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Geology and crystallization conditions of the Särkiniemi intrusion and related nickel-copper ore, central Finland – implications for depth of emplacement of 1.88 Ga nickel-bearing intrusions

Hannu V. Makkonen[1*] and Pekka Tuisku[2]

[1] *Suomen Malmitutkimus Oy, Leimaajantie 7, FI-70150 Kuopio, Finland*

[2] *Oulu Mining School, P.O.Box 8000, FI-90014 University of Oulu, Finland*

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Abstract

Several Ni-Cu deposits occur within the Kotalahti area, central Finland, in proximity to an Archaean gneiss dome surrounded by a Palaeoproterozoic craton-margin supracrustal sequence comprising quartzites, limestones, calc-silicate rocks, black schists and banded diopside amphibolites. The geology of the area and age of the Ni-bearing intrusions (1.88 Ga) are similar to the Thompson Ni belt in the Canadian Trans-Hudson Orogen. The small mafic-ultramafic and Ni-Cu -bearing Särkiniemi intrusion, closely associated with the Archaean basement core of the Kotalahti Dome, is composed of a western peridotite and eastern gabbro body, both of which are mineralized. The eastern gabbro has a contact aureole several meters thick, consisting of orthopyroxene +/- cordierite bearing hornfels between the intrusion and the migmatites. Geochemically, the Särkiniemi intrusion shares many features in common with other Svecofennian mafic-ultramafic intrusions, including crustal contamination and nickel depletion. The related Ni-Cu deposit has a low Ni/Co value (15) and low nickel content in the sulphide fraction (2.8 wt.%), together with a low estimated magma/sulphide ratio of around 170.

Svecofennian 1.88 Ga mafic-ultramafic intrusions occur in terrains of variable metamorphic grade (from low-amphibolite to granulite facies) and are likely to represent emplacement at different crustal depths. Multi-equilibrium thermobarometry indicates that the contact aureole at Särkiniemi reached equilibrium at pressures of 4.5–6 kbar (15–20 km depth) and temperatures of 600–670 °C. Combined with the results of earlier research on the Svecofennian intrusions, this study indicates that a depth of 15–20 km crustal level was favourable, along with other critical factors, for nickel sulfide deposition at 1.88 Ga.

Keywords: Svecofennian, nickel, contact aureole, hornfels, thermobarometry, crustal level, Finland

* Corresponding author (e-mail: hannu.makkonen@malmitutkimus.fi)

Editorial handling: Arto Luttinen (email: arto.luttinen@helsinki.fi)

1. Introduction

Nickel sulfide deposits formed throughout the Fennoscandian and Canadian Shields at 1.88 Ga. Examples include the Kotalahti and Vammala Nickel Belts in Finland, the Västerbotten Nickel Belt in Sweden (Weihed et al., 1992) and Thompson and Cape Smith Nickel Belts in Canada (e.g. Hulbert et al., 2005; Lesher, 2007; Layton-Matthews et al., 2011; Naldrett, 2011). Most of the 1.88 Ga intrusive Svecofennian nickel deposits occur within the Kotalahti and Vammala belts in central and southern Finland respectively, surrounding the Central Finland Granitoid Complex (CFGC). The Kotalahti belt is located to the NE of the CFGC close to the Archaean craton margin, in a setting similar to that of the Thompson Belt, whereas the Vammala belt occurs further to the south west on the opposite side of the CFGC. The belts converge in the east (Fig. 1) and are characterized by bimodal ca. 1.91–1.88 Ga plutonism: granitic-dioritic juvenile intrusions dominate, while intrusions hosting the Ni-deposits represent less voluminous mantle-derived basic rock types. High-T–Low-P regional metamorphism, is usually upper amphibolite-facies grade but granulite-facies rocks are especially common in the Kotalahti belt. The Kotalahti belt, however, contains older ca. 1.91–1.93 gneissose rocks interpreted as having formed in a primitive island arc setting, correlative with similar rocks in the Skellefteå and Knaften belts in Northern Sweden, where ages extends back as far as 1.96 Ga (Huhma, 1986; Korsman et al., 1999; Koistinen et al., 2001; Guitreau et al., 2014; Makkonen et al., 2017; Mineral Deposits and Exploration).

The total ore production from Svecofennian nickel mines in Finland has been about 45 Mt @ 0.7 % Ni and the total pre-mining resource of all deposits known to date is about 73 Mt @ 0.6 % Ni. The belts are characterised by amphibolite facies to granulite facies metamorphic grade and abundant schollen- and schlieren-migmatites. The intrusions were emplaced during peak deformation and metamorphism. This resulted in highly variable settings of the intrusions and, in many cases, their dismemberment. The weakly differentiated, dominantly ultramafic Vammala-type intrusions consist almost entirely of olivine cumulates and represent magma conduits. The more strongly differentiated, mafic and mafic-ultramafic, Kotalahti-type intrusions consist of olivine cumulates, pyroxene cumulates and plagioclase-bearing cumulates. The parental magma for most intrusions contained 10–12 wt.% MgO. The least evolved magma was derived from a depleted mantle source (initial ε_{Nd} + 4) and probably contained around 15 wt.% MgO as indicated by the high Fo contents up to 89 at Kotalahti. Geochemically, the magma was similar to E-MORB in both belts (Makkonen, 2015).

For nickel exploration, the composition of the parental magma is important. The more evolved the magma the lower the MgO and nickel contents of the magma. During magma ascent from mantle into the crust fractional crystallization of olivine is a common phenomenon, resulting in lower MgO and nickel contents in the complementary residual magma compared to the primary magma. Based on this assumption, intrusions at lower crustal levels should have crystallized from more nickel-rich magma than those emplaced at higher levels. However, magmatic systems are typically not so simple. Commonly the magma conduits work repeatedly allowing magmas of separate pulses to ascend. Magmas may also be trapped at different levels and fractionate to different degrees, resulting in a wide range of magmas at higher levels. The resulting intrusions and related nickel ores thus may have been formed by a combination of magmas and processes (e.g. Yang et al., 2013). In case of the Svecofennian 1.88 Ga intrusions in Finland the composition of the host intrusions and nickel ores can be attributed to derivation from a single magma type, namely a high-Mg basaltic magma. Some intrusions were formed by multiple magma pulses of this magma (Makkonen, 2015 and references therein). The large number of the known Svecofennian 1.88 Ga intrusions in different metamorphic environments is interpreted as rep-

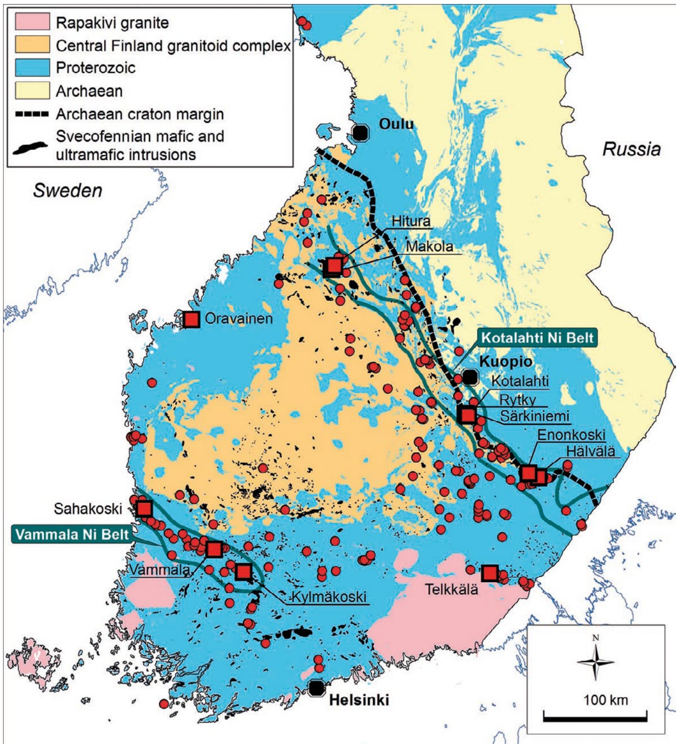

Figure 1. The main domains of the Svecofennian Ni deposits on a simplified lithological map (Bedrock of Finland-DigiKP, Geological Survey of Finland). The Särkiniemi deposit is located within the Kotalahti Ni Belt close to the Kotalahti and Rytky deposits. Red squares indicate the most important Ni deposits and red dots the minor deposits. Modified from Makkonen (2015).

resenting emplacement at different crustal levels (assuming that they were not intruded after peak metamorphism) and thus provides a good basis for studying the depth of emplacement.

Some studies have previously been published on estimating emplacement depths of mafic-ultramafic intrusions from the pressure and temperature during crystallization. Tuisku and Makkonen (1999) estimated, on the basis of the chemistry of orthopyroxene-clinoamphibole-spinel coronas located between plagioclase and olivine, that the crystallisation depth for the Saarijärvi intrusion in south eastern Finland was 17–20 km (900 °C, 5–6 kbar). In comparison, a similar study by Trudu and Hoatson (2000) of the 1.8 Ga East Kimberley intrusions in Australia, resulted in a range from 2.4 to 6.7±0.6 kb, which equates to upper-middle crustal depths of around 8–23 km. According to Bodorkos et al. (2002) the high-T, low-P metamorphism of the Halls Creek Orogen in the East Kimberley region reflects the middle crustal response to a mantle-derived thermal pulse, which would explain the perturbed thermal regime associated with felsic and mafic plutonism. In Finland, the Ni-belts surrounding the CFGC record an association of HT/LP metamorphism, voluminous felsic plutonism and mafic magmatism with mantle signature (Makkonen, 1996; Korsman et al., 1999; Makkonen and Huhma, 2007; Makkonen et al., 2017).

Mancini (1996) and Mancini et al. (1996a, b) studied crystallization and metamorphic equilibration of some intrusions of the Vammala belt. According to crystal chemistry of magnesian minerals an early high T phase of crystallization at 900–800 °C was afterwards overprinted by regional peak metamorphism at 700–730 °C and 4–5 kbar.

The Särkiniemi intrusion occurs in the Kotalahti area as a discrete small gabbro-peridotite intrusion hosting an economic nickel deposit (Figs. 1 and 2). The intrusion is surrounded by a distinct hornfels, which is rare within the Svecofennian intrusions. The Särkiniemi intrusion thus provides a good opportunity to study the PT conditions during the magma crystallization, not overprinted and obliterated by regional metamorphism. Makkonen and Tuisku (2017) have briefly summarized preliminary results of the PT study (~600–670 C and ~4.5–6 kbar). Because there are no earlier publications on the Särkiniemi intrusion and the Ni deposit, the Särkiniemi geology is described here in detail and olivine analyses are presented, based on reports of the Geological Survey of Finland and Finn Nickel Oy.

2. Study material, chemical analyses and methodology

Samples were obtained from 17 drill cores with a further 8 grab samples from outcrops. Twelve drill core samples were selected for whole rock analysis (Suvanto, 2015). In addition, 24 whole-rock analyses from earlier studies at Särkiniemi by the Geological Survey of Finland (GTK) were available (Forss et al., 1999). Electron microprobe analyses were made from 11 polished thin sections for silicate minerals.

Major and minor element whole rock analyses were performed by X-ray fluorescence (XRF, method code 175X) on pressed powder pellets at the GTK Espoo laboratory (GTK studies) and in Labtium Oy (XRF, method code 175X; new samples for this study). The sample preparation procedure is described by Labtium Oy (see:http://www.labtium.fi/en/our-services/exploration-and-mining). The reference samples used for quality control were international standard QCGBMS304–6 from GEOSTATS Pty Ltd and national in-house standards QC1 ja QC2. Typically, the precision of geochemical methods is in the range of 5–10 % and for assays 1–5 %. The quality of the data is monitored by repeated analyses of certified (e.g. STSD–4, SY–4, QCGBMS304–6) and internal reference materials (QC1 and QC2). The data of the standards must fall within the range of acceptance, which is generally 5 % but can be up to 20 % for certain trace elements. For further details about the analytical methods, precisions and detection limits see Rasilainen et al. (2007). Documents of all used analytical methods and detection limits are available in (http://www.labtium.fi/en/our-services/exploration-and-mining). Whole rock analyses made for this study and quality control data are provided in Electronic Appendix A.

Microprobe analyses were carried out on a JEOL JXA 8200 electron microprobe at the Center of Material Analysis, University of Oulu. Analyses were performed with a beam current of 15 nA and accelerating voltage of 15 kV and 10 μm beam diameter. The peak counting time was 10 s and that for the background 5 s. Standard used were wollastonite for SiO_2 and CaO, synthetic oxides for Al_2O_3 and MgO, metal for TiO_2, MnO, NiO and ZnO, chromite for Cr_2O_3, hematite for FeO, jadeite for Na_2O, orthoclase for K_2O, tugtupite for Cl and BaF_2 for F. Microprobe analyses are provided in Electronic Appendix B. Analyses of olivines from the intrusion were carried out by Cameca Camebax SX50 microprobe by Lassi Pakkanen and Bo Johanson at the Geological Survey of Finland, Espoo. Pyrope standard, accelerating voltage of 25kV, beam current of 49 nA and beam diameter of 5 μm were used during olivine analyses. For Ni and Co natural pentlandite and cobaltite standards respectively, extended 60 s peak and 30 s background counting times were used. Olivine microanalyses are listed in Electronic Appendix C.

The TWQ software package of Berman (1991, 2006) was used to calculate PT-conditions of crystallization of the host migmatites and the contact metamorphic hornfelses at Särkiniemi. The Berman (1988) dataset with the update by Berman and Aranovich (1996) was used for the calculations. Errors were estimated from the intersections of 3 or 4 independent equilibria by exclusion of intersections outside of 1.5σ and parallel (< 20°) equilibria. The bulk composition of the samples was used to calculate isochemical phase diagrams in order to test the consistency of the results with the observed mineral assemblage, and possible influence of disequilibrium in the results. The Theriak/Domino software package of de Capitani and Petrakakis (2010) was used in the construction of phase diagrams. The datasets used were the same as in the PT-calculations, but we also tested the Holland and Powell (1998) dataset.

3. Kotalahti Nickel Belt and geology of the Kotalahti area

The Kotalahti Nickel Belt joins the Savo supracrustal belt, which is mainly formed by migmatized mica gneisses derived from greywacke and mudrock protoliths. Felsic and mafic volcanic rocks, as well as graphite schists and gneisses, are locally abundant (Kähkönen, 2005). Volcanic rocks form distinct large scale areas, but also occur as narrow discontinuous belts or limited occurrences within both metasedimentary and intrusive complexes. The volcanic rocks can be classified into ca. 1.92 Ga bimodal and to 1.88 Ga mafic-intermediate age groups (Kousa and Lundquist, 2000). The former, attributed to volcanism withing a primitive arc complex in central Finland, are of economic significancse due to the presence of volcanic-massive Cu-Zn sulphide deposits. The 1.88 Ga nickel-rich mafic-ultramafic intrusions mostly occur within the mica gneisses, but also within and at the contact zone of the Archaean basement gneisses, as in the Kotalahti area (Fig. 1).

The eastern parts of the Savo belt, in particular, are characterised by fault bounded blocks with variable metamorphic and structural histories. The metamorphic grade varies from medium-T amphibolite facies (550–600 °C) to granulite facies (up to 800–880 °C in places) at pressures of 5 ± 1 kbar (Hölttä, 1988, 1995). The metamorphic evolution culminated close to an extensive phase of granitoid magmatism at ca. 1885 Ma. Deformation was polyphase and, in many places, produced complex interference patterns. The two earliest folding phases produced isoclinal to tight recumbent folds with east-to-northeast vergence; a regionally pervasive foliation or gneissose banding also developed during these phases. A third folding phase reoriented the flat-lying structures into subvertical attitudes and resulted in approximately N-oriented elongate antiforms and synforms, which characterize the overall structural pattern of the Savo belt (Kähkönen, 2005). Recently, the deformation history of the area has been revised and the deformation phases have been dated by U-Pb method from zircons and monazites. The history was shown to be more complicated and prolonged than previpously thought, with successive folding and shearing phases from ca. 1.9 to 1.79 Ga (Woodard et al., 2016).

Most of the mafic-ultramafic Ni-mineralised intrusions in the Kotalahti nickel belt are rather small, with only a few attaining 10 km in diameter at the present erosion level. Typically, the maximum horizontal dimension at the bedrock surface is less than 2 km. The intrusions show compositional differentiation ranging from ultramafic to gabbroic (locally to dioritic and quartz dioritic) rocks. Intrusions composed solely of ultramafic rocks are rare. The initial ε_{Nd}(1880 Ma) values for the intrusions show a wide range (from –2.4 to +3.1 ,+/- 0.4), which is attributed to variation in the amount, type and age of assimilated material (Makkonen, 1996; Makkonen and Huhma, 2007). Intrusions are mainly found in areas of relatively high metamorphic grade suggesting a relatively deep crustal section and/or an elevated thermal gradient.

The Kotalahti area is characterized by the Kotalahti Dome, which is composed of Archaean gneiss surrounded by a Palaeoproterozoic craton-margin supracrustal sequence of quartzites, limestones, calc-silicate rocks, black schists and banded diopside amphibolites. Metamorphism reached the amphibolite facies, causing gneissose and migmatitic textures in the supracrustal rocks. Several nickel deposits have been found in the Kotalahti area and in its vicinity. The most important include Kotalahti, Rytky (alias Valkeisenranta), Särkiniemi, Sarkalahti and Hanhisalo. The Särkiniemi intrusion lies within mica gneiss, higher in the stratigraphy than Kotalahti and Rytky, which occur within the Archaean gneiss or in the contact zone between the Archaean gneiss and Proterozoic schists (Fig. 2).

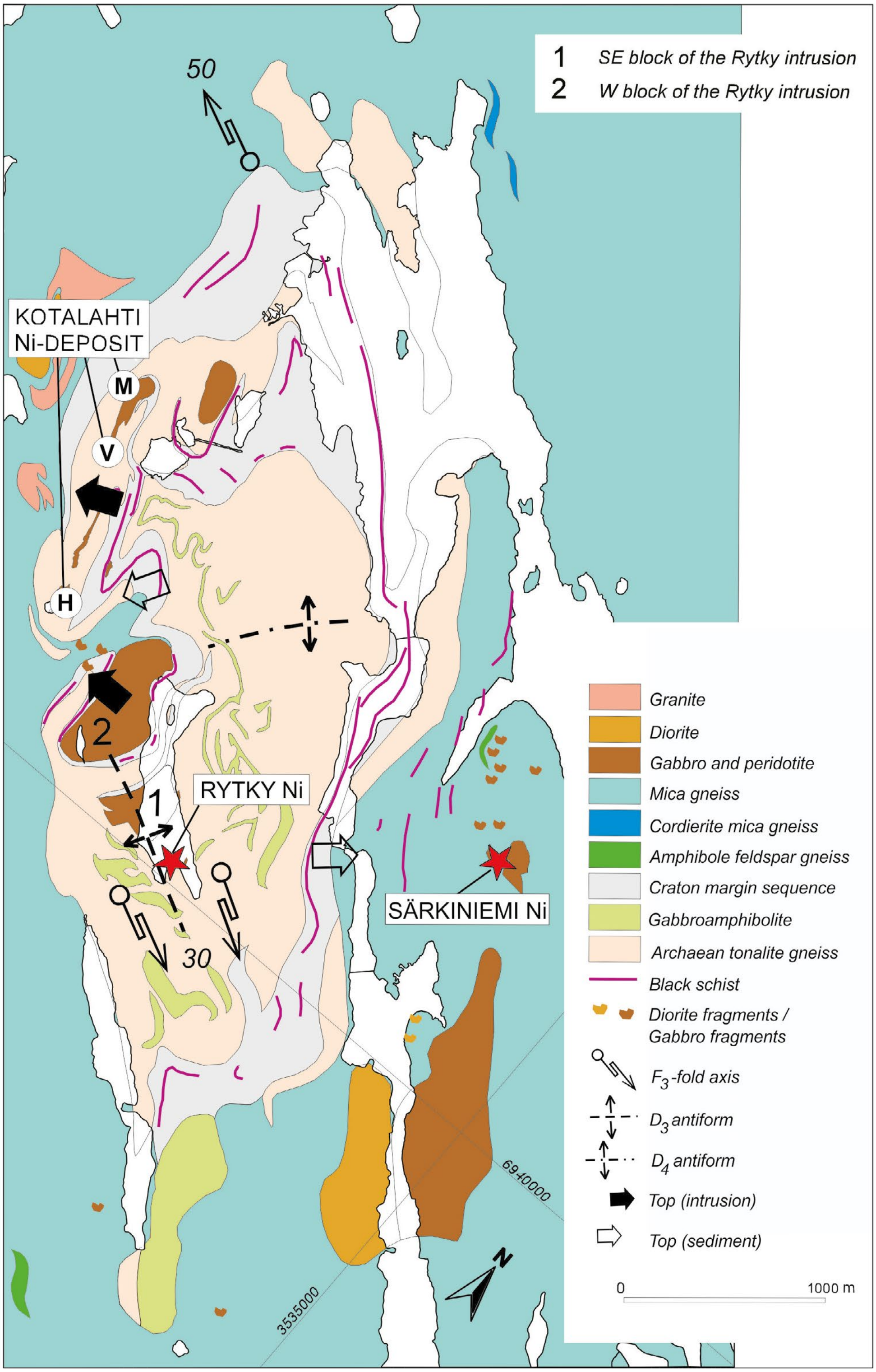

Figure 2. Kotalahti Dome geology. In the Kotalahti deposit the ore bodies: M = Mertakoski, V = Välimalmio, H = Huuhtijärvi. Lake areas indicated by white color. Coordinates refer to Finnish national YKJ system. Modified from Mäkinen and Makkonen (2004).

4. Särkiniemi

4.1. Särkiniemi intrusion and its thermal aureole

The Särkiniemi intrusion is located within schollen-schlieren migmatites between major shear zones. As a result of this deformation, the mafic-ultramafic intrusions have been segmented into smaller bodies. In the Särkiniemi area numerous small gabbro bodies and enclaves are found (from centimetre scale upwards), whereas the largest one, forming the main Särkiniemi intrusion covers an area of around 100 x 200 m at the surface section. It is composed in the western part of metaperidotite and metagabbro in the east. The gabbroic, eastern part of the intrusion extends down to the 120 m level, whereas the western, peridotitic part is shallow and is bounded on both sides by faults. A distinct contact metamorphic aureole several meters thick, especially between the intrusion and the migmatites around the eastern gabbro body, is represented by hornfels comprising orthopyroxene, anthophyllite and cordierite (Kontoniemi and Forss, 1997) (Figs. 3 and 4).

The metaperidotite contains abundant secondary amphibole and can locally be described as an amphibole rock. Primary olivine is preserved in places, usually as partly serpentinized grains. Talc and chlorite alteration is common in the

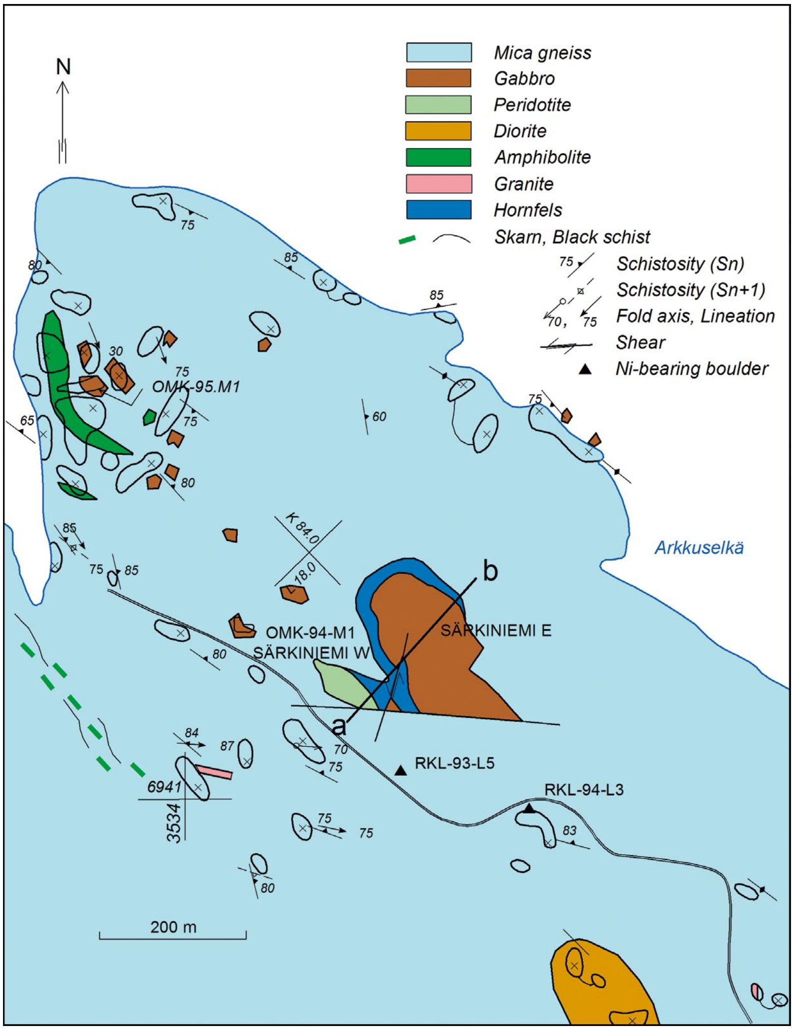

Figure 3. Bedrock geology of the Särkiniemi area. Northing and easting coordinates refer to Finnish national YKJ system and KL coordinates to the local Särkiniemi mine grid. Line a-b marks the location of the cross section in Figure 4. Modified from Kontoniemi and Forss (1997).

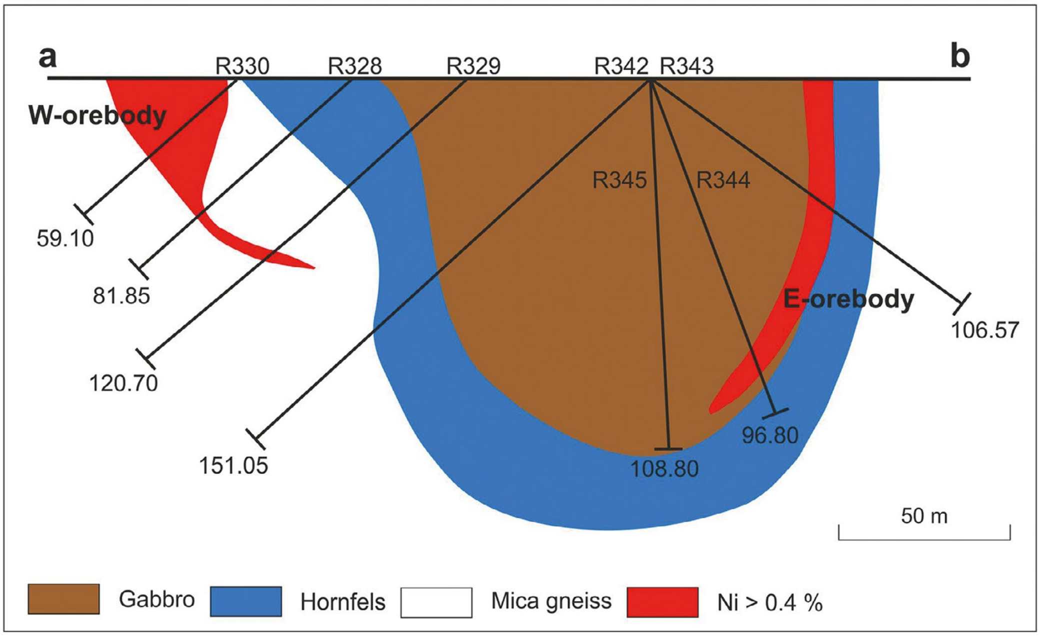

Figure 4. Cross section through the Särkiniemi deposit (line a-b in Fig. 3). Drill hole ID numbers and depths (m) of each drill hole marked. Modified from Kontoniemi and Forss (1997).

metaperidotite. The gabbroic differentiates range from melagabbro through olivine gabbro and pyroxene gabbro to ophitic leucogabbro. A distinct rock series zonation was mapped during evaluations by Finn Nickel Oy in the Särkiniemi open pit: migmatitic mica gneiss – hornfels – pyroxene gabbro – disseminated ore in melagabbro – disseminated to net-textured nickel ore in meta-peridotite – massive nickel ore (Fig. 5). The gentle southwards dip of the layers and the internal pseudostratigraphy of the intrusion suggests that the rock assemblages have been tectonically thrust from south to north and locally overturned. An internal pseudostratigraphy within the intrusion is also indicated in the eastern gabbro body by increasing whole rock Mg-number towards the eastern contact (Kontoniemi and Forss, 1997).

Hornfels (Fig. 6) differs from the migmatitic wall rock gneiss by the almost total absence of neosome material. Kontoniemi and Forss (1997) recognized following types of hornfelses: a) biotite –amphibole gneiss, b) pyroxene-cordierite gneiss and c) pyroxene gneiss. According to Suvanto (2015) the following dominant mineral assemblages are found within different hornfelses (mineral abbreviations after Kretz, 1983):

1) Bt-Pl-Qtz-Crd,
2) Bt-Pl-Opx-Qtz-Crd,
3) Bt-Pl-Opx-Ath-Qtz-Crd-(±Spl and Tur),
4) Ath-Crd-Bt-Pl±Qtz±St,
5) Bt-Pl-Opx-Ath-Qtz,
6) Opx-Pl-Bt-Ath and
7) Hbl-Pl-Bt.

The different hornfels types occur irregularly in different drill cores. There is no clear zoning except that the amount of pyroxene seems to increase towards the intrusive contact. Especially in quartz-rich types the oriented, gneissic fabric of the rock is overprinted by randomly oriented orthopyroxene, anthophyllite and cordierite porphyroblasts and poikiloblasts. This gives the rocks typical hornfels fabric and clearly shows the intrusion induced thermal overprinting of the earlier gneissose fabric in the country rock and intensive recrystallization of the aureole. Orthopyroxene has generally grown over matrix biotite and may form large skeletal poikiloblasts (Fig. 6) whereas cordierite

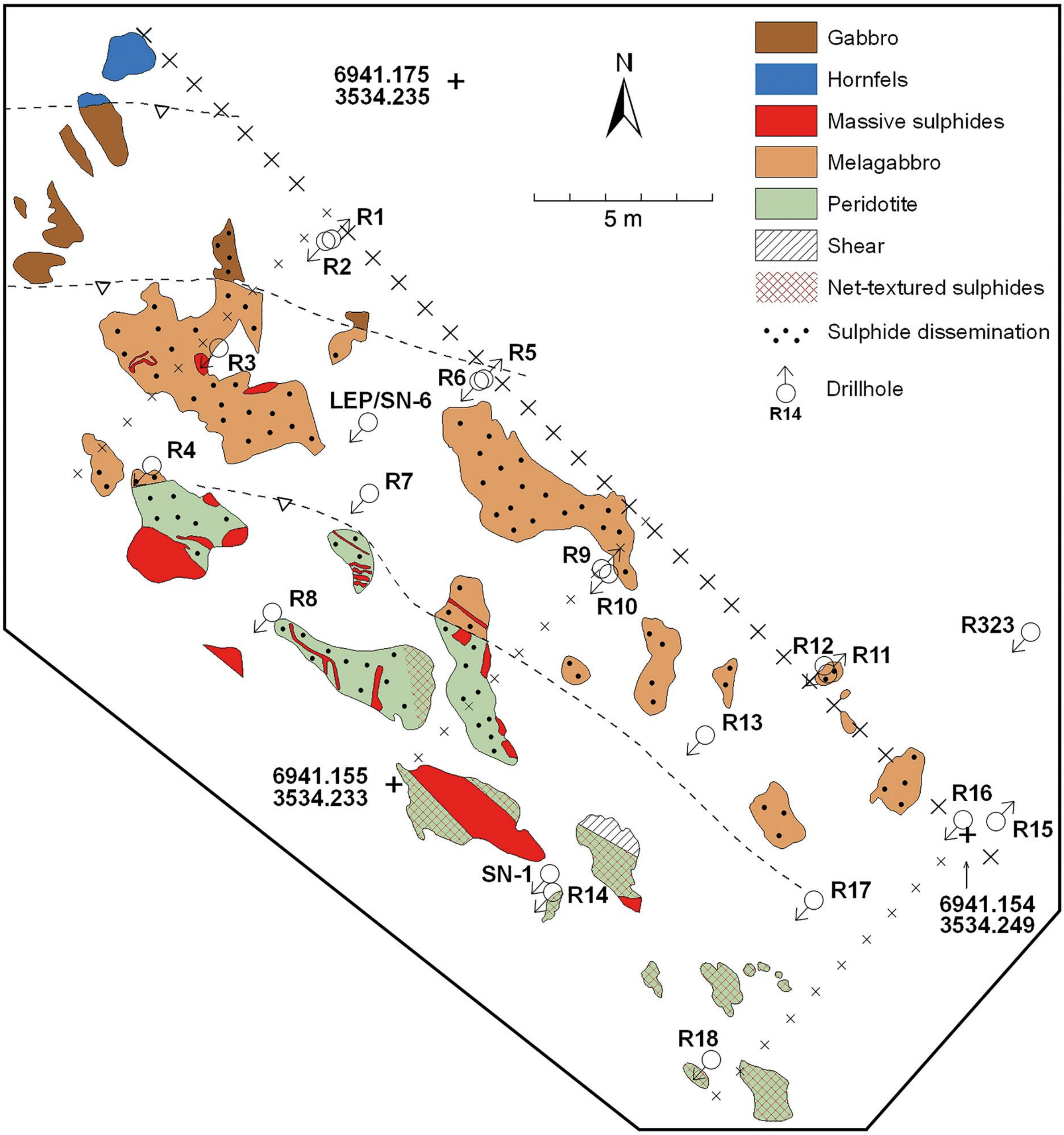

Figure 5. Detailed surface map from the NE border of the Särkiniemi W ore. Coordinates refer to Finnish national YKJ system. Data from Finn Nickel Oy fieldwork.

porphyroblasts are more or less ellipsoidal and have an internal relict schistosity revealed by relic biotite inclusions (Fig. 6). In some drilling profiles, the contact between the hornfels and gabbro is visually unclear, but the nickel content drops rapidly from gabbro to hornfels. This indicates that there was no involvement of the most immobile elements in any possible local contact metasomatic mixing in the aureole. Also Rb/Sr ratios are an order of magnitude lower in the gabbro compared to the country rock (consequently appr. 0.04 and 0.55, Electronic Appendix A). Pyrrhotite disseminations

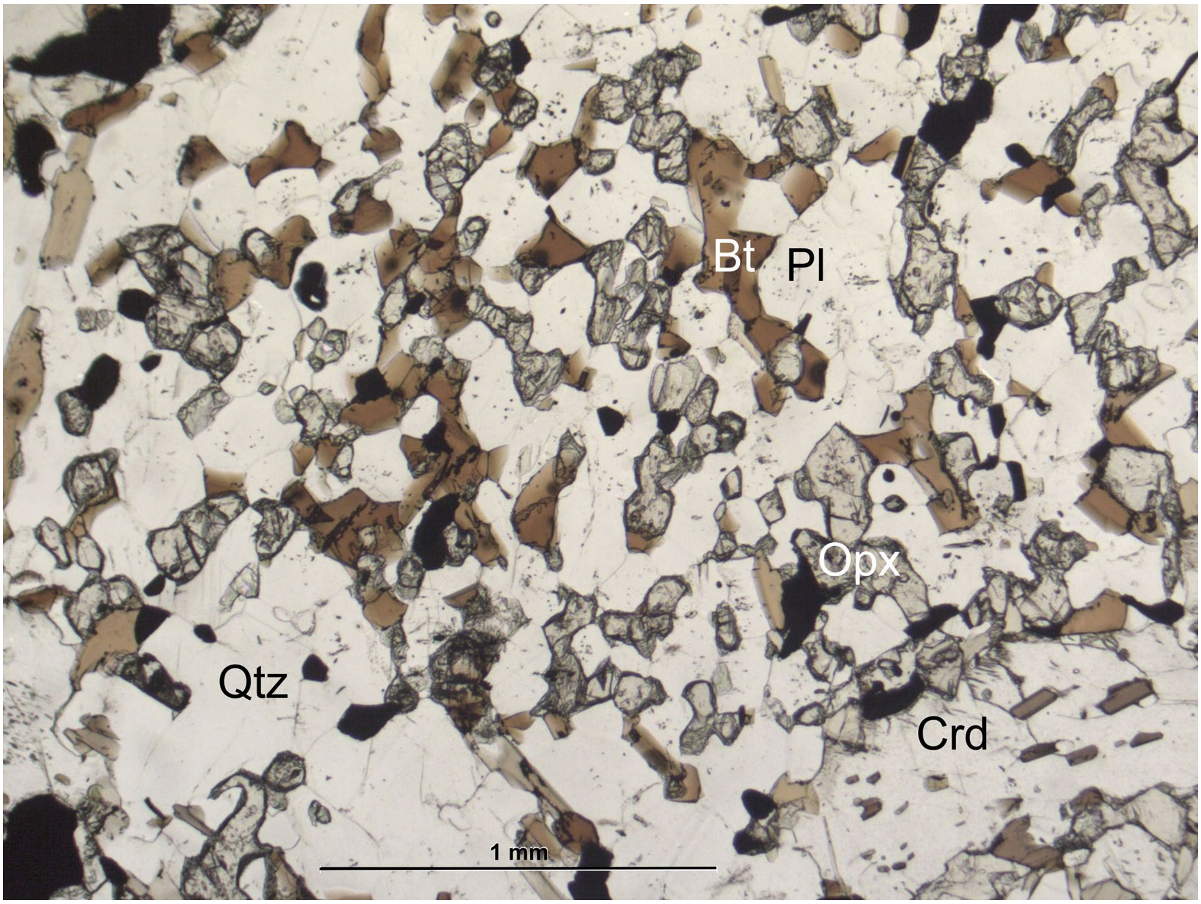

Figure 6. Microphotograph of biotite-plagioclase-orthopyroxene-quartz-cordierite hornfels. Oriented biotite (Bt) is replaced by orthopyroxene (Opx), cordierite (Crd) includes oriented biotite relics as internal schistosity Si. Schistose matrix is mainly composed of plagioclase (Pl), quartz (Qtz) and Bt. Sample R335/73.60m, thin section KU24140.

are abundant within the gabbro, hornfels as well as mica gneiss near the contact.

4.2. Särkiniemi Ni deposit

The Särkiniemi nickel deposit was found by the Geological Survey of Finland (GTK) in 1994 during the GTK's nickel exploration project in the Kotalahti nickel belt. The first indications found of mineralization were the discovery of nickel-rich glacial boulders 100–200 m southeast of the deposit in 1993 (Fig. 3) (Kontoniemi and Forss, 1997). The western, peridotite-hosted ore body was mined during 2007–2008 by Finn Nickel Oy, totalling 0.12 Mt at 0.92 % Ni and 0.44 % Cu. The total premining mineral resources were estimated to have been 292 700 t at 0.91 % Ni, 0.53 % Cu, 0.06 % Co and 12.32 % S (Heino, 1997).

Sulfide phases (pyrrhotite-pentlandite-chalcopyrite) occur disseminated throughout the eastern, gabbro-hosted orebody and disseminated, net-textured and massive in the western, peridotite hosted orebody (Fig. 7).

The major sulfide minerals in the *western orebody* are hexagonal pyrrhotite, pentlandite and chalcopyrite. Pentlandite occurs as euhedral grains, as aligned grains between pyrrhotite crystals and as fine-grained inclusions in pyrrhotite. Pentlandite has been altered to violarite along fractures and at grain boundaries. Pentlandite and violarite contain

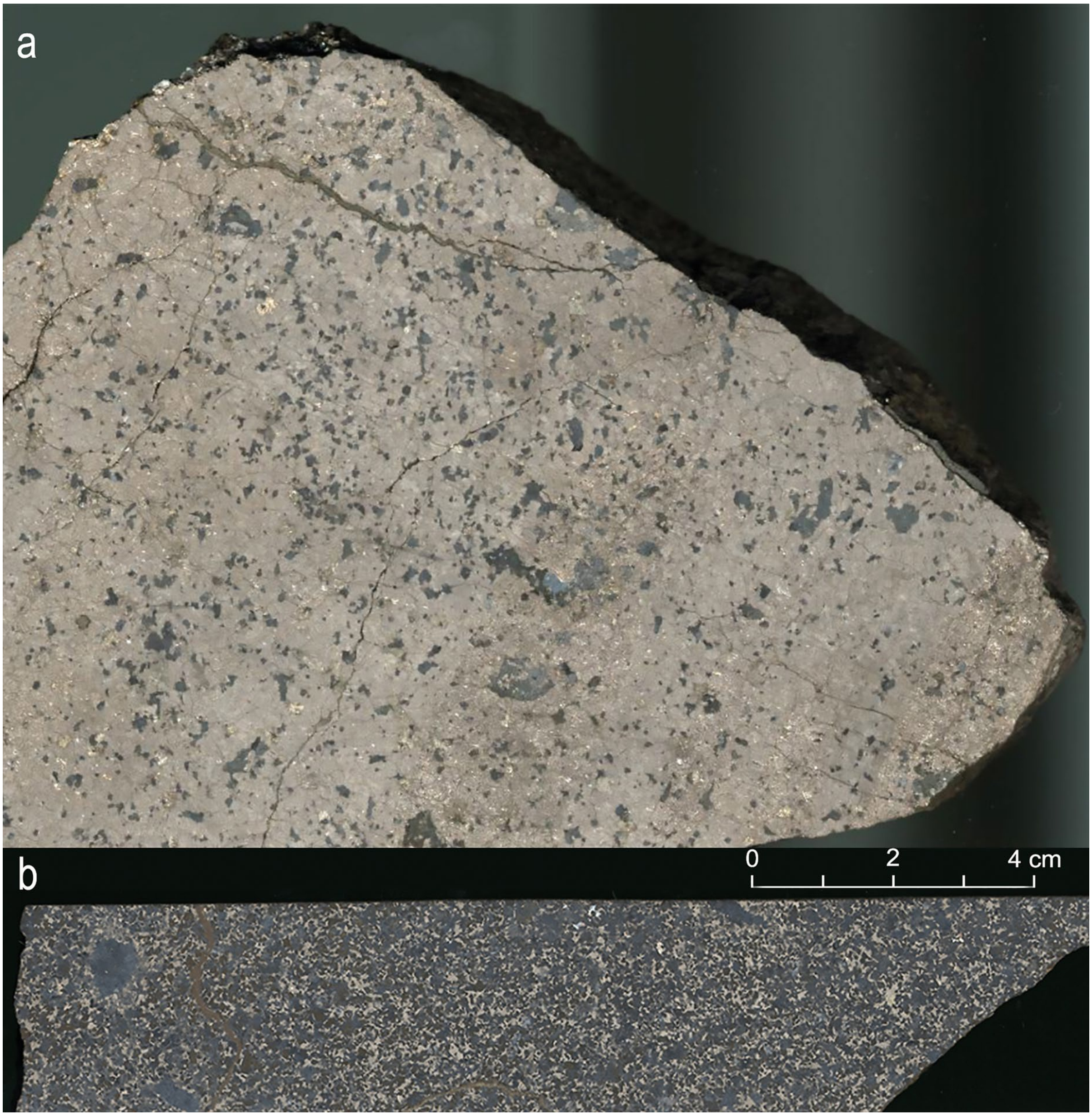

Figure 7. a) Massive pyrrhotite-pentlandite ore from the Särkiniemi W-ore pit. b) Net-textured ore in metaperidotite, Särkiniemi W-ore.

on average 2.8 wt.% and 2.9 wt.% Co respectively. Chalcopyrite occurs with pyrrhotite but also as inclusions and fracture fillings in silicates. The oxidic ore minerals are ilmenite and magnetite, which occur in fractures in both sulfides and silicates. Graphite is found sporadically. Based on the microprobe and whole rock analyses 85 % of nickel and 80 % of cobalt is combined in pentlandite and the rest in pyrrhotite (Kojonen et al., 1995).

The sulfides in the *eastern ore body* occur as heterogeneous disseminations, as stringer and breccias as well as narrow compact portions. The dominant and usually the only sulfide minerals are pyrrhotite, pentlandite and chalcopyrite. Some secondary pyrite occurs. Ilmenite is a typical oxide mineral.

Pyrrhotite occurs as anhedral grains which are unaltered. The average nickel content of four pyrrhotite samples from the drill core SN27 is 0.48 wt.%. Pentlandite occurs usually as unaltered subhedral grains in pyrrhotite or at the margin of the pyrrhotite grains. The largest grains are > 1 mm in diameter but usually the grain size is < 0.5 mm. In places the grains form rows at the contact of silicates and sulfides. Occasionally, pentlandite occurs as flame like exsolution lamellae (< 0.05 mm) in pyrrhotite. Chalcopyrite occurs as anhedral grains in pyrrhotite or in the silicates. In the latter case chalcopyrite is filling spaces between the silicates, thus the form of the chalcopyrite grains is controlled by the silicates. Chalcopyrite is also present as narrow crack fillings and veins within silicates. The main difference in the ore mineralogy between the western and eastern ore bodies is that pentlandite in the western ore body is altered to violarite whereas pentlandite in the eastern ore body is unaltered (Makkonen, 2008).

Amongst the Finnish Svecofennian nickel deposits Särkiniemi has relatively low Ni/Co value and nickel content of the sulfide fraction (Ni(sf)), around 15 and 2.8 wt.% respectively (Fig. 8). For comparison, in the neighbouring Rytky (Valkeisenranta) deposit the Ni/Co value is ≥ 20 and Ni(sf) around 6.4 wt.% (Mäkinen and Makkonen, 2004) and in the Kotalahti deposit the average Ni/Co value is 23 and Ni(sf) 6.5 wt.% (Papunen and Vorma, 1985, table 3). The Ni/Cu value in the Särkiniemi deposit has a wide range with an average of 1.7. The PGE contents are low, as is typical of Svecofennian deposits (Makkonen, 2015).

4.3. Geochemistry

Olivine in the peridotite has been partly altered to serpentine, chlorite and talc. Olivine has been analysed from five samples during the studies by the Geological Survey of Finland (GTK), four from the western and one from the eastern body and Fo values range from 71.8 to 75.3. The Ni content of olivine varies between 320–460 ppm in the western body, whereas the olivine in the sample from the eastern body contains 1040 ppm Ni (Electronic Appendix C). Based on the maximum analysed Fo value the MgO content of the parental magma was estimated to around 8 wt.% by Makkonen et al. (2017).

The average compositions of the rock types in the Särkiniemi E intrusion and the surrounding hornfels and mica gneiss are shown and compared to the average composition of the mica gneisses

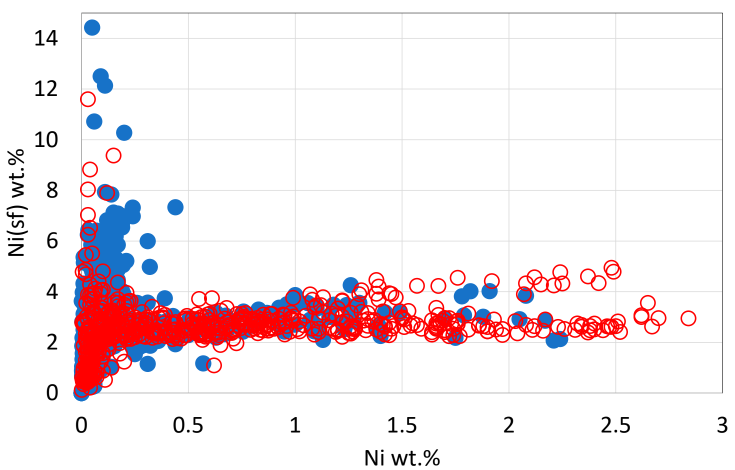

Figure 8. Nickel in sulfide fraction (Ni(sf)) vs. nickel in whole rock for the W (red) and E (blue) orebodies. Note the two trends for the nickel contents with > 1 wt.%. Ni(sf) is calculated based on the sulfur content of 37.5 wt.% in the sulfide fraction.

in the Kotalahti nickel belt in Table 1 and Fig. 9. Important is to note that the hornfels and associated mica gneiss have MgO contents almost as high as that of the gabbro norite (7.5–9 wt.%) whereas the average MgO content of the mica gneiss in the Kotalahti nickel belt is around 3 wt.%. The most distinctive compositional difference with respect to major elements between hornfels+mica gneiss and the intrusion are the higher CaO and Na_2O contents in the intrusive rocks. Of the trace elements, rubidium abundances are distinctly lower in the intrusive rocks than in the hornfels and mica gneiss and a barium-minimum is also obvious in hornfels and associated mica gneiss. The Rb/Sr ratio is much higher in the country rocks than in the intrusion. Chromium content on the other hand, is at the same level or even higher in some hornfels samples compared to the gabbros. Hornfels thus has element concentrations typical of both the intrusive rocks and the surrounding gneiss, suggesting partial mixing of the mafic magma and the gneiss.

Table 1. Average chemical compositions of rock types in the Särkiniemi E intrusion and the surrounding hornfels+mica gneiss. Data for Särkiniemi from Suvanto (2015) and Forss et al. (1999) and for mica gneiss regional and near intrusion from Mäkinen (1995). Major elements in wt.% and trace elements in ppm. GBNO = gabbro norite, OLGBNO = olivine gabbro norite.

	GBNO Särkiniemi	OLGBNO Särkiniemi	HORNFELS Särkiniemi	MICA GNEISS Särkiniemi, next to hornfels	MICA GNEISS Kotalahti Ni Belt, near intrusions	MICA GNEISS Kotalahti Ni Belt, regional
n	20	3	9	4	22	50
SiO2	48.04	44.63	49.19	50.30	64.45	63.94
TiO2	0.87	0.71	0.80	0.97	0.73	0.75
Al2O3	18.68	13.30	15.87	16.73	15.09	14.77
FeOtot	9.05	11.40	13.51	10.15	5.96	6.24
MnO	0.13	0.16	0.10	0.08	0.09	0.08
MgO	7.57	17.57	9.39	7.75	2.84	3.23
CaO	8.68	6.57	2.69	2.76	2.49	2.55
K2O	0.56	0.33	1.68	3.08	3.03	2.92
Na2O	2.48	1.82	1.37	1.86	2.95	2.84
P2O5	0.15	0.13	0.09	0.14	0.14	0.13
Total	96.21	96.62	94.69	93.80	97.77	97.45
Ba	165	158	176	352	670	633
Cl	112	132	105	169	152	169
Cr	171	438	445	319	118	136
Cu	236	89	412	197	34	48
Ga	22	16	29	34	23	24
La	10	14	16	28	47	43
Nb	6	5	5	6	13	13
Ni	411	571	453	210	50	63
Pb	21	16	21	30	32	31
Rb	20	14	71	125	113	109
S	5093	1793	23135	14100	1722	2466
Sc	24	21	39	19	15	15
Sr	292	231	208	239	233	230
V	165	132	296	212	140	151
Y	15	13	9	9	28	25
Zn	97	97	190	170	103	103
Zr	62	57	85	125	185	183

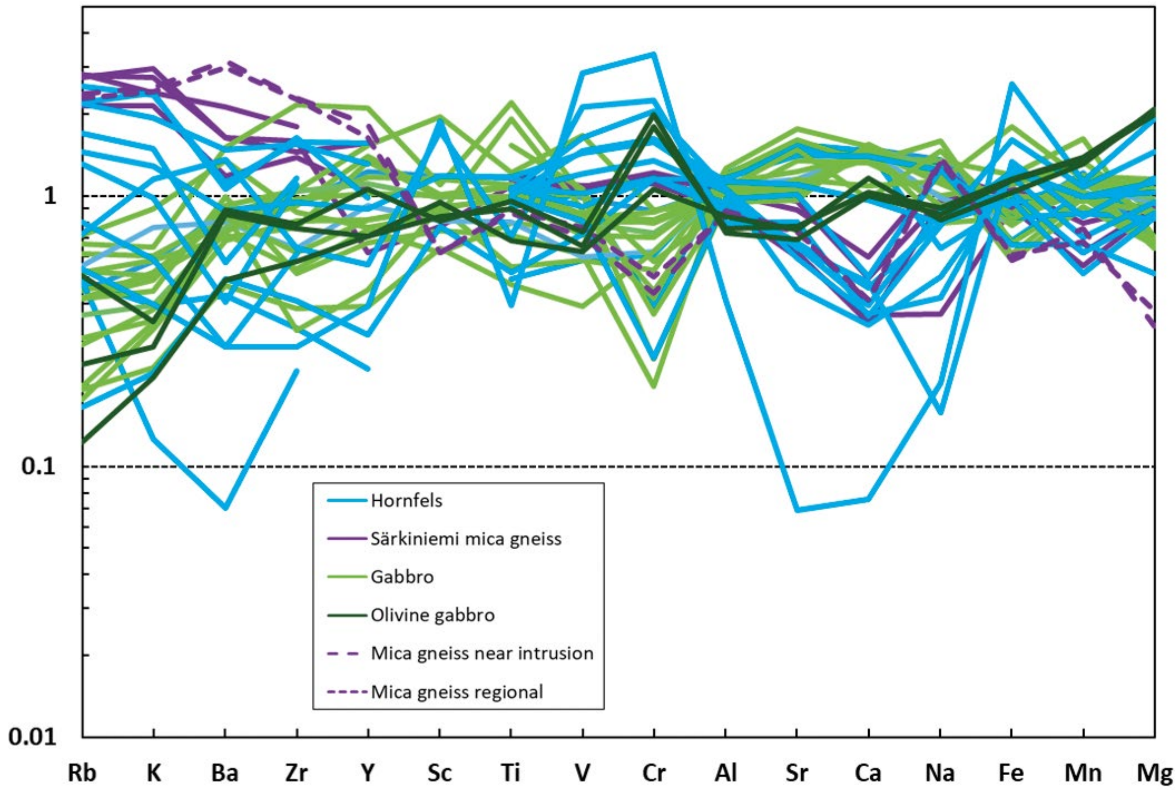

Figure 9. Spidergram for selected elements (normalized by the average of drawn) depicting the composition differences between gabbros, hornfelses and mica gneisses. Average compositions for the rock types in Table 1. Särkiniemi mica gneiss = Särkiniemi mica gneiss next to the hornfels; Mica gneiss near intrusion = mica gneiss near an intrusion in the Kotalahti Ni Belt; Mica gneiss regional = regional mica gneiss in the Kotalahti Ni Belt.

4.4. P-T study

The results of multi-equilibria thermobarometry are presented in Electronic Appendix D and Fig. 10. Generally, the calculated P and T of the hornfelses were within the fields of observed assemblages in the phase diagram, which is interpreted to reflect the attainment of equilibrium during the heating of the aureole and minor re-equilibration during cooling. Minerals were usually homogeneous, but some plagioclase grains showed little variation in the anorthite content and garnet in the Fe/Mg ratio between the rim and core. For consistency, the rim compositions of minerals are used in the calculation results given here. In the case of zoning, the calculated rim and core error ellipses in the PT space did actually overlap.

The migmatites, however, gave lower T than expected from the observed assemblage, which might indicate re-equilibration during cooling combined with the prolonged cooling due to extra heat from the crystallizing intrusion. In migmatites the analysis of core compositions of garnet gave slightly higher P and T than obtained from rims, but still with overlapping error ellipses.

5. Discussion

5.1. Ore forming processes

The composition of the Särkiniemi intrusion is typical for Kotalahti-type intrusions. The crystallization trend is dominated by orthopyroxene and

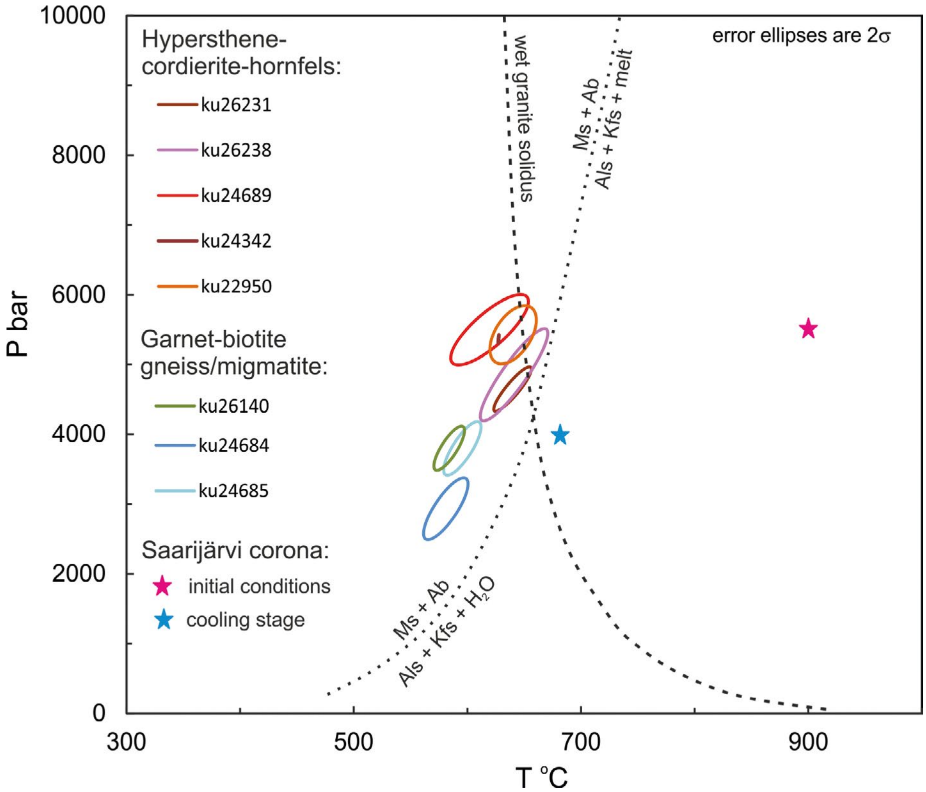

Figure 10. Thermobarometry of the hornfelses and garnet-bearing gneisses and migmatites near the Särkiniemi intrusion (ellipses) indicating 4.5–6 kbar pressure for the hornfels formation. For comparison, stars indicate initial subsolidus and cooling stage conditions of the Saarijärvi intrusion (in the igneous body itself) in the Juva area 65 km south of Särkiniemi (Tuisku and Makkonen 1999). Some key equilibria for melting and dehydration are given for reference.

plagioclase and the intrusion has elevated LREE contents compared to barren intrusions in the Kotalahti belt, suggesting crustal contamination (Makkonen et al., 2008).

Based on the low Ni/Co value (15) and low Ni tenor (2.8 wt.% Ni in the sulfide fraction) of the Särkiniemi nickel ore compared to the composition of the parental magma (MgO content around 8 wt.%, Ni content around 210 ppm) the magma had access to abundant sulfur in order for the sulfide ore to form. Most probable sulfur sources were the sulfide-bearing black schist intercalations within the surrounding mica gneisses. Interaction of sulfide-rich wall rock by a relatively small amount of mafic magma resulted in a low R-factor and low nickel tenor. Using 210 ppm as the estimate for the nickel content of the parent magma (calculated from Ni ppm = 8.36 x MgO 1.55 wt.%, Makkonen et al., 2017), 600 as $D_{Ni}^{sul/sil}$ and the calculated average sulfide fraction nickel content of 2.77 wt.% an R-factor (Campbell and Naldrett, 1979) of around 170 can be calculated (assuming that the metals were derived from the magma).The low R-factor is consistent with the low nickel content of the olivine. However, post magmatic equilibration of nickel between olivine and adjacent sulfides must also be considered as one possible process for lowering the primary nickel content in olivine, as seen in many other Svecofennian nickel deposits in Finland (e.g. Häkli, 1971; Mäkinen and Makkonen, 2004). The Ni/Co value of the ore is lower than in most other Svecofennian Ni deposits, being on average 15.7 for the W ore and 14.2 for the E ore. The small difference in the observed Ni/Co value between the W and E ore bodies may be due to the slightly higher silicate nickel content in the olivine-rich W ore. The low Ni/Co value of the Särkiniemi deposit is consistent with the low R-factor. Ratios of metals with large differences, of an order of magnitude or more in the D value (sulfide melt/silicate melt) reflect the R-factor and this is depicted by the Ni/Co value in the ore. In the Ni(sf) vs. Ni plot there are two trends for the higher (> 1 wt.%) nickel contents, within both W and E ores (Fig. 9). More studies should be done to make a more reliable interpretation but it may have been caused by upgrading of the nickel grade in the sulfide fraction by fresh magma and local variations in the R-factor. Consequently, from the point of view of exploration and evaluation of further ore potential in the area this is an important matter to review.

5.2. Estimated intrusion level – Implications for the mineral system

The metamorphic grade distribution in the Svecofennian bedrock of Finland suggests that there may have been various depths of emplacement for the 1.88 Ga intrusions. These observations include 1) the correlation of the metamorphic grade with the number and primitiveness of the intrusions and 2) the form of the intrusive bodies. The Svecofennian mafic–ultramafic intrusions occur throughout the Svecofennian of central and southern Finland, but most of the nickel-bearing intrusions occur within the Kotalahti and Vammala nickel belts to the south and east of the Central Finland Granitoid Complex (Fig. 1). The metamorphic grade within these two belts is upper amphibolite to granulite facies (low P, high T, Bedrock of Finland-DigiKP 2018) and the original magmatic mineralogy of the intrusions has commonly been strongly recrystallized, if not obliterated. Intrusions outside these belts and within a lower metamorphic grade areas record better preserved primary magmatic features. Comagmatic volcanic rocks (tholeiites-picrites, Barnes et al., 2009) also occur within the areas of lower metamorphic grade, suggesting the presence of shallower crustal depth than in the areas of upper amphibolite to granulite facies metamorphism (Makkonen, 2015).

Shallow intrusions are expected to have a more sill-like form than those crystallized at a greater depth as a result of subhorizontal magma flow because of the smaller density difference between magma and the host rock and lower lithostatic load. This is observed e.g. in southern Savo province in SE Finland where gabbro-diorite intrusions form sills that were later folded into upright orientations, such that they now outcrop as narrow and elongated bodies. These intrusions can be interpreted to represent the most fractionated and higher-level melts (low Ni/Cu in related sulphide ores), compared to the peridotite and peridotite-gabbro bodies outside the gabbro-diorite belt, which are characterized by more rounded and less elongated bodies (Makkonen, 1996, 2015).

The P-T determinations of the crystallization conditions for the intrusions provide more accurate crustal depth estimate than the comparative geological observations. The equilibrium constant isopleths of thermo-barometric reactions mostly have positive slopes in PT space. This usually leads to a slight underestimation of maximum P and T due to re-equilibration during cooling. The degree of underestimation depends on several factors including initial P and T, cooling and decompression rate, and H_2O content of the system (Perchuk, 2011). In our case, the temperature was not extremely high, the cooling rate from maximum T was probably fast relative to regional metamorphic rocks, as the hornfels zone is not very wide, and the rocks were already rather anhydrous, due to regional metamorphic dehydration events. Moreover, the minerals are relatively homogeneous in hornfelses at thin section scale. Consequently, the results are considered to represent the pressure and temperature conditions of the formation of the mineral assemblages in the hornfelses.

The crustal depth estimations of 15–20 km (4.5–6 kbar) for the Särkiniemi intrusion and 17–20 km (5–6 kbar) for the Saarijärvi intrusion (Tuisku and Makkonen, 1999) are similar within error limits. Both intrusions host nickel mineralization, which indicates that this crustal level at 1.88 Ga was favorable for the formation of magmatic nickel sulfide ores. Finnish Svecofennian mafic-ultramafic intrusions, which occur within areas of relatively low metamorphic grade seldom host nickel sulphide deposits.

6. Conclusions

The Särkiniemi intrusion has crystallized from a more fractionated parental magma (MgO ~ 8 wt.%) than most of the Svecofennian nickel-bearing intrusions (Makkonen et al., 2017), resulting in a low average Ni/Cu value (1.7) for the related sulfide ore. The intrusions located within the Archaean gneiss or in the contact zone of the Archaean gneiss and Palaeoproterozoic rocks in the Kotalahti area (e.g. Kotalahti and Rytky) have a more primitive parental magma (MgO ≤ 15 wt.%) and distinctly higher Ni/Cu value (2.5) in the sulfide ore (Mäkinen and Makkonen, 2004; Makkonen, 2015). This suggests a correlation between the crustal depth and primitiveness of the parental magmas for the intrusions. However, to study this correlation carefully, data from a larger number of deposits should be gathered.

Ascending magma will meet several kinds of wall rocks, physical environments, and possibly sulfur-rich rocks. At Särkiniemi the R-factor is low, which suggests effective assimilation/melting of sulfur-bearing crustal rocks. The closely associated sulfide-rich black schists of the Kotalahti area are good source rock candidates for sulfur.

In conclusion, if the intrusion level can be defined and the critical parameters for ore formation at that depth and below can be mapped or estimated, there is a good basis for ore potential evaluation. The intrusion level itself is not the main controlling factor but the critical parameters, such as crustal sulfur source and dynamic magma flow are sensitive to crustal level. In Figure 11 the proposed relative levels of the Särkiniemi and Saarijärvi intrusions are marked together with an estimate of the intrusion level for the Kotalahti and Rytky intrusions.

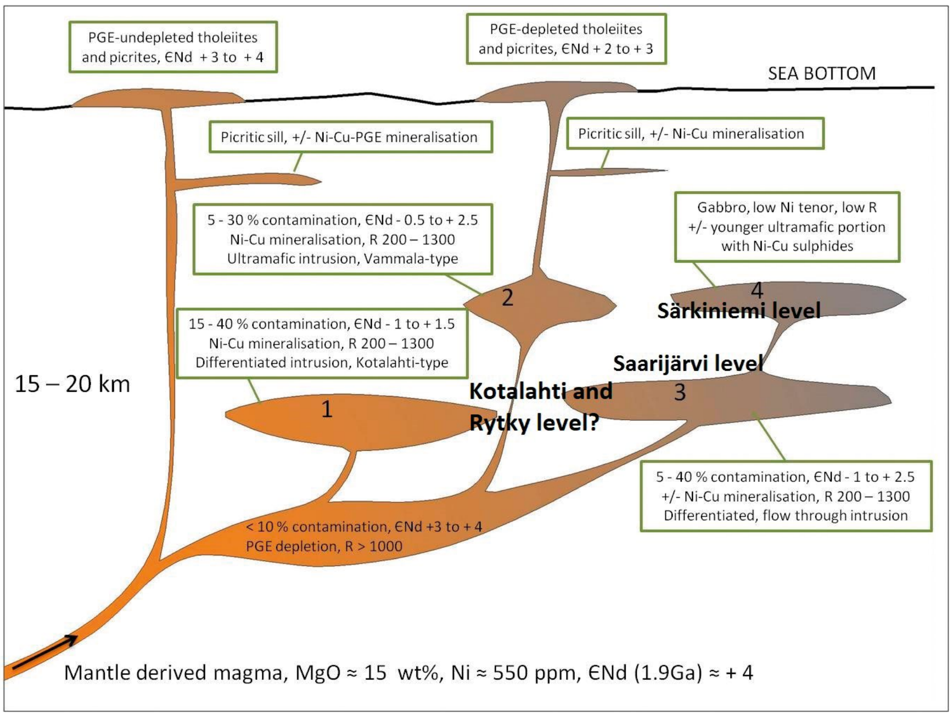

Figure 11. The estimated relative crustal levels for the Särkiniemi and Saarijärvi intrusions in the schematic intrusion model for Svecofennian mafic-ultramafic intrusions in Finland. The estimate of the intrusion level for the Kotalahti and Rytky intrusions is based on geology: their occurrence within and in the contact zone of the Archaean basement, and the fact that they have a more primitive parental magma than most of the Kotalahti Belt intrusions (Makkonen et al. 2017, table 3). Numbers 1–4 refer to (1) Kotalahti-type intrusions, where differentiation produced layered ultramafic to gabbroic rocks; (2) Vammala-type intrusions, representing ultramafic, weakly differentiated magma conduits; (3) ultramafic cumulate bodies from which the residual melt has been efficiently expelled upward; (4) gabbroic intrusions, with or without peridotite as a result of later pulses of olivine-bearing melt from lower magma chambers. Modified from Makkonen (2015).

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Supplementary Data

Electronic Appendices A-D for this article are available via Bulletin of the Geological Society of Finland web page.

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