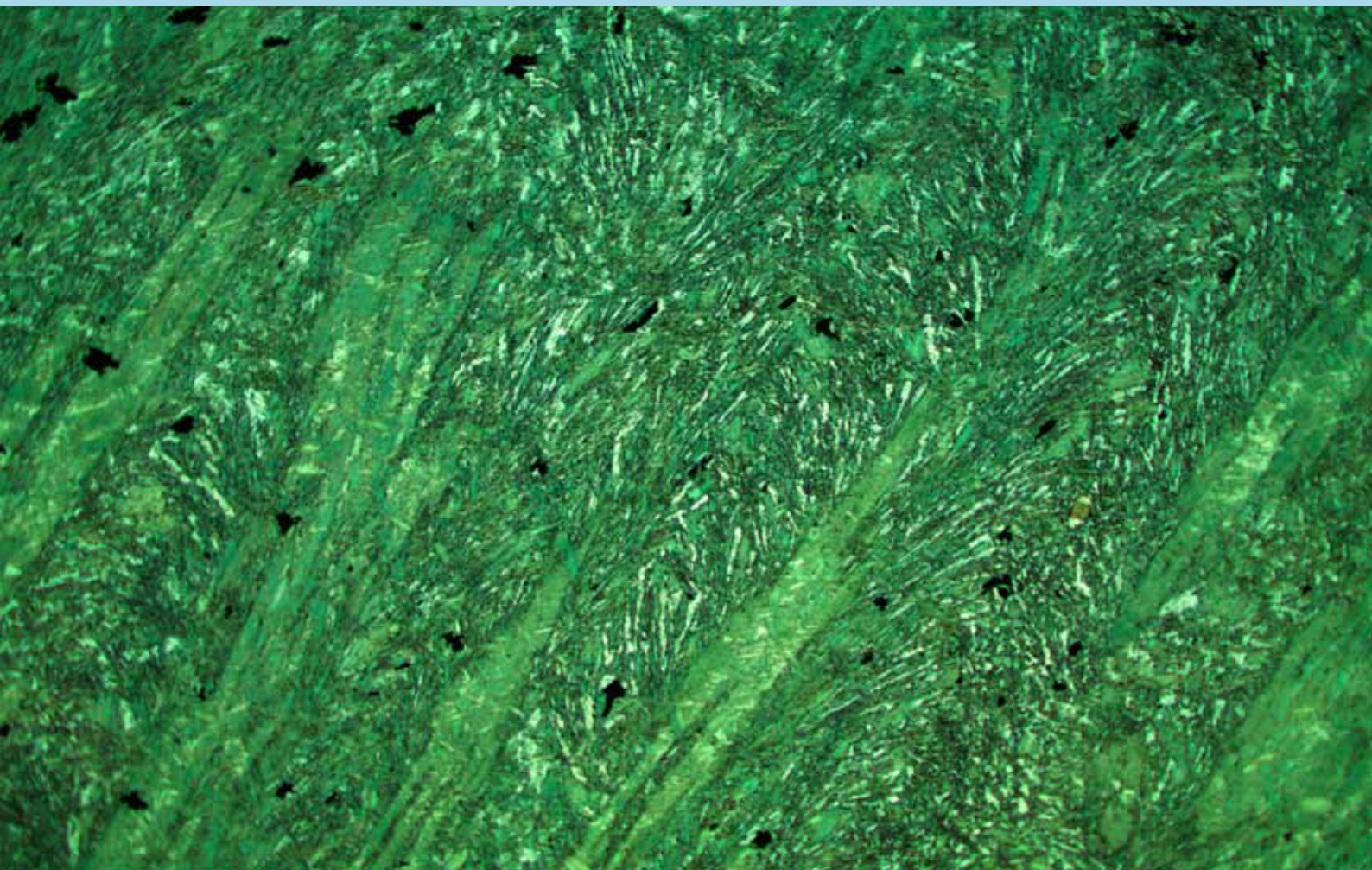


Komatiite-hosted Ni-Cu-PGE deposits in Finland: Their characterization, PGE content, and petrogenesis

Jukka Konnunaho



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**KOMATIITE-HOSTED Ni-Cu-PGE DEPOSITS IN FINLAND:
THEIR CHARACTERIZATION, PGE CONTENT, AND PETROGENESIS**

by

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Front cover: Spinified-textured lava flow from the Kuhmo-Suomussalmi greenstone belt.
Photo: Jukka Konnunaho, GTK.

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ABSTRACT

Komatiites are ultramafic volcanic rocks with high MgO and Cr and low TiO₂ and SiO₂ contents. Komatiitic magmas are also enriched in base and precious metals, such as Ni, Cu, and PGE, and have a high capacity to dissolve sulfur. Besides their chemistry, physical properties, especially high temperature and low viscosity, play an important role in the genesis of komatiite-hosted sulfide deposits. Komatiite-related Ni-Cu-PGE deposits are an important source of base (Ni, Cu, Co) and precious metals (Pd, Pt) globally. In Finland, several komatiite-hosted sulfide deposits occur in Archean and Paleoproterozoic greenstone belts, but only one of them has so far been exploited. However, the recently discovered Sakatti Cu-Ni-PGE deposit, which is associated with komatiitic to picritic magmatism, has great potential to be economic.

This thesis focuses on Archean (~2.8 Ga) (Tainiovaara, Vaara, Sarvisoaivi, Ruossakero, Hietaharju, Peura-aho) and Paleoproterozoic (~2.05 Ga) (Hotinvaara, Lomalampi) komatiite-hosted Ni-Cu-PGE deposits occurring in eastern and northern Finland, with an emphasis on their characterization, PGE content, and petrogenesis. Most of the studied deposits consist of disseminated sulfides (type II deposits), with some of them also containing massive sulfides (type I deposits) and/or post-magmatically modified sulfide concentrations (type IV and V deposits). Based on their metal contents, the Finnish deposits can be classified into two main groups: A) Ni-(Cu-PGE) deposits commonly related to komatiitic basalt to low-Mg komatiitic magmatism, as exemplified by the Vaara and Hietaharju deposits, and B) Ni-(Cu) deposits associated with high-Mg komatiites, such as the Ruossakero and Hotinvaara deposits. The deposits of the former group contain significant amounts of Ni, but are also enriched in Cu and PGE or, in rare cases, such as in the Lomalampi deposit, PGE are the most important metals. This deposit is also unique due to its high Pt/Pd (~2) compared to other deposits (~0.5). These kinds of PGE-enriched deposits are relatively rare among the komatiite-hosted sulfide deposits globally. Group B represents classic Ni-enriched deposits, which sometimes contain considerable amounts of Cu, but commonly only small amounts of PGE. The Finnish komatiite-related deposits that are associated with low-Mg komatiites and komatiitic basalts are commonly characterized by lower Ni/Cu, Ni/Co, (Ni+Cu)/(Pd+Pt), and Pd/Ir, and higher PGE and slightly higher Cu compared to the deposits related to high-Mg komatiites.

In general, the generation of komatiite-hosted sulfide deposits is linked to a high degree of mantle melting (>20%), which controls the distribution of chalcophile elements between the mantle residue and partial melts, and in many cases, the role of contamination and external sulfur has been important in the genesis of Ni-Cu-PGE ores. This thesis demonstrates that post-magmatic modification and the relatively high metamorphic grade of komatiitic rocks in Finland may limit the use of rare earth elements for the detection of a contamination signal. On the other hand, the Finnish Archean Ni-Cu-PGE deposits and their S-bearing country rocks record a varying degree of mass-independent fractionation of sulfur isotopes (MIF-S), demonstrating a significant role of the assimilation of external sulfur in ore formation, analogously with some other sulfide deposits in Canada and Australia. The PGE-enriched deposits that are associated with

komatiitic basalts and low-Mg komatiites were commonly generated under a higher R factor (silicate/sulfide melt mass ratio), being up to 500 in the Lomalampi deposit, compared to high-Mg komatiitic Ni-(Cu) deposits. In some cases, such as the Vaara deposit, post-magmatic alteration processes have drastically upgraded the metal tenors as a result of S loss related to oxidation of the magmatic pyrrhotite-pentlandite-chalcopyrite assemblage to a secondary pyrrhotite-free pyrite-millerite-pentlandite-violarite-chalcopyrite assemblage.

Thick ultramafic cumulate sequences (e.g., channelized or conduit environments), and especially their Cr-poor olivine cumulates generated from high-Mg komatiites, are favorable targets for exploration, as indicated by several deposits in Finland. The occurrence of contamination signals, PGE depletion, and S-bearing country rocks significantly raises the exploration potential. In summary, Finnish komatiitic basalts to low-Mg komatiites are highly prospective for PGE-enriched sulfide deposits, and high-Mg komatiites for classical Ni-(Cu) deposits.

Keywords (GeoRef Thesaurus, AGI): komatiite, nickel ores, copper ores, platinum ores, greenstone belts, mineral exploration, Finland

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ORIGINAL PUBLICATIONS AND AUTHOR CONTRIBUTION

This dissertation is based on the following four original articles. The publications are reproduced with kind permission from the publishers.

Paper I: Konnunaho, J. P., Hanski, E. J., Bekker, A., Halkoaho, T. A. A., Hiebert, R. S. & Wing, B. A. 2013. The Archean komatiite-hosted, PGE-bearing Ni-Cu sulfide deposit at Vaara, eastern Finland: evidence for assimilation of external sulfur and post-depositional desulfurization. *Mineralium Deposita* 48 (8), 967–989.

Paper II: Konnunaho, J. P., Halkoaho, T. A. A., Hanski, E. J. & Törmänen, T. 2015. Komatiite-hosted Ni-Cu-PGE deposits in Finland. In: Maier, W., Lahtinen, R. & O'Brian, H. (eds) *Mineral Deposits of Finland*. Amsterdam: Elsevier, 93–128.

Paper III: Törmänen, T., Konnunaho, J. P., Hanski, E., Moilanen, M. & Heikura, P. 2016. Paleoproterozoic komatiite-related PGE mineralization in the Central Lapland greenstone belt, northern Finland. *Mineralium Deposita*, accepted (online version available)

Paper IV: Konnunaho, J. P., Hanski, E., Wing, B., Bekker, A., Lukkari, S. & Halkoaho, T. 2016. The Hietaharju PGE-enriched komatiite-hosted sul-

fide deposit in the Archean Suomussalmi greenstone belt, eastern Finland. *Ore Geology Reviews*, 72(1), 641–658.

The author's (J.K.) contribution to the multi-authored papers is as follows:

Jukka Konnunaho is the corresponding author for papers I, II, and IV, and the second author of paper III, and he wrote 70% of paper I, 80% of paper II, 50% of paper III and 75% of paper IV. He formulated the research scope with Eero Hanski (papers I, II, IV) and Tuomo Törmänen (paper III). Most of the geological and lithogeochemical data were collected during exploration projects of the Geological Survey of Finland (papers I, II, III), Outokumpu Oy (papers I, II, IV) and Altona Mining Ltd (presently New Boliden) (papers II, IV). Jukka Konnunaho studied, re-logged and re-sampled most of the representative drillcores from the deposits. Data processing and analyzing were carried out by J. Konnunaho and E. Hanski in papers I, II, IV and III with T. Törmänen under the guidance of E. Hanski. All the co-authors and paper reviewers also helped in writing the papers and Vienna Arvola from the Geological Survey of Finland finalized most of the figures.

1 INTRODUCTION

Komatiite-hosted magmatic sulfide deposits provide a significant source of Ni, Cu, Co, and PGE globally. In 2006, approximately 20% of global Ni resources were estimated to be associated with komatiites (Hronsky & Schodde 2006). The recent remarkable discovery of the Sakatti Cu-Ni-PGE ore deposit (Brownscombe et al. 2015) from the Central Lapland greenstone belt and earlier discoveries from Finnish greenstone belts (Konnunaho et al. 2015) demonstrate that komatiitic and picritic rocks are highly prospective in Finland and also in the whole Fennoscandian Shield. This Ph.D. thesis concerns Archean and Paleoproterozoic komatiitic rocks and associated Ni-Cu-PGE deposits occurring in eastern and northern Finland, focusing on their characterization, PGE (i.e., platinum group element) content and petrogenesis. It summarizes previous exploration and new geochemical data from the most significant

komatiite-hosted Ni-Cu-PGE deposits in Finland and classifies them based on their geochemical features. The Finnish deposits are compared to similar sulfide deposits globally, highlighting the occurrence of PGE-enriched deposits in Archean and Paleoproterozoic greenstone belts in Finland, which are relatively rare globally. Additionally, multiple sulfur isotope analysis, a recently adopted isotopic technique, is applied to Finnish deposits and their S-bearing country rocks to examine the role of crustal contamination, which is one of the key factors in the genesis of magmatic Ni-Cu-PGE sulfide deposits (e.g., Arndt et al. 2005, Bekker et al. 2009, Keays & Lightfoot 2010, Konnunaho et al. 2013, Ripley & Li 2013, Konnunaho et al. 2016). Finally, implications of the geochemical observations of this research for mineral exploration are discussed.

2 KOMATIITES

Komatiites are ultramafic volcanic rocks with high MgO, Ni, and Cr contents and low SiO₂ and TiO₂ contents (Arndt & Nisbet 1982, Arndt et al. 2005), and they show the highest PGE contents among the mantle melts (Barnes et al. 2015). Komatiitic magmas have also been emplaced as sills, dikes and intrusions (Fig. 1) (Arndt et al. 2008, Fiorenzini et al. 2012, Barnes et al. 2016). The melts producing these rocks have been generated by a high degree of mantle melting (>20%) (e.g., Leshner & Stone 1996, Arndt et al. 2005, Arndt et al. 2008). Physically, komatiitic magmas are relatively hot, with temperatures of ~1400 to 1600°C (basalts ~1160 °C), and have a relatively low viscosity of ~0.13 to 0.74 Pa·s (basalts ~39 Pa·s) (Huppert &

Sparks 1985, Herzberg 1992, Williams et al. 2002). Compared to basalts, these melts are enriched in Ni, Cu, and PGE and have a higher capacity to dissolve sulfur (i.e., komatiites are normally highly S undersaturated) (e.g., Leshner & Stone 1996, Keays 1995, Crocket 2002). All these features play an important role in the genesis of komatiite-hosted sulfide ore deposits (Fig. 1) (Arndt et al. 2005).

Ultramafic lavas and their textures (e.g., spinifex) were already investigated in the first part of the 20th century by several geologists around the globe (e.g., Keep 1929, Berry 1940, Bailey & McCallien 1953, Wiles 1957). However, experimental petrological studies showed that the existence of ultramafic melts is questionable (Bowen 1928).

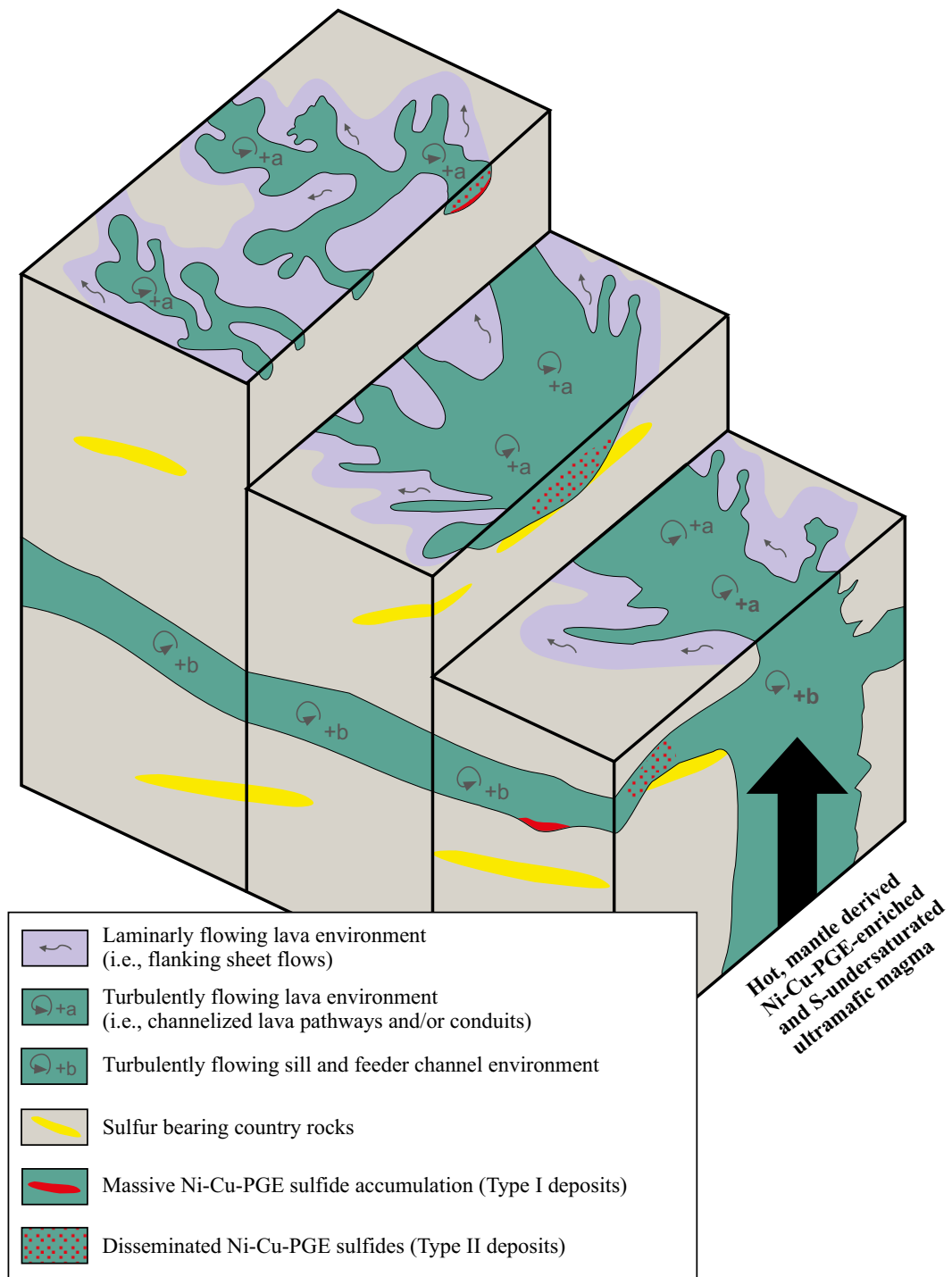


Fig. 1. Simplified komatiitic extrusive flow field, intrusive magmatic environments, and associated Ni-Cu-PGE deposits and principal factors for their genesis. Modified after Fiorentini et al. (2012).

In 1969, the Viljoen brothers described ultramafic lavas from the Komati River area in the Barberton greenstone belt, South Africa (Viljoen & Viljoen 1969a, b), which finally demonstrated the existence of highly magnesian silicate melts. These discoveries soon launched extensive komatiite studies worldwide (e.g., McCall & Leishman 1971, Pyke et al. 1973).

Nowadays, komatiites have been described from all continents. Komatiites and komatiitic basalts mainly occur in the Archean (e.g., Yilgarn Craton, Western-Australia; Hoatson et al. 2006; Superior Province, Canada; Sproule et al. 2002) and Paleoproterozoic greenstone belts (e.g., Cape Smith belt, Canada; Leshner 2007; Central Lapland, Finland; Lehtonen et al. 1988, Hanski et al. 2001; Northern

Guangxi Province, China; Zhou et al. 2000), linked to ancient Earth's high heat flux (Herzberg et al. 2007). However, some Phanerozoic komatiites are also known (e.g., Gorgona Island, Colombia; Arndt et al. 1997; northern Vietnam; Hanski et al.

2004), the genesis of which is thought to be related to intracontinental mantle plumes.

Figure 2 illustrates the distribution of komatiite-bearing greenstone belts in eastern and northern Finland and associated sulfide deposits. Mikkola

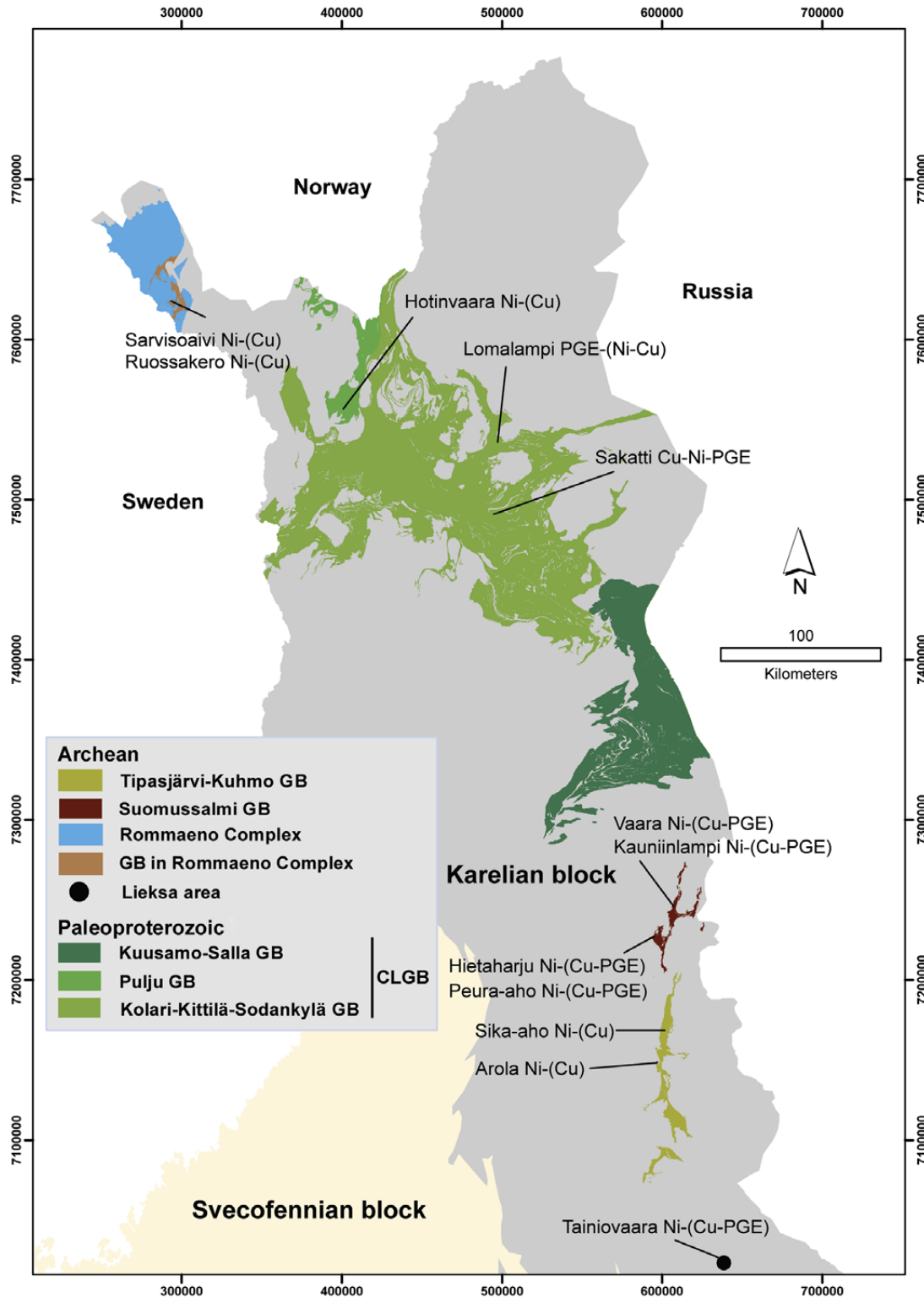


Fig. 2. Komatiite-hosted Archean and Paleoproterozoic Ni-Cu-PGE deposits investigated in this thesis study and the recently discovered Sakatti Cu-Ni-PGE deposit. GB = greenstone belt, CLGB = Central Lapland greenstone belt. Modified after Konnunaho et al. (2015).

(1941) was the first to describe ultramafic lavas from the Paleoproterozoic Central Lapland greenstone belt. In their Master's theses, Papunen (1960) and Vartiainen (1965) documented ultramafic lavas and their textures from eastern Finland, the Archean Kuhmo and Tipasjärvi greenstone belts, respectively, but did not call these rocks komatiites because the komatiite terminology was not yet in use. Mutanen (1976) recognized the Central Lapland ultramafic lavas as komatiites, and the first spinifex-textured komatiites were described from the Archean Kuhmo greenstone belt by Hanski (1980). Subsequently, Archean and Paleoproterozoic komatiitic lavas have also been recognized elsewhere in the eastern and northern parts of the Fennoscandian Shield, in NW Russia (e.g., Puchtel et al. 1996, 1998) and northern Norway (e.g., Henriksen 1983, Barnes & Often 1990). The Archean komatiites in the Fennoscandian Shield range in age from ca. 2.82 to 2.92 Ga (Huhma et al. 2012, Svetov et al. 2001), whereas there were two main episodes of Paleoproterozoic komatiitic magmatism, of which the earlier one took place roughly at 2.4–2.5 Ga and the later one at ca. 2.06 Ga (Hanski 2012).

Komatiites are well-known for their spinifex textures, which commonly occur in rapidly cooled lava units (i.e., in the A-zone of differentiated lava flows). The name comes from the spinifex grass (i.e., *Triodia spinifex*) that grows in Western Australia. Due to rapid crystallization, the spinifex textures consist of large platy and skeletal crystals of olivine and/or acicular pyroxene grains in a fine-grained, partly glassy groundmass (e.g., Nesbitt 1971, Arndt et al. 2008). They are characteristic of komatiites, but not necessarily restricted to these rocks, because spinifex textures have also been found in some other high-Mg lavas, such as ferro-

picrites (Hanski 1992). Massive lava flows are also common. On the other hand, post-magmatic processes may have destroyed these textures in highly deformed greenstone belts.

Two major classes of komatiitic rocks are distinguished in terms of their MgO content (Arndt & Nisbet 1982, Arndt et al. 2008): a) komatiites (>18 wt% MgO and <1 wt% TiO₂) and b) komatiitic basalts (<18 wt% MgO and <1 wt% TiO₂). The term komatiitic basalt has been used for magnesian basaltic rocks that are associated with komatiitic magmatism; otherwise, the name high-Mg basalt has been used (Arndt et al. 2008). Based on the Al₂O₃/TiO₂ and MREE/HREE (middle rare earth element/heavy rare earth element) ratios, komatiitic rocks have been classified into two major subgroups (Nesbitt & Sun 1976, Nesbitt et al. 1979, Arndt et al. 2008): a) Al-depleted komatiites (i.e., ADK or Barberton type) with Al₂O₃/TiO₂ <15 and suprachondritic MREE/HREE and b) Al-undepleted komatiites (i.e., AUK or Munro type) with Al₂O₃/TiO₂ >15 and chondritic MREE/HREE. Additionally, some other komatiite types have been recognized, such as Ti-enriched komatiites (i.e., Karasjok type) (Barnes & Often 1990, Hanski et al. 2001), which have low Al₂O₃/TiO₂ ratios and often “hump”-shaped chondrite-normalized REE patterns, and Al-enriched komatiites (i.e., Gorgona type) (Jahn et al. 1982, Arndt et al. 2008) with suprachondritic Al₂O₃/TiO₂. These geochemical features reflect the thermal conditions and composition of the mantle, which have changed over geological time (i.e., ~3.5 Ga Barberton komatiites vs. ~2.7 Ga Munro komatiites) and from area to area, as manifested, for example, by variations in the chemistry of komatiites and komatiitic basalts in the Abitibi greenstone belt (Sproule et al. 2002, Arndt et al. 2008).

3 KOMATIITE-HOSTED Ni-Cu-PGE DEPOSITS

Komatiite-hosted Ni-Cu-PGE sulfide deposits have been mined since the 1960s, with the Alexo Mine in Canada being one of the oldest mines. Several Ni-Cu sulfide discoveries made in the Kambalda area of Western Australia in the mid-1960s, together with the recognition of the link between komatiites and Ni-Cu-PGE sulfide deposits, launched an exploration boom for komatiite-hosted Ni-Cu-PGE deposits around the world

in the 1970s (e.g., Woodall & Travis 1970, Eckstrand 1972, Naldrett & Gasparri 1971, Ross & Hopkins 1975, Naldrett & Turner 1977). Currently, approximately 20% of global nickel sulfide resources with significant amounts of Cu, Co, and PGE are estimated to be associated with komatiites (Hronsky & Schodde 2006, Leshner & Barnes 2009). The most significant deposits are located in Western Australia and Canada.

Table 1. Classification of Finnish komatiite hosted Ni-Cu-PGE deposits (GB = greenstone belt; AUK = aluminium undepleted komatiite, CLGB = Central Lapland greenstone belt).

Deposit name	Area	Age	Magma Type	Host rock	Deposit type	Mineralization type			Ratios (average)				
						I	II	IV-V	Al ₂ O ₃ /TiO ₂	Ni/Cu	Pt/Pd	Pd/Ir	(Ni+Cu)/(Pd+Pt)*10 ⁵
Vaara	Suomussalmi GB	Archean	AUK	oOC to oMC	Ni-(Cu-PGE)		x		19	13	0.4	28	1.1
Hietaharju	Suomussalmi GB	Archean	AUK	oOC to oMC	Ni-(Cu-PGE)	(x)	x		15	4	0.5	22	1
Peura-aho	Suomussalmi GB	Archean	AUK	oOC to oMC (+ surrounding schists)	Ni-(Cu-PGE)	(x)	x	x	15	3	0.5	14	0.9
Tainiovaara	Ultramafic body within Archean basement	Archean	AUK	oMC	Ni-(Cu-PGE)	(x)	x		23	19	0.4	10	6.4
Lomalampi	Kolari-Kittilä-Sodankylä GB (CLGB)	Paleoproterozoic	AUK	oOC to oMC	PGE-(Ni-Cu)		x		15	4	2	15	0.7
Hotinvaara	Pulju GB (CLGB)	Paleoproterozoic	AUK	oMC to oAC	Ni-(Cu)	(x)	x	(x)	34	36	0.6	10	94.9
Ruossakero	Rommaeno Complex	Archean	Ti-depleted	oMC to oAC	Ni-(Cu)		x		46	55	0.4	15	10.7
Sarvisoaivi	Rommaeno Complex	Archean	Ti-depleted	oMC to oAC	Ni-(Cu)		x		37	15	0.2	47	2.4

oOC = olivine orthocumulate
oMC = olivine mesocumulate
oAC = olivine adcumulate
Deposit type () = minor metal
Mineralization type () = minor type

In Finland, no significant, economically viable komatiite-hosted Ni-Cu-PGE deposits have so far been discovered, although several small, low-grade, mainly disseminated sulfide deposits occur in Archean and Paleoproterozoic greenstone belts in eastern and northern Finland (Fig. 2 and Table 1) (Konnunaho et al. 2015). One exception may be the very promising Sakatti Cu-Ni-PGE sulfide deposit found in Central Lapland in 2009, which is potentially related to picritic or komatiitic magmatism, but more research is needed to classify the deposit (Brownscombe et al. 2015). In the late 1960s, Outokumpu Oy discovered the Hietaharju and Peura-aho Ni-Cu-PGE deposits in the Archean Suomussalmi greenstone belt, but in those days, their komatiitic affinity was not yet recognized (Pehkonen 1963). The small Tainiovaara deposit was mined in 1989 by Outokumpu Oy, but the others remain unexploited (Fig. 2 and Table 1).

Komatiite-hosted Ni-Cu-PGE deposits are classified into three magmatic (I to III) and two post-magmatically modified (IV to V) types of deposits (Leshner & Keays 2002, Leshner & Barnes 2009): I) massive sulfide deposits, which commonly occur at the base of komatiitic cumulate bodies (Fig. 2); II) disseminated sulfide deposits, which consist of sulfide dissemination within komatiitic cumulate bodies (Fig. 2); III) reef-type sulfide deposits,

which are commonly sulfide poor and occur at the contact zone of the ultramafic and gabbroic cumulates; IV) hydrothermal-metamorphic deposits, which were originally magmatic but have been modified by post-magmatic processes. These deposits are commonly associated with country rocks close to a komatiitic unit; V) tectonic sulfide deposits associated with fault or shear zones. Type I and II deposits are the most common, but several of the above-mentioned groups can be recognized in a single deposit (i.e., type I massive sulfide deposits are commonly post-magmatically altered and often include disseminated sulfides).

Another way to classify the komatiite-hosted Ni sulfide deposits is according to their metal content. In Finland, there are two main groups (Konnunaho et al. 2015): A) Ni-(Cu-PGE) deposits and B) Ni-(Cu) deposits (Table 1). The former group encompasses deposits containing economic amounts of Ni, but they are also enriched in Cu and PGE (i.e., the Raglan-type deposits), or in rare cases, PGE are the most important metals, as in the Lomalampi deposit (Törmänen et al. 2016). The latter group represents classic Ni-enriched deposits, which sometimes contain significant amounts of Cu, but only small amounts of PGE (i.e., the Kamalalda-type deposits).

4 ORIGIN OF KOMATIITE-HOSTED NI-CU-PGE DEPOSITS

4.1 Chalcophile elements

As mentioned above, komatiitic melts are generated by a high degree (>20%) of mantle melting. With an increasing degree of partial melting, sulfides, oxides, alloy phases, and major silicates (e.g., olivine) are transferred from the mantle source to the partial melt. These phases are most important for controlling the behavior and concentrations of base and precious metals, such as Ni, Cu, and platinum group elements (PGE). If the degree of melting is insufficient to consume all important phases from the source, a significant amount of metals remain in the source region and the generated partial melt is depleted in metals (e.g., Keays 1995, Arndt et al. 2005, Barnes & Lightfoot 2005).

In komatiitic systems, the base metals Ni, Cu, and Co have high partition coefficients (D), and precious metals, such as Pt and Pd, have extreme-

ly high D values between sulfide and silicate melts (100–200 for Ni, 600–650 for Cu, 30 for Co and ca. 10^5 for PGE; Leshner & Campbell 1993) and even higher D values in basaltic systems (300–1000 for Ni, 900–1400 for Cu, 15 to 80 for Co and 10^4 – 10^6 for PGE; Francis 1990, Fleet et al. 1991, 1996, 1999, Ballhaus et al. 1994, Peach et al. 1990, 1994, O'Neill et al. 1995, Peach & Mathez 1996, Sattari et al. 2002). This means that these metals are highly chalcophile elements in nature. Nickel also shows a lithophile character, having moderate olivine/silicate melt partition coefficients (1.5 to 13) (Kinzler et al. 1990, Barnes & Lightfoot 2005), and nickel is consequently strongly controlled by olivine in the mantle melting processes and during the early fractional crystallization of primitive melts. It is noteworthy that the olivine/melt partition

coefficient of Ni decreases as the degree of partial melting of mantle and the MgO content of the melt increase (Hart & Davis 1978, Barnes & Lightfoot 2005). In contrast to Ni, the chalcophile elements Cu, Pd, and Pt do not partition significantly into olivine or other silicates, and their behavior is therefore mainly controlled by sulfides (Barnes & Lightfoot 2005). Several experimental, theoretical, and empirical studies have shown that D values are influenced by physical and chemical factors, including fO_2 , fS_2 , pressure, temperature, and melt composition (Fleet et al. 1991, Leshner & Campbell 1993, Peach et al. 1994, Fleet et al. 1996, Holzheid et al. 1998). Based on the behavior of chalcophile elements in Ni-Cu sulfide systems, they can be divided into two groups: 1) IPGE (Ir, Os, Ru), Ni, and Co, which favor Ni-Fe sulfides and alloys, and 2) PPGE (Pd, Pt, Rh) and Cu, which favor Cu-rich sulfides (Barnes et al. 1985, Keays 1995, Leshner & Stone 1996).

High-Mg komatiites, which are generated via a very high degree of mantle melting, show higher Ni/Cu, but lower Pd/Ir ratios and Pd+Pt contents (Figs. 4 and 7B) compared to low-Mg komatiites and komatiitic basalts, which have been generated by lower degrees of partial melting. As mentioned above, olivine is a major phase in mantle (~70 wt%) compared to sulfides (~0.054 wt%), and substantially controls the behavior of Ni during melt formation. Model calculations indicate (e.g., Naldrett 2010) that with an increasing degree of melting of mantle, and thus olivine, the Ni (+Co) content of the melt slowly increases. In contrast, the Cu content of the melt increases first, reaching the highest values at 15–20% of partial melting, and beyond this point, when all sulfur has been consumed in the source mantle, the generated melt becomes continuously diluted in Cu, resulting in higher Ni/Cu (Lorand 1993, Barnes & Lightfoot 2005, Leshner & Stone 1996) (Figs. 3 and 4).

In general, platinum-group element concentrations in melts increase as a function of increasing mantle melting until 20–25% of mantle melting is reached, and slowly decrease after this point, suggesting that these elements are largely controlled by sulfides in the mantle and little affected by the presence of alloys, such as Pt-Fe (Naldrett 2010). Mantle estimates for Pd/Ir are around 1.2 to 2 (Barnes and Maier 1999, Bekker et al. 2006). The ratio is approximately 6 in high-degree partial melts, such as high-Mg komatiites, and up to 20 in komatiitic basalts (Taylor & McLennan 1985,

Dowling & Hill 1992, Barnes & Picard 1993, Mainville 1994).

Estimates of the Pt and Pd contents of komatiitic parental melts are generally approximately 10 ppb for both elements, meaning that Pt and Pd occur in a subchondritic ratio close to one (Barnes & Maier 1999, Barnes & Lightfoot 2005, Fiorentini et al. 2011, Fischer-Gödde et al. 2011) and similar to the ratio in lunar breccias, potentially representing the PGE proportions of the Earth's convecting mantle (Pt/Pd ~1.2) (Norman et al. 2002, Barnes et al. 2015). Based on modeling of mantle melting, Pd contents of the melt can rise up to 5 times that of primitive mantle, that is 15–20 ppb, at the point when all sulfur has been consumed (Barnes & Lightfoot 2005, Naldrett 2010). On the other hand, the late veneer hypothesis, involving a major flux of primitive meteorites after core formation (Cottrell & Walker 2006, Maier et al. 2009), suggests that the upper mantle has chondritic relative PGE abundances and a Pt/Pd ratio of 1.75–2 (Barnes et al. 1987, McDonough & Sun 1995, Barnes & Maier 1999, Palme & O'Neill 2003, Maier et al. 2012).

In contrast to the estimates of the Pt/Pd ratio in komatiitic parental melts and non-mineralized komatiites in general, which are mostly around unity and thought to approach that of the mantle source (Barnes & Maier 1999, Puchtel et al. 2004, Barnes & Lightfoot 2005, Mungall & Naldrett 2008, Barnes et al. 2009, Fiorentini et al. 2011), komatiitic Ni-Cu-PGE deposits commonly have subchondritic Pt/Pd ratios of ca. 0.5 (Fiorentini et al. 2010, Barnes et al. 2012). This discrepancy in Pt/Pd between non-mineralized and mineralized komatiites still awaits a satisfactory solution (Fiorentini et al. 2010), and no conclusive explanation has been provided for the low Pt/Pd ratios in komatiite-hosted sulfide deposits (Fiorentini et al. 2010, Barnes et al. 2012). The published estimates for PGE contents for mantle vary widely, especially for Pt (e.g., Fiorentini et al. 2010, Becker et al. 2006). There is some compositional variation, which Fiorentini et al. (2011) suggest to be related to provincial heterogeneity in the mantle source of komatiites, but their data show that komatiites with chondritic Pt/Pd ratios are rare. According to Maier (2015), the Pt variability may have resulted from heterogeneously mixed Pt-rich late veneer or components of the Earth's core in the mantle. The discrepancy between the Pt/Pd ratio in the chondritic mantle and komatiitic melt has been explained by the presence of several phases (e.g., Fe-Pt alloys,

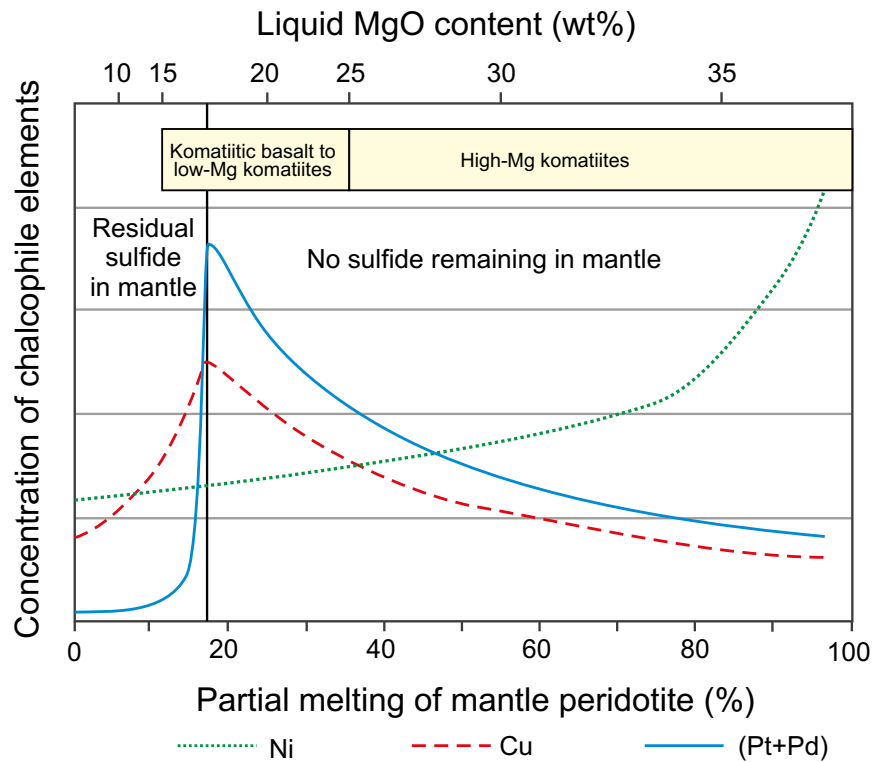


Fig. 3. Concentrations of chalcophile elements and MgO in partial melts with increasing partial melting of mantle peridotite. The yellow field shows the area of komatiitic melts. Modified after Naldrett (2009).

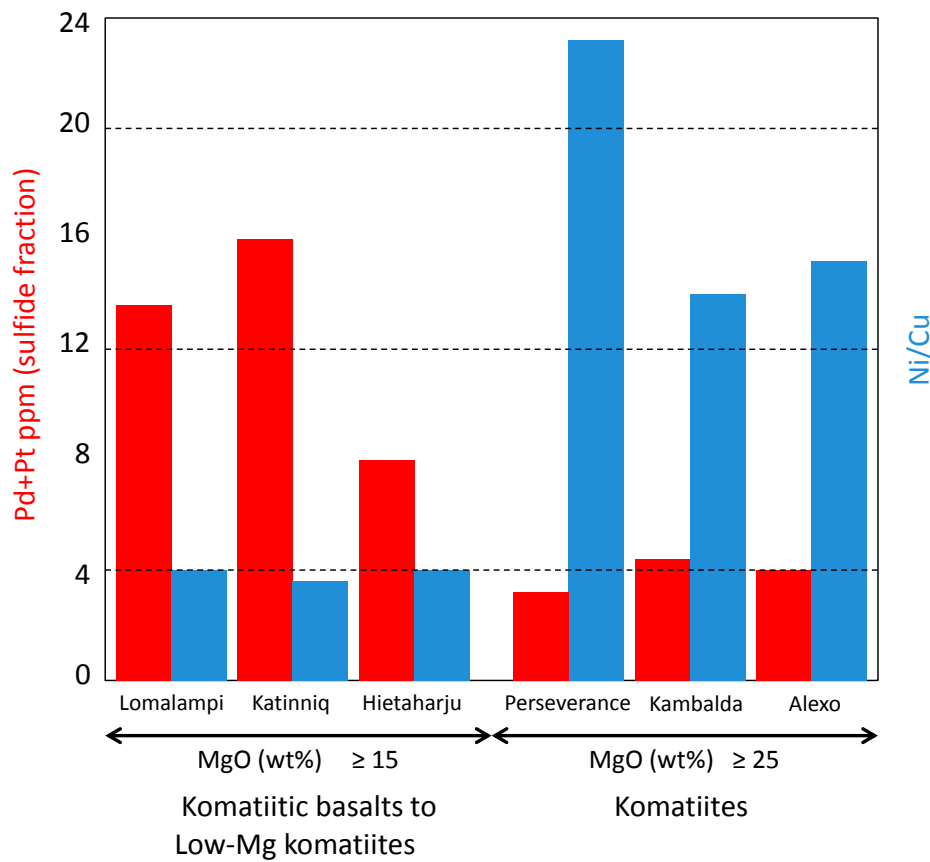


Fig. 4. Discrimination between Ni-Cu-PGE deposits hosted by komatiite (Perseverance, Kambalda, and Alexo) and komatiitic basalt/low-Mg komatiite (Lomalampi, Katinniq, and Hietaharju) and their PGE (Pd+Pt) contents and Ni/Cu ratios. Red Bar = Pd+Pt, blue bar = Ni/Cu. Reference data: Katinniq (Leshar 2007 and references therein), Kambalda and Alexo (Naldrett 2004 and references therein), and Perseverance (Leshar & Keays 2002 and references therein).

monosulfide solid solution, spinel) in the mantle, which incorporate PGE, especially Pt+IPGE, even at very high degrees of mantle melting (Leshner & Stone 1996, Barnes & Lightfoot 2005, Arndt et al. 2005). Higher sulfide/silicate melt D values for Pd compared to Pt (Barnes et al. 1997) or kinetic factors affecting the rate of diffusion of Pt and Pd from silicate melt into sulfide melt (Mungall 2002, Fiorentini et al. 2010, Barnes et al. 2012) may explain the variability in Pt/Pd. Based on recent studies (Arndt et al. 2005, Barnes & Lightfoot 2005, Naldrett 2009, Fiorentini et al. 2010), we can summarize that the distribution of chalcophile ele-

ments between residual mantle and silicate melt is controlled by several, partly not well-understood factors (e.g., degree of partial melting, associated phases, and D values). Nevertheless, theoretical considerations of the behavior of chalcophile elements during mantle melting suggest that at lower degrees of partial melting, komatiitic basalt melts have slightly higher PPGE contents than high-Mg komatiites, having the potential to produce PPGE-enriched Ni-Cu deposits, whereas high-Mg komatiites are more likely to produce Ni-(Cu) deposits with moderate levels of PPGE (Figs. 3 and 4).

4.2 Sulfur and sulfur saturation

The amount of sulfur in the upper mantle is around 100–400 ppm (avg. 200 ppm) (Lorand 1993, Keays 1995), and the S capacity of komatiitic melts is at least 500–1000 ppm (i.e., S^{2-} content at the sulfide saturation point) (Wendlandt 1982, Mavrogenes & O'Neil 1999, Naldrett 2009). This means that high-degree partial melts, such as komatiites, are commonly undersaturated in S when they approach the Earth's surface (e.g., Arndt & Leshner 1992, Keays 1995, Leshner & Stone 1996). The following factors may variably increase the solubility of S in the magma: a) increasing temperature, b) increasing activity of FeO, and c) increasing fugacity of S. On the other hand, the following factors decrease the solubility: a) increasing pressure, b) increasing fugacity of O_2 , c) increasing activity of SiO_2 and Na_2O , and d) an increasing sulfate/sulfide ratio, which increases as a function of increasing fO_2 and alkalinity (e.g., Mavrogenes & O'Neil 1999, Li et al. 2001, Arndt et al. 2005, Barnes & Lightfoot 2005). Several studies have pointed out that high-Mg magmas are sulfur undersaturated when they segregate from their mantle source, and the magmas become even more undersaturated with decreasing pressure during their adiabatic ascent

into the crust, with the falling temperature having only a slight counter-effect (Mavrogenes & O'Neil 1999). Consequently, to reach early sulfide saturation, high-Mg magmas need other processes than decreasing pressure and temperature or progressive fractionation, most importantly the assimilation of S from an external source (Leshner & Groves 1986, Li et al. 2001, Arndt et al. 2005). The depth at which sulfur saturation and accumulation takes place is also important. If it occurs at a very great depth in the crust, any metal-rich sulfides that may accumulate are unlikely to be mined. On the other hand, a large amount of silicates, particularly olivine, can accumulate and deplete nickel in the magmas (Arndt et al. 2005). An important, but less discussed phenomenon is the behavior of S during subaerial lava eruptions. The loss of S may be significant in subaerial and shallow-water (<200 m) eruptions (Moore & Schilling 1973, Sakai et al. 1982). This might be important in some areas, such as the Paleoproterozoic Central Lapland greenstone belt, where some of the komatiites were erupted in subaerial or shallow-water environments (Räsänen 1996, Lehtonen et al. 1998, Hanski & Huhma 2005).

4.3 Contamination

Ripley & Li (2013) discussed the following potential contamination mechanisms of magmas: 1) the assimilation of volatiles (H_2O , CO_2 , CH_4 , H_2S and HS^-), 2) the assimilation of siliceous country rock material, 3) the mixing of magmas, and 4) the addition of external sulfur. The first three mechanisms may variably reduce the solubility of sulfur,

but have only a limited potential to result in sulfur saturation and significant ore formation in komatiitic systems, and can possibly lead to sulfur saturation in more basaltic compositions (e.g., MacLean 1969, Li et al. 2001, Ripley & Li 2013; see their Fig. 3). However, contamination by itself does not necessarily lead to sulfide saturation and ore for-

mation (Leshner et al. 2001), as demonstrated, for example, by the strongly contaminated nature (up to 30%) of the barren Paringa basalts at Kambalda (Leshner & Arndt 1995). Assuming that saturation occurs without significant S addition, the mass of the generated sulfide is likely to be economically insignificant (e.g., Li & Ripley 2005). Significant fractional crystallization (20–40%) of olivine and pyroxenes in large mafic-ultramafic bodies may increase the S concentration of the melt and eventually lead to sulfide saturation (i.e., producing a cotectic proportion of sulfide liquid). In this case, significant crystallization depletes the magma in Ni, but the generation of a PGE-(Cu) reef is still possible.

As mentioned above, the highly S-undersaturated nature of komatiitic magmas requires an input of external sulfur to generate notable Ni-Cu-PGE sulfide ore bodies, being the most efficient and direct pathway to S saturation (Fig. 1) (e.g., Keays & Lightfoot 2010). Ripley & Li (2013) pointed out one exception. A large volume of magma (e.g., open systems, such as associated with flood basalts and their ores) may collect sulfide melt that precipitated from earlier magma pulses of the same igneous system. In the case of sulfur-undersaturated komatiites, even extensive cooling or significant contamination by S-poor crustal material may not drive the magma to S saturation (Leshner & Arndt 1995).

Based on Leshner et al. (2001) and Arndt et al. (2005), the amount of contamination required to trigger sulfide melt saturation in komatiite mainly depends on the following factors: 1) the silicate melt composition (e.g., the S capacity of the magma and

its volatile content), 2) temperature and other physical properties (e.g., the degree of superheating of the magma and its viscosity), 3) the flow rate and style of magma movement (turbulent vs. laminar flow), 4) the composition of country rocks (e.g., S, Si, Fe content), and 5) the physical, structural and stratigraphical characteristics of the country rocks (e.g., thickness and continuity of substrate). In the case of komatiites, the addition of external sulfur and contamination may occur via thermal erosion, including wholesale to incongruent melting and devolatilization of the substrate, and mechanical erosion, including physically induced scavenging of the substrate (Huppert et al. 1984, Huppert & Sparks 1985). Together, these processes form a powerful assimilation mechanism called thermo-mechanical erosion, which is characteristic of komatiitic environments and important for the genesis of komatiite-hosted Ni-Cu-PGE deposits (Fig. 1) (e.g., Arndt & Nisbet 1982, Groves et al. 1986, Cas & Beresford 2001, Williams et al. 2004, Houle et al. 2012).

Based on several studies (e.g., Leshner & Keays 2002, Leshner et al. 2009), type I komatiite-hosted massive sulfide deposits have commonly incorporated proportionately large amounts of external sulfur, and sulfides have segregated in early stages of magma crystallization, whereas type II disseminated sulfide deposits have incorporated smaller amounts of external S and sulfides have segregated at a later stage of crystallization. Type III (e.g., reef-type) deposits might be generated without external S and sulfur saturation occurring in a late stage after significant crystallization.

4.4 Detection of contamination signals

As mentioned above, the genesis of komatiite-hosted Ni-Cu-PGE deposits is strongly linked to contamination. Contamination might be directly detected from the occurrence of country rock xenoliths and hybrid rocks or geochemically in the form of crustal trace element and isotope signatures of komatiitic rocks. Compared to primitive mantle, uncontaminated komatiites are commonly relatively depleted in highly incompatible lithophile elements (U, Th, Nb, Ta, light rare earth elements (LREE)) and only slightly enriched in moderately incompatible lithophile elements (MREE, HREE, Zr, Y) (Leshner & Stone 1996, Leshner et al.

2001, Leshner & Barnes 2009). Additionally, some contaminants, e.g., pelitic upper crustal rocks are enriched in Si and depleted in Nb, Ta and Ti compared to other incompatible elements. Based on these geochemical features, useful tools to identify contamination signals include increased La/Sm, La/Yb, and Zr/Y ratios and decreased Nb/La and Nb/Th ratios (e.g., Jochum et al. 1991, Leshner & Barnes 2009).

Most of the komatiitic rocks have undergone post-magmatic alteration (e.g., hydration, CO₂ metasomatism) and deformation after their emplacement. Several studies have demonstrated the

mobility of some of the above-mentioned elements, including LREE (e.g., Gruau et al. 1992, Lahaye et al. 1995, Leshner & Stone 1996, Leshner et al. 2001, Barnes et al. 2004a). Cumulates are more sensitive in marking changes in trace element ratios by metasomatic alteration than spinifex-textured rocks due to the lower incompatible element contents of the former (Barnes et al. 2004a). This may lead to misinterpretations of potential geochemical contamination signals.

One way to detect crustal contamination in komatiitic magmas is to use stable or radiogenic isotope analyses. The source of sulfur (i.e., mantle vs. crust) in mineralized magmatic systems can potentially be discriminated using sulfur isotope measurements. In the conventional $\delta^{34}\text{S}$ approach, sulfur isotope compositions are expressed as $\delta^{34}\text{S}$ values in parts per mil (‰), defined as

$$\delta^{34}\text{S} = \left(\frac{{}^{34}\text{S}/{}^{32}\text{S}_{\text{sample}}}{{}^{34}\text{S}/{}^{32}\text{S}_{\text{V-CDT}}} \right) \times 1000$$

where V-CDT refers to the Vienna-Cañon Diablo Troilite standard. Mantle-derived magmas generally show close to chondritic $\delta^{34}\text{S}$ values, mostly varying between -2 to +2‰ (Ripley & Li 2003). Deviances from these values may indicate contamination with country rock material having either a light or heavy $\delta^{34}\text{S}$ composition. The measured $\delta^{34}\text{S}$ values in komatiite-hosted Ni-Cu-PGE deposits vary widely, in the range of -6 to +6‰, but are nevertheless often close to the mantle values (Fiorentini et al. 2012; see their Figures 8 and 5, Konnunaho et al. 2015; see their Figure 3.2.20). Country rocks of Ni-Cu-bearing intrusions do not necessarily show $\delta^{34}\text{S}$ values that are different from mantle values, and hence $\delta^{34}\text{S}$ alone does not always provide unequivocal evidence for the presence of external sulfur (e.g., Penniston-Dorland et al. 2008, Bekker et al. 2009, Fiorentini et al. 2012). This especially concerns Archean metasediments, in which the range of $\delta^{34}\text{S}$ is much smaller than that in Phanerozoic metasediments, due to the less efficient organic-driven fractionation (Ripley 1999).

Recent developments in multiple sulfur isotope (^{32}S , ^{33}S , ^{34}S , ^{36}S) analysis (Farquhar et al. 2000) have provided a new powerful tool to detect the assimilation of external sulfur in magmatic systems (e.g., Bekker et al. 2009, Fiorentini et al. 2012, Konnunaho et al. 2013). This stems from the fact that Archean metasedimentary rocks often display

mass-independent fractionation of sulfur isotopes (MIF-S) due to UV-induced photochemical reactions of SO_2 in the oxygen- and ozone-free atmosphere of the Archean time, whereas mantle-derived magmas show strict mass-dependent fractionation of sulfur isotopes (Farquhar et al. 2000, Farquhar & Wing 2003). Deviations from the empirical mass-dependent relationship between $\delta^{33}\text{S}$ and $\delta^{34}\text{S}$ ($\delta^{33}\text{S} \approx 0.515 \delta^{34}\text{S}$; Johnston 2011) are quantified by $\Delta^{33}\text{S}$ values, which are calculated as:

$$\Delta^{33}\text{S} = \delta^{33}\text{S} - \left[\left(\frac{\delta^{34}\text{S}}{1000} + 1 \right)^{\lambda_{\text{RFL}}} - 1 \right] \times 1000$$

where λ_{RFL} (0.515) is the slope of the reference mass-dependent fractionation line for $\delta^{33}\text{S}$ and $\delta^{34}\text{S}$. The observed $\delta^{33}\text{S}$ values in Archean metasedimentary rocks extend as far as from -3 to +12‰, whereas in Paleoproterozoic or younger sedimentary rocks, $\Delta^{33}\text{S}$ is very close to zero (e.g., Johnston 2011). This discovery demonstrates the absence of the ozone shield in the Archean and provides one of the most precise methods to determine the timing of the “Great Oxygenation Event” (Reuschel et al. 2013).

Bekker et al. (2009) and Fiorentini et al. (2012) demonstrated that several Archean komatiite-related Ni-Cu deposits in Western Australia and Canada display mass-independent fractionation of sulfur isotopes, providing strong evidence for the presence of atmospherically recycled sulfur in these deposits. Furthermore, they showed that Archean black shales typically have positive $\Delta^{33}\text{S}$ values, whereas massive sulfide deposits (VMS) commonly show negative $\Delta^{33}\text{S}$ values. Because komatiite-related Ni-Cu deposits in Western Australia also display negative $\Delta^{33}\text{S}$ values, they concluded that hydrothermal massive sulfide lenses hosted within felsic volcanic rocks are likely sources of sulfur in these Ni deposits.

In the present work, multiple isotope analyses were applied to the komatiite-related Ni-Cu-PGE ores and their country rocks at Vaara and Hietaharju in the Suomussalmi greenstone belt and Lomalampi in the Central Lapland greenstone belt (Konnunaho et al. 2013, Konnunaho et al. 2016, Törmänen et al. 2016). In addition, samples from two sulfide ore deposits associated with felsic magmatism were analysed from the Suomussalmi and Tipasjärvi greenstone belts. The results of these studies are discussed in Chapter 5.

4.5 R factor in komatiite-hosted Ni-Cu-PGE deposits

The mass ratio of silicate magma to sulfide liquid (i.e., the mass of silicate magma from which the sulfide collects the metals) is called the R factor, as originally coined by Campbell & Naldrett (1979). High R values show that a large amount of silicate liquid equilibrated with a small amount of sulfide liquid, whereas low R values mean that relatively large amounts of sulfide liquid had equilibrated with relatively small amount of silicate liquid (e.g., Li et al. 2001, Mungall 2005). Estimated R factor values for large magmatic and commonly PGE-enriched systems, such as Norilsk and the Merensky Reef of the Bushveld Complex, South Africa, are >1000 (e.g., Naldrett 1989, Arndt et al. 2008), whereas in less voluminous systems, such as komatiite-hosted and base metal-dominant sulfide deposits, R factors vary commonly from hundreds up to one thousand (Leshner & Keays 2002, Mungall 2005, Arndt et al. 2008).

The application of the R factor has been widely discussed in many articles (e.g., Naldrett 2004, Barnes & Lightfoot 2005, Mungall 2005). The composition of the sulfide liquid as a function of the R factor can be calculated using the following equation (Campbell & Naldrett 1979):

$$C_s = C_L D(R+1)/(R+D)$$

where C_s is the calculated metal concentration in the sulfide liquid, C_L is the estimated metal concentration in the parental silicate liquid, D is the partition coefficient of a metal between sulfide and silicate liquid and R is the mass ratio of silicate/sulfide magma.

Modeling of the R factor is commonly dependent on the estimated metal concentrations in the sulfide and silicate liquids and the partition coefficients between sulfide and silicate liquid, which are variable (e.g., base metals vs. precious metals) and sensitive to physical and chemical changes, as mentioned above. Campbell & Barnes (1984) showed that if $R < 10D$, the metal concentration in the silicate and sulfide melts depends more on R than D. Because of the significant differences in D values between base metals (Cu, Ni) and PGE, the Cu and Ni concentrations in the sulfide melt are less dependent on R than the PGE concentrations (Mungall 2005). In R factor modeling, it has been recommended to use elements with very high ($D > 10R$) sulfide-silicate partition coefficients (Camp-

bell & Barnes 1984, Leshner & Keays 2002). Most of the magmatic Ni-Cu-PGE deposits were formed under circumstances where R was less than $D_{PGE}^{Sul/Sil}$ (Fiorentini et al. 2010).

In the Kambalda area, komatiite-hosted massive sulfide ores show R factor values of around 100–500 (Leshner & Campbell 1993), and in the Raglan area, R factors have been estimated to be 300–1000 (Barnes & Picard 1993, Gillies 1993, Leshner 1999). On the other hand, disseminated sulfide deposits formed at R factors of around 140 at Mount Keith, 370 at Dumont (Leshner & Keays 2002) and 500–1000 at Lomalampi (Törmänen et al. 2016). These values are far lower than those calculated for the Norilsk ores (1000–10 000) (Barnes & Lightfoot 2005). In general, komatiite-hosted Ni-Cu-PGE deposits were formed under low to intermediate R factor values (Leshner & Barnes 2008). Calculated R factor values are slightly higher for the ores generated from komatiitic basalts and low-Mg komatiites (Barnes & Picard 1993, Leshner 2007) compared to those generated from high-Mg komatiites (Leshner & Campbell 1993, Barnes et al. 2011). Estimated R factor values for komatiitic Ni sulfide deposits result from relatively low PGE tenors of 500 to 3000 ppb for Pd (Barnes 2006, Barnes et al. 2012), whereas for deposits hosted by komatiitic basalts, the higher estimated R factors result from considerably higher PGE tenors, such as >2000 ppb for Pd and Pt and in some cases up to 25000 and 6600 ppb, as in the Raglan massive to disseminated deposits (Leshner 2007). The differences in the obtained R factor values can be explained by several factors: 1) the magma composition (e.g., lower R in low viscosity high-Mg komatiites than in relatively viscous komatiitic basalts; Leshner & Campbell 1993), 2) the complexity of the magmatic systems, including crystallization of Ni-rich olivine (Duke 1986, Barnes et al. 1988, Leshner & Burnham 2001), 3) the crystallization history of sulfides (e.g., *in situ* sulfide crystallization or transport of sulfide droplets) (Rice & Moore 2001, Leshner & Keays 2002, Barnes & Lightfoot 2005), and 4) the geometry and dynamics of the ore-forming environment (e.g., relatively dynamic magma conduits or relatively non-dynamic sills) (Leshner & Barnes 2008). In theory, komatiite-related massive sulfide deposits are expected to form at lower R than disseminated sulfide deposits and at a much lower R than S-poor reef-type deposits (Leshner & Keays 2002, Leshner & Barnes 2009).

In summary, metal concentrations are strongly controlled by mantle melting processes (i.e., komatiitic basalts and low-Mg komatiites are enriched in PGE and Cu compared to Ni-enriched, but PGE- and Cu-poor high-Mg komatiites), and the same relationship has also been clearly observed in metal concentrations in associated mineralization of these magma types globally from the

Archean to the Proterozoic. The high R factor is clearly influential in the notable “upgrading” of the metal tenor in certain environments, such as magma conduits or active lava channels (e.g., Ripley & Li 2011; Voisey's Bay deposit, Lesher 2007; Raglan deposit), where fresh metal-rich magma may interact with sulfides under a high effective R factor.

4.6 Post-magmatic modification and enrichment

Most komatiite-hosted Ni-Cu-PGE deposits have undergone various degrees of post-magmatic alteration processes (e.g., oxidation, serpentinization, carbonatization, and desulfurization). These processes have modified primary silicate, oxide and sulfide assemblages and affected the geochemistry of the rocks. In some cases, modification of the primary sulfides may have drastically changed the metal tenors, including secondary upgrading of the sulfide fraction, especially in low-grade ores (e.g., Stone et al. 2004, Lesher & Barnes 2009, Barnes et al. 2009, Konnunaho et al. 2013). Disseminated ore types are more susceptible to post-magmatic modification (e.g., oxidation) than net-textured and massive ore types, which are more likely to be self-buffered (e.g., Eckstrand 1975, Stone et al. 2004). In massive ores, the modal proportion of sulfides to silicates is higher than in disseminated ores, and metals, such as Ni, mainly reside in sulfides, whereas in disseminated ores Ni is bound in both sulfides and silicates. As shown by several studies (Barnes et al. 2009, Konnunaho et al. 2013), strong talc-carbonate alteration (i.e., CO₂ metasomatism) may oxidize primary pyrrhotite-pentlandite-chalcopyrite sulfide assemblages and replace pyrrhotite and other iron sulfides with secondary magnetite (Konnunaho et al. 2013; see their Figures 5A–E). Strong oxidation also releases S and Ni from pyrrhotite and pentlandite, and the primary pyrrhotite-pentlandite assemblage may be transformed to a pyrite-millerite-magnetite assemblage, as in the Black Swan and Vaara deposits

(Barnes et al. 2009, Konnunaho et al. 2013). Part of the sulfur may escape (i.e., desulfurization) from the system, releasing Ni from Ni-rich sulfides and forming secondary millerite, violarite, and heazlewoodite. Sulfur liberation, migration, and the formation of new sulfides by fluids under favorable fO_2 and fS_2 conditions have been demonstrated in several studies (e.g., Frost 1985, Klein & Bach 2009, Gole 2014). Some earlier studies (e.g., Eckstrand 1975, Donaldson 1981) have noted that a marked amount of Ni has been released by reducing fluids from olivine during serpentinization processes. Grguric et al. (2006) demonstrated that the released nickel is bound in sulfides occurring in serpentine as micro-inclusions, upgrading the sulfide tenor. In the case of the Vaara and Black Swan deposits (Barnes et al. 2009, Konnunaho et al. 2013), a Ni-rich sulfide assemblage developed during serpentinization processes without significant talc-carbonate alteration (e.g., Konnunaho et al. 2013). On the other hand, strongly talc-carbonate-altered ultramafic bodies may have undergone insignificant sulfide modification, as in the completely talc-carbonate-altered Hietaharju deposit (Konnunaho et al. 2016). In addition, it should be noted that Ni-rich, millerite-bearing sulfide parageneses are not necessarily a result of secondary alteration, as there is also evidence for the occurrence of extremely Ni-rich primary sulfide phases, e.g., in the Betheno (Barnes et al. 2011) and Kevitsa deposits (Yang et al. 2013).

5 KOMATIITE-HOSTED Ni-Cu-PGE DEPOSITS IN FINLAND: OVERVIEW AND DISCUSSION

5.1 Deposit distribution

Several economically interesting komatiite-hosted Ni-Cu-PGE deposits have been discovered in eastern and northern Finland, occurring both in Archean and Paleoproterozoic greenstone belts. The Archean deposits include the Vaara, Hietaharju, and Peura-aho deposits in the Suomussalmi greenstone belt, the Tainiovaara deposit in a small 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

have been discovered in the Kuhmo-Suomussalmi greenstone belt. Paleoproterozoic deposits, including the Hotinvaara and Lomalampi deposits, occur in the Central Lapland greenstone belt (Fig. 2 and Table 1) (Konnunaho et al. 2015). This list of komatiite-related deposits may possibly be augmented by the significant Sakatti deposit in the Central Lapland greenstone belt (Brownscombe et al. 2015), but this new discovery is beyond the scope of this thesis and the published information on it is still scarce.

5.2 Classification and characteristic features

The parental magmas of the Finnish komatiite-related Ni deposits differ chemically, varying from komatiitic ($\text{MgO} > 25 \text{ wt\%}$) (Sarvisoaivi, Ruossakero and Hotinvaara) to low-Mg komatiitic ($\text{MgO} > 15 \text{ wt\%}$) or komatiitic basalt (Vaara, Tainiovaara, Hietaharju, Peura-aho and Lomalampi) (Konnunaho et al. 2015). The deposits are mostly associated with the Al-undepleted komatiite type (AUK) ($\text{Al}_2\text{O}_3/\text{TiO}_2 = 15\text{--}20$), but Ti-depleted komatiites ($\text{Al}_2\text{O}_3/\text{TiO}_2 > 20$) are predominant in the Hotin-

vaara, Ruossakero and Sarvisoaivi areas (Konnunaho et al. 2015) (Fig. 5A and Table 1).

The Finnish komatiite-related Ni-Cu-PGE deposits mainly belong to the type II (i.e., disseminated type) deposits, but some belong to the type I (i.e., massive type) and type IV–V (i.e., post-magmatically modified type) deposits (cf. Leshner & Keays 2002, Barnes 2006, Konnunaho et al. 2015). Some deposits represent a mixture of types II, I and/or IV–V (Table 1 and Fig. 6). All eight

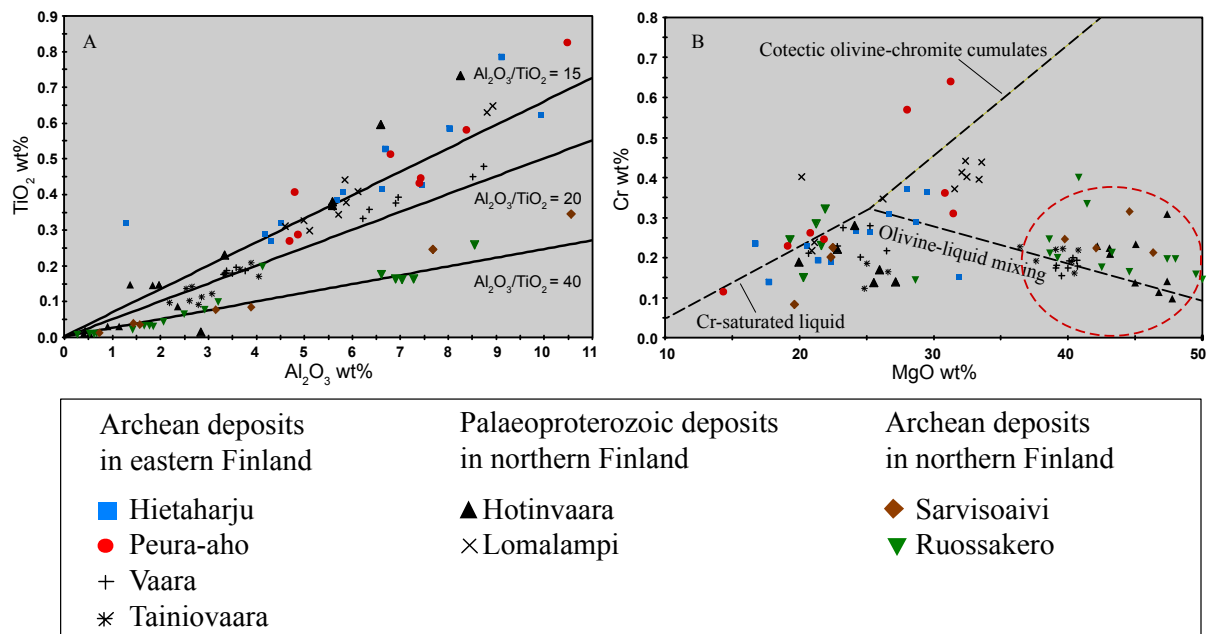


Fig. 5. Variation diagrams for unmineralized komatiitic rocks from Finland. A) Al_2O_3 versus TiO_2 . B) MgO versus Cr . The dashed red circle represents cumulates of high-Mg and some of low-Mg komatiitic systems associated with mineralization. Fractionation trends from Barnes & Fiorentini (2012).

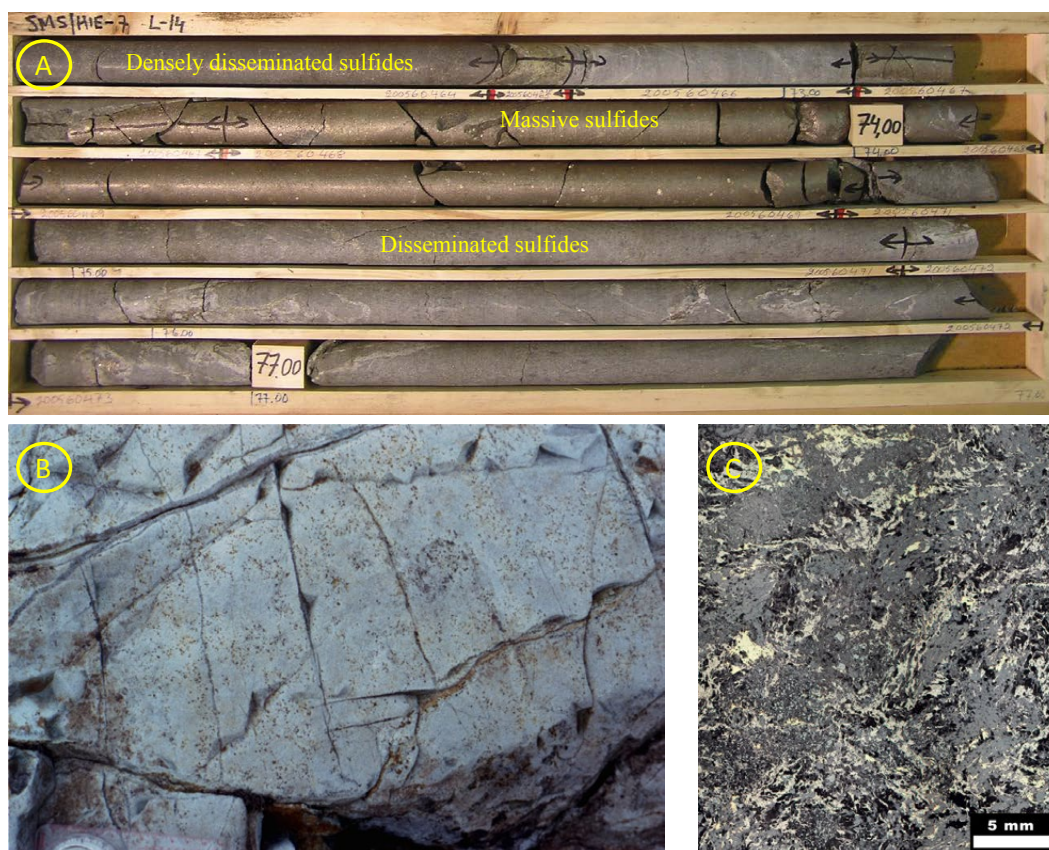


Fig. 6. Various ore textures in Finnish komatiite-hosted Ni-Cu-PGE deposits. A) Densely disseminated, massive and disseminated sulfides (pyrrhotite+pentlandite+chalcophyrite) in drillcores from the Hietaharju deposit. B) Rusty disseminated sulfides (pyrite, pentlandite, millerite, violarite, chalcopyrite-(±pyrrhotite)) in outcrop from the Vaara deposit. C) Reworked magmatic sulfides (pyrrhotite+pentlandite+chalcopyrite) in thin section from the Hietaharju deposit. Figure (A) photo taken by Altona Mining staff (presently New Boliden), (B) by Tapio Halkoaho, and (C) by Marko Moilanen.

main deposits are associated with MgO-rich and Cr-poor cumulate portions of komatiitic to komatiitic basalt or low-Mg komatiitic units (Fig. 5B), and they mostly consist of disseminated sulfides (e.g., Vaara, Lomalampi, Ruossakero, and Sarvisoaivi) with additional minor massive to semi-massive sulfides in some cases (e.g., Tainiovaara, Hietaharju, and Peura-aho). Some of the deposits were modified by post-magmatic processes to various degrees, which has resulted in an increase in the metal contents of the sulfide fraction, notably in the Vaara deposit (Konnunaho et al. 2013). In some deposits, Ni-Cu sulfides are partly located in the country rocks, including the Peura-aho deposit and the Sika-aho and Arola showings in the Kuhmo-Suomussalmi greenstone belt (Fig. 2 and Table 1) (Konnunaho et al. 2015).

In Finland, the komatiite-related Ni-Cu-PGE deposits are divided into two main groups based on their metal contents and ratios: 1) Ni-(Cu-PGE) deposits, which are enriched in PGE (Pd+Pt

>500 ppb) and Cu (Ni/Cu <13) (e.g., Vaara, Hietaharju, Peura-aho, and Lomalampi), and 2) Ni-(Cu) deposits, which are enriched in Ni (Ni/Cu >15) and have low PGE contents (e.g., Sarvisoaivi, Ruossakero, and Hotinvaara). The Tainiovaara deposit has an intermediate composition between these two groups (Figs. 7A, 7D, and Table 1). Both deposit types occur in Archean and Paleoproterozoic terranes (Fig. 2 and Table 1). The Lomalampi deposit is unique, because it has high levels of PGE compared to base metals (i.e., PGE-(Ni-Cu) deposit) and a Pt/Pd ratio of around 2, as opposed to Pt/Pd of around unity characteristic of most other komatiite-hosted Ni-Cu-PGE deposits globally (Fig. 7D). Group 1 deposits, such as Hietaharju and Lomalampi (Konnunaho et al. 2015), as well as Raglan (Barnes & Lightfoot 2005, Lesher 2007), have high Pd/Ir (>15) compared to typical group 2 Ni-(Cu) deposits (<10; Barnes & Maier 1999) (Fig. 7D). Group 1 deposits commonly have low Ni/Co ratios (<20) compared to group 2 deposits,

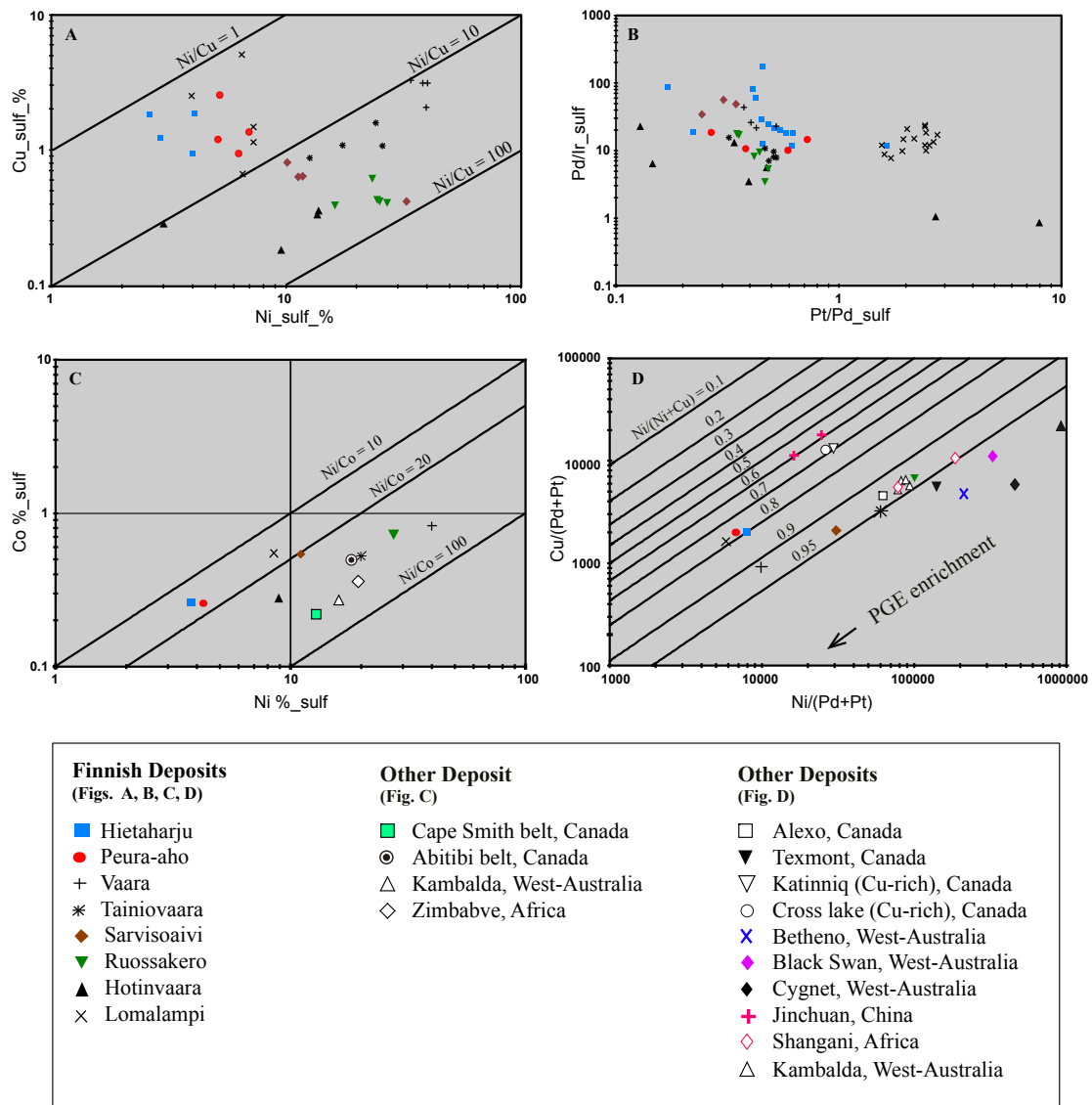


Fig. 7. Composition of the sulfide fraction in Finnish komatiite-related Ni-Cu-PGE deposits compared to some other Ni-Cu-PGE sulfide deposits. A) Cu versus Ni, B) Pt/Pd versus Pd/Ir, C) Ni versus Co, D) Ni/(Pd+Pt) versus Cu/(Pd+Pt). Reference data in figure C: Abitibi, Cape Smith, Kambalda, Zimbabwe (Naldrett 2004 and references therein) and figure D: Jinchuan, Texmont, Shangani and Kambalda (Naldrett 2011), Cross Lake and Katinniq (Leshner 2007), Alexo (Barnes & Naldrett 1987), Cygnet (Barnes 2004), Betheno (Barnes et al. 2011).

which are commonly related to high-Mg komatiitic magmatism (Fig. 7C). Group 1 (PGE-enriched) deposits are characterized by disseminated (i.e., S-poor) (e.g., Lomalampi and Vaara) or massive to

semi-massive or heavily disseminated (i.e., S-rich) sulfides (e.g., Hietaharju and Peura-aho) (Fig. 2 and Table 1) (Konnunaho et al. 2015).

5.3 Sulfur isotope systematics

The sulfur isotope composition ($\delta^{34}\text{S}$) of uncontaminated mantle-derived magmas is around -2 to +2‰ (Ripley & Li 2003) and in komatiite-hosted Ni-Cu-PGE deposits $\delta^{34}\text{S}$ is commonly close to zero or moderately positive (e.g., Ripley 1999, Leshner & Keays 2002). Determinations of $\delta^{34}\text{S}$

from Finnish komatiite-hosted Ni-Cu-PGE deposits show variable $\delta^{34}\text{S}$ values ranging from -0.7 to +15.0‰. In the Paleoproterozoic Lomalampi deposit, the measured $\delta^{34}\text{S}$ values are the highest, varying from +9.8 to +15.0‰, and the associated black schists show even heavier sulfur isotope

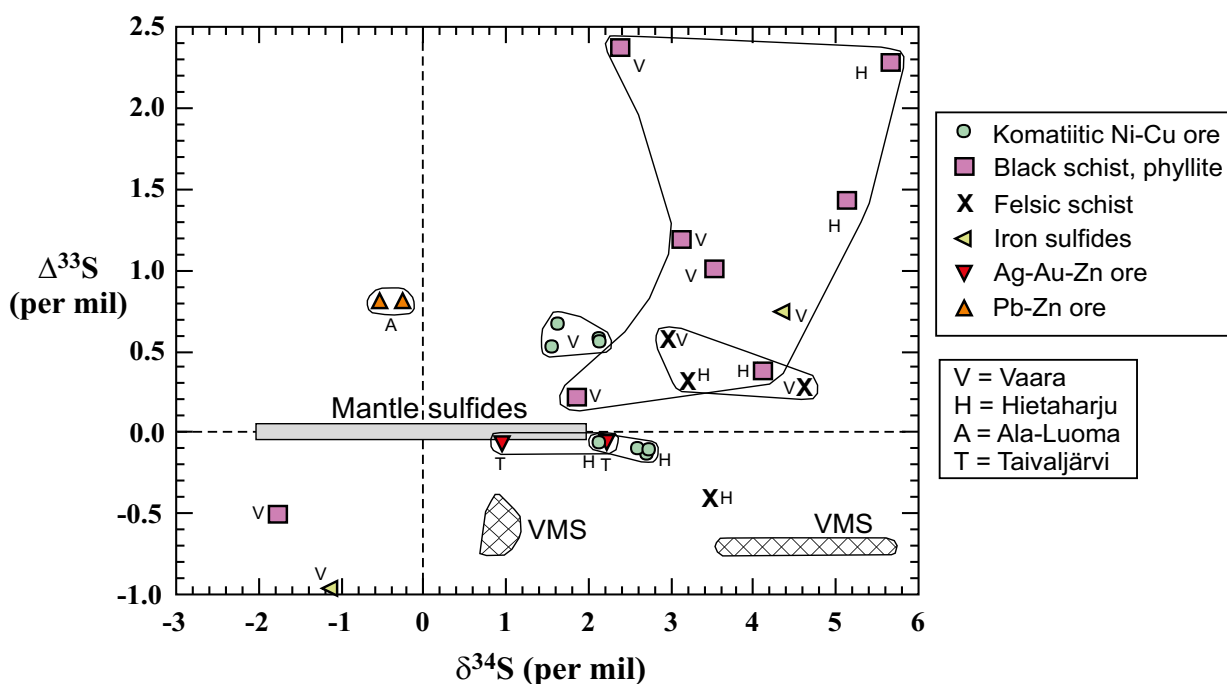


Fig. 8. Multiple sulfur isotope composition of sulfides from komatiite-hosted Hietaharju and Vaara Ni-Cu deposits and associated sedimentary and felsic volcanic rocks, and the Taivaljärvi Ag-Au-Zn deposit and Ala-Luoma Pb-Zn deposit. Ranges of $\delta^{34}\text{S}$ and $\Delta^{33}\text{S}$ values for the mantle are plotted for reference. The VMS fields represent the isotopic compositions of distal barren sulfides of VMS deposits in the Agnew-Wiluna belt, Western Australia (Bekker et al. 2009). Modified after Konnunaho et al. (2016).

compositions (+17.2 and +24.4‰) (Törmänen et al. 2016). These data imply a strong crustal sulfur component in the Lomalampi sulfides. In the case of the Archean Vaara and Hietaharju deposits, $\delta^{34}\text{S}$ falls between -0.7 and +2.7‰ (Konnunaho et al. 2015, Konnunaho et al. 2016), and in sulfide-bearing country rocks, $\delta^{34}\text{S}$ ranges from -1.8 to +4.6‰ at Vaara (Konnunaho et al. 2013, Konnunaho et al. 2015) and from -0.26 to +5.7‰ at Hietaharju (Konnunaho et al. 2016). Thus, these two deposits show $\delta^{34}\text{S}$ values that overlap with those of the country rocks, but are not clearly distinguishable from the mantle sulfide composition (Fig. 8).

Compared to the conventional method of using $\delta^{34}\text{S}$, a more powerful tool for the detection of external sulfur in Ni-Cu-PGE deposits is the use of multiple sulfur isotope analyses ($\Delta^{33}\text{S}$) (e.g., Bekker et al. 2009). Mineralized komatiites from the Vaara deposit show $\Delta^{33}\text{S}$ values of +0.53 to +0.66‰ and the Hietaharju deposit has yielded $\Delta^{33}\text{S}$ values of -0.076 to -0.154‰ (Fig. 8). In common with Archean S-bearing metasedimentary rocks elsewhere (Hiebert & Bekker 2010, Fiorentini et al. 2012), phyllites and black schist samples from both the Hietaharju and Vaara areas show mostly positive $\Delta^{33}\text{S}$ values between +0.2 and +2.4‰ and rarely

negative values (-0.5‰) (Konnunaho et al. 2013, Konnunaho et al. 2015, Konnunaho et al. 2016) (Fig. 8). Sulfides from the Ala-Luoma Pb-Zn mineralization have positive $\Delta^{33}\text{S}$ values but slightly negative $\delta^{34}\text{S}$ values, and sulfides from the Taivaljärvi Ag-Au-Zn deposit show strongly positive $\delta^{34}\text{S}$ values (+0.97 and +2.20‰) and slightly negative $\Delta^{33}\text{S}$ (~-0.08‰), being similar in $\Delta^{33}\text{S}$ to the Hietaharju Ni-Cu-PGE ore samples (Fig. 8). These small negative $\Delta^{33}\text{S}$ values contrast with the more negative $\Delta^{33}\text{S}$ values recorded in distal barren sulfides associated with Archean volcanic massive sulfide (VMS) deposits in Western Australia (Fig. 8), but are similar to the $\Delta^{33}\text{S}$ values observed in sub-seafloor volcanic-hosted mineralization in the Abitibi belt of Canada (Jamieson et al. 2013, Sharman et al. 2015).

In the case of the Vaara deposit, sulfur isotope compositions are a strong signal of magmatic interaction with sulfur-bearing black shales and phyllites and/or felsic volcanic country rocks. The analyzed sulfide samples from the Hietaharju deposit are different from those of the Vaara deposit in that they display only small negative $\Delta^{33}\text{S}$ values, but on the other hand, they are similar to sulfides in the Kambalda komatiite-hosted Ni

deposits (Bekker et al. 2009, Fiorentini et al. 2012). The different sulfur isotope compositions of the Hietaharju and Vaara deposits may be related to different parental magma compositions and emplacement histories. The more fractionated nature of the parental magma for the Hietaharju deposit is consistent with a longer residence time in a staging magma chamber, with more time for the parental magma to interact with a variety of different country rocks, potentially at a deeper level in the crust. Such a process can lead to more homogeneous and diminished $\Delta^{33}\text{S}$ values that approach a crustal average (cf. Penniston-Dorland et al. 2012) compared to the magma–country rock interactions that produced the Vaara deposit. The measured $\Delta^{33}\text{S}$ values for the Hietaharju deposit are close to the mantle values and the sulfur in the deposit could have originally been derived from the parental silicate magma. Changing magmatic parameters (e.g., $f\text{O}_2$, SiO_2), rather than S addition, could have triggered sulfide saturation in this case. Nevertheless, the multiple S isotope compositions of the Hietaharju sulfides do not exclude a significant role of external sulfur in the formation of the ore. Under the assumption that mass-dependent fractionation of S isotopes is minimal under magmatic conditions, they require that any exogenous S added to the Hietaharju parental magma had $\delta^{34}\text{S}$ values that were slightly positive, with slightly negative $\Delta^{33}\text{S}$ values. Interaction of the silicate melt with such external S would draw the S isotope composition of the ultimate sulfide liquid towards the origin on a $\Delta^{33}\text{S}$ – $\delta^{34}\text{S}$ plot (Fig.

8). Massive sulfides associated with Archean VMS deposits tend to have moderately heavy $\delta^{34}\text{S}$ and slightly negative $\Delta^{33}\text{S}$ values (e.g., Sharman et al. 2015), similar to those required in the scenario outlined above. We noted that VMS deposits with similar S isotope systematics have not yet been recognized in the Archean Tipasjärvi-Kuhmo-Suomussalmi greenstone belt. However, an epithermal Ag-Au-Zn deposit (the Taivaljärvi deposit) occurs in the Tipasjärvi area, showing similar $\Delta^{33}\text{S}$ values to those of the Hietaharju Ni-Cu-PGE deposit (Fig. 8) (Konnunaho et al. 2016). Sulfide deposits of this kind or a hidden sulfur source (e.g., Archean VMS deposit) may explain the Hietaharju $\Delta^{33}\text{S}$ values.

In summary, multiple sulfur isotope analyses show a varying degree of mass-independent fractionation of sulfur isotopes in the Vaara and Hietaharju deposits, their country rocks, and Archean sulfide deposits, demonstrating a significant role of external sulfur assimilation in the ore formation (Konnunaho et al. 2013, Konnunaho et al. 2015, Konnunaho et al. 2016), analogous to some other Archean deposits in Canada and Australia (e.g., Bekker et al. 2009, Fiorentini et al. 2012). In the Lomalampi deposit, no MIF-S is observed, despite the fact that $\delta^{34}\text{S}$ indicates a strong input of external sulfur during crustal contamination. This is consistent with the Paleoproterozoic age of the country rock black shales, which were deposited after the Great Oxygenation Event and are expected to display no mass-independent fractionation of sulfur isotopes (cf. Reuschel et al. 2013).

5.4 Finnish deposits compared to other deposits

In many ways, the komatiite-hosted Ni-Cu-PGE deposits in Finland are similar to komatiite-related sulfide deposits worldwide, but there are also some differences. The Finnish deposits are commonly associated with AUK magmatism in Archean (2.82 to 2.92 Ga; Huhma et al. 2012) and Paleoproterozoic (2.4–2.5 Ga and ca. 2.06 Ga; Hanski 2012) greenstone belts, whereas globally, sulfide deposits associated with high-Mg komatiites are generally ca. 2.7 Ga in age and those associated with komatiitic basalts to low-Mg komatiites are ca. 1.9 Ga in age (Condie 2001, Arndt et al. 2008). Furthermore, komatiitic rocks in Finland are less voluminous compared to Western Australia and Canada.

Sulfides are similarly disseminated within MgO-rich cumulate portions and/or massive (\pm semi-

massive, net-textured or brecciated) portions at or close to the base of MgO-rich cumulate units, and favor Cr-poor cumulates (Fig. 5B) in the Vaara (Konnunaho et al. 2013; see their Figs. 5 and 8) and Ruossakero deposits (Konnunaho et al. 2015; see their Fig. 3.2.15). They consist of a magmatic sulfide assemblage of pyrrhotite+pentlandite+chalcopyrite and post-magmatically modified sulfide assemblages typically containing pyrite, pentlandite, millerite, heazlewoodite, and violarite. Several Archean and Paleoproterozoic komatiite-related deposits in Finland are highly enriched in PGE (Pd+Pt) and have clearly elevated contents of Cu compared to komatiite-related deposits worldwide (Fig. 7D). The PGE-enriched deposits are commonly similar to deposits in the Paleoproterozoic

Cape Smith belt in Canada. The Lomalampi deposit is unique among the disseminated deposits

in showing abnormally high Pt/Pd (ca. 2.0) and (Pt+Pd)/(Ni+Cu) ratios (Törmänen et al. 2016).

5.5 Exploration of komatiite-hosted Ni-Cu-PGE deposits

All MgO-rich komatiitic to picritic environments are generally prospective for Ni-Cu-PGE deposits. This remains valid for different magma types (i.e., AUK and ADK, etc.) and a range of liquid compositions (komatiitic basalt, komatiites, and picrites, etc.) (Arndt et al. 2005, Leshner & Barnes 2009; see their Table 2.2). Voluminous ultramafic cumulates (commonly meso- to adcumulates) and thick cumulate sequences (e.g., channelized or conduit environments) are more favorable than thin, differentiated, and less voluminous lava flow sequences (e.g., sheet flow environments) (Fig. 1) (Barnes 2006, Arndt et al. 2008, Leshner & Barnes 2009, Barnes et al. 2016). Magnesium-rich magmatism associated with S-bearing country rocks and displaying signs of contamination and PGE depletion significantly raise the exploration potential. Of course, direct indications, that is the presence of base metal sulfides in outcrops and/or boulders, and conductors inside of the host body and close to the contact zone are promising features.

Komatiite-related sulfide deposits are normally associated with MgO-rich olivine-(±pyroxene) cumulates. However, several studies (e.g., Barnes & Brand 1999, Barnes et al. 2004b, Barnes & Fiorentini 2012, Konnunaho et al. 2013, Konnunaho et al. 2015) have shown that the most favorable host rocks for Ni-Cu-PGE deposits are Cr-poor olivine cumulates, which have formed from Cr-undersaturated magma, as in the Vaara and Ruossakero deposits (Konnunaho et al. 2013, Konnunaho et al. 2015), even though Cr-enriched cumulates occur in the same areas. In Ni-Cu-PGE exploration, the use of the Cr content to find more prospective Cr-poor cumulates is not as practical in more fractionated low-Mg komatiitic (e.g., Hietaharju and Lomalampi) environments as in high-Mg komatiitic environments, because in the former case, both the mineralized and non-mineralized cumulate bodies are characterized by olivine-chromite cotectic trends (Fig. 5B) (e.g., Leshner 2007, Barnes & Fiorentini 2012, Konnunaho et al. 2013).

Crustal contamination is a positive signal, but not necessarily sufficient evidence for the operation of ore-forming processes. Other positive sig-

nals include indicators of sulfide liquid extraction (Barnes et al. 1988, Barnes 1990), such as high Cu/Pd in high-R systems and low Cu/Zr in low-R systems, provided that these elements have not been significantly disturbed by post-magmatic processes (Li et al. 2001). This is based on their different partition coefficients between sulfide and silicate liquid (Li et al. 2001). However, Li et al. (2001) did not recommend the use of these ratios for altered and strongly metamorphosed rocks. Fiorentini et al. (2010, 2011), Heggie et al. (2013), and Maier et al. (2013) have pointed out anomalous PGE depletion in barren komatiitic magma suites, as this may indicate sulfide saturation elsewhere. Positive correlations between primitive mantle-normalized ratios, such as Pt/Ti_{MN} , Pd/Ti_{MN} , Pt/Al_{MN} , and Pd/Al_{MN} , are very sensitive indicators for sulfide fractionation or extraction (Fiorentini et al. 2010, Heggie et al. 2013; see their Fig. 7). They also include deviations from the global Pt/Ti_{MN} baseline of unmineralized komatiites (average ca. 0.7–0.9), as revealed by the MgO vs. Pt/Ti_{MN} plot (Fiorentini et al. 2010, Maier et al. 2013; see their Fig. 15). Based on Lamberg's (2005) studies, $Co\# (100 \times Co/(Ni+Cu+Co))$ is also useful for the detection of sulfide segregation in mafic to ultramafic systems.

Over the past several decades, 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 & Naldrett 1978, Leshner & Groves 1986, Makkonen 1996, Leshner et al. 2001), but other studies have questioned whether mineralized komatiite environments show detectable Ni depletion haloes (Barnes & Fiorentini 2012). In any case, the lack of primary magmatic olivine in the Finnish komatiites precludes the use of this method.

In summary, there is no single geochemical detector for indicating the presence of komatiite-hosted Ni-Cu-PGE deposits (Leshner & Barnes 2009), but a range of lithogeochemical methods can provide tools to select favorable targets for Ni-Cu-PGE exploration. Barnes et al. (2016) have also highlighted that Ni-Cu-PGE-mineralized ultramafic bodies and ore deposits are very irregularly distributed among similar ultramafic bodies. This

is also the case with the Lomalampi mineralized and unmineralized bodies (Törmänen et al. 2016) and the Vaara deposits, among the other ultramafic bodies in the area (Konnunaho et al. 2013).

6 SUMMARY AND CONCLUSIONS

Komatiitic rocks were named in 1969 by the Viljoen brothers, even though ultramafic lavas had been described much earlier by Mikkola (1945) from Central Lapland area, for example. Komatiites are ultramafic lavas with high MgO, Cr, Ni, and PGE contents and low SiO₂ and TiO₂ contents. Komatiitic lavas with MgO around 15 to 25 wt% are called low-Mg komatiites or komatiitic basalts if they are associated with komatiitic magmatism, and lavas with MgO higher than 25 wt% are komatiites proper. They have also been classified into three main subgroups based on their Al₂O₃/TiO₂: a) Al-undepleted, b) Al-depleted, and c) Ti-enriched komatiites. Magmas producing these rocks were generated by high degrees of mantle melting.

The first komatiite-hosted Ni-Cu-PGE deposits were explored in the 1960s in Canada and Western Australia. Nowadays, around 20% of global Ni resources are estimated to associate with komatiites. Several komatiite-hosted Ni-Cu-PGE deposits have been discovered in Archean and Paleoproterozoic greenstone belts in the eastern and northern parts of the Finland (Fig. 2 and Table 1). Economically, the known deposits are small in size and dispersed, and the Ni concentrations are low, but some of the deposits, such as the Hietaharju, Peura-aho, and Lomalampi deposits, show high PGE contents.

Komatiite-hosted Ni-Cu-PGE deposits are classified into three magmatic (I to III) and two post-magmatically modified (IV to V) types (Leshner & Keays 2002, Leshner & Barnes 2009). The deposits commonly consist of massive-(±disseminated) (i.e., type I deposits) and disseminated (i.e., type II) sulfides, which can be post-magmatically modified (i.e., types IV–V) (Fig. 6). Based on their chalcophile element concentrations, the komatiite-hosted Ni-Cu-PGE deposits can be divided into two groups: (i) Ni-(Cu-PGE) deposits with elevated Pd+Pt and Cu levels and (ii) Ni-(Cu) deposits with low PGE and Cu concentrations (Figs. 7A, D, and Table 1). The Lomalampi deposit is a

Understanding the differences between unmineralized and mineralized bodies is challenging and requires further study (Barnes et al. 2016).

unique example because of its exceptionally high PGE/(Ni+Cu) ratio (i.e., PGE-(Ni-Cu) deposit) and high Pt/Pd (Figs. 7A, D, and Table 1). All komatiite-hosted Ni-Cu-PGE deposits in Finland belong to the type II komatiitic mineralization of Leshner & Keays (2002), and in most cases, sulfides are associated with cumulates having low Cr contents (Fig. 5B). Some of the deposits contain small massive to semi-massive sulfide accumulations, as is common in type II deposits. The deposits are magmatic in origin, but they have been modified to various degrees by post-magmatic processes (i.e., type IV–V deposits) (Table 1 and Fig. 6). The parental magmas of the Finnish deposits vary in composition from komatiitic basalt (e.g., Hietaharju) to low-Mg komatiite (e.g., Vaara) and komatiite (e.g., Ruossakero). Most of the deposits formed from the Al-undepleted komatiite magma type, being similar to most of the komatiite-hosted Ni-Cu-PGE deposits around the globe. In the case of Ruossakero, Sarvisoaivi, and Hotinvaara, the magma was Ti-depleted komatiite (Table 1).

As summarized in Figure 1, the genesis of the komatiite-hosted Ni-Cu-PGE sulfide deposits is thought to be related to a high degree of partial melting of the mantle source and thermo-mechanical erosion of crustal rocks induced by hot komatiitic magma. The generated mantle melt is enriched to various degrees in Ni, Cu, and PGE (i.e., low-Mg komatiites have slightly higher PGE+Cu content as komatiites), but the melt is sulfur undersaturated due to its high capacity to dissolve sulfur. During magma ascent or emplacement in the Earth's surface, the most effective way for the magma to become sulfur saturated is through its interaction with S-bearing crustal rocks. After S saturation, sulfide droplets react with the Ni-, Cu- and PGE-rich magma. To form an economic deposit, these sulfides have to be sufficiently accumulated in mechanically favorable traps. Komatiite lava fields are non-prospective if: 1) some sulfides remain in the mantle source due to an insufficient degree of mantle melting, 2) contamination is

insufficient or the contaminant is poor in sulfur, and 3) the magmas reach sulfur saturation and sulfide accumulation takes place deep in the crust. Turbulently flowing magma with a high temperature and low viscosity, capable of physical scavenging of the substrate, forms a powerful assimilation mechanism, which is termed thermo-mechanical erosion. This is characteristic of komatiitic environments and important in the genesis of komatiite-hosted Ni-Cu-PGE deposits. Metal tenors of the sulfide fraction are strongly dependent on the R factor and the composition of the parental magma.

Because contamination is an important factor in the genesis of komatiite-hosted sulfide deposits, exploration can potentially benefit from searching for signs of contamination in potential host rocks of deposits (e.g., the occurrence of country rock xenoliths and hybrid rocks or geochemical signatures). Evidence for contamination may be revealed by the trace element and isotope compositions of komatiitic rocks. However, most of the komatiitic rocks have undergone post-magmatic alteration (e.g., hydration, CO₂ metasomatism) and deformation since their emplacement, and several studies have demonstrated the mobility of many elements, including LREE (e.g., Gruau et al. 1992, Lahaye et al. 1995, Leshner & Stone 1996, Leshner et al. 2001, Barnes et al. 2004a). The use of multiple sulfur isotopes has recently provided a powerful tool to detect the assimilation of external sulfur in komatiitic systems (e.g., Bekker et al. 2009, Fiorentini et al. 2012, Konnunaho et al. 2013, Konnunaho et al. 2016). Conventional sulfur isotope compositions ($\delta^{34}\text{S}$) of mantle-derived magmas are generally close to chondritic values, varying between -2 and +2‰ (Ripley & Li 2003). In the Finnish komatiite-hosted Ni-Cu-PGE deposits, the compositions are between -0.7 and +15‰, being close to mantle values in the Archean deposits and much higher in the Paleoproterozoic Lomalampi deposit (Konnunaho et al. 2015; see their Fig. 3.2.20). Deviances from the mantle values may indicate contamination with country rock material having either a light or heavy $\delta^{34}\text{S}$ composition. However, the country rocks of Ni-Cu-bearing intrusions do not necessarily show $\delta^{34}\text{S}$ values that are different from mantle values, and hence $\delta^{34}\text{S}$ alone does not always provide unequivocal evidence for the presence of external sulfur (e.g., Penniston-Dorland et al. 2008, Bekker et al. 2009, Fiorentini et al. 2012). In contrast, the use of multiple sulfur isotopes (^{32}S , ^{33}S , ^{34}S and ^{36}S) is a more useful tool for recogni-

zing the sulfur source in Archean supracrustal environments (e.g., Fiorentini et al. 2012). Multiple sulfur isotope analyses show a varying degree of MIF-S in the Archean Vaara and Hietaharju Ni-Cu-PGE deposits (+0.53 to +0.66‰ and -0.08 to -0.15‰, respectively) (Fig. 8), their country rocks, and sulfide deposits in Archean greenstone belts, demonstrating a significant role of external sulfur assimilation in the ore formation (Fig. 8) (Konnunaho et al. 2013, Konnunaho et al. 2015, Konnunaho et al. 2016), analogously with some other Archean Ni deposits in Canada and Australia (e.g., Bekker et al. 2009, Fiorentini et al. 2012).

Most of the Finnish komatiite-hosted Ni-Cu-PGE deposits are geochemically similar to komatiitic deposits globally. Finnish deposits are associated with Al-undepleted (AUK) ($\text{Al}_2\text{O}_3/\text{TiO}_2=15\text{--}20$) and Ti-depleted komatiites ($\text{Al}_2\text{O}_3/\text{TiO}_2>20$) (Fig. 5A and Table 1) (Konnunaho et al. 2015). Some of the Finnish deposits are highly enriched in PGE (Pd+Pt) and are hence of particular economic and scientific interest (Fig. 7D). The Lomalampi deposit is unique among the disseminated deposits in showing an abnormally high PGE content in the sulfide fraction, a high Pt/Pd ratio, and low S and base metal contents. In this respect, the Lomalampi and other Finnish PGE-enriched deposits are similar to the Raglan deposits in the Paleoproterozoic Cape Smith belt, Canada, where they are also associated with low-Mg komatiitic magmatism.

All MgO-rich komatiitic to picritic environments are generally prospective for Ni-Cu-PGE deposits, including different magma types (i.e., AUK and ADK, etc.) and a range of liquid compositions (komatiitic basalt, komatiites, and picrites, etc.) (Arndt et al. 2005, Leshner & Barnes 2009; see their Table 2.2). Voluminous ultramafic cumulates (commonly meso- to adcumulates) and thick cumulate sequences (e.g., channelized or conduit environments) are more favorable than thin, differentiated, and less voluminous lava flow sequences (e.g., sheet flow environments) (Barnes 2006, Arndt et al. 2008, Leshner & Barnes 2009, Barnes et al. 2016). Magnesium-rich magmatism associated with S-bearing country rocks and displaying signs of contamination and PGE depletion significantly raise the exploration potential (Fig. 1). Several studies (e.g., Barnes & Brand 1999, Barnes et al. 2004b, Barnes & Fiorentini 2012, Konnunaho et al. 2013, Konnunaho et al. 2015) have shown that the most favorable host rocks for Ni-Cu-PGE deposits

are Cr-poor olivine cumulates, which have formed from Cr-undersaturated magma, as in the case of the Vaara deposit, even though Cr-enriched cumulates occur in same areas (Konnunaho et al. 2013) (Fig. 5B). This method is not as useful in more fractionated, low-Mg komatiitic environments as it is in high-Mg komatiitic environments, because both the mineralized and non-mineralized cumulate bodies are chemically characterized by cotectic olivine-chromite trends (e.g., Leshner 2007, Barnes & Fiorentini 2012, Konnunaho et al. 2013). Other tools for exploration include the detection of PGE depletion in komatiitic magma suites, as this may indicate sulfide saturation (Fiorentini et al. 2010, Fiorentini et al. 2011, Heggie et al. 2013, Maier et al. 2013), and the use of Co# (Lamberg 2005) or Ni depletion in olivine and pyroxenes (e.g., Häkli 1971, Duke & Naldrett 1978, Makkonen 1996, Leshner et al. 2001) as an indicator of sulfide segregation in mafic to ultramafic systems. However, the lack of primary magmatic silicate minerals due to alteration in the Finnish komatiites normally precludes the use of this method.

The main results of this Ph.D. study and recommendations for further research can be summarized as follows:

- This study has provided the first overview of komatiite-hosted Ni-Cu-PGE deposits in Finland, summarizing previous exploration and new geochemical data from the most significant sulfide deposits.
- Komatiite-hosted Ni-Cu-PGE deposits in Finland are broadly similar to their counterparts globally. Some of the studied deposits (e.g., Vaara, Hietaharju, Lomalampi) are significantly enriched in PGE and Cu compared to “classical” Ni deposits generated from high-Mg komatiitic parental magmas. The occurrence of PGE-enriched deposits in Finland is related to less magnesian parental magmas and long-term (Archean to Paleoproterozoic) favorable conditions in the mantle that has produced these melts.
- Some of the sulfide deposits occurring in serpentinite bodies (e.g., Vaara and Ruossakero) have been strongly oxidized by post-magmatic hydrothermal processes and the original magmatic sulfides have changed to Ni-rich sulfide assemblages showing very high metal tenors. In talc-carbonate-altered bodies (e.g., Hietaharju), this type of “up-grading” has not taken place.
- The genesis of komatiite-related sulfide deposits is linked to the assimilation of S-bearing country rocks, and the detection of contamination signals is therefore important in exploration. In some cases, such as the Paleoproterozoic Lomalampi deposit, the presence of externally derived sulfur is indicated by heavy $\delta^{34}\text{S}$ compositions, but this method does not work so well with deposits formed in the Archean, with less intense bacterial isotope fractionation of sedimentary sulfur. Instead, as the studies on the Archean Vaara and Hietaharju deposits have shown, multiple sulfur isotope analysis, a recently adopted isotope technique, is a powerful tool for the detection of country rock assimilation because of the existence of mass-independently fractionated sulfur in the Archean supracrustal rocks.
- This study has pointed out the significance of Cr-poor olivine cumulates, among associated ultramafic bodies in high-Mg to low-Mg komatiitic systems, as potential host rocks of Ni-Cu-PGE deposits, being linked to the early separation of sulfide liquid before depletion of Ni in the silicate liquid. This method is not useful in Cr-saturated komatiitic basalt systems.
- This study and other investigations of Finnish komatiite-hosted Ni-Cu-PGE deposits have demonstrated the considerable exploration potential of Archean and Paleoproterozoic komatiitic extrusive and intrusive environments for new Ni-Cu-PGE discoveries (e.g., Sakatti). Finnish komatiitic basalts to low-Mg komatiites are prospective for PGE-enriched sulfide deposits, and high-Mg komatiites for “classical” Ni deposits.
- It is recommended that further studies of komatiite-hosted sulfide deposits focus on the reasons for the occurrence of PGE-enriched deposits in Finland and the Fennoscandian Shield, the conditions of the post-magmatic modification of primary sulfide assemblages in variably altered cumulate bodies, and applying further isotopic analysis (S and Re-Os) to unravel the sulfur and PGE source of the deposits, as well as developing other indirect methods to localize mineralized systems.

7 REVIEW OF THE ORIGINAL ARTICLES

Paper I: Konnunaho, J. P., Hanski, E. J., Bekker, A., Halkoaho, T. A. A., Hiebert, R. S. & Wing, B. A. 2013. The Archean komatiite-hosted, PGE-bearing Ni-Cu sulfide deposit at Vaara, eastern Finland: evidence for assimilation of external sulfur and post-depositional desulfurization. *Mineralium Deposita* 48 (8), 967–989.

In Finland, several small, low-grade sulfide deposits have been found in komatiites, including the ca. 2.8 Ga Vaara deposit in the Archean Suomussalmi greenstone belt. In this first paper, we describe the komatiite-hosted and PGE-enriched Ni sulfide deposit at Vaara, focusing on its petrological features, metal tenor, and upgrading of the ore by post-magmatic modification. We utilized multiple sulfur isotope analyses to examine the crustal potential contamination and to detect the source of S in the Vaara deposit.

The Vaara deposit occurs in the central part of the serpentinized olivine cumulate zone of a komatiitic extrusive body. It is composed of disseminated interstitial sulfides consisting of pyrite, pentlandite, millerite, violarite, and chalcopyrite accompanied by abundant magnetite. Although currently subeconomic, the mineralization is interesting due to the very high chalcophile element contents of the sulfide fraction (38 wt% Ni, 3.4 wt% Cu, 0.7 wt% Co, 22.4 ppm Pd, and 9.5 ppm Pt). The sulfides occur in relatively Cr-poor olivine cumulates, suggesting their formation from chromite-undersaturated magma. The parental magma was an Al-undepleted komatiite with an estimated MgO content of at least 24 wt%.

Extensive replacement of interstitial sulfides by magnetite and the presence of millerite- and violarite-bearing, pyrrhotite-free sulfide assemblages indicate significant post-magmatic, low-temperature hydrothermal oxidation of the primary magmatic pyrrhotite-pentlandite-chalcopyrite assemblage and related sulfur loss, which led to a significant upgrading of the original metal tenors of the Vaara deposit.

In contrast to most komatiites in the Archean greenstone belts in eastern Finland, the Vaara rocks are moderately enriched in LREE relative to MREE, suggesting that crustal contamination played an important role in the genesis of the Vaara deposit. Multiple sulfur isotope data reveal considerable mass-independent sulfur isotope fractionation both in country rock sedimentary sulfides,

showing a $\Delta^{33}\text{S}$ range from -0.50 to +2.37‰, and in the Vaara mineralization, with $\Delta^{33}\text{S}$ falling in the range of +0.53 to +0.66‰. These sulfur isotope compositions provide strong evidence for the incorporation of atmospherically-recycled, crustal sulfur in ore formation.

Paper II: Konnunaho, J. P., Halkoaho, T. A. A., Hanski, E. J. & Törmänen, T. 2015. Komatiite-hosted Ni-Cu-PGE deposits in Finland. In: Maier, W., Lahtinen, R. & O'Brian, H. (eds) *Mineral Deposits of Finland*. Amsterdam: Elsevier, 93–128.

This second paper is part of the book *Mineral Deposits of Finland* and presents an overview of the komatiite-hosted Ni-Cu-PGE sulfide deposits in Finland. The article focuses on the regional distribution, general petrological features (e.g., metal content, lithogeochemistry) and S isotope composition of the deposits and their classification.

Eight economically interesting komatiite-hosted sulfide deposits have so far been discovered in eastern and northern Finland. They are related both to Archean (Tainiovaara, Hietaharju, Peura-aho, Vaara, Ruossakero, and Sarvisoaivi) and Paleoproterozoic (Hotinvaara and Lomalampi) komatiite to komatiitic basalt magmatism. The deposits are mostly associated with the Al-undepleted komatiite type (AUK) ($\text{Al}_2\text{O}_3/\text{TiO}_2 = 15\text{--}20$), but Ti-depleted komatiites ($\text{Al}_2\text{O}_3/\text{TiO}_2 > 20$) 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 re-mobilized massive veins are associated with thick, MgO-rich and Cr-poor metacumulates. In some cases, sulfide mineralization is partly hosted in associated schists, as in the Peura-aho deposit.

Most of the Ni-Cu-PGE deposits have been modified by post-magmatic processes to various degrees, resulting in a notable increase in metal contents of the sulfide fraction in some of the deposits, particularly the Vaara deposit. The deposits are divided into two main groups based on their metal content: 1) deposits that are relatively 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 relatively low PGE contents (Sarvisoaivi, Ruossakero, and Hotinvaara). The Tainiovaara deposit shows an intermediate composition between

these two groups. The Lomalampi deposit is unique, because it has 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, which have Pt/Pd around unity.

The 2.06 Ga Lomalampi deposit contains isotopically heavy sulfur, with $\delta^{34}\text{S}$ ranging from +10 to +15‰, which demonstrates the presence of a large proportion of crustal sulfur in this deposit. Most of the Finnish Ni-Cu-PGE deposits have $\delta^{34}\text{S}$ 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, consistent with a significant role of external sulfur assimilation in the formation of the ore. Although no significant economic deposits have so far been found, the number of known mineralized ultramafic bodies and the high PGE contents in some of them indicate that komatiites in Finland still provide potential targets for future Ni-Cu-PGE exploration.

Paper III: Törmänen, T., Konnunaho, J. P., Hanski, E., Moilanen, M. & Heikura, P. 2016. Paleoproterozoic komatiite-related PGE mineralization in the Central Lapland greenstone belt, northern Finland. *Mineralium Deposita*, accepted (online version available)

The third article describes a PGE-enriched and S-poor, komatiite-hosted PGE-(Ni-Cu) deposit in the Lomalampi area, which is part of the Paleoproterozoic Central Lapland greenstone belt. The paper focuses on petrological characterization and the genesis of the Lomalampi deposit, which represents a unique deposit type among the komatiite-related sulfide deposits worldwide.

The Lomalampi PGE-(Ni-Cu) deposit is associated with a peridotitic cumulate body in the ca. 2.06 Ga Sattasvaara Formation in the Paleoproterozoic Central Lapland greenstone belt. The sulfides in the deposit occur in disseminated form, with the whole-rock sulfur content being 0.4–2 wt%. The Ni and Cu contents are ≤ 0.5 and ≤ 0.4 wt%, respectively, and the PGE contents exceed 500 ppb. The sulfides consist of a magmatic pentlandite-pyrrhotite-chalcopyrite assemblage and have not been substantially modified by metamorphic processes. Palladium minerals are associated with sulfides and silicates, but the only Pt-bearing phase, sperrylite, mainly occurs within silicates.

The host rock of the deposit is a chromite-under-saturated Al-undepleted high-Mg basalt or low-Mg komatiite. In contrast to most other komatiite-hosted Ni-Cu-PGE deposits worldwide, having Pt/Pd around 0.5, the Lomalampi deposit is enriched in Pt over Pd (Pt/Pd = 2). Only a weak contamination signal in the host-cumulate is evident in REE data, but a strong signal is evident in S isotope ratios ($\delta^{34}\text{S}$ +10 to +15‰), which differ substantially from the mantle value (0 ± 2 ‰). Geochemical characteristics (e.g., PGE enrichment) and R factor modeling indicates similarities between the Lomalampi and Paleoproterozoic Raglan Ni-Cu-PGE deposits in Canada. The combined data suggest that the Lomalampi deposit formed through the contamination of PGE-rich magma with S-rich country rocks. This suggests that the extensive Central Lapland Greenstone belt is favorable for komatiite-hosted Ni-Cu-PGE deposits, which are substantially enriched in platinum and palladium.

Paper IV: Konnunaho, J. P., Hanski, E., Wing, B., Bekker, A., Lukkari, S. & Halkoaho, T. 2016. The Hietaharju PGE-enriched komatiite-hosted sulfide deposit in the Archean Suomussalmi greenstone belt, eastern Finland. *Ore Geology Review* 72(1), 641–658.

In this article, we describe the Hietaharju Ni-Cu-PGE sulfide deposit, which is associated with komatiitic basalt magmatism in the Archean Suomussalmi greenstone belt, approximately 18 km SW of the Vaara deposit studied by Konnunaho et al. (2013). The Hietaharju deposit is highly enriched in PGE, similarly to the Raglan deposits in Canada. We have mainly focused on petrological issues, especially the PGE content, and the use of multiple sulfur isotope data for assessing the role of crustal contamination and the genesis of the Hietaharju deposit.

The Hietaharju Ni-Cu-PGE deposit is associated with high-Mg basalts and low-Mg komatiitic rocks. It represents a PGE-enriched type among komatiite-related Ni-Cu deposits. The deposit consists of several mineralized lenses in highly altered olivine-pyroxene cumulates (i.e., talc-carbonate-chlorite rocks) and contains disseminated, massive to semi-massive and brecciated sulfides. Post-magmatic carbonate metasomatism and shearing has not significantly changed the primary magmatic sulfide assemblage (i.e., pyrrhotite-pentlandite-chalcopyrite), but has possibly remobilized the sulfide aggregates and strongly

modified the sulfide textures. Although the deposit is currently subeconomic, it has a high PGE content in the sulfide fraction, averaging 5.7 ppm Pd and 2 ppm Pt (average of all ore types), being highest in disseminated sulfides.

The parental magma of the ultramafic rocks at Hietaharju represents an intermediate type between Al-undepleted and Al-depleted komatiites and differs from most other komatiitic rocks in the Tipasjärvi-Kuhmo-Suomussalmi greenstone belt complex, which are normally of the Al-undepleted type. The relatively fractionated nature of the komatiitic basalt parental magma of the Hietaharju deposit is consistent with the low Ni/Cu (<4) and Ni/Co (<18) and high Pd/Ir (<25) ratios of the sulfide fraction, which are similar to the values in the Paleoproterozoic Raglan belt deposits of Canada. The use of REE to constrain crustal contamination

is hampered by the highly altered nature of komatiitic rocks in the Hietaharju area. Sulfides in the country rock metasediments that host the Hietaharju Ni-Cu-PGE deposit show clear mass-independent sulfur isotope fractionation (MIF-S), consistent with their age and earlier S isotope data from the Suomussalmi belt (Vaara area). In contrast, sulfides of the Hietaharju Ni-Cu-PGE deposit only possess a small degree of MIF-S, providing limited direct evidence for the role of local metasedimentary sulfur in the ore formation. Archean base metal sulfide mineralization is among the potential sources of sulfur, however, and, as shown by the epithermal Taivaljärvi Au-Ag-Zn deposit, can have mass-independent sulfur isotope fractionation that is similar in magnitude and sign to that of the Hietaharju Ni-Cu-PGE deposit.

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My interest in geology began in 1984, when I took a hammer and started to collect rocks, fossils and minerals around the world and ore boulders in my home area in Ostrobothnia, western Finland. Then, later on, my dreams came true and my hobby became my occupation.

I became familiar with komatiitic rocks and related Ni-Cu-PGE deposits in 1997–1999, when I worked in the Archean Kovero greenstone belt area in eastern Finland. It was a great time to be part of the exploration team of the Outokumpu Mining Company. In particular, I want to express my sincere gratitude to Mr Jarmo Lahtinen, who managed the exploration project in that area and constantly gave his support to my work. These field investigations have been summarized in my Master's thesis: "*Kuusijärven jakson komatiitit ja niiden malmipotentiali Koveron arkeaisella vihreäkivivyöhykkeellä*" (*Komatiites and their ore potential in the Kuusijärvi area, Kovero Archean greenstone belt*). At the University of Oulu, Prof. Tuomo Alapieti († 2007) was my supervisor and he always endorsed and encouraged me in my studies. Rest in peace!

Early in 2000, I again joined the exploration team of the Outokumpu Company, studying komatiite-related Ni-Cu-PGE sulfide deposits in the Suomussalmi greenstone belt. Several discussions with my colleagues in the exploration team, including

Mr Jarmo Vesanto, Mr Risto Pietilä, Mr Jyrki Liimatainen and Mr Jukka Jokela, deepened my knowledge of this topic.

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In 2004, strong emotions and interest in mineral exploration and bedrock mapping led me to the Rovaniemi Office of the Geological Survey of Finland (GTK). However, komatiites and their ores stayed in and disturbed my mind, until 2010, when Prof. Eero Hanski from the Department Geosciences, University of Oulu, contacted me and proposed that I continue my research and finalize my

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Komatiite-hosted sulfide deposits are an important source of base and precious metals globally. This Ph.D. thesis comprises a synopsis and four original papers dealing with komatiite-hosted Archean and Paleoproterozoic Ni-Cu-PGE sulfide deposits in Finland, focusing on their geological, mineralogical, and lithogeochemical characterization, PGE content, and petrogenesis. In Finland, no significant komatiite-hosted Ni-Cu-PGE deposits have so far been discovered, although several small, low-grade deposits occur in Archean and Paleoproterozoic greenstone belts in eastern and northern Finland. Some of the studied deposits, which are associated with low-Mg komatiite to komatiitic basalt magmatism, are substantially enriched in PGE. The occurrence of komatiitic rocks with a clear signal of assimilation of external sulfur, their similarity with ore-bearing komatiitic rocks worldwide, and the discovered mineralization demonstrate that Finnish komatiitic rocks, and the mafic-ultramafic magmatism in general, have considerable exploration potential for Ni-Cu-PGE ores, as shown by the recently discovered Sakatti Cu-Ni-PGE deposit in Central Lapland. This thesis deepens our understanding of the Finnish deposits, and the results can be utilized in mineral exploration.



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