_3, (B) Cr vs. MgO, and (C) Ni vs. MgO for unmineralized komatiitic cumulate and noncumulate rocks.

Source: *From the Hietaharju, Hotinvaara, Lomalampi, Peura-aho, Ruossakero, Sarvisoaivi, Tainiovaara, and Vaara deposits.*

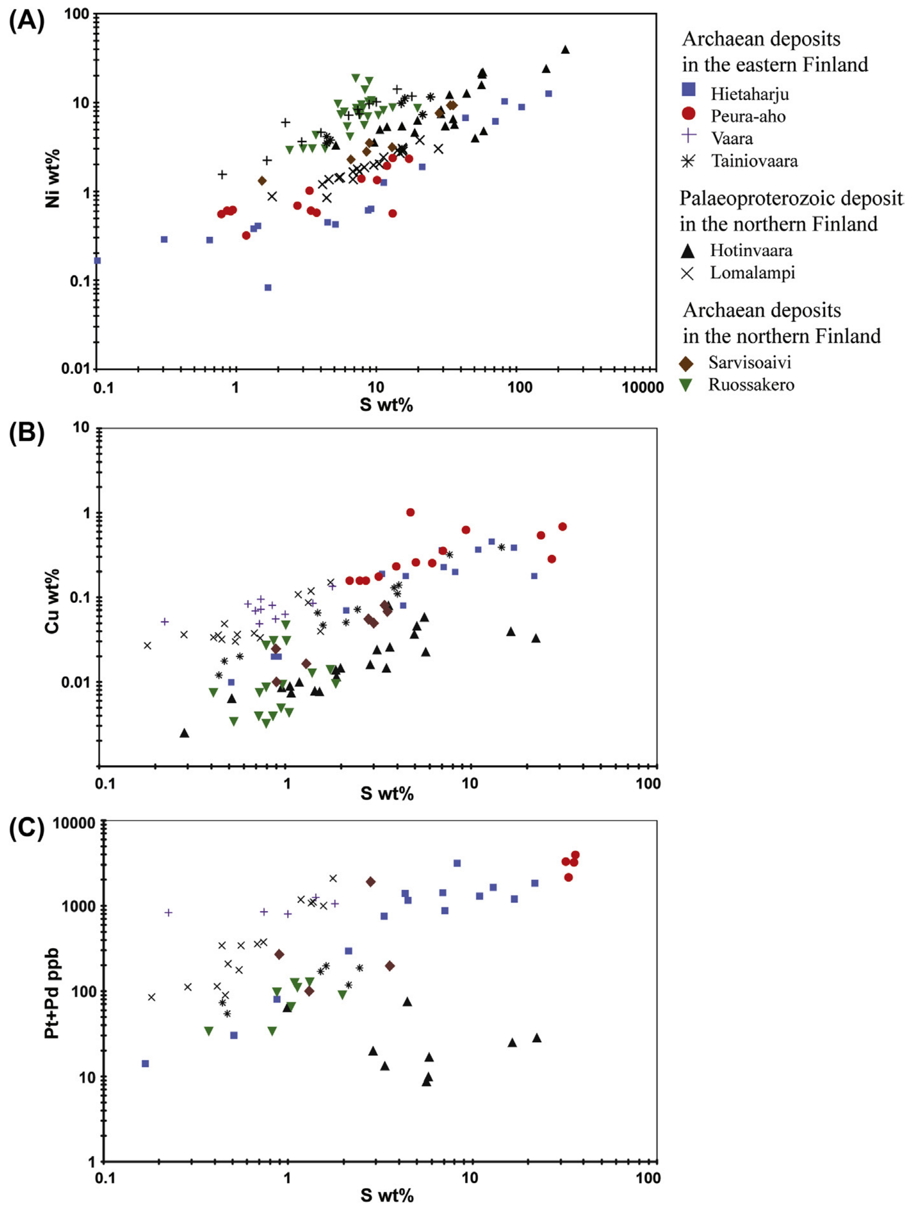

FIGURE 3.2.17 Plots of (A) Ni vs. S, (B) Cu vs. S, and (C) Pt + Pd vs. S for mineralized komatiitic cumulate samples.

Source: *From the Hietaharju, Hotinvaara, Lomalampi, Peura-aho, Ruossakero, Sarvisoaivi, Tainiovaara, and Vaara deposits.*

deep. The eastern part of the main komatiitic body hosts poorly investigated mineralization, which has a surface extent of ~1300 m, is 100–300 m wide, and extends to a depth of more than 400 m below the surface (Fig. 3.2.12). The preliminary feasibility study of the Ruossakero deposit performed by Outokumpu Oy suggests inferred resources of 4.2 Mt ore at 0.52 wt% Ni (0.5 wt% Ni cutoff) or 35.6 Mt ore at 0.33 wt% Ni (0.3 wt% Ni cutoff) (Lahtinen, 1996). The mineralized main body at Sarvisoaivi is rounded in shape, has a size of ~700 m × 700 m on the surface and reaches a depth of 200–300 m. No reliable resource estimates have so far been generated for the Sarvisoaivi deposit.

Despite the overall similarity of their host rocks and tectono-metamorphic history, the two ore deposits differ in terms of their sulfide mineralogy. At Ruossakero, the sulfide assemblage is dominated by pyrite, millerite, and pyrrhotite, whereas pyrrhotite and pentlandite are predominant at Sarvisoaivi. At Ruossakero, the mode of occurrence of pyrite varies from a fine-grained dissemination to 5-mm-sized, euhedral grains. Millerite occurs as rounded or elongate crystals (Ø 0.1–0.5 mm). In some cases, rounded millerite crystals are replaced by violarite. Chalcopyrite and pentlandite have also been occasionally found among other sulfide minerals. The Ruossakero deposit is similar to the Vaara deposit (Konnunaho et al., 2013) in terms of the presence of a millerite- and violarite-bearing sulfide assemblage. However, the former does not show such a high degree of replacement of sulfides by secondary magnetite as is the case at Vaara (refer to Figs. 3.2.4(A,F)).

The Sarvisoaivi mineralized body contains pentlandite and pyrrhotite as a fine- to medium-grained dissemination. Pentlandite also forms flames within pyrrhotite grains. Pyrite is found as cataclastic grains (Ø < 1 mm). Fractures cutting pyrite grains are often filled by pyrrhotite (Korhonen, 1981). Minor chalcopyrite is associated with other sulfides. Ni-rich sulfides (heazlewoodite, millerite, and violarite) occur as alteration products of Ni-bearing sulfides in the most altered and weathered ultramafic rocks of the deposit (Korhonen, 1981). Some thin (10–30 cm), massive pentlandite-pyrrhotite veins have also been observed. The presence of pyrrhotite, pentlandite, chalcopyrite, and pyrite at Sarvisoaivi indicates a primary magmatic nature of the sulfide assemblage.

Platinum-group minerals have not been found in the Ruossakero and Sarvisoaivi deposits, and measured PGE abundances are very low. Thus both deposits belong to the PGE-poor group of komatiite-hosted Ni-(Cu) deposits in Finland (Table 3.2.1).

GEOCHEMISTRY OF THE FINNISH KOMATIITE-HOSTED NI-CU-PGE DEPOSITS

WHOLE-ROCK GEOCHEMISTRY

Most of the komatiite-hosted Ni-Cu-PGE deposits in Finland are associated with the Al-undepleted komatiite type (see Table 3.2.1), showing moderate Al_2O_3/TiO_2 (15–22). Undifferentiated lava flows at Hietaharju, Peura-aho, Lomalampi, and Hotinvaara have subchondritic Al_2O_3/TiO_2 ratios (~15). Komatiites in the Enontekiö area and differentiated komatiitic lava flows with extensive cumulate bodies in the Hotinvaara area exhibit higher Al_2O_3/TiO_2 (20-65), whereas komatiites of the Tainiovaara area represent intermediate Al_2O_3/TiO_2 (20–30) (Fig. 3.2.16(A)).

The Hietaharju and Peura-aho deposits occur in the cumulate portions of lava flows generated from komatiitic basalt. The MgO content of the cumulates varies from 20–31 wt%. The MgO content of the noncumulates ranges between 14 and 21 wt%. The Lomalampi, Vaara, and Tainiovaara deposits are associated with cumulates of low-MgO komatiitic flow units. The MgO content of the cumulates is

20–41 wt%, with relatively high MgO contents in the Vaara and Tainiovaara cumulates (~36–40 wt%). The MgO content of noncumulates ranges from 20–27 wt%. Komatiitic cumulates of the Sarvisoaivi, Ruossakero, and Hotinvaara deposits have the highest MgO contents (40–50 wt%) and noncumulate rocks display MgO contents of 19–29 wt% (Figs. 3.2.16(B,C)). The absence of preserved spinifex-textured rocks, flow-top units, and magmatic silicate minerals (e.g., olivine) have handicapped the precise estimation of the MgO contents of the komatiitic parental melts of the Ni-Cu deposits in Finland.

Cumulates of komatiitic basalt in the Hietaharju and Peura-aho areas have Cr contents of 0.2–0.65 wt%, while the Cr content in the Lomalampi cumulates varies between 0.2 and 0.45 wt%. These komatiites show a positive correlation between MgO and Cr, following a cotectic olivine-chromite cumulate trend; thus, they were derived from Cr-saturated magmas (Fig. 3.2.16(B)). The Cr contents in cumulates of low-Mg komatiites (Vaara and Tainiovaara) and komatiites (Sarvisoaivi, Ruossakero, and Hotinvaara) vary between 0.2 and 0.4 wt%. These komatiites show a weakly negative or weakly positive correlation (Tainiovaara) between Cr and MgO. The corresponding cumulates were derived from Cr-undersaturated magmas with their compositional trend following an olivine-liquid mixing trend (cf. Barnes and Fiorentini, 2012 see their Fig. 8A).

Most of the studied areas (e.g., Sarvisoaivi, Ruossakero, Vaara, and Hotinvaara) comprise cumulates that have Cr contents clearly outside of the previously described trend (i.e., MgO-rich cumulates that plot between the cotectic olivine-chromite cumulate line and the olivine-liquid mixing line). This is common in mineralized systems, but not in komatiitic basalt systems, as discussed by Barnes and Brand (1999) and Barnes and Fiorentini (2012). However, most of the Ni-Cu-PGE-mineralized rocks comprise Mg-rich cumulates plotting close to the olivine-liquid mixing line (e.g., Barnes and Fiorentini, 2012; see Fig. 3.2.8(A)), as in the Vaara deposit (Konnunaho et al., 2013). This is also the case with the Sarvisoaivi, Ruossakero, and Vaara deposits, which are associated with Cr-poor cumulates (Figs. 3.2.3, 3.2.15, and 3.2.16(B)).

Ni contents show a positive correlation with MgO, reflecting Ni control by olivine in unmineralized samples ($S < 0.2$ wt%) at all studied localities (Fig. 3.2.16(C)). In the komatiitic basalts (Hietaharju and Peura-aho), Ni contents ($S < 0.2$ wt%) vary from 0.04–0.15 wt%, with high values occurring in cumulates. Unmineralized low-Mg komatiites in the Lomalampi area show Ni contents between 0.06 and 0.17 wt%, while in the Tainiovaara and Vaara areas, Ni contents of unmineralized rocks ($S < 0.2$ wt%) vary from 0.1–0.3 wt%. The scatter in Ni is relatively pronounced in the Sarvisoaivi, Ruossakero, and Hotinvaara komatiites. In the Hotinvaara area, Ni contents vary between 0.02 and 0.25 wt% and in the Ruossakero and Sarvisoaivi areas, they fall in the range of 0.03–0.4 wt%, and are highest in cumulates. The Tainiovaara and Vaara samples are slightly enriched in Ni compared to samples from the other localities. The Hotinvaara cumulates are clearly depleted in Ni, and a similar depletion has also been observed in some low-S (<0.2 wt%) Ruossakero samples. The Hotinvaara cumulates consist of metamorphic silicates (olivine and pyroxenes) and they have apparently partly lost part of their primary Ni content. The same feature has been found in some cumulates at Ruossakero (Fig. 3.2.16(C)).

BASE METAL AND PGE GEOCHEMISTRY

The studied deposits consist mainly of disseminated sulfides. The S contents of the deposits are commonly less than 5 wt%, except for less-abundant densely disseminated samples that may contain up to 5–10 wt% sulfur. Sulfur-rich samples ($S > 15$ wt%) represent massive to semimassive ores from the Hietaharju, Peura-aho, Hotinvaara, and Tainiovaara deposits (Figs. 3.2.17(A,B,C)). Base metals (Ni, Cu) generally show a positive correlation with sulfur in mineralized komatiitic rocks in all deposits, except at Ruossakero and Hotinvaara, where there is no clear correlation between S and Ni or there are sample populations with different correlations. This feature has also been observed between S and Cu in Ruossakero (Figs. 3.2.17(A,B)) and is likely related to different ore types within the deposit (i.e., variety of sulfide mineralogy and host rock types). Platinum and palladium show a positive correlation with S in most of the deposits, except for the Hotinvaara deposit (Fig. 3.2.17(C)).

Even though nickel is the most important base metal in all deposits, Figs. 3.2.17(B) and 3.2.18(A) clearly show that the Lomalampi, Vaara, Peura-aho, and Hietaharju deposits are enriched in Cu compared to the other deposits. Ruossakero, Sarvisoaivi, and Hotinvaara are low in Cu although there are some moderately Cu-enriched parts in the deposits. The Tainiovaara deposit represents intermediate compositions between these groups. The Ni/Cu ratio in the Cu-enriched deposits is ~3–13, whereas in the Cu-depleted deposit, the ratio is ~15–36 and at Tainiovaara, it is 19 (Table 3.2.1). The Cu-enriched deposits are also clearly enriched in PGE, especially Pd and Pt, compared to the other deposits (Figs. 3.2.17(B,C) and 3.2.18(A,B)). Low Ni/Cu (<6) is typical for Ni-Cu-(PGE) deposits in the Raglan and Delta Horizon areas of the Cape Smith belt, Canada, whereas higher Ni/Cu ratios (>13) are typical for other komatiite-hosted Ni-Cu-(PGE) deposits around the world (e.g., Naldrett, 2004; Lesher, 2007).

Figure 3.2.17(A) shows that some of the S-poor (<2 wt% S) disseminated deposits (Vaara, Tainiovaara, Ruossakero) are relatively rich in Ni (Ni/S > 0.7). The composition of flotation test concentrates demonstrate that the Ni content of the sulfide fraction in the Vaara deposit is extremely high, reaching 38 wt%, which has been explained by postmagmatic oxidation of sulfides (Konnunaho et al., 2013). Based on bromine-methanol leaching of representative mineralized samples, Ni-rich sulfides are also present in the Ruossakero (ave. Ni ~23 wt%), Tainiovaara (ave. Ni ~20 wt%), and Sarvisoaivi (ave. Ni ~16 wt%) deposits. The most Ni-poor sulfides are found in the Hietaharju (~3 wt% Ni on average), Peura-aho, and Lomalampi (~6 wt% Ni) deposits, which are also relatively rich in Cu (>1 wt%), analogous to the Vaara deposit (Fig. 3.2.18(A)). In some deposits, the scatter of whole-rock Ni is very large, preventing precise estimation of the Ni tenor (Hotinvaara Ni ~3–14 wt%, Tainiovaara Ni ~13–26 wt%). The metal content of the sulfide fraction at Peura-aho and Tainiovaara was estimated using whole-rock ICP-OES compositions from which silicate-bound Ni was subtracted.

The Vaara and Ruossakero deposits consist of Ni-rich sulfide (millerite, violarite) disseminations, whereas the Hotinvaara, Sarvisoaivi, and Tainiovaara deposits consist of Ni-rich pentlandite disseminations. Nickel-rich sulfides (e.g., violarite and millerite) are also found in the Sarvisoaivi deposits. The Cu-enriched deposits (Hietaharju, Peura-aho, Vaara, and Lomalampi) contain a slightly higher amount of chalcopyrite than the other deposits. The Cu content of the sulfide fraction ranges from ~1–4 wt% in the Cu-enriched deposits, and is highest in the Vaara (~4 wt%) and Lomalampi deposits (~3 wt%), whereas in the other deposits, the Cu tenor is less than 1 wt% (Fig. 3.2.18(A)).

In the Finnish komatiite-hosted Ni-Cu-PGE deposits, the average Pd and Pt contents vary in the range of 170–2160 and 300–1080 ppb, respectively. In disseminated sulfide samples, Pd ranges from 170–760 ppb and Pt from 305–408 ppb. The highest average Pd + Pt concentrations occur in the Peura-aho (3240 ppb), Hietaharju (1080 ppb), Vaara (960 ppb), and Lomalampi (580 ppb) deposits, all of which represent PGE-enriched deposits. The sum of Pt and Pd in the other deposits averages less than 190 ppb (Fig. 3.2.17(C)). Figure 3.2.18(C) shows Pt/Pd and Pd/Ir ratios in the Finnish deposits. Average Pt/Pd is ~0.4 in all deposits except Lomalampi, where the average ratio is significantly higher, at approximately 2.0. Typically, komatiite-hosted Ni-Cu-PGE deposits around the world are enriched in Pd over Pt, and their Pt/Pd ratio is similar to that in most Finnish deposits (e.g., Lesher and Keays, 2002; Fiorentini et al., 2010), but the Lomalampi

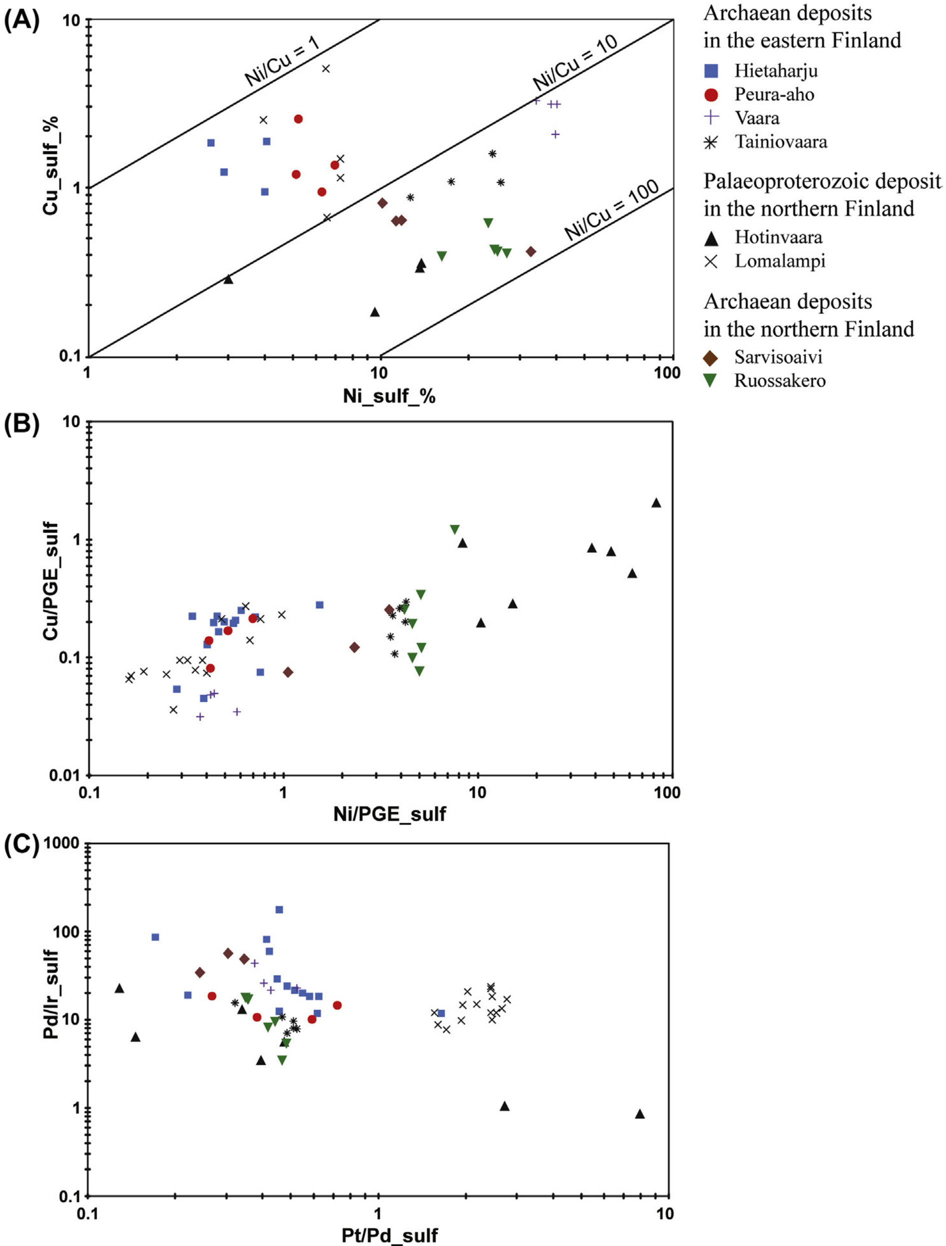

FIGURE 3.2.18 Plots of (A) Cu vs. Ni, (B) Cu/PGE vs. Ni/PGE, and (C) Pd/Ir vs. Pt/Pd for mineralized komatiitic cumulate samples.

Source: *From the Hietaharju, Hotinvaara, Lomalampi, Peura-aho, Ruossakero, Sarvisoaivi, Tainiovaara, and Vaara deposits. In (A), Cu and Ni contents in the sulfide fraction was estimated based on flotation test concentrates for Vaara, bromine-methanol leaching for Hietaharju, Hotinvaara, Lomalampi, Ruossakero, and Sarvisoaivi, and aqua regia leaching for Peura-aho and Tainiovaara with a silicate Ni correction in the two last cases.*

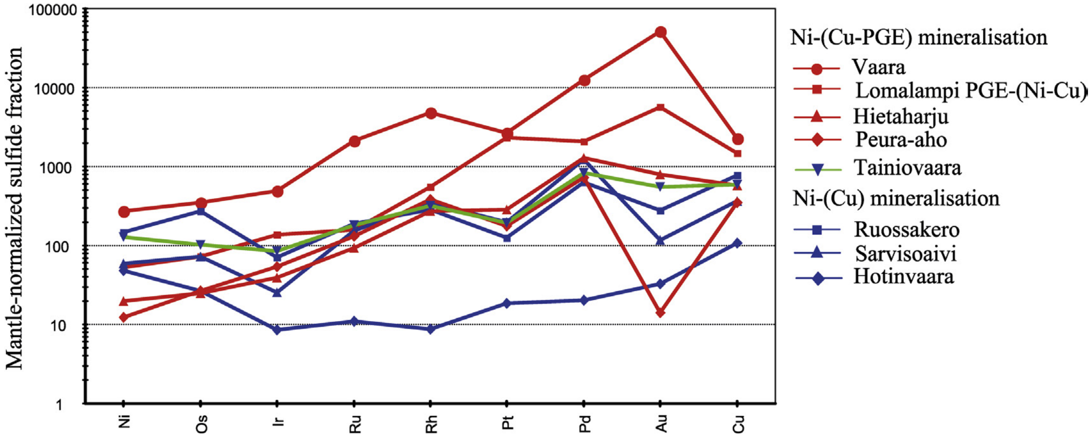

FIGURE 3.2.19 Primitive mantle-normalized chalcophile element patterns (metal contents normalized to 100% sulfide).

Source: *From the Hietaharju, Hotinvaara, Lomalampi, Peura-aho, Ruossakero, Sarvisoaivi, Tainiovaara, and Vaara mineralizations. Normalization values are from Palme and O'Neill (2004).*

deposit has a uniquely high Pt/Pd ratio (Fig. 3.2.18(C)). The average Pd/Ir in all Finnish deposits is ~20. The Hietaharju, Vaara, and Sarvisoaivi deposits have slightly higher Pd/Ir (29-47) than the other deposits, exhibiting more fractionated PGE patterns (Figs. 3.2.18(C), 3.2.19, and Table 3.2.1). Figure 3.2.19 shows that the Hotinvaara deposit has a "U-shaped" and unfractionated metal pattern and all PGE (except Os) are depleted compared to the other deposits.

PGM occur in most deposits and are mainly associated with base metal sulfides or, to a lesser degree, with silicates. Sperrylite is the most abundant Pt mineral in all deposits, but Pd is commonly associated with several Te-Bi-Sb-bearing phases.

S ISOTOPES

The sulfur isotope composition ($\delta^{34}S$) of uncontaminated mantle-derived magmas is around −2 to +2‰ (Ripley and Li, 2003) and in komatiite-hosted Ni-Cu-(PGE) deposits $\delta^{34}S$ is commonly close to zero or moderately positive (e.g., Ripley, 1999; Lesher and Keays, 2002). Determinations of $\delta^{34}S$ from Finnish komatiite-hosted Ni-Cu-(PGE) deposits show variable values between −0.7 to +15.0‰ (Fig. 3.2.20). In the Lomalampi deposit, the measured $\delta^{34}S$ values are the highest, varying from +9.8–15.0‰ (Törmänen et al., 2013, *in preparation*), while the associated black schists have an even heavier sulfur isotope composition (+17.2‰ and +24.4‰). These data imply a considerable crustal component in the Lomalampi sulfides. In the Vaara and Hietaharju deposits, $\delta^{34}S$ is between −0.7 and +2.7 ‰ (Konnunaho et al., 2013; unpublished data) and in sulfide-bearing country rocks, $\delta^{34}S$ ranges from −1.8 to +4.6 ‰ at Vaara and from −0.26–3.44 ‰ at Hietaharju (Fig. 3.2.20). Thus, these two deposits show $\delta^{34}S$ values that overlap with those of the country rocks, but are not clearly distinguishable from the mantle-sulfide composition. However, the available multi-isotope analyses have revealed considerable mass-independent fractionation of sulfur isotopes in both deposits and their country rocks, demonstrating a significant role of external sulfur assimilation in ore formation (Konnunaho et al., 2013; unpublished data), analogously with some other Archean deposits in Canada and Australia (e.g., Bekker et al., 2009; Fiorentini et al., 2012a).

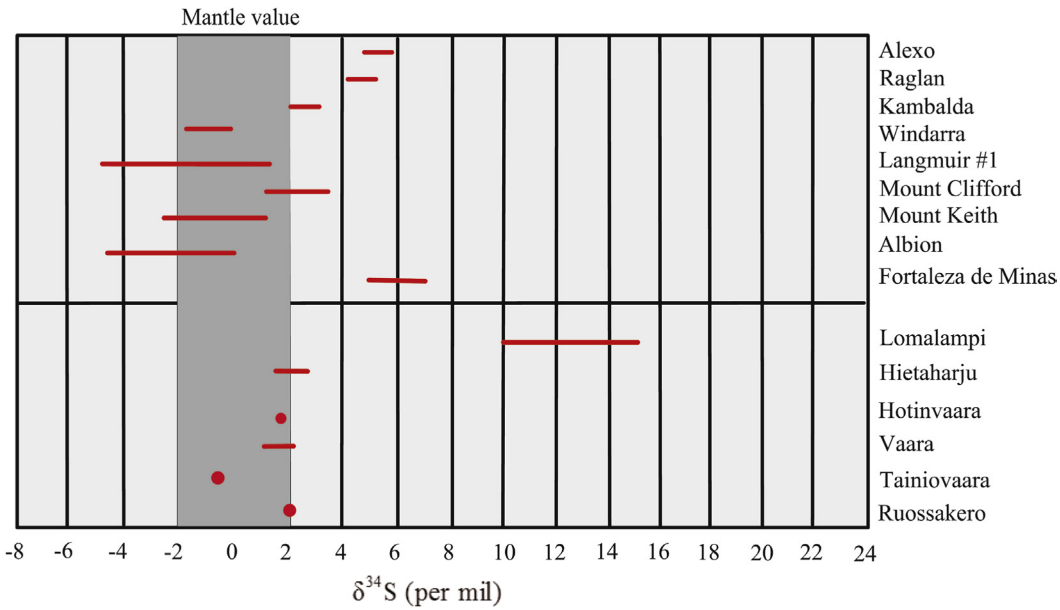

FIGURE 3.2.20 Sulfur isotope compositions ($\delta^{34}S$) of Finnish komatiite-hosted Ni-Cu-PGE deposits and other komatiite-hosted Ni-Cu-PGE deposits globally.

Source: *Reference data from Fiorentini et al. (2012a) and Choudhuri et al. (1997).*

SUMMARY

Several komatiite-hosted Ni-Cu-PGE deposits have been discovered in Archean and Paleoproterozoic greenstone belts in the eastern and northern parts of Finland (Fig. 3.2.1 and Table 3.2.1). Economically, the known deposits are small in size and dispersed, and the concentrations of nickel are low (<0.5 wt%). Part of the Tainiovaara deposit was mined in the 1980s, but the other deposits remain unexploited. Parental magmas of the deposits varied from komatiitic basalt (at Hietaharju and Peura-aho) to low-Mg komatiite (at Vaara, Lomalampi, and Tainiovaara) and komatiite (Hotinvaara, Ruossakero, and Sarvisoaivi). Most of the deposits formed from Al-undepleted magma types, but in the case of Ruossakero, Sarvisoaivi, and Hotinvaara, the magma was Ti-depleted komatiite (Table 3.2.1). Most of the ultramafic bodies hosting the deposits are extrusive in origin, but the Hotinvaara, Ruossakero, Sarvisoaivi, and Lomalampi metacumulate bodies might represent sills.

All komatiite-hosted Ni-Cu-PGE deposits in Finland belong to the type II komatiitic mineralization of Lesher and Keays (2002), and in most cases sulfides are associated with cumulates having low Cr contents (e.g., Vaara, Ruossakero, Tainiovaara, and Sarvisoaivi). Some of the deposits contain small massive or semimassive sulfide accumulations (e.g., Tainiovaara, Hietaharju, and Peura-aho). The deposits are magmatic in origin, but they have been modified to various degrees by postmagmatic metamorphic processes. Some sulfides (e.g., Peura-aho) can also occur within associated country rocks close to the komatiitic host rocks due to remobilization of sulfides.

Based on their chalcophile element concentrations, the komatiite-hosted Ni-Cu-PGE deposits can be divided into two groups:

(1) Ni-Cu-PGE (Hietaharju, Peura-aho, Vaara, and Lomalampi) deposits with elevated Pd + Pt and Cu levels (Pd + Pt > 500 ppb and Ni/Cu ~3–13)
(2) Ni-(Cu) deposits (Ruossakero, Sarvisoaivi, and Hotinvaara) with low PGE and Cu concentrations (Pd + Pt < 500 ppb and Ni/Cu ~15–36)

The Tainiovaara deposit has an intermediate composition between these two groups. Lomalampi is a unique deposit because it has an exceptionally high PGE/(Ni + Cu) ratio (i.e., PGE-(Ni-Cu) deposit) (Figs. 3.2.16 through Fig. 3.2.18 (B)). Most of the Finnish komatiite-hosted Ni-Cu-PGE deposits show mantle-like $\delta^{34}S$ values (Fig. 3.2.20), but the Paleoproterozoic Lomalampi deposit contains heavier sulfur, with $\delta^{34}S$ from +9.8–15 per mil. Available multiple S isotope data ($\delta^{34}S$ and $\Delta^{33}S$) from some Archean deposits show that contamination with S-bearing substrate has played an important role in the genesis of the sulfides (e.g., Vaara; Konnunaho et al., 2013).

Most of the Finnish komatiite-hosted Ni-Cu-PGE deposits are geochemically similar to komatiitic deposits globally. Some of the Finnish deposits are highly enriched in PGE (Pd + Pt) and, thus, generated particular economic and scientific interest. The Lomalampi deposit is unique among the disseminated deposits in showing abnormally high Pt/Pd (~2.0) and (Pt + Pd)/(Ni + Cu) ratios.

The Cr content of olivine cumulates can be used to identify the most favorable rocks to host sulfide mineralization in komatiitic magmatic systems; for example, at Vaara (Fig. 3.2.3) and Ruossakero (Fig. 3.2.15). Nickel depletion or enrichment in olivine and their host rocks has been used in Ni exploration in environments containing mafic–ultramafic rocks (e.g., Häkli, 1971; Duke and Naldrett, 1978; Makkonen, 1996; Lesher et al., 2001) but other studies have questioned whether mineralized komatiite environments show detectable Ni depletion haloes (Barnes and Fiorentini, 2012). However, the lack of magmatic silicate minerals in the Finnish komatiites precludes the use of this method. One potential method is to look for signs of anomalous PGE depletion in barren komatiitic magma suites, as this may indicate sulfide saturation elsewhere (Fiorentini et al., 2010; Fiorentini et al., 2011; Heggie et al., 2013; Maier et al., 2013). In any case, there is no single geochemical detector for indicating the presence of komatiite-hosted Ni-Cu-PGE deposits (Lesher and Barnes, 2009). In the view of the present authors, the discovered mineralizations show that Archean and Paleoproterozoic Finnish komatiites show considerable exploration potential for Ni-Cu-PGE ores.

ACKNOWLEDGMENTS

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