CHAPTER

NICKEL DEPOSITS OF THE 1.88 GA KOTALAHTI AND VAMMALA BELTS

3.8

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ABSTRACT

The Kotalahti and Vammala belts in central and southern Finland, respectively, contain most of the 1.88 Ga intrusive Svecofennian nickel deposits. The Kotalahti belt is located close to the Archean craton margin, while the Vammala belt occurs further to the southwest within the Svecofennian domain. The total ore production from the 10 Svecofennian nickel mines in Finland has been about 45 Mt at 0.7% Ni and the total premining resource of all deposits known to date is about 73 Mt at 0.6% Ni. The belts are characterized 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. In both belts, the parental magma was basaltic with MgO contents mostly around 10–12 wt%. Sulfide segregation took place via crustal contamination when sulfur was added to the magma from the wall rocks. The mass ratio of silicate melt/sulfide melt (R factor) varied mostly between 200 and 1300 and, consequently, a wide range in nickel tenor is observed.

Keywords: Finland; Svecofennian; nickel; basalt; contamination; migmatites; olivine.

INTRODUCTION

The nickel-(copper) sulfide deposits hosted by the Svecofennian 1.88 Ga mafic–ultramafic intrusions have played a major role in Finnish nickel mining history. Altogether, 10 deposits have been mined, beginning in 1941 with the Makola deposit and extending to 2013 at the Hitura mine, which has become the largest nickel deposit of this type in Finland (the total amount of hoisted ore is about 16.5 Mt at 0.6% Ni and 0.2% Cu). The total ore production of the Svecofennian nickel mines in Finland stands at about 45 Mt at 0.7% Ni. The total premining resource of all the deposits known to date is about 73 Mt at 0.6% Ni, 0.3% Cu, and 0.03% Co (Tables 3.8.1 and 3.8.2). The current estimate for undiscovered resources down to a depth of 1 km (50% probability) is at least 480,000 t Ni, 200,000 t Cu, and 23,000 t Co (Rasilainen et al., 2012), representing a similar amount of metals as the total premining resources.

Owing to the synorogenic timing of the magmatism, the intrusions have a complicated tectonomagmatic history. This makes the Svecofennian intrusions quite distinct when compared to anorogenic nickel-sulfide-bearing intrusions such as Sudbury (Canada) or Norilsk (Russia). However,

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Table 3.8.1 Svecofennian nickel mines, total hoisted ore and average metal grades, in Finland 1941–2013

Mine	Mt	Ni (%)	Cu (%)	Ni (met. t)
Hitura	16.50	0.60	0.20	99,000
Kotalahti	12.36	0.66	0.26	81,576
Vammala	7.57	0.68	0.42	51,476
Enonkoski	6.71	0.76	0.22	50,996
Kylmäkoski	0.69	0.36	0.27	2484
Telkkälä	0.61	1.29	0.33	7869
Makola	0.41	0.81	0.43	3321
Hälvälä	0.25	1.41	0.35	3525
Särkiniemi	0.12	0.92	0.44	1104
Puumala	0.02	0.67	0.24	134
Total	**45.24**	**0.67**	**0.26**	**301,485**

deposits that resemble the Finnish ones in terms of tectonic setting are known from the Lappvattnet nickel belt in Sweden (Weihed et al., 1992); the Sveconorwegian (Norway) and Grenville (Canada) belts (Boyd and Mathieson, 1979; Boyd et al., 1988; Lamberg, 2005); the Variscan orogeny of southwestern Spain (Aguablanca; e.g., Piña et al., 2010); the circum-Superior belt of Canada, which contains the Thompson nickel belt (1.88 Ga; Hulbert et al., 2005), Fox River belt (1.88 Ga; Heaman et al., 1986), and Lynn Lake belt (1.87 Ga; Turek et al., 2000); and the mafic–ultramafic intrusions of the Halls Creek orogen in the East Kimberley, Western Australia (Hoatson and Blake, 2000).

The Svecofennian nickel-bearing intrusions of Finland have been comprehensively studied since the 1960s, by academic institutions and exploration geologists of the Outokumpu Company and the Geological Survey of Finland (Häkli, 1963, 1968, 1970, 1971; Papunen, 1970, 1974, 1980, 1985, 1986, 1989, 2003, 2005; Gaál, 1972, 1980; Häkli et al., 1975, 1976, 1979; Papunen et al., 1979; Papunen and Mäkelä, 1980; Grundström, 1980, 1985; Papunen and Koskinen, 1985; Papunen and Vorma, 1985; Papunen and Gorbunov, 1985; Mäkinen, 1987; Isomäki, 1994; Peltonen, 1995a, 1995b, 2005; Papunen and Penttilä, 1996; Makkonen, 1996, 2005; Mäkinen and Makkonen, 2004; Lamberg, 2005; Makkonen and Huhma, 2007; Makkonen et al., 2008, 2010; and Barnes et al., 2009).

Peltonen (2005) summarized the age data for the Svecofennian mafic–ultramafic intrusions. Since then, only one new age determination has been made. The Keskimmäinen gabbro-pyroxenite intrusion in the Siilinjärvi area yielded a U-Pb zircon age of 1879 ± 6 Ma (in situ laser ablation mass spectrometer; Kalliomäki, 2013). Most of the mafic–ultramafic intrusions record ages between 1875 and 1885 Ma, and all Ni-bearing intrusions belong to the 1880 Ma age group. Notably, this is the same age as that for the Paleoproterozoic nickel belts of Thompson, Cape Smith, Fox River, and Lynn Lake in Canada.

AREAL DISTRIBUTION OF DEPOSITS

The Svecofennian 1.89–1.87 Ga 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. 3.8.1).

Table 3.8.2 Svecofennian nickel deposits in Finland, estimated premining ore tonnages and average metal grades

Deposit	Status	Tonnage	Ni (%)	Cu (%)	Co (%)
Hitura	Mine	19,300,000	0.61	0.21	0.020
Kotalahti	Mine	13,300,000	0.66	0.26	0.030
Vammala	Mine	9,200,000	0.64	0.40	0.040
Laukunkangas	Mine	7,900,000	0.72	0.20	0.030
Ruimu	Deposit	3,500,000	0.32	0.28	0.040
Sääksjärvi	Deposit	3,500,000	0.24	0.33	0.030
Niinimäki	Deposit	2,700,000	0.40	0.14	0.018
Sahakoski	Deposit	1,600,000	0.65	0.19	0.030
Rytky	Deposit	1,540,000	0.71	0.29	0.030
Oravainen	Deposit	1,300,000	0.95	0.16	0.030
Ekojoki	Deposit	1,140,000	0.53	0.42	0.024
Kovero-oja	Mine	1,100,000	0.40	0.33	0.017
Makola	Mine	1,000,000	0.80	0.45	0.050
Hyvelä	Deposit	807,000	0.52	0.26	0.034
Kylmäkoski	Mine	690,000	0.36	0.27	0.010
Telkkälä	Mine	605,000	1.29	0.33	0.050
Makkola	Deposit	526,000	0.52	0.18	0.034
Mäntymäki	Deposit	466,000	0.73	0.20	0.010
Hälvälä	Mine	448,000	1.50	0.36	0.075
Rausenkulma	Deposit	375,000	0.36	0.49	0.023
Särkiniemi	Mine	292,000	0.91	0.53	0.063
Liakka	Deposit	250,000	0.37	0.78	0.020
Ilmolahti	Deposit	210,000	0.37	0.28	0.040
Sarkalahti	Deposit	190,000	1.02	0.33	0.027
Tevanniemi	Deposit	182,000	0.63	0.15	0.030
Hanhisalo	Deposit	143,000	0.61	0.20	nd
Törmälä	Deposit	116,000	0.60	0.33	0.030
Mäkisalo	Deposit	104,000	0.43	0.28	0.030
Niinikoski	Deposit	83,000	0.43	0.13	0.045
Rietsalo	Deposit	56,000	0.53	0.53	0.015
Heiskalanmäki	Deposit	55,000	0.55	0.25	0.015
Kekonen	Deposit	50,000	0.54	0.21	0.019
Härmäniemi	Deposit	37,000	0.84	0.24	0.040
Vehmasjoki	Deposit	36,000	0.94	0.69	0.060
Kitula	Mine	34,600	0.87	0.24	0.067
Pihlajasalo	Deposit	20,000	0.84	0.17	0.020
Total		**72,855,600**	**0.61**	**0.27**	**0.029**

Source: *Modified from Rasilainen et al. (2012, Table 1) and references therein. Tevanniemi after Eeronheimo and Pietilä (1988), Hälvälä after Eeronheimo (1985), and Hanhisalo after Kontoniemi and Forss (1998).*

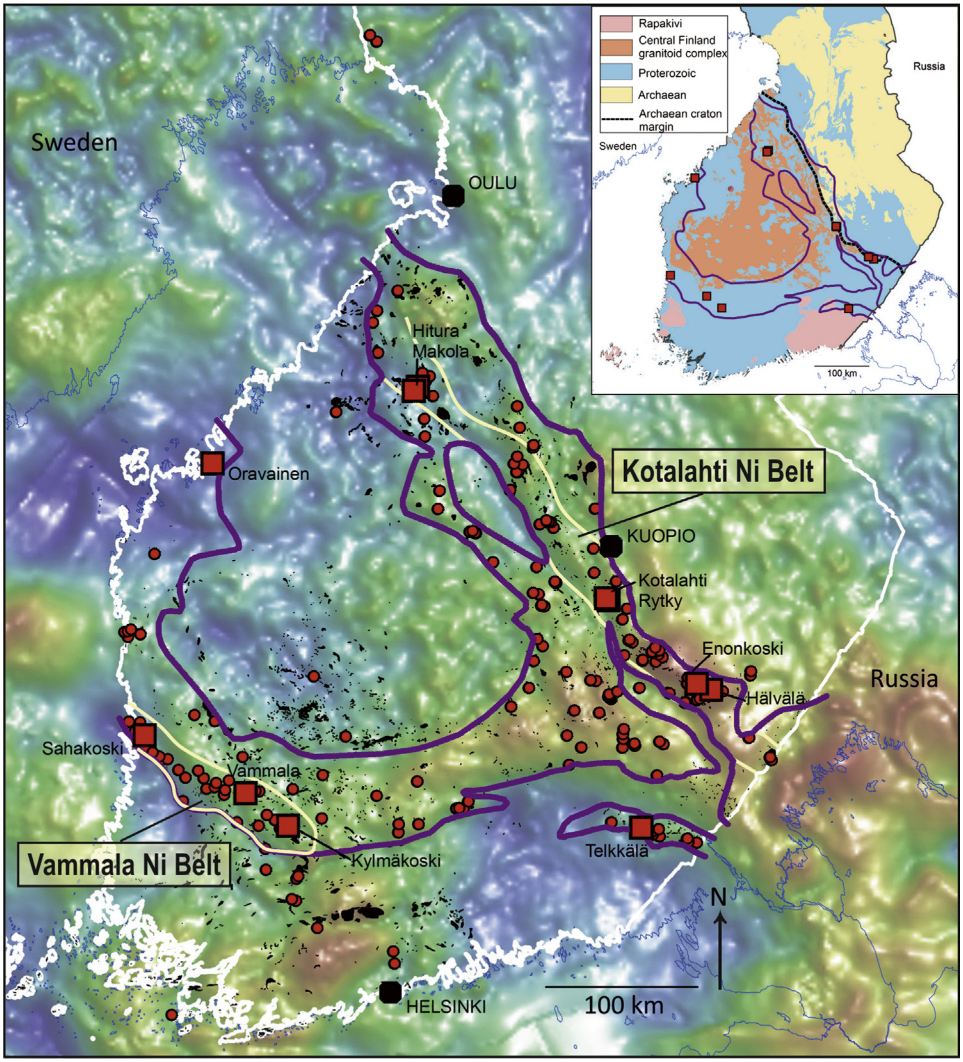

FIGURE 3.8.1 Gravimetric map showing the main domains of the Svecofennian Ni deposits and prospects in central and southern Finland (purple lines).

Nickel deposits are concentrated in the Kotalahti and Vammala Ni belts (highlighted by light yellow lines). The most important Ni deposits are indicated by red squares. The definition for the main Ni domains has been made on the basis of deposit distribution, lithology, regional metamorphic grade, gravity, and related tract definition by Rasilainen et al. (2012). Svecofennian mafic and ultramafic intrusions are shown in black. Gravimetric map is a hill-shaded (from northeast) Bouguer anomaly map with maximum intensity shown in red and minimum intensity in blue; map by Jouni Lerssi, GTK. Inset shows the main Ni domains superimposed on a simplified geological map, based on the GTK bedrock map database (Bedrock of Finland–DigiKP).

Peltonen (2005) classified the Svecofennian mafic–ultramafic intrusions into three groups on the basis of their geotectonic setting. Only the Group I hosts nickel deposits, and these were divided into (1) intrusions located close to the craton margin (Group Ia, referred to as the Kotalahti nickel belt) and (2) intrusions of the Tampere and Pirkanmaa belts (Group Ib, referred to as the Vammala nickel belt). Originally, the Kotalahti nickel belt was defined as a very narrow belt located at the craton margin (Gaál, 1972), but subsequently, nickel deposits located further to the southwest of the craton margin were included in the Kotalahti belt (e.g. Mäkinen and Makkonen, 2004; Makkonen, 2005). The Telkkälä nickel belt is a separate belt north of the Mesoproterozoic Viborg rapakivi massif. The Liakka nickel deposit within the Haaparanta suite north of Oulu constitutes a distinct Svecofennian deposit (Fig. 3.8.1).

The host rocks to the Svecofennian nickel-bearing intrusions are of a highly variable nature. The Vammala nickel belt occurs in the Pirkanmaa migmatite suite, which continues eastward to the Juva area in southern Savo province where several further nickel deposits occur. The Juva area, in turn, belongs partly to the Häme migmatite suite. East of the Juva area is the Haukivesi complex, which hosts the nickel deposits of the Kotalahti nickel belt. Thus, in the southeast corner of the Central Finland Granitoid Complex several lithological suites meet, giving rise to local overthrusting, with all of them containing Svecofennian nickel deposits (Fig. 3.8.1). This suggests that the exposed nickel deposits probably represent different crustal levels.

The distribution of the Svecofennian metapicrites can be used as a guide to determine the areal distribution of the Svecofennian nickel-bearing intrusions. Both lithologies host nickel mineralization, they occur together (e.g., in the southern Savo area), and are thought to represent the same magmatic event (Makkonen, 1996; Makkonen and Huhma, 2007; Barnes et al., 2009). The metapicrites are found all around the Central Finland Granitoid Complex, similar to the nickel-bearing intrusions. An analogy is found within the Thompson nickel belt, Canada, where the Opswagen group hosts nickel-bearing ultramafic sills and comagmatic mafic to ultramafic volcanic rocks (picrites) (Bleeker, 1990).

Most of the nickel deposits related to the Svecofennian Group I intrusions occur within zones characterized by amphibolite facies to granulite facies metamorphic grade, schollen and schlieren migmatite-textured sulfide- and graphite-bearing metasedimentary rocks, abundant mafic–ultramafic intrusions, and a high regional gravity signature. Gravity maps suggest the presence of more voluminous intrusions, notably to the east of the Vammala belt (Fig. 3.8.1).

MODE OF OCCURRENCE

The Svecofennian nickel-bearing mafic and ultramafic intrusions are mainly found within migmatitic mica gneisses, which often include graphite-bearing layers. However, in the Kotalahti belt, and especially in the Kotalahti area, some intrusions occur within Archean gneisses or within rocks of the craton margin sequence composed of Paleoproterozoic quartzites, limestones, calc-silicate rocks, black schists, and diopside-bearing banded amphibolites.

The most typical and easily recognized migmatite within the nickel belts is the schollen migmatite (Fig. 3.8.2), but schlieren migmatites are also common. The migmatite belts are considered as the most prospective areas for 1.88 Ga nickel deposits in Finland and they have thus been mapped in detail (e.g., Aarnisalo, 1988; Jokela, 1994). A genetic relationship between the migmatites and nickel-bearing intrusions has been suggested by Korsman et al. (1999), who proposed that the low-P/high-T metamorphism and the generation of tonalite-trondhjemite migmatites in the Svecofennian crust were caused by extensive

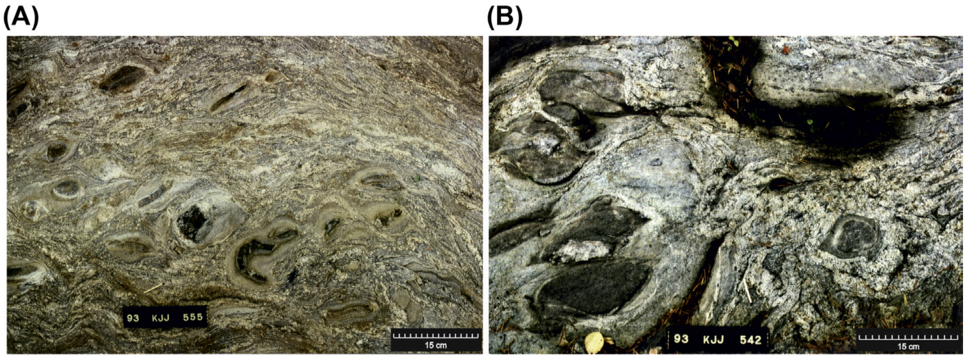

FIGURE 3.8.2 Migmatites from the Kotalahti Ni belt. (A) Schollen migmatite with calc-silicate rock and psammitic fragments (from Jokela, 1994, Fig. 30), (B) Gabbro fragments within schlieren-schollen migmatite (from Jokela, 1994, Fig. 42).

magma under/intraplating during and soon after subduction and crustal thickening (1885 Ma). According to the study of Lyubetskaya and Ague (2010) on migmatites in Scotland, the peak temperatures in crustal rocks around basaltic intrusions may be increased by more than 100 °C. In Scotland, the emplacement of mafic intrusions at midcrustal depths of 15–35 km produced minerals of low-pressure/high-temperature metamorphic grade such as cordierite-biotite-K-feldspar. Makkonen (2005) suggested that the heat of the mafic magma, together with the latent heat produced by the crystallization of the magma, enabled migmatite neosome formation within the Svecofennian nickel belts. In extensional environments, neosome formation was promoted by pressure release and the melt concentrated as tonalitic bodies.

Two different variants of Svecofennian nickel-bearing intrusions can be distinguished (e.g. Mäkinen, 1987; Lamberg, 2005; Peltonen, 2005). The weakly differentiated, dominantly ultramafic Vammala-type intrusions consist almost entirely of olivine cumulates and occur as small boudinaged lenses or pipes with a diameter of 100–1000 m within polydeformed paragneisses. The strongly differentiated, mafic and mafic–ultramafic, Kotalahti-type intrusions consist of olivine cumulates, pyroxene cumulates, and plagioclase-bearing cumulates, and are commonly up to several kilometers (km) long and a few hundred meters wide at surface. Magmatic layering is locally visible, although the original layered structure is commonly obscured by polyphase deformation.

The intrusions were emplaced during peak deformation and metamorphism (e.g., Marshall et al., 1995; Koistinen et al., 1996; Kilpeläinen, 1998; Mäkinen and Makkonen, 2004; Makkonen, 2005; Peltonen, 2005). The country rocks surrounding the intrusions were in most cases extensively metamorphosed and deformed during the early stage of the Svecofennian orogeny (Gaál, 1980; Koistinen, 1981; Kilpeläinen, 1998; Mäkinen and Makkonen, 2004). Overthrusting and faulting resulted in fragmentation of both the intrusions and the country rocks. Consequently, the shape of the intrusions in surface plan view varies widely, depending on the structural history and the depth of exposure. The dimensions of the intrusions also vary, from decimeter-scale schollen-migmatite fragments to more than 10-km-long intrusive bodies. The intrusions often form oval-shaped bodies in surface plan section and may consist of gabbro only, peridotite only, or gabbro-peridotite.

The intrusions show D2 structures and they seem to be elongated along the F2 fold axis. Excluding the sill-like intrusions, the cross section perpendicular to the F2 fold axis is often roundish. Thus, the form of the surface section varies according to the dip of the F2 fold axis; in areas with steep F2 fold axes, roundish and oval-shaped sections dominate, while in areas with gentle F2 fold axes, elongated sections are typical. Because D2 structures were formed subhorizontal (e.g., Koistinen, 1981), intrusions emplaced along F2 were also originally subhorizontal. Gravitative fractionation was therefore probable during magma flow in the chamber and, as a result, ultramafic cumulates and sulfides were concentrated at the base of the intrusions. When these ore-bearing intrusions were tilted with the F2 fold axis, the result in the surface section is an elongated/oval body with the nickel ore and ultramafic cumulates, and gabbros and more felsic differentiates, at opposing ends of the body. This observation is important from the exploration point of view. In most of the studied intrusions within the Kotalahti belt, it has been possible to recognize the stratigraphic footwall of the intrusions as the most prospective locality for nickel ore (e.g., Forss et al., 1999; Makkonen et al., 2003). However, in the case of the weakly differentiated, ultramafic Vammala-type intrusions, it is not possible to define the facing of the intrusion. In fact, some of the intrusions are concentric, suggesting they represent feeder conduits (Peltonen, 1995b; Lamberg, 2005).

In theory, the shallow intrusions would be expected to have a more sill-like form than those crystallized at a greater depth, as is seen in southern Savo province where gabbro-diorite intrusions form sills that were later folded upright. These intrusions can be interpreted to represent the most fractionated and high-level melts, whereas the peridotite and peridotite-gabbro bodies occur as more rounded and less elongated bodies (c.f. Makkonen, 1996). Tuisku and Makkonen (1999) estimated, on the basis of the chemistry of orthopyroxene-clinoamphibole-spinel coronas located between plagioclase and olivine, that the crystallization depth for the Saarijärvi intrusion in southern Savo was 17–20 km (900 °C, 5–6 kbar). In comparison, a similar study by Trudu and Hoatson (2000) of the East Kimberley intrusions resulted in a range from 2.4–6.7 ± 0.6 kb, which equates to upper-middle crustal depths of around 8–23 km. Fig. 3.8.3 summarizes the structural history of the Svecofennian intrusions.

GEOTECTONIC SETTING

According to Eilu and Lahtinen (2013), the Svecofennian nickel deposits (as well as the orogenic gold and Ti-V-Fe deposits) formed during collisions between arcs and microcontinents, and incipient amalgamation of Fennoscandia and Laurentia. The mafic magma intruded into tensional structures above the subduction zone (Nironen, 1997; Peltonen, 2005), and the rocks show evidence for syncrystallization deformation and assimilation of country rocks. The intrusions of the Vammala belt in southern Finland represent conduits of arc basalts or were emplaced within an accretionary wedge (Lahtinen, 1994; Peltonen, 1995b), whereas the intrusions of the Kotalahti belt along the Archean craton margin were emplaced along major transtensional shear zones during the Svecofennian arc–Archean craton collision (Peltonen, 2005).

In terms of their geochemical signatures, the Svecofennian intrusions and comagmatic volcanic rocks in southeast Finland conform to a back-arc environment. The southeast Finnish metatholeiites representing the parental magma to the Svecofennian nickel-bearing intrusions occur together with limestones, cherts, and iron formations and commonly exhibit pillow structures. These features, together with the fact that the tholeiitic magmas have an enriched mid-ocean ridge basalt (EMORB) affinity, suggest a cratonic margin or marginal basin environment; for example, a back-arc setting (Makkonen, 1996; Makkonen and Huhma, 2007).

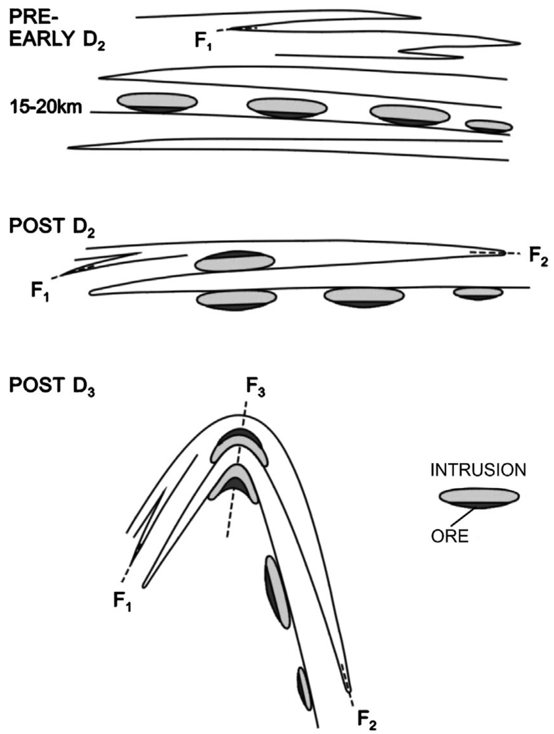

FIGURE 3.8.3 Simplified structural model for the intrusions.

Note that individual intrusions may represent boudinaged fragments of originally larger sill-like intrusions.

Comparison can be made with the circum-Superior belt in Canada. The tectonic evolution of the Thompson nickel belt probably involved an early stage of rifting during the onset of the Ospwagan group sedimentation and a later stage of peak deformation and mafic–ultramafic volcanism (Zwanzig, 2005). Subsequent emplacement of the mineralized ultramafic sills and mafic dikes possibly occurred in a continental back-arc environment and was associated with felsic calc-alkaline magmatism (Percival et al., 2004, 2005; Zwanzig et al., 2007, and references therein). The change from stable platform deposits to syntectonic filling and emplacement of mafic intrusions in the Ospwagan group is attributed to the convergence between the Reindeer Zone and the Superior Province at 1891–1885 Ma (Machado et al., 2011).

According to Heaman et al. (2009), the Molson magmatic event (1.88 Ga) in the northwest Superior craton was relatively short-lived (<8 Ma), and consists of a dike swarm emplaced parallel to the craton margin (Molson dike swarm), mafic–ultramafic volcanic sequences in both the Thompson nickel and Fox River belts, and sill complexes. Synchronous and geochemically similar mafic/ultramafic magmatism occurs in the Cape Smith belt and New Québec orogen, indicating that 1.88 Ga magmatism occurred for more than 3000 km along the previously rifted margin of the Superior craton. On the basis of the MORB-like affinity of the magmas, the Molson magmatic event possibly represents a series of back-arc basins, local transtensional pull-apart basins, or large-scale passive upwelling of asthenospheric mantle and concentration of magmatism along an already thinned and rifted margin of the Superior craton.

In summary, the craton margin in both the Fennoscandian and Canadian shields was intruded at ~1.88 Ga by mafic–ultramafic mantle-derived magma, resulting in the formation of nickel-copper sulfide deposits. The geotectonic setting was likely one of a marginal (or possibly back-arc) basin. The event is related to a major crustal growth period at ~1.9 Ga, interpreted to mark the amalgamation of the Columbia supercontinent (Groves and Bierlein, 2007).

NICKEL ORES

The parental magma for the 1.88 Ga intrusions in Finland contained up to 15 wt% MgO, but more usually around 10–12 wt%. Depending on the amount of sulfur available during sulfide segregation (i.e., the R factor) and on the state of fractionation of the silicate melt, the nickel content of the sulfide fraction is between 2–14 wt% and Ni/Cu between 1–4. The R factor varied mostly between 200 and 1300 (e.g., Makkonen et al., 2003). The nickel content of the ore is dependent on the amount of sulfides. In disseminated ore types, the average nickel grade is usually ≤1 wt%. In massive ores the nickel content can be up to 7 wt%.

Tables 3.8.1 and 3.8.2 give the average metal contents of the Svecofennian nickel deposits. Only in a few deposits is the average nickel grade higher than 1%, and all deposits are low in nickel when compared to nickel deposits globally. The average nickel grade calculated for the deposits in Table 3.8.2 is 0.61 wt%.

The nickel ores are usually located in the stratigraphically lowermost portions of the intrusions. In addition, the ores are often zoned, with the most massive ore being located at the basal contact. The massive ore can be up to a few meters thick, and it often forms breccias with the wall rock. The disseminated ores are the most common, and they too show compositional zoning, in that Ni/Co and Ni tenors of the sulfides increase toward the stratigraphic base (e.g., Mäkinen and Makkonen, 2004). With increasing amount of sulfide, disseminated ore turns into net-textured ore in which the sulfides form an interconnected network enclosing silicate minerals. In some peridotitic intrusions, a special nodular or orbicular texture is present, for example, at Kylmäkoski, Ekojoki, and Vammala (Papunen, 1980; Lamberg, 2005). Svecofennian Ni deposits often include so-called *offset ores*, which are hosted by the wall rocks (mica gneiss, black schist), likely in the stratigraphic floor of the bodies, and tend to be separated from the main intrusion by about 50–200 m. Typical examples are the Jussi ore body at Kotalahti (Papunen and Koskinen, 1985) and the Leo ore body at Laukunkangas (Grundström, 1985). At Telkkälä, the "B" ore consists of a massive sulfide dike within mica gneiss (Eeronheimo and Pietilä, 1988a,b). At Stormi, the sulfides extend for 10 m into the mica gneiss (Häkli and Vormisto, 1985). In the small Ni deposits of the Juva area, the offset ores are thin but similar in mode of occurrence to those mentioned earlier.

Platinum-group element (PGE) contents of the Svecofennian intrusions are typically low, and mantle- or chondrite-normalized spidergrams usually show a negative Pt anomaly (Papunen, 1986, 1989; Makkonen and Halkoaho, 2007) (see Fig. 3.8.4) At Hitura, the nickel ore contains subeconomic values of PGE, about 0.2 ppm Pt + Pd on average. In some other deposits that are not mined, elevated average values are observed, for example, Ekojoki, Uudiskorhola (Papunen, 1989), Tiemasoja (Makkonen and Forss, 2003), and Vehmasjoki (Makkonen and Forss, 1999). Papunen (1989) attributed the negative Pt anomalies to redistribution of Pt during metamorphism and alteration of the host rocks. According to

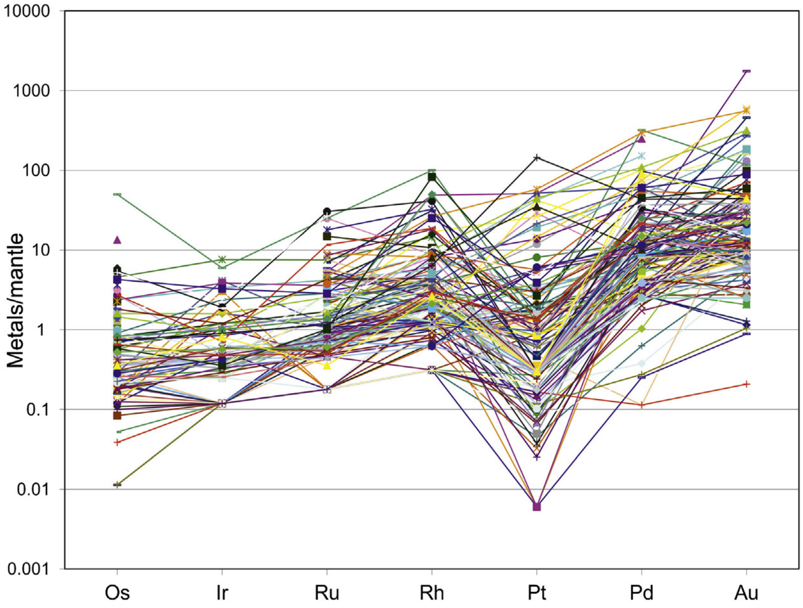

FIGURE 3.8.4 Mantle-normalized multielement diagram for noble metals in Svecofennian nickel-copper deposits.

Number of samples =147. Platinum values of 0.5 by detection limit were used for samples below the detection limit.

Source: *Data from Papunen (1989), Lamberg (2005), and Makkonen and Halkoaho (2007). Mantle values after Barnes (2006).*

Barnes (2006), massive ores are typically enriched in the Ir platinum-group elements (IPGE; Os, Ir, Ru) and Rh relative to Pt and Pd, and have negative Pt anomalies, whereas matrix and disseminated ores are enriched in Pt and Pd. This is explained by the concentration of IPGE into early crystallizing nickel-rich pyrrhotite or monosulfide solid solution (MSS). Fractionated, IPGE-depleted sulfide liquid becomes progressively concentrated within the overlying matrix ore. The PGE data on the Svecofennian deposits are consistent with this model: there is an overall positive correlation between the sulfur content and the magnitude of the negative Pt anomaly as noted also by Papunen (1989). However, other factors may also have caused the negative Pt anomaly, as indicated by the scatter in Fig. 3.8.5. A negative Pt anomaly has also been observed in the massive, semimassive, and overlying net-textured nickel ores at Jinchuan (Tang et al., 2009) and in nickel ores of the Thompson belt (Bleeker, 1990; Layton-Matthews et al., 2011).

A large amount of analytical data has been collected from the Svecofennian nickel ores (e.g., Makkonen et al., 2003; Lamberg, 2005) making it possible to evaluate the distribution of nickel between different phases. Preliminary estimates for the $D_{Ni}^{sul/sil}$ values in 14 nickel-bearing intrusions that have sufficient data on both the nickel ore and parental magma, vary between 310 and 1080, for an MgO content in the parental magma of between 7.3 and 10.4 wt%. A negative correlation with the MgO content of the parental magma is observed, consistent with the empirical and experimental results (c.f. data compilations by Lamberg, 2005, and Naldrett, 2011).

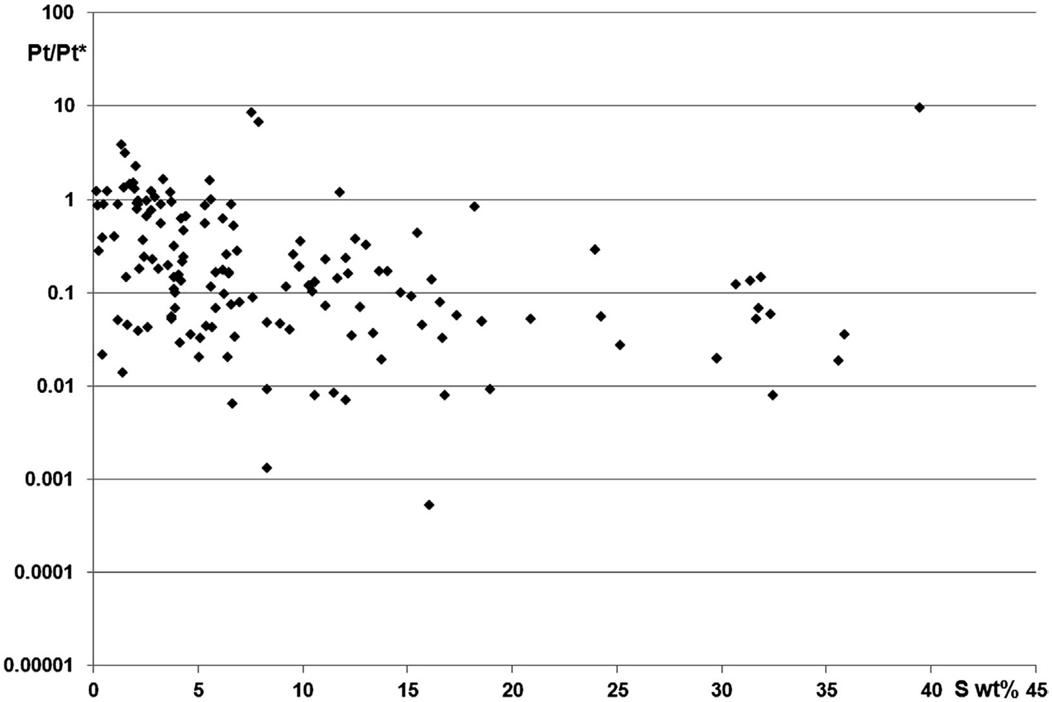

FIGURE 3.8.5 Diagram of platinum anomaly (Pt/Pt*) versus sulfur in Svecofennian nickel deposits.

Pt* = (Pdmn × Rhmn)$^{0.5}$. Number of samples = 147. Platinum values of 0.5 by detection limit were used for samples below the detection limit.

Source: *Data from Papunen (1989), Makkonen (1996), Makkonen and Forss (2003), Lamberg (2005), and Makkonen and Halkoaho (2007). Mantle values after Barnes (2006).*

ORE MINERALOGY

The ore mineralogy of many Svecofennian nickel deposits was comprehensively studied by Papunen during the 1970s and 1980s. (e.g., Papunen, 1970; 1974; 1980; Papunen et al., 1979). Because the deposits formed via concentration of immiscible sulfide liquid that segregated from basaltic magma, followed by fractionation of MSS, the ore mineral assemblage typically consists of pyrrhotite-pentlandite-chalcopyrite. More detailed data on the ore mineralogy is given in the chapters describing the type intrusions (p. 264-274).

In addition to magmatic processes producing the present ore mineral assemblage, one must consider the effect of metamorphism. According to Tomkins et al. (2007), massive Ni-Cu-PGE deposits undergo insignificant melting under common crustal metamorphic conditions. Only the highly fractionated low-temperature melts (crystallized as arsenopyrite, gersdorffite, cobaltite, nickeline, maucherite, löllingite, westerveldite, safflorite, chalcopyrite, and cubanite) may be subject to remelting, and thus mobilization, during amphibolite- to granulite-facies metamorphism. In the Svecofennian nickel deposits, small-scale metamorphic remobilization of sulfides can be traced along lithological contacts and shear zones, but only for a maximum distance of a few meters (Papunen, 2003; present author).

Chalcopyrite veins of various thicknesses are common within and near the contact of the Svecofennian nickel deposits, especially within areas characterized by upper-amphibolite to granulite-facies metamorphism. This suggests mobilization of magmatic chalcopyrite. Pentlandite may also occur as veins or bands and crack fillings (e.g., Makkonen, 1996; Kojonen, 1999; Kojonen et al., 2002), whereby it is possible that in some deposits, some of the primary pentlandite was mobilized during high-temperature metamorphism. Alternating pentlandite- and pyrrhotite-rich bands in nickel ores have been attributed to breakdown of metamorphic MSS within a stress field (McQueen, 1987).

The fact that the Svecofennian intrusions were emplaced during peak metamorphism, that is, into a hot environment of upper-amphibolite to granulite-facies metamorphism, makes it difficult to distinguish between late magmatic phases and phases crystallized from metamorphic MSS.

TYPE DEPOSITS

As noted earlier, the intrusions of the Vammala and Kotalahti belts show some systematic geological and compositional differences. In the following section, the Kotalahti and Rytky deposits are described as examples of the Kotalahti type deposits and, although geographically separate from the Vammala belt, the Hitura deposit as an example of Vammala-type deposits. Of the remaining economically important deposits (refer to Table 3.8.1), the Enonkoski and Vammala deposits have been described in detail by Lamberg (2005).

KOTALAHTI AND RYTKY

Most of the mafic–ultramafic Ni-mineralized intrusions in the Kotalahti Ni belt are rather small, with only a few being up to 10 km in diameter at the present erosion level. Typically, the maximum horizontal dimension is less than 2 km. The intrusions are differentiated from ultramafic to gabbroic (locally to dioritic and quartz dioritic) rocks. Intrusions composed solely of ultramafic rocks are rare. Intrusions are mainly found in areas of relatively high metamorphic grade, suggesting a relatively deep crustal section. These areas are commonly located within local gravimetric highs, in part because of the abundance of mafic–ultramafic rocks, but also because of the abundance of relatively dense minerals in the country rocks.

The Kotalahti and Rytky intrusions are located within the Kotalahti dome, which is composed of Archean gneiss surrounded by a Paleoproterozoic craton-margin supracrustal sequence of quartzites, limestones, calc-silicate rocks, black schists, and banded diopside amphibolites. The Särkiniemi intrusion lies within mica gneiss, higher in the stratigraphy than Kotalahti and Rytky (Fig. 3.8.6). Metamorphism reached the amphibolite facies, causing gneissose and migmatitic textures in the supracrustal rocks.

The Kotalahti deposit has been of high importance for the Finnish nickel industry. The discovery of the deposit in 1954 and the opening of the mine in 1959 led to the establishment of a nickel smelter at Harjavalta. The smelter has been in operation since 1959 and has a capacity of 50,000 tons of Ni per annum. In total, 12.35 Mt of ore at 0.66% Ni, 0.26% Cu, and 0.03% Co was mined at Kotalahti from 1959–1987 (Puustinen et al., 1995).

The Kotalahti intrusion has been dated at 1883 ± 6 Ma (Gaál, 1980). It forms a subvertical sheet with a length of approximately 1.3 km and a maximum width of 200 m. The southernmost intrusive segment extends to a depth of more than 1000 m (Papunen, 2003). The wall rocks of the intrusion consist mainly of Archean gneiss (Fig. 3.8.6).

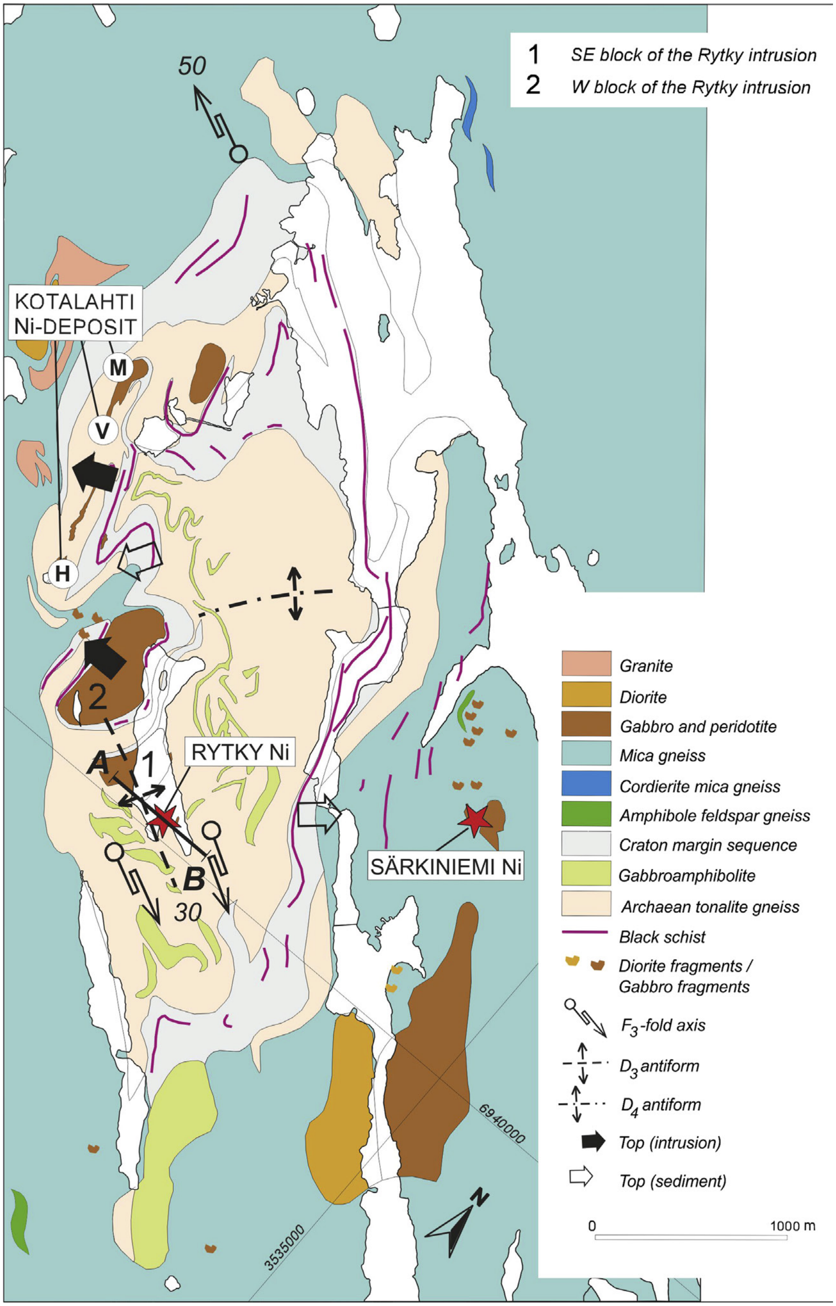

FIGURE 3.8.6 Geological map of the Kotalahti dome, showing location of Huuhtijärvi (H) Välimalmi (V) and Mertakoski (M) ore bodies.

The Rytky and Särkiniemi Ni deposits are indicated by red stars. The line AB represents the location of the cross section shown later in Fig. 3.8.11

Source: *Modified from Mäkinen and Makkonen (2004).*

The intrusion consists of olivine- and olivine-enstatite cumulates, orthopyroxenites, poikilitic gabbros, ophitic gabbronorites, and diorites (Papunen, 2003). Among the peridotitic rocks, coarse-grained lherzolite forms the stratigraphically lowest unit. It is overlain by medium-grained lherzolite (Mäkinen and Makkonen, 2004). From north to south, the ore bodies include Mertakoski, Välimalmio, Vehka, and Huuhtijärvi (Fig. 3.8.7). A separate, mostly massive offset deposit, called the Jussi ore body, is present as a subvertical slab hosted by black-schist and calc-silicate wall rock (but also by peridotite; Seppä, 2009) some 150 m east of the Vehka ore body. The Jussi ore body extends to a depth of more than 1000 m. Disseminated sulfides are common in ultramafic rocks and poikilitic gabbros, whereas ophitic gabbros and diorites are almost barren. Breccia-type sulfides occur as irregular masses, commonly along lithological contacts in the relatively thin central part of the intrusion (Papunen, 2003). Figure 3.8.8 shows examples of ore types at Kotalahti.

According to Papunen and Vorma (1985), the Kotalahti ore averages 0.70% Ni, 0.27% Cu, 0.03% Co, and 4.00% S. The main sulfide minerals are pyrrhotite, pentlandite, and chalcopyrite; in the Jussi ore body, pyrite is also significant. In the disseminated ores, pyrrhotite occurs as troilite or hexagonal pyrrhotite, whereas in the breccia ores (vein network ores) and, in particular, the Jussi ore body, monoclinic pyrrhotite predominates. Gersdorffite, mackinawite, and argentian pentlandite are common accessory sulfides. The Jussi ore body also contains portions enriched in millerite and bornite (Papunen and Koskinen, 1985). The PGE content of the Kotalahti ore is economically insignificant. The PGE patterns show a distinct negative Pt anomaly, as in most of the Svecofennian nickel deposits (Papunen, 1989; Makkonen and Halkoaho, 2007). The $\delta^{34}S$ in ores hosted by ultramafic rocks is +1.4 to +2.6‰, similar to the Jussi ore body (+1.4 to +2.8‰) (Papunen and Mäkelä, 1980).

In terms of its geology, host rocks, and ore composition, the Kotalahti deposit resembles the neighboring Rytky deposit. At Kotalahti, forsterite contents reach 89 mole% (Mäkinen, 1987), which indicates an MgO content of the parental magma of approximately 17 wt% (c.f. Fig. 3.8.15b). A similar estimation can be made from the whole-rock composition (data from Seppä, 2009). Based on the TiO_2 and Al_2O_3 versus MgO plots of samples with MgO > 10 wt%, the maximum Fo content is 88.9. The MgO content of the chilled margin samples at Rytky varies within the range 9.17–10.50 wt%, which corresponds to the value calculated from the Fo content (Fo = 78.6–84.7 m%; MgO = 9.0–11.2 wt%) (Mäkinen and Makkonen, 2004). Thus, at Kotalahti the magma was more primitive than at Rytky.

In the study by Seppä (2009), the peridotitic host rock of the Kotalahti deposit was found to be layered, analogous to the Rytky intrusion. Layering is seen, for example, in the gradual change of the whole-rock Mg-number, MgO, and Ni/Co values toward the eastern basal intrusion contact. In the Jussi ore body, layered peridotite was found as the host rock. Magmatic contact phenomena, found in places, include the occurrence of fine-grained amphibolitic rock at the margins of the intrusion and the disappearance of S2 schistosity in the wall rock (Mäkinen and Makkonen, 2004). These observations suggest that the Kotalahti and Rytky intrusions originally formed subhorizontal bodies, which were later folded into a subvertical orientation.

The surface section (0.5 × 1 km) of the Rytky intrusion comprises two blocks separated by Proterozoic supracrustal rocks and Archean tonalite gneisses (see Fig. 3.8.6). The southeast block is surrounded mainly by Archean rocks, whereas the northwest block is surrounded mainly by Proterozoic rocks. Primarily, the intrusion is funnel-shaped and layered. A minor part of the intrusion is represented by sills located stratigraphically below the intrusion, within the Archean tonalite gneiss. The magma was emplaced during D2 and detached fragments of the intrusion are found in the surrounding gneisses. During D3 and D4, the magmatic layering and the ores were folded into a subvertical position (c.f. Fig. 3.8.9) (Mäkinen and Makkonen, 2004).

The following stratigraphic sequence is proposed, from base to top: (1) coarse-grained lherzolites and websterites/melagabbros, (2) medium-grained lherzolites, websterites, and gabbronorites, and

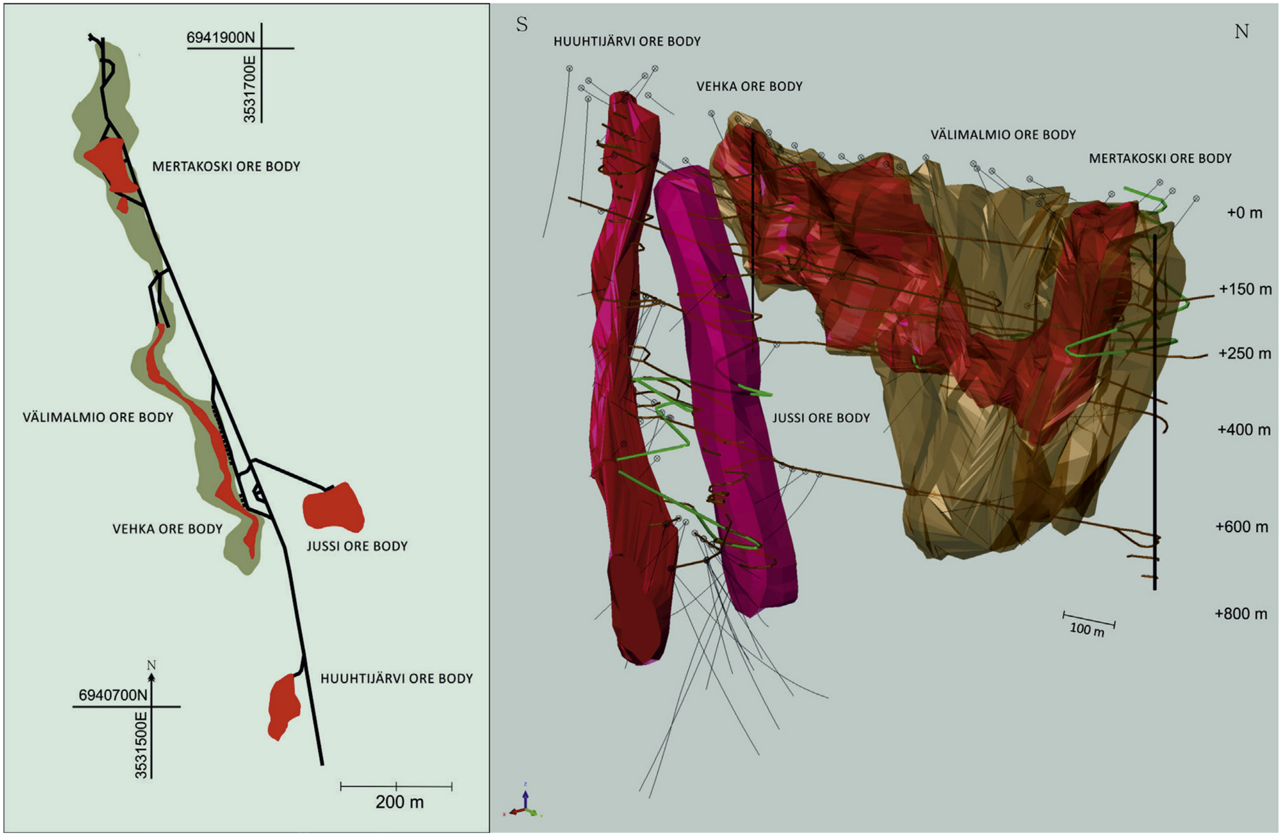

FIGURE 3.8.7 Plan section (level 250 m) and 3D bird's-eye view from northeast of the Kotalahti deposit.

Ore bodies are shown in red and the host intrusion in brown. Some tunnels and boreholes are also shown.

Source: *Figures generated by Janne Hokka, GTK.*

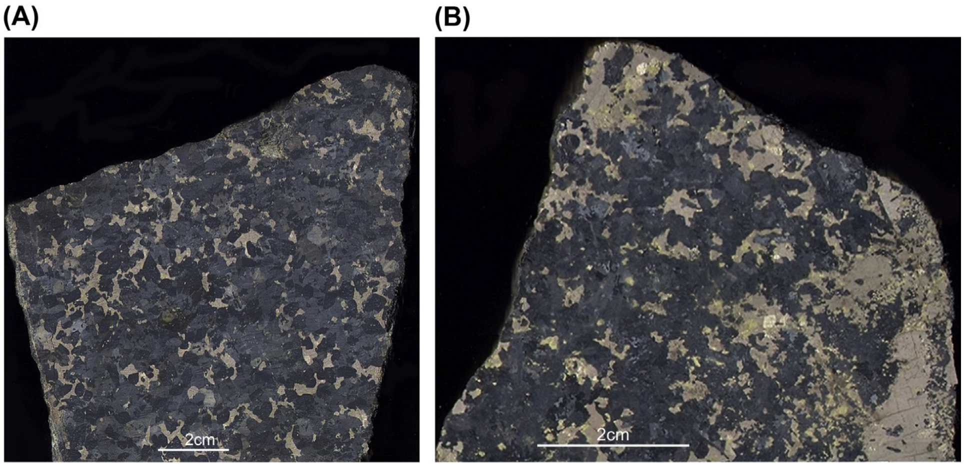

FIGURE 3.8.8 Scanned sections of ore samples from Kotalahti.

(A) Pyrrhotite-pentlandite dissemination in coarse-grained lherzolite. (B) Disseminated-breccia ore in metapyroxenite, showing abundant dull pyrrhotite, yellow chalcopyrite veinlets and disseminations, and bright pentlandite grains.

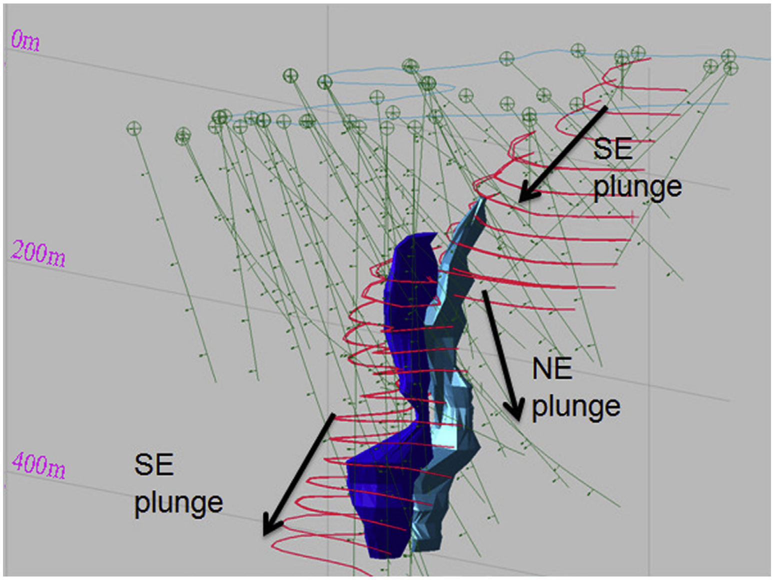

FIGURE 3.8.9 3D bird's-eye view from the southeast depicting the complex structural control of the Rytky deposit.

The ore hosted by coarse-grained lherzolite is shown in dark blue and the ore hosted by medium-grained lherzolite is shown in light blue. The contact of the intrusion is marked by red lines.

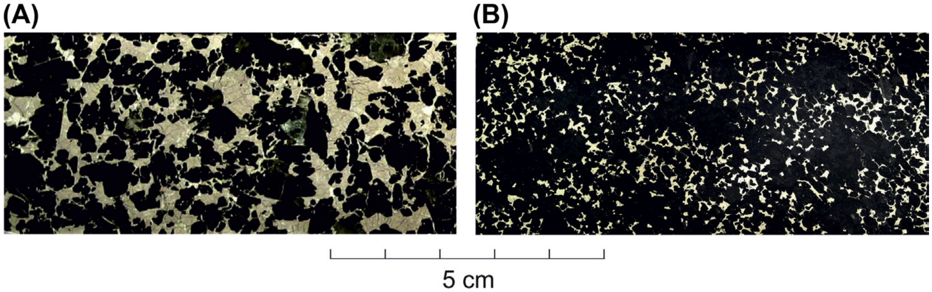

FIGURE 3.8.10 Scanned sections of the main ore types at Rytky.

(A) Matrix ore in coarse-grained lherzolite. (B) Disseminated ore in medium-grained lherzolite.

(3) subophitic gabbros. The first rock suite is up to 35-m thick and found at the margin of the intrusion. The coarse-grained lherzolite also occurs as sills separate from the main intrusion. The most typical feature of this rock type is the occurrence of euhedral to subhedral elongated olivine grains, or medium- to coarse-grained aggregates (<14 mm; c.f. Fig. 3.8.10), showing a mesocumulate texture. The medium-grained lherzolite is located above the coarse-grained lherzolite, but has been observed to crosscut it. The contact between the coarse-grained and the medium-grained lherzolite is sharp. The thickest and most uniform part of the medium-grained lherzolite occurs in the southeast part of the intrusion and indicates a decrease in the amount of olivine and sulfides toward the top. The transition from lherzolites to websterites is indicated by a zone of lherzolite/websterite interlayering. Most of the intrusion is composed of the second phase of rocks (i.e., medium-grained lherzolites, websterites, and gabbronorites). Subophitic and granular textured gabbros with varying grain sizes form a relatively minor portion of the intrusion and they crosscut the websterites. Fragments of a chilled margin are encountered in outcrops near the western edge of the intrusion.

The chemostratigraphy of the intrusion and the nickel ore is depicted in Fig. 3.8.11. The Ni/Co ratio of the sulfide fraction is highest in the ore hosted by the coarse-grained lherzolite, at the base of the cumulate pile. Aluminum and Ti contents increase toward the top of the intrusion.

The ore types in the Rytky deposit comprise fine-grained disseminations, coarse-grained disseminations, matrix (net-textured) ore, and massive ore (Fig. 3.8.10). The major sulfide ore minerals are pyrrhotite, pentlandite, and chalcopyrite. Cubanite is occasionally observed in the form of lamellae in chalcopyrite, cobaltite may form euhedral grains in the sulfides, and mackinawite inclusions occur in chalcopyrite and pentlandite.

Electron microprobe analyses of pyrrhotite (N = 572) mainly show a hexagonal NC (57.5%), NC + 4C (21%), or troilite composition (8.7%). Only a minor proportion of the analyses (4.7%) indicate a monoclinic 4C composition. The average Fe content of all pyrrhotite samples is 47.75 wt%, corresponding to the hexagonal NC type. The main carrier of nickel is pentlandite, which occurs in subhedral to euhedral grains, up to several millimeters in diameter, forming bands between pyrrhotite grains having a grain size of 75–200 microns, and in flame-like inclusions within pyrrhotite, usually 10–30 microns long and 5–10 microns wide (Kojonen et al., 2002).

HITURA

Hitura is the largest Svecofennian nickel deposit in Finland, with total resources of 19.3 Mt at 0.61% Ni, 0.21% Cu, and 0.02% Co (Rasilainen et al., 2012). Mining started in 1970 and was continued until

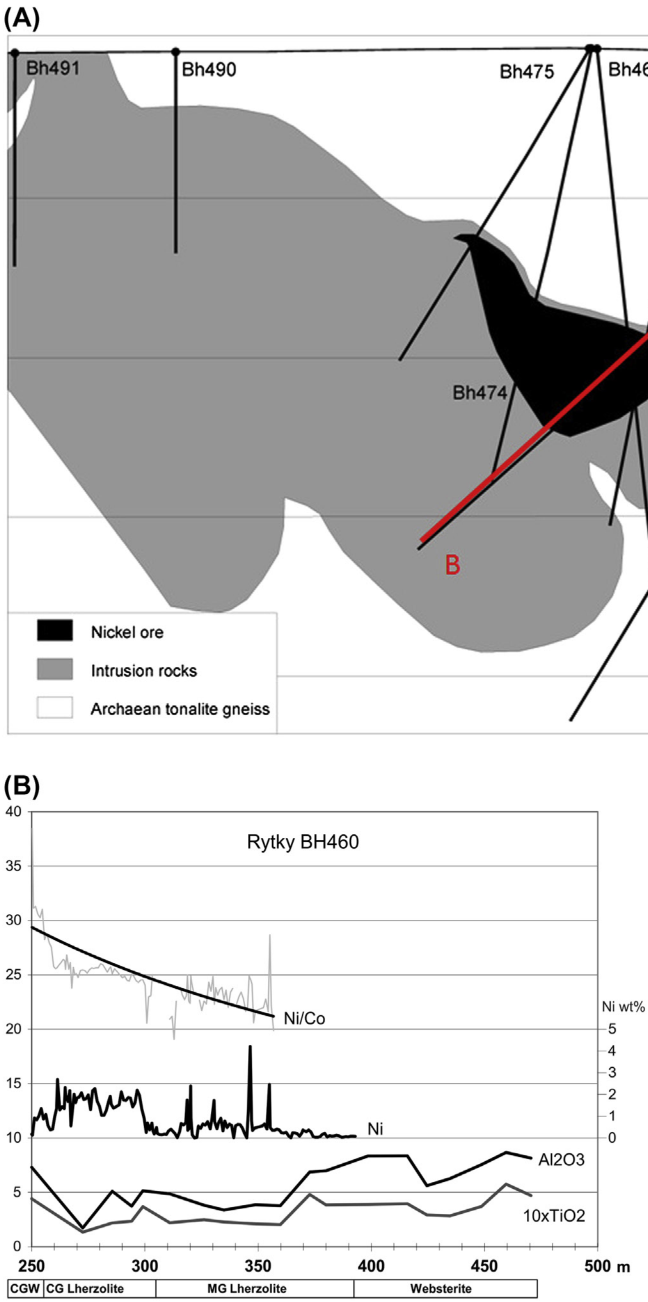

FIGURE 3.8.11 (A) Cross section through the Rytky nickel deposit (along line AB in Fig. 3.8.6) and (B) related chemostratigraphy. (along line AB in the cross section).

Ni/Co ratio (with trend line) is shown for samples where the nickel content is >0.4 wt%. CGW = coarse-grained websterite. Units for TiO_2, Al_2O_3 (in wt%), and Ni/Co are given at the left vertical axis.

Source: *Modified from Mäkinen and Makkonen (2004).*

2013 with intermittent breaks. A total of 16.5 Mt ore at 0.6% Ni was mined. Although geographically within the Kotalahti nickel belt, the Hitura deposit is geologically similar to the intrusions of the Vammala belt in that it contains weakly differentiated olivine cumulates and is strongly serpentinized.

According to Isohanni et al. (1985), the main rock types around Hitura (i.e., in the Nivala area) are intensely metamorphosed metasediments, intervening metavolcanics and extensive felsic intrusives. The stratigraphy of the lower group of the supracrustals consists of migmatitic mica gneisses and interlayers of graphite- and sulfide-bearing gneisses and amphibolites. The migmatitic mica gneiss forms the country rock to the ultramafic intrusions at Hitura, Makola, and many other locations. The least migmatized country rocks consist of medium-grained banded metagraywacke. The bulk of the mica gneiss has undergone intense migmatization and now consists of veined gneiss. Based on geophysical data, the amphibolites constitute long and narrow ribbon-like zones that often occur either at the contact between plutonic rocks and migmatitic mica gneiss or as interlayers in the migmatitic and gneissic metasediments. The amphibolites are banded or striped in structure. The well-preserved portions suggest that the amphibolites derive from pyroclastic lavas and dikes. The upper group of supracrustals consists of two volcanic suites between which there is a sequence of sedimentary rocks composed mainly of graywackes.

The Hitura ultramafic complex consists of three separate, closely-spaced serpentinite massifs surrounded by migmatized mica gneiss (Figs. 3.8.12 and 3.8.13) The metamorphic grade in the Hitura area

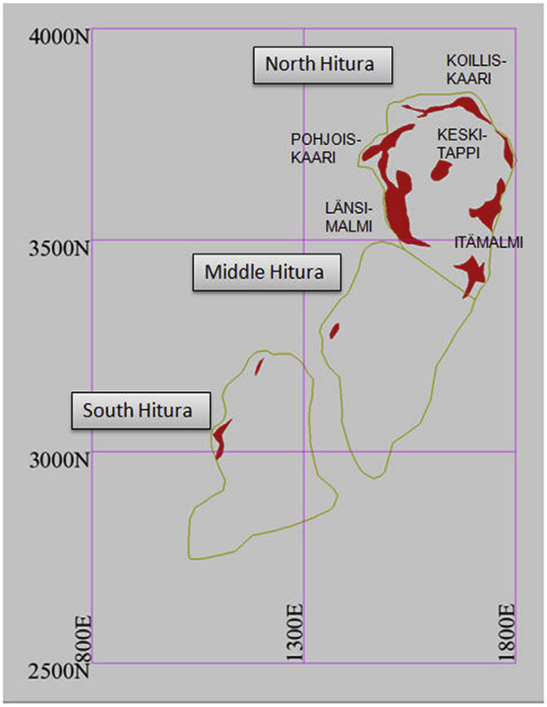

FIGURE 3.8.12 Plan view at the 200-m level of the Hitura nickel deposit.

The margins of the intrusion are shown by a brown line and the ore is shown in red. Map coordinates are shown in meters.

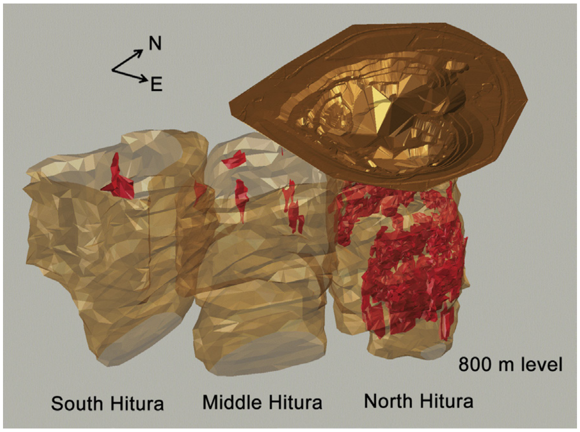

FIGURE 3.8.13 3D bird's-eye view from southeast of the Hitura deposit.

This shows the three serpentinite bodies (in brown) and the ores (in red). Open pit is also shown.

is at upper-amphibolite facies, which peaked during D2 and produced various types of migmatites, including schollen migmatite typical to all Svecofennian nickel prospects. In addition to migmatized gneisses, a belt of sulfide- and graphite-bearing schists and mylonitic rocks occurs in the vicinity of the Hitura body. The horizontal extent of the ultramafic complex is 0.3 × 1.3 km. The deepest drilling intersections reach a depth of about 800 m. Geophysical surveys indicate that the intrusion continues to a depth of, at least, 1000 m below the surface. The core of the complex is serpentinite and the marginal zones consist of amphibole-rich ultramafic rocks, originally representing olivine adcumulates and olivine orthocumulates or olivine-orthopyroxene cumulates (Papunen and Penttilä, 1996). Crosscutting pegmatitic dikes, with an age of 1877 ± 2 Ma, are not uncommon (Isohanni et al., 1985).

The contacts of the Hitura complex against gneissic wall rocks are commonly tectonic. The contact zone is characterized by dislocated mafic blocks, erratic wall-rock inclusions, and, locally, by massive sulfide lumps in a soft talc-rich matrix, indicating late-tectonic movement and faults. The gneiss near the contact ("contact gneiss") is typically homogenous and contains small garnet crystals and large pale dots of feldspars and quartz. Pyrrhotite disseminations are common in the gneisses near the serpentinite body. Some small serpentinite tongues in mica gneisses, partly nickel mineralized, are found at the western side of the Hitura massif. Shear zones with narrow tongues of mica gneiss separate the three ultramafic massifs (Papunen and Penttilä, 1996; Meriläinen et al., 2008).

Several nickel ore bodies are situated at the contact zones and in the core of the North Hitura serpentinite massif. From west to east, the ore bodies in the contact zones are Länsimalmi, Pohjoiskaari, Koilliskaari, and Itämalmi. In the center of the North Hitura body, there is the Keskitappi (central core) ore body (Fig. 3.8.12). Low-grade nickel mineralization occurs in the intrusive rocks between the core zone and the contacts. The mineral resources of the Middle and South Hitura massifs are not known (Meriläinen et al., 2008). According to Papunen and Penttilä (1996), three main ore types can be recognized in the North Hitura ore body: (1) scattered fine-grained sulfides disseminated in the serpentinite core zone, (2) medium- to coarse-grained sulfide disseminations in the marginal serpentinite-amphibole rock, (3) high-grade interstitial disseminated sulfides and massive accumulations in the amphibole rock locally extending into the gneissic wall rock (see Fig. 3.8.14).

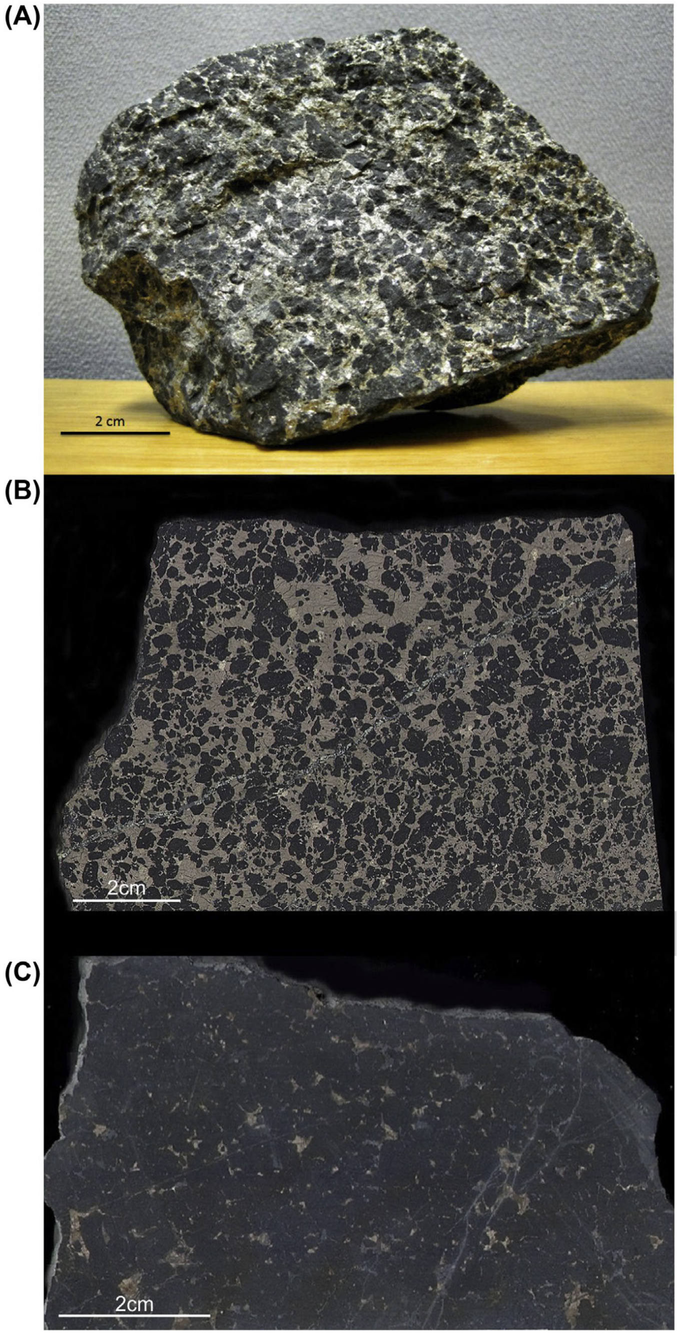

FIGURE 3.8.14 Ore samples from North Hitura.

(A) Net-textured ore at level 550 m, photo Hannu Makkonen; (B) net-textured ore in serpentinite (primarily olivine cumulate) at level 350 m, scanned section; (C) disseminated ore in serpentinite, scanned section.

The main ore minerals at Hitura are pyrrhotite and pentlandite, but in places, valleriite, mackinawite, chalcopyrite, and cubanite are abundant. Pentlandite is the main nickel-bearing mineral but mackinawite containing up to 6 wt% Ni is locally also important. Copper is mainly hosted in valleriite, but locally by chalcopyrite and cubanite. Many accessory minerals have been identified, including pyrite, violarite, maucherite, niccolite, gersdorffite, and millerite. Pyrite occurs only in joints associated with carbonates. Platinum-group minerals, such as sperrylite, michenerite, irarsite, iridarsenite, and hollingworthite, have also been detected and the ore averages around 0.2 ppm Pt + Pd. Platinum contents as high as 600 ppm have been found in a sperrylite-rich sulfide concentration in chlorite-amphibole rock at the intrusion margin (Häkli et al., 1976; Papunen and Penttilä, 1996; Meriläinen et al., 2008). A new mineral species, tarkianite, with a general formula $(Cu,Fe,Co,Ni)(Re,Mo,Os)_4S_8$, was discovered in sulfide concentrates. The average Re content in the concentrate is 20 ppb (Kojonen et al., 2004).

The internal stratigraphy of the northern ultramafic body is reflected in increases in whole-rock MgO, normative olivine, forsterite and Ni/Co of the sulfide fraction; and decreases in whole-rock SiO_2 content toward the contact of the intrusion (Suikkanen, 2011). A possible mechanism for generating this chemostratigraphy was a combination of flow differentiation and gravitational settling. Calculated and analyzed nickel and forsterite contents of olivine indicate that the mineral crystallized under sulfur-saturated conditions. The North and Middle Hitura bodies have similar nickel contents of olivine whereas the South Hitura body has distinctly lower Ni contents, suggesting more depleted parent melts (Makkonen et al., 2011).

The parental magma at Hitura was basaltic. Estimates of the MgO content of the magma vary from about 11 wt% (Papunen and Penttilä, 1996) to 12.5 wt% (Suikkanen, 2011). According to Papunen and Penttilä (1996), the shape of the Hitura complex implies that the melt fractionated in a tubular body, probably a feeder channel to the overlying volcanic rocks. Alternatively, the Hitura complex can be interpreted as a tubular or sill-like body, which was subsequently folded (mainly in D3). Consequently, the richest nickel sulfide ore is found in the marginal zone of the ultramafic complex, which represents the stratigraphic footwall of the body (Makkonen et al., 2011).

PARENTAL MAGMA AND CRUSTAL CONTAMINATION

On the basis of whole rock and olivine composition, the parental magma to the Svecofennian nickel-bearing intrusions was tholeiitic basalt with an MgO content of mostly 10–12 wt% (e.g., Peltonen, 1995a; Makkonen, 1996) and trace element contents similar to EMORB (Makkonen, 1996; Lamberg, 2005; Makkonen and Huhma, 2007). Ultramafic metapicrites and adjacent metatholeiites have been proposed to represent the extrusive counterparts of the intrusions (Makkonen, 1996; Makkonen and Huhma, 2007). Hill et al. (2005) and Barnes et al. (2009) concluded that the parent magmas to the intrusions and the extrusive picrites had a common mantle source, but the magmas ascended through different routes into the upper crust. The intrusive phases were more contaminated by crustal material than the extrusive phases. Initial epsilon Nd (1.9 Ga) values around +4 have been determined for the metapicrites, suggesting a depleted mantle source. The CaO-MgO-Al_2O_3 (CMA) plot (Fig. 3.8.15a) indicates the distinct differentiation series of the clinopyroxene-dominated Vammala-type and the orthopyroxene-plagioclase-dominated Kotalahti-type. The Al_2O_3-FeOtot-MgO (AFM) plot (Fig. 3.8.15b) highlights the tholeiitic trend of the rocks. The MgO/FeO ratio of the most MgO-rich cumulates correlates with the MgO content of the parental magma.

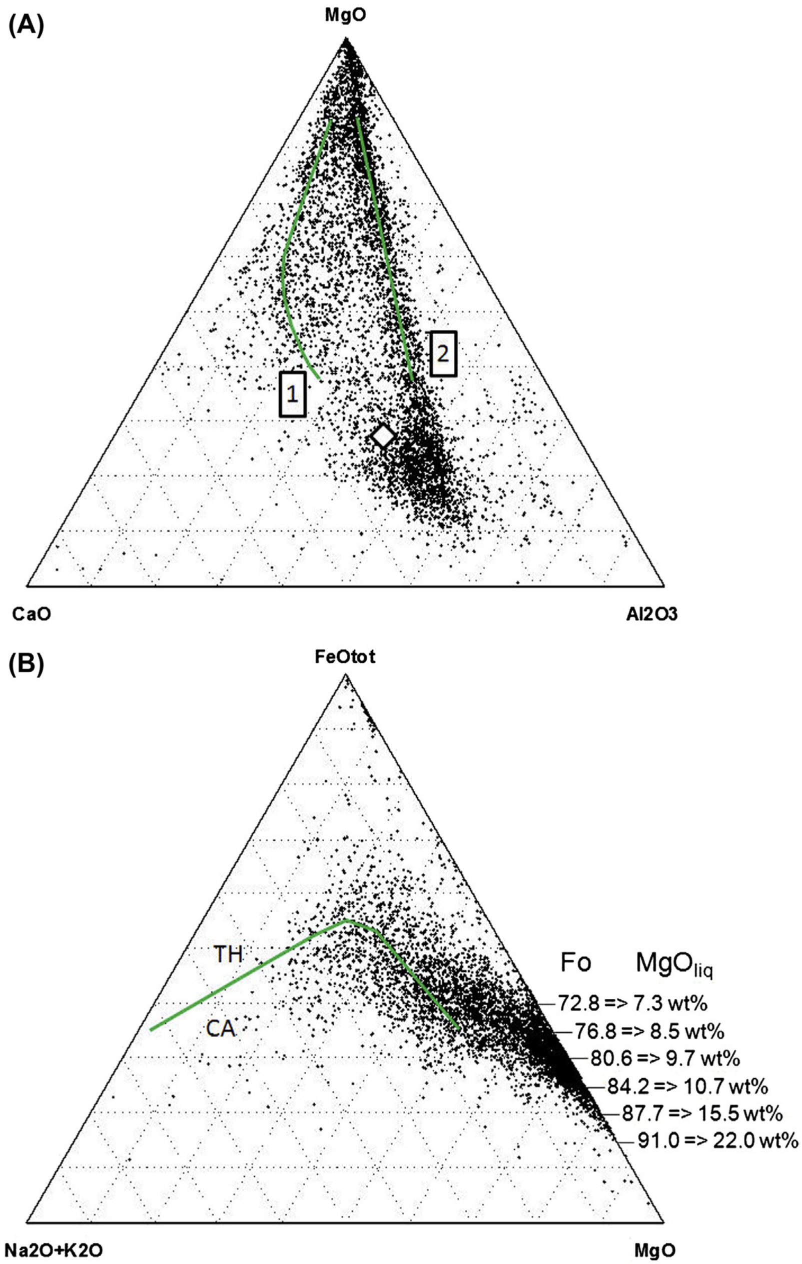

FIGURE 3.8.15 CMA (A) and AFM (B) ternary diagrams for the Svecofennian mafic–ultramafic intrusions.

In the CMA diagram, the fractionation trends of the Vammala-type (1) and the Kotalahti-type (2), toward plagioclase are shown by green lines. The proposed parental magma composition of Makkonen and Huhma (2007) is marked by a diamond. In the AFM diagram, the boundary line between the tholeiitic (TH) and calc-alkaline (CA) compositions is drawn after Irvine and Baragar (1971). The MgO/FeO ratio for the parental magma was calculated using K_D value of 0.33. The MgO content was then calculated from the correlation of the MgO and Mg number in the comagmatic tholeiites-picrites (Makkonen and Huhma, 2007; Barnes et al., 2009) as follows: Mg-number = 0.2189 × ln MgO (wt%) + 0.0981, and for the three lowest Fo contents based on the equation: $\log MgO_{Liq}$ (wt%) = (logFo-log (252.7833 – 0.7825 × Fo))/0.4602 + 1.795 (Makkonen, 1996). Number of samples = 6192.

Source: *Data from Mäkinen (1987), Makkonen et al. (2003), and Lamberg (2005).*

Crustal contamination of the mafic magma has been indicated in both the Vammala (Peltonen, 1995a; Barnes et al., 2009) and Kotalahti belts (Makkonen, 1996; Mäkinen and Makkonen, 2004; Lamberg, 2005; Makkonen et al., 2008; Makkonen and Huhma, 2007; Barnes et al., 2009). Evidence for wall rock/country rock assimilation is seen in many outcrops, in the form of xenoliths of metasediments enclosed in the mafic–ultramafic intrusive rocks.

In the Vammala Ni province, black schist was an important contaminant of the magma. The circulation of H_2S-bearing C-O-H-S fluids enabled selective transfer of large quantities of S and Zn from black schist into the cooling magma (Peltonen, 1995a). At Enonkoski, sulfide saturation was caused by black schist contamination (Lamberg, 2005). Graphite is ubiquitous in the intrusions and its abundance correlates broadly with that of sulfides. Hybrid rocks and remnants of graphite schist are associated with anomalously high contents of V, Mo, Mn, and Zn in the ore and its surroundings. In the Kotalahti belt, crustal assimilation of 5–40% by mass has been suggested (Makkonen, 1996; Makkonen and Huhma, 2007), similar to the estimates of Mungall (2007) in the 1.88 Ga Expo Intrusive Suite of the Cape Smith fold belt, Canada.

In Fig. 3.8.16 the Sm-Nd data for the Svecofennian intrusions and related picrite/tholeiite suites are compared to those of Svecofennian metasediments and Archean felsic rocks in Finland. Mixing between the volcanics, metasediments, and Archean rocks can produce the composition of the intrusive rocks.

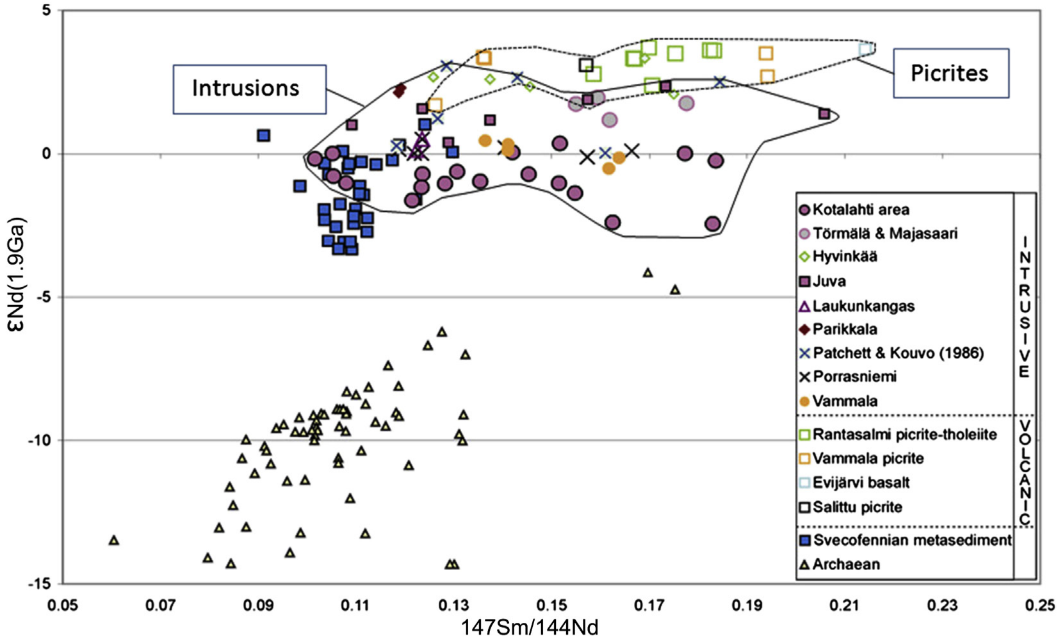

FIGURE 3.8.16 Sm-Nd isotope data for Svecofennian mafic–ultramafic intrusions, as well as for metapicrites and metabasalts, representing the proposed parental magma, the Svecofennian metasediments, and Archean felsic rocks in Finland.

εNd (1.9 Ga) in intrusions ranges from −2.4 to +3.1 (±0.4), in picrites from +1.7 to +3.7 (±0.4).

Source: *Modified from Makkonen and Huhma (2007).*

To obtain a negative εNd value for the intrusions, bulk contamination of about 10% of Archean gneiss and about 30% of Svecofennian metasediment is required. The composition of the intrusive rocks is controlled by the type of the country rock, as indicated by the fact that intrusions adjacent to Archean rocks have the lowest (negative) εNd values (Figs. 3.8.16 and 3.8.17) (Makkonen and Huhma, 2007).

Peltonen (1995a) found that in the Vammala area, the ore-bearing intrusions have higher S/Se than barren intrusions, consistent with country rock assimilation. The results of a similar study in the Kotalahti area are less clear. The S/Se of most of the nickel ores is much higher than the mantle value (28 samples, average S/Se = 9000, ranging from 2430–14,650—data by the author; mantle S/Se = 3333—McDonough and Sun, 1995), suggesting that external sulfur was added to the magma. However, the S/Se in the black schists and mica gneisses of the Kotalahti area is in the range of the mantle (6 samples, average S/Se = 4230, ranging from 2440–5500—data by the author) and in the B1 and B2 boundary zones of the Kotalahti belt, with S/Se averages of 10,500 and 5100, respectively (Lahtinen, 2000).

Consequently, assimilation of the metasediments cannot explain the high S/Se in some of the ores by a simple bulk contamination process. Queffurus and Barnes (2015) have shown that S/Se ratios are controlled by several processes, including addition of S from sedimentary rocks, variations in the R factor during sulfide liquid segregation, depletion of the silicate magma in Se by early segregation of the sulfide liquid, and moderate incompatibility of Se into the first sulfide minerals to crystallize from the MSS, resulting in a change in S/Se ratio between the Fe-rich and Cu-rich zones of magmatic sulfide ores. The overall low PGE values for the Svecofennian deposits are consistent with early sulfide segregation, but more work is required to constrain the processes controlling the S/Se ratio in the Svecofennian nickel deposits.

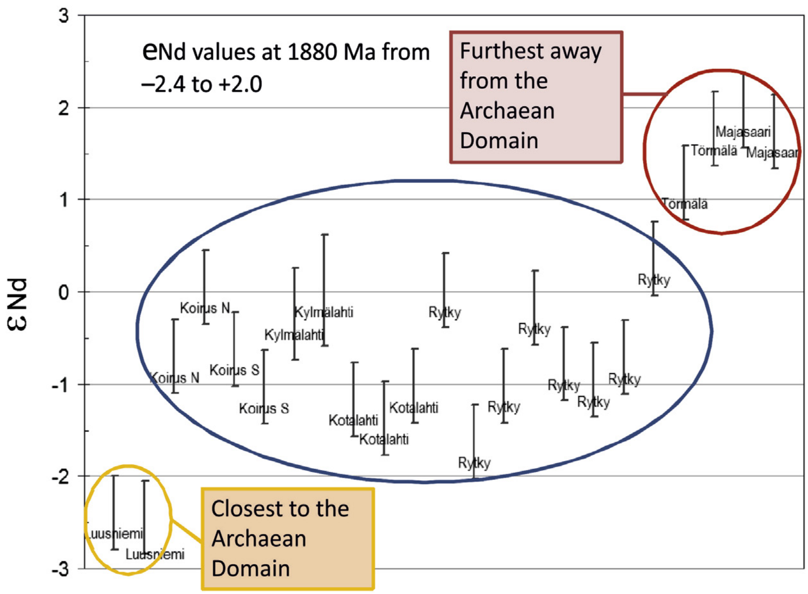

FIGURE 3.8.17 εNd (1880 Ma) values for intrusions from the Kotalahti nickel belt.

These are grouped according to proximity relative to the Archean crust. Intrusions within Kotalahti area are within the blue ellipse.

Source: *Modified from Makkonen and Huhma (2007).*

ORE MODELS

Because of their economic importance, numerous Svecofennian nickel deposits have been studied in great detail, particularly with regard to their sulfide mineralization. These data provide a good basis for ore petrological studies (e.g., Lamberg, 2005).

Peltonen (1995a) proposed that the intrusions of the Vammala belt were emplaced above an active subduction zone during progressive regional metamorphism and deformation. During their ascent to higher crustal levels, some of the magma intruded sulfidic black schist layers. Assimilation of external sulfur triggered segregation of an immiscible sulfide melt, forming the nickel deposits at the stratigraphic base of the intrusions. The residual barren magmas ascended to higher crustal levels and formed the unmineralized intrusions.

Papunen (2003) proposed a slightly different model for synorogenic differentiated intrusions and related ores (e.g., Kotalahti) whereby the magma was contaminated at an early stage, followed by fractionation and segregation of sulfide melt in a lower crustal magma chamber prior to final emplacement to the present position in the form of distinct magma pulses. Sulfides were injected separately into low-stress areas due to tectonic filter pressing, forming high-grade ores either in the mafic–ultramafic intrusions or as high-grade offset ores.

To explain the intrusions containing only ultramafic cumulates (e.g., at Vammala), it was proposed that the residual mafic magma efficiently escaped from the magma chamber to the surface (Papunen, 2005).

The offset ores have been economically important because their nickel content is higher than in other ore types (around 3–6% vs. 1%). The offset ores are thus important exploration targets. Häkli et al. (1975) proposed that at Telkkälä, the wall rocks of the intrusion were fractured during cooling of the intrusion, resulting in infiltration of sulfide liquid and the formation of breccia and massive ore. Papunen (2003) suggested that pulses of silicate and sulfide melt were injected upward and outward of the magma chambers during tectonism, with the sulfide melt forming the last pulse. A similar model was proposed by Piña et al. (2010) for the Aguablanca deposit in Spain. Mobilization and concentration of magmatic sulfides by deformation has been proposed for the origin of the Svecofennian offset ores (e.g., Peltonen, 2005). Arndt et al. (2013) argued that sulfide melts that had accumulated at relatively high levels in intrusions could percolate to the base of intrusions and into their footwall.

In the experience of the author, offset ores tend to occur in the stratigraphic footwall of the intrusions, usually where the intrusion is thickest and contains the greatest proportion of ultramafic cumulates and sulfides. This suggests that the offset ores formed during the primary magmatic stage. The sulfide melt concentrated at the bottom of the intrusion and invaded the wall rock along synintrusion fractures produced during deformation and/or by partial melting of the wall rock.

Fig. 3.8.18 shows a schematic model for the formation of the Svecofennian nickel ores. Mantle-derived tholeiitic magma rises along different paths resulting in different amounts of crustal assimilation. Some magmas reach the surface without undergoing significant assimilation. This is consistent with their initial εNd (1880 Ma) values of around +4, and by the fact that chalcophile element depletion (Ni, PGE) is relatively minor (Barnes et al., 2009). In contrast, most of the Svecofennian intrusions are strongly depleted in PGE. The initial εNd (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 and type of assimilated material (Makkonen, 1996; Makkonen and Huhma, 2007). Sulfide segregation took place within the magma

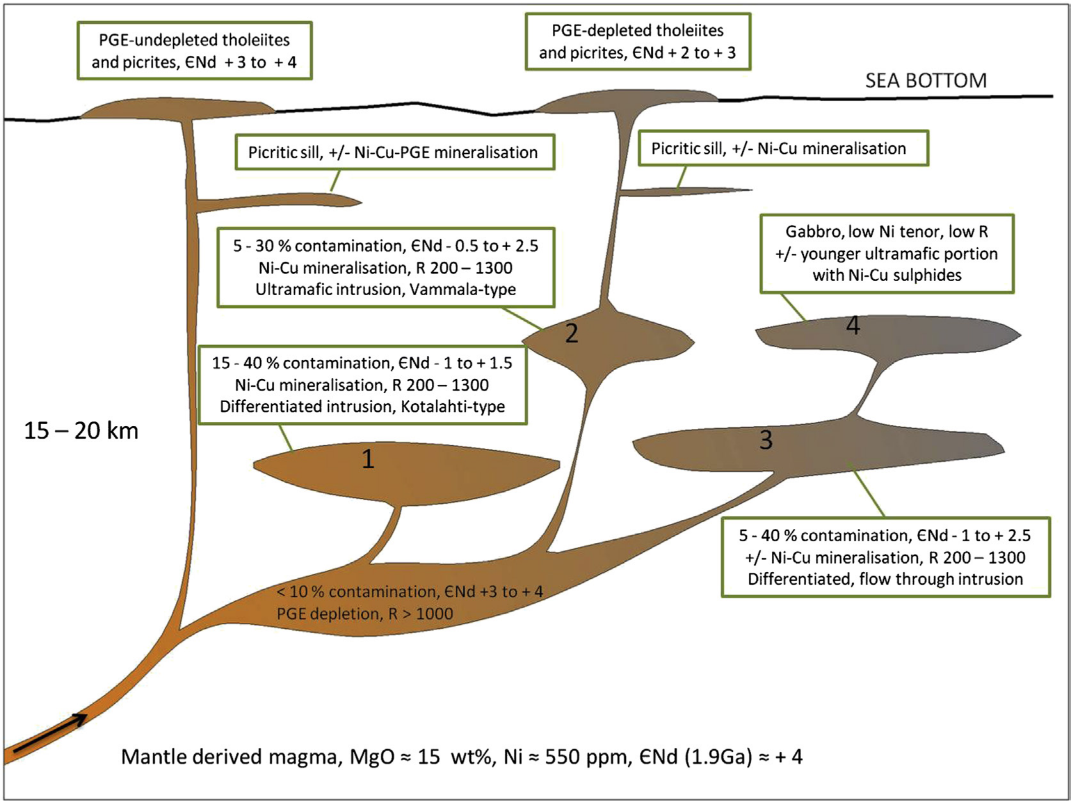

FIGURE 3.8.18 Schematic model for Svecofennian mafic–ultramafic magmatism and related nickel deposition.

Mantle-derived tholeiitic magma with MgO content of around 15 wt% intrudes sulfur-bearing sedimentary rocks at a crustal depth of 15–20 km. Magma ascends along different routes while fractionating olivine, so that the parental magma composition for each individual intrusion varies. Contamination by the sedimentary rocks is most effective in relatively large magma chambers. The amount and type of the assimilated sulfur-bearing sediment resulted in a large range of R values and, thus, Ni tenor as well as initial Nd isotope values (the Nd isotope values shown in the text boxes relate to cases where the contaminant is a Svecofennian sedimentary rock; in intrusions near the Archean rocks, εNd is lower).
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.

conduits and in somewhat larger chambers. Sulfide segregation was mainly caused by assimilation of sulfur-bearing sedimentary rocks. The level where this assimilation took place varies. If sulfur saturation was reached after significant olivine fractionation, the intrusion may contain Cu ± PGE rich mineralization; for example, in gabbros in the Juva area and in hornblendites in central and eastern Finland.

In the Kotalahti and Vammala belts, the largest intrusions are not known to contain significant Ni-Cu mineralization. Examples include Ylivieska, Alpua in Vihanti, and Saarela in Pielavesi. This is consistent with the model of Maier et al. (2001), which shows that economically important magmatic Ni-Cu sulfide deposits tend to occur in dynamic magma conduit systems rather than within large layered intrusions. The conduits are characterized by a highly dynamic flow environment characterized by multiple flows of magma. Sulfides are concentrated in the widened parts of the conduits, owing to a decrease in the flow velocity of the magma.

Many of the intrusions contain a gabbroic and an ultramafic portion separated by a sharp contact. The ultramafic phase often shows intrusive relationships relative to the gabbroic portion and thus appears to be younger, analogous to many Alaskan-type intrusions (Ripley, 2009). This relationship can be explained by the following model. The ascending magma fractionated in a staging chamber below the final level of emplacement. The relatively differentiated magma at the top of the staging chamber was the first to ascend further. Subsequently, olivine-rich slurries, with 15–20 wt% MgO, followed via the same route and intruded the gabbroic body. Flow differentiation may have led to further concentration of olivine and sulfide, forming sulfidic peridotites.

EXPLORATION

Successful exploration methods for Svecofennian nickel deposits include geophysics, lithogeochemistry, and location of sulfides in outcrops and glacial boulders. Results of till geochemistry are often obscured by the silicate nickel from the host rocks, but the use of ratios and other derivatives from the till geochemical data can be successful. Stratigraphic considerations are also important.

All economically important Svecofennian nickel deposits are hosted by ultramafic cumulates in the basal part of the intrusion. Intrusions with only gabbroic differentiates are thus considered to have low nickel ore potential.

GEOPHYSICS

Gravity maps can define potential target areas and locate the intrusions. Areal gravity highs represent relatively high metamorphic grade, suggesting a deeply exposed section of the crust (refer to Fig. 3.8.1). In targeting individual intrusions, one must remember that the serpentinites produce gravity lows.

The olivine-bearing cumulates show up well in magnetic maps. The ore itself is often detectable by magnetic ground measurements because magnetic (monoclinic) pyrrhotite is the predominant sulfide mineral. However, in peridotites, pyrrhotite is often hexagonal and less magnetic (antiferromagnetic). Distinguishing sulfide disseminations from magnetite in serpentinized olivine-bearing cumulates is difficult using geophysical methods. In some cases, remanent magnetism also complicates the interpretations. Once the nickel ore has been located, mise-a-la-masse (charged potential) is useful to trace the continuation of the ore. Usually, economic nickel contents require such a large amount of sulfides that the conductivity of the rock is high enough for the mise-a-la-masse method. Different kinds of magnetic and electro-magnetic borehole measurements also proved to be useful.

LITHOGEOCHEMISTRY

Since the 1960s, lithogeochemistry has been used in nickel exploration in Finland (Häkli, 1963, 1971). Around 20,000 rock samples were analyzed to determine the compositions of whole rocks, olivine, pyroxene, and amphibole during the Ni exploration of the Outokumpu Company, which began in 1960 (c.f. Lamberg, 2005). From the beginning of the 1980s, the Geological Survey of Finland carried out similar studies. The most important processes and features that can be constrained by lithogeochemical studies are (1) magma composition, (2) magma contamination, (3) chalcophile element depletion, and (4) internal structure of an intrusion.

The MgO content of the magma provides information on the state of differentiation of the magma. In sulfide undersaturated magmas, the Ni content correlates positively with MgO, thus the less evolved the magma is, the more potential exists for the formation of Ni-rich sulfide ores. The MgO content of the magma from which the intrusion crystallized can be estimated from the whole rock cumulate composition, from olivine composition, or from the composition of chilled margins of the intrusion.

Magma contamination by the country rocks may result in elevated contents of SiO_2 (which in turn may result in orthopyroxene being more abundant than clinopyroxene), Al_2O_3, CaO, incompatible and high field strength (HFS) elements, and rare earth elements (REE) (Fig. 3.8.19). Isotope and S/Se studies can also reveal magma contamination, but as noted earlier, interpretations can be complicated in S/Se studies.

Chalcophile element depletion has been widely used to evaluate prospectivity. Studies on the nickel content of olivine have been particularly abundant. Other useful methods include plots of whole rock nickel versus MgO or Mg-number. PGE depletion has also been tested (Barnes et al., 2009) but more studies are needed to prove its effectiveness. One rarely used but worthwhile method may be Tl depletion. Univalent thallium follows rubidium in magmatic differentiation but because it also has a chalcophile nature it is depleted in sulfur-saturated systems (McGoldrick et al., 1979). Plots of Tl versus Rb (also K and Na) can be used to study the depletion (Forss et al., 1999).

Olivine is commonly at least partly preserved in most of the primary olivine cumulates and, thus, can be analyzed by microprobe. Orthopyroxene can be used in a similar way to olivine (c.f. Lamberg, 2005). Fig. 3.8.20 shows the Ni versus Fo plot for olivines analyzed from the mafic–ultramafic intrusions in the Kotalahti belt. The majority of the samples plot in the sulfur-saturated field. The most prospective intrusions are those that show a steep trend from high Fo (>80 m%) and Ni (>1500 ppm) contents toward low Ni contents (≈500 ppm). This trend suggests that sulfide segregation took place within the intrusion, (i.e., in situ). In contrast, if an intrusion contains only nickel-depleted olivine, this suggests that fractionation and/or nickel depletion occurred prior to final emplacement, resulting in low ore potential.

In addition to the magmatic trend shown in the plot, at least two further factors affect the composition of olivine: (1) Reaction between olivine and intercumulus melt can lower both the primary forsterite and nickel contents. The process was referred to as “trapped liquid shift” by Barnes (1986) and can produce significant scatter in the nickel versus forsterite plot. (2) Reaction between sulfide and olivine ($NiSi_{0.5}O_2 + FeS = NiS + FeSi_{0.5}O_2$; Fleet et al., 1977) can produce a positive correlation between Ni and Fe contents in olivine, resulting in scatter or a negative correlation between the nickel and forsterite contents in olivine.

In cases where a representative set of chemical data for a range of intrusions is available, a fertility analysis combining a number of critical factors in nickel ore formation (Lamberg, 2005) can be a useful tool to discriminate between barren and ore-bearing intrusions.

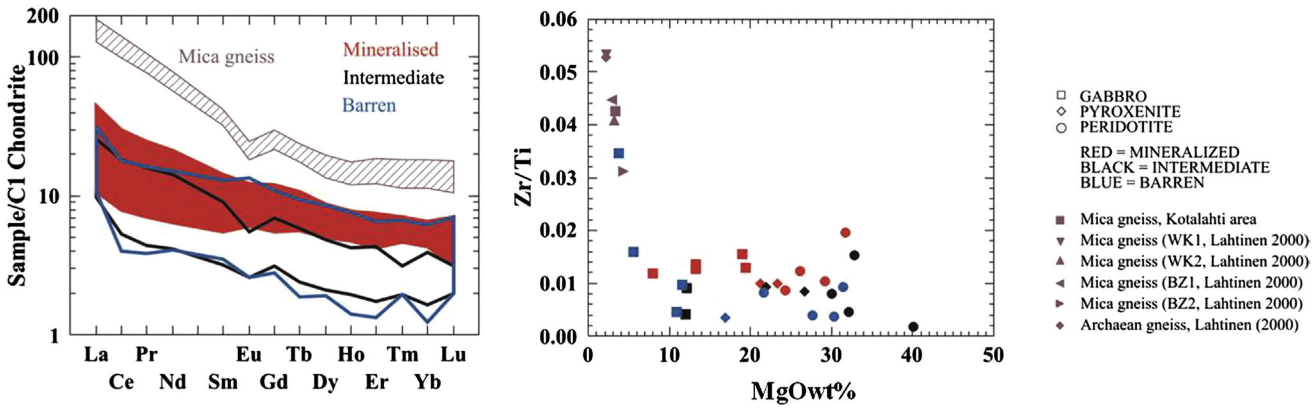

FIGURE 3.8.19 Diagrams showing the average compositions of mineralized (red), intermediate (black), and barren (blue) intrusions.

These are from the Kotalahti belt. In the REE diagram the composition ranges for peridotites only are shown. MgO as vol. free. total number of samples is 663. Compositions of the most probable contaminants are also given, namely mica gneiss (purple square and triangles) and Archean gneiss (purple diamond; data from Lahtinen, 2000).

Source: *Modified from Makkonen et al. (2008).*

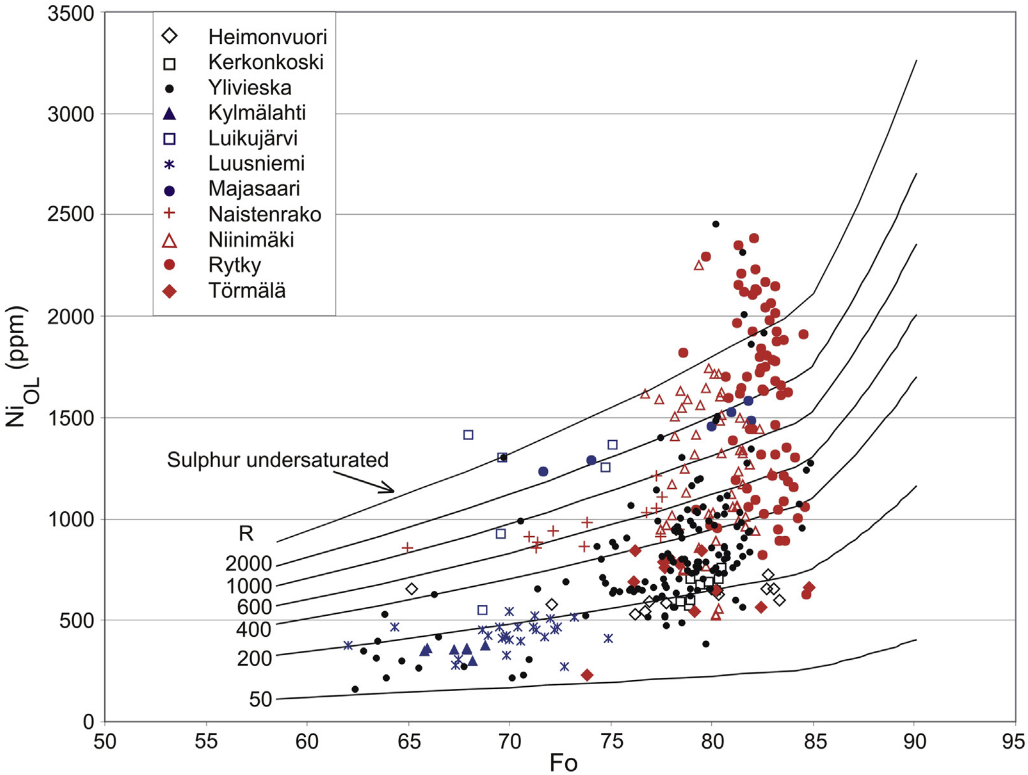

FIGURE 3.8.20 Diagram of nickel versus Fo contents in olivine for some intrusions of the Kotalahti belt.

Number of samples = 374. Olivines from strongly mineralized intrusions are shown in red, weakly mineralized intrusions in black, and barren intrusions in blue. The model curves show the composition of olivine crystallizing from parent tholeiite assuming different mass ratios between the silicate melt and sulfide melt (R). The curves are for different degrees of batch equilibrium crystallization. R values are calculated after Campbell and Naldrett (1979), using the following equations: logMgOLiq = (logFo – log(252.7833 – 0.7825 × Fo))/0.4602 + 1.795 and MgOLiq = $^{0.2588}\sqrt{(0.9554/(100/Fo - 0.67))}$ (Makkonen, 1996), NiLiq = 2.1257 × MgOLiq$^{2.05}$ (Makkonen et al., 2008), $D_{Ni}^{Oi/Liq} = e^{(4.961 - 1.266 \times \ln MgOLiq)}$ (Duke and Naldrett, 1978), $D_{Ni}^{sul/sil} = 350$ (Francis, 1990).

Source: *Reprinted from Makkonen et al. (2008, Fig. 3).*

SUMMARY

Most of the Svecofennian mafic–ultramafic intrusions record ages between 1875 and 1885 Ma, and all Ni-bearing intrusions belong to the 1880 Ma age group.

The total ore production of the 10 Svecofennian nickel mines in Finland is about 45 Mt at 0.67% Ni and 0.26% Cu, and the total premining resource of all the deposits known to date is about 73 Mt at 0.6% Ni and 0.3% Cu. From the mined deposits, only the four biggest, Hitura, Kotalahti, Vammala, and Enonkoski contained several million tons of ore.

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 east and south of the Central Finland Granitoid Complex. The Kotalahti nickel belt extends close to the Archean craton margin. Most of the nickel-deposits occur within zones characterized by amphibolite facies to granulite facies metamorphic grade, schollen- and schlieren-migmatite-textured sulfide- and graphite-bearing metasedimentary rocks, abundant mafic–ultramafic intrusions, and a high regional gravity signature.

The intrusions were emplaced during peak deformation and metamorphism. Two different variants of Svecofennian nickel-bearing intrusions can be distinguished. The weakly differentiated, dominantly ultramafic Vammala-type intrusions consist almost entirely of olivine cumulates and occur within polydeformed paragneisses as small boudinaged lenses or pipes with a diameter of 100–1000 m. The differentiated, mafic and mafic–ultramafic, Kotalahti-type intrusions consist of olivine cumulates, pyroxene cumulates, and plagioclase-bearing cumulates, and are commonly up to several kilometers long and a few hundred meters wide at surface section. Magmatic layering is locally visible, although the layered structure is commonly obscured by polyphase deformation. The intrusions were emplaced during or before the main deformation phase of D2 and underwent further deformation during D3–D4, resulting in highly complex structures.

The parental magma for most intrusions contained 10–12 wt% MgO and 240–350 ppm Ni. The least evolved magma was derived from a depleted mantle source (initial εNd + 4) and probably contained around 15 wt% MgO and 550 ppm Ni as indicated by the high Fo contents up to 89 at Kotalahti. Geochemically, the magma was similar to EMORB. It intruded sulfur-bearing sedimentary rocks, resulting in crustal contamination of the mafic magma, indicated in both the Vammala and Kotalahti belts. In the Vammala Ni province, black schist was an important contaminant. In the Kotalahti area, contamination by both Svecofennian sediments and Archean gneiss took place. The distinct fractionation trends of the clinopyroxene-dominated Vammala type and the orthopyroxene-plagioclase-dominated Kotalahti type probably resulted from differences in the amount and type of assimilated crust. In the more contaminated Kotalahti-type intrusions, SiO_2 was added to the magma in abundance resulting in orthopyroxene crystallization. Based on Nd isotope data, the amount of the assimilated material varied between 10% and 40% by mass.

The metal contents of the parental magma control the composition of the related ores. Depending on the sulfur amount available during sulfide segregation (R factor) and on the fractionation of the silicate melt, the nickel content of the sulfide fraction varies between 2 and 14 wt% and Ni/Cu between 1 and 4. The nickel ore is located stratigraphically in the basal part of the intrusion. The ore is often zoned, with the most massive ore located at the basal contact. The PGE contents are typically low and PGE patterns usually show negative Pt anomalies in mantle- or chondrite-normalized spidergrams. The Svecofennian Ni deposits often contain offset ores, which are located 50–200 m below the main intrusion within mica gneiss and black schist. The ore mineral assemblage in the Svecofennian nickel-copper ores typically is pyrrhotite-pentlandite-chalcopyrite. The composition of pyrrhotite (monoclinal, hexagonal, troilite) varies between deposits and also between ore bodies in one deposit.

Sulfide segregation took place when sulfur was added to the magma from the wall rock in the magma conduit or in the final magma chamber. The ratio of silicate melt to sulfide melt (R factor) varied mostly between 200 and 1300 and, consequently, a wide range in nickel tenor is observed. Ultramafic, weakly differentiated Vammala-type intrusions can be interpreted as flow conduits. Kotalahti-type intrusions are more strongly differentiated and contain layered rocks, suggesting crystallization in a more quiescent magma chamber. Tholeiitic and picritic volcanic rocks spatially closely associated with the intrusions may represent the same magmatic event as the intrusions, but the magma probably ascended via different routes into the upper crust. Geochemical differences suggest that contamination was more significant for the intrusive phases. This is in accordance with the fact that nickel-copper mineralization is rare within the extrusive rocks.

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