CHAPTER

3.3

PGE-(CU-NI) DEPOSITS OF THE TORNIO-NÄRÄNKÄVAARA BELT OF INTRUSIONS (PORTIMO, PENIKAT, AND KOILLISMAA)

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ABSTRACT

The layered intrusions of the Tornio-Näränkävaara belt in north-central Finland host Europe's most significant platinum-group element (PGE) deposits. At the most advanced stage of exploration are contact-type deposits of the Portimo complex (i.e., those at Ahmavaara and Konttijärvi), where the total PGE-Ni-Cu resources are ~263 million tons. The contact-type Haukiaho and Kaukua deposits of the Koillismaa intrusion are also reported to contain significant PGE-Ni-Cu resources, amounting to approximately 46.8 Mt. In addition to the contact-type deposits, the intrusions host several other styles of PGE mineralization, including internal PGE reefs (most significant being the SJ and PV Reefs of the Penikat intrusion and the SK Reef of the Portimo complex), and offset-type mineralization below the Narkaus intrusion in the Portimo complex. We present key geological features of various deposits and place them into a stratigraphic context with their host intrusions. We also refer to an exploration model that was successfully used in the discovery of these metal enrichments.

Keywords: Platinum-Group Elements; nickel mineralization; copper mineralization; Portimo; Suhanko; Penikat; Koillismaa; PGE reef; contact-type deposit.

INTRODUCTION

Northern Fennoscandia contains approximately two dozen Paleoproterozoic layered mafic–ultramafic intrusions (Fig. 3.3.1) (Alapieti et al., 1990). Based on U-Pb zircon and Sm-Nd whole-rock isotope data, the mean age for the Finnish intrusions is 2440 Ma (Huhma et al., 1990, 2011). These intrusions belong to bimodal igneous activity, which resulted in mafic and felsic, plutonic and extrusive formations not only in Finland but also in northwest Russia. The igneous activity was related to mantle plume-generated rifting of Archean continent (Amelin et al., 1996; Hanski et al., 2001) and many of the formations form long linear belts following intracratonic rift zones (Fig. 3.3.1). In Finland, the 2.44 Ga intrusions are concentrated into two zones: one, as represented by the Koitelainen and Akanvaara intrusions (Mutanen, 1997; Maier, 2015) is located in central Lapland and the other one forms the approximately 300-km-long, west–east trending Tornio-Näränkävaara belt (TNB) that starts from the

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Finnish-Swedish border and extends into Russia. Based on the similarities in their stratigraphy, some of the TNB igneous bodies represent dismembered fragments of larger intrusions.

The intrusions of the western part of the Tornio-Näränkävaara belt have Archean basement complex on their footwall side and the hanging wall rocks are younger Paleoproterozoic subracrustal sequences

FIGURE 3.3.1 Generalized geological map of the northeastern Fennoscandian Shield, with Paleoproterozoic layered intrusions.

The intrusions mentioned in the text are highlighted.

Source: *Modified from Karinen (2010).*

deposited on partly eroded and block-faulted intrusions, referring to a rather shallow intrusion depth and rapid uplift. In the east, the Koillismaa intrusion has its Paleoproterozoic volcanic roof rocks partly preserved (Lauri et al., 2003). The easternmost body, the Näränkävaara intrusion, was emplaced totally into Archean basement rocks. Magmatic layering of the intrusions dips toward the overlying subracrustal rocks, and gravity and seismic surveys indicate intrusions to plunge underneath Proterozoic rocks. Modal mineralogy of intrusions varies from ultramafic dominated (Tornio and Näränkävaara) to intrusions composed almost exclusively of mafic cumulates (Koillismaa). A more detailed description of the Tornio-Näränkävaara belt can be found in Iljina and Hanski (2005).

Many of the ~2.44–2.50 Ga Paleoproterozoic layered intrusions are platinum-group element (PGE) and Ni-Cu mineralized, most notably Portimo, Penikat, and Koillismaa in the Tornio-Näränkävaara belt, and Monchegorsk, Fedorova Tundra, and Pana Tundra in the Kola Peninsula, Russia, although none of them is currently exploited for PGE (several deposits hosted by the Monchegorsk intrusion were mined for Ni and Cu(-PGE) from 1935–1975). In the present chapter, the geology and PGE mineralization styles in intrusions of the Tornio-Näränkävaara belt are described. This belt is of considerable economic and academic interest because it hosts several forms of PGE enrichment, including reef-, contact-, and offset-type mineralization.

THE PORTIMO COMPLEX AND ITS MINERALIZATION

STRUCTURAL UNITS AND STRATIGRAPHIC SECTIONS

The Portimo complex (Fig. 3.3.2) is composed of four principal intrusive blocks/structural units (Alapieti et al., 1989; Iljina, 1994, 2005; Iljina and Hanski, 2005), including the Narkaus, Suhanko, and Konttijärvi intrusions. These blocks represent tectonically dismembered bodies of one or two originally larger intrusions. The Portimo complex was deformed and metamorphosed during several tectonic events. During these events, almost all primary magmatic minerals were altered to secondary minerals. In the mafic

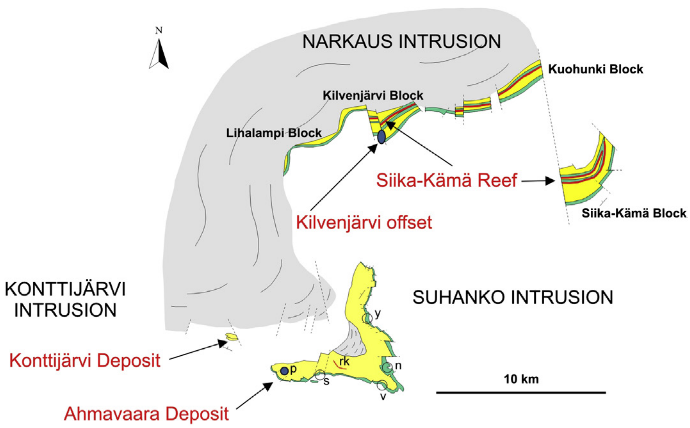

FIGURE 3.3.2 General geological map and principal PGE occurrences of the Portimo layered igneous complex.

rk = Rytikangas PGE Reef, p = clinopyroxene pegmatite pipe; the massive sulfide deposits in the Suhanko intrusion are also shown: s = Suhanko proper, v = Vaaralampi, n = Niittylampi, and y = Yli-Portimojärvi.

Source: *Modified after Iljina, 1994.*

rocks, the metamorphic assemblage consists of amphiboles and plagioclase. Polyphase metamorphism, probably comprising several prograde and retrograde phases (Iljina, 1994), is expressed by greenish hornblende rims around colorless amphiboles and the subsequent development of colorless amphibole around greenish amphibole. In spite of the metamorphic alteration, it is usually possible to recognize the original cumulus textures based on the pseudomorphs of the original minerals. Clinopyroxene and orthopyroxene relicts in the similar, but less altered Penikat intrusion are augitic and bronzitic in composition, respectively. Therefore, where it is possible to distinguish two different pyroxenes in the Portimo rocks on the grounds of the habitus of their pseudomorphs, the clinopyroxene has been generally referred to as augite and the orthopyroxene as bronzite. These terms are also used in the rock nomenclature. Where the nature of the primary minerals is unclear, less-specific rock names, such as pyroxenite and peridotite, are used.

Each individual block of the Portimo complex contains a basal marginal series of variable thickness and an overlying layered series (Fig. 3.3.3). In all cases, the footwall consists of Archean granite-gneiss, or locally also quartzite and mafic volcanic rocks of Archean greenstone belts. The marginal series of the Narkaus intrusion differs from those in the Suhanko and Konttijärvi intrusions in its thickness and prevailing rock types. The Narkaus marginal series generally varies from 10–20 m in thickness, whereas the Suhanko and Konttijärvi marginal series reach a thickness of 40–80 m and 100–150 m, respectively. The

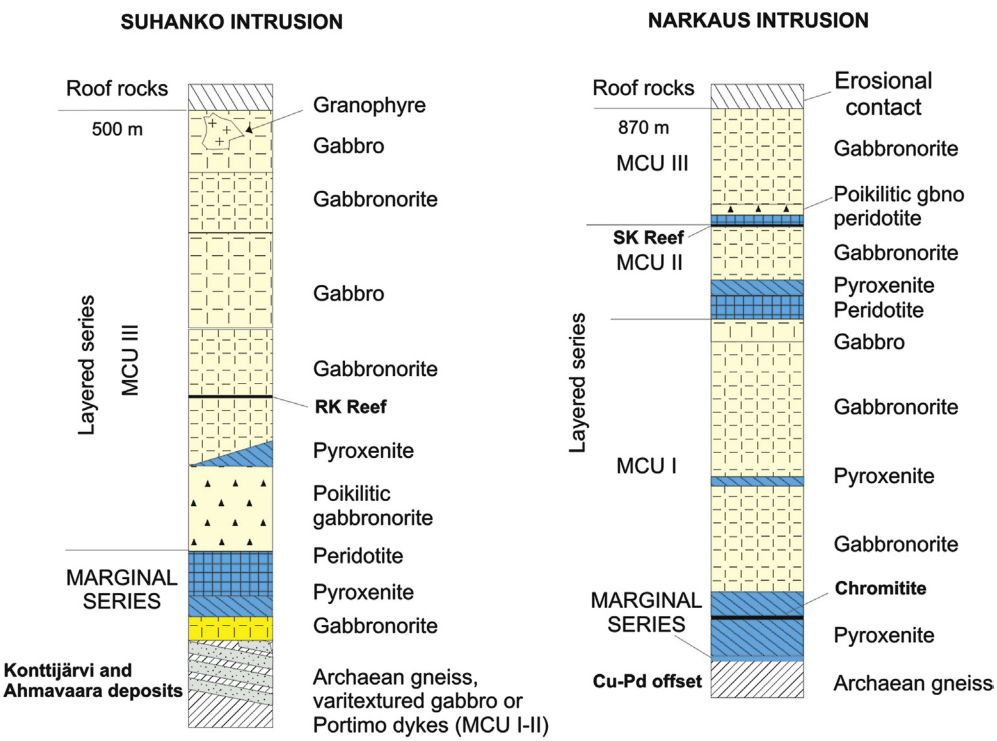

FIGURE 3.3.3 Cumulus stratigraphy of the Narkaus and Suhanko intrusions and locations of the principal PGE occurrences.

MCU = megacyclic unit.

Source: *Modified after Iljina (1994).*

Narkaus marginal series is mainly composed of pyroxenite, with some relatively feldspathic varieties in its lower parts, whereas the Suhanko and Konttijärvi marginal series contain thick, olivine-rich cumulates (lherzolite) in their upper portions, which are underlain by pyroxenite and then gabbronorite (Fig. 3.3.3).

Fine-grained, granular-textured gabbronoritic bodies or fragments, ranging in thickness from a few centimeters to a few tens of meters and reaching several hundred meters in length, occur in many places in the Suhanko marginal series (Figs. 3.3.4B and 3.3.5). The chemical composition of these rocks seems to vary along the strike. For example, at Ahmavaara, they have a distinctly higher Cr content and slightly higher MgO content than in the southeastern portion of the Suhanko intrusion; for example, in the Niittylampi area (refer to Fig. 3.3.7). The Ahmavaara fragments resemble chemically the Portimo dikes located below the Konttijärvi and Ahmavaara marginal series, whereas the chemical composition of the Niittylampi fragments is similar to the mean composition of the Suhanko intrusion (see Table 3.3.4 later in chapter). The chemical features and the mode of occurrence of these fine-grained gabbronoritic rocks have led to the idea that they are autoliths and represent chilled margin rocks that were disrupted and entrained by subsequent magma pulses (Iljina, 1994).

At the base of the layered series of the Suhanko intrusion are gabbronoritic orthocumulates (with poikilitic augite), which also contain some pyroxenitic interlayers up to a few meters in thickness. The poikilitic gabbronorite is separated from the overlying, rather monotonous gabbronoritic adcumulates by a few-meters-thick pyroxene-rich layer (except at Konttijärvi and Ahmavaara, see the following heading). Approximately midway in the stratigraphy of the layered series, bronzite disappears as a cumulus mineral, but returns higher up in the sequence. Four poikilitic anorthosite layers also occur in the upper Suhanko layered series. Granophyric material is found as discontinuous patches and cross-cutting dikes in both the upper Suhanko and upper Konttijärvi layered series.

In the Narkaus intrusion, the layered series contains thick peridotite layers that are absent at Suhanko and Konttijärvi. The peridotite layers have been interpreted to represent compositional reversals resembling those in the Penikat intrusion which enables the subdivision of the Narkaus layered series into three megacyclic units (MCU I–III, Fig. 3.3.3). The lowermost unit (MCU I) commences with a thick (~80 m) orthopyroxenite sequence that hosts a massive, 30-cm-thick chromitite in its middle part. The rest of MCU I comprises mainly gabbronoritic adcumulates. MCU II is found only in the Kilvenjärvi block and fades away eastward. It consists of a basal peridotite overlain by pyroxenite and gabbronorite. MCU III commences with a peridotite layer overlain by gabbronorite orthocumulates (plagioclase-bronzite cumulates with poikilitic augite) followed by gabbronorite adcumulates.

Mafic and ultramafic dikes, known as the Portimo dikes, occur in the basement below the Konttijärvi intrusion and in the Ahmavaara area of the Suhanko intrusion (Figs. 3.3.3, 3.3.6, and 3.3.11). They have also been detected as fragments in the Konttijärvi marginal series (Fig. 3.3.4D). The dikes have not been dated and their association to the main intrusions is based on geochemical and geologic observations, as discussed in the following. The dikes strike subparallel to the basal contact of the intrusions and merge locally with them.

Special stratigraphic features of the Konttijärvi and Ahmavaara areas

The highest grade of PGE mineralization within the Portimo complex occurs in the Konttijärvi intrusion and in the Ahmavaara area at the western end of the Suhanko intrusion. The geology and stratigraphy of these areas is therefore discussed in more detail in the following.

The lowermost homogenous gabbronoritic cumulates of the Konttijärvi marginal series are underlain by the varitextured gabbro zone (also called the *transition* or *mixing zone*), which constitutes a heterogeneous mixture of pyroxene cumulates that have been infiltrated by variable proportions of felsic melts

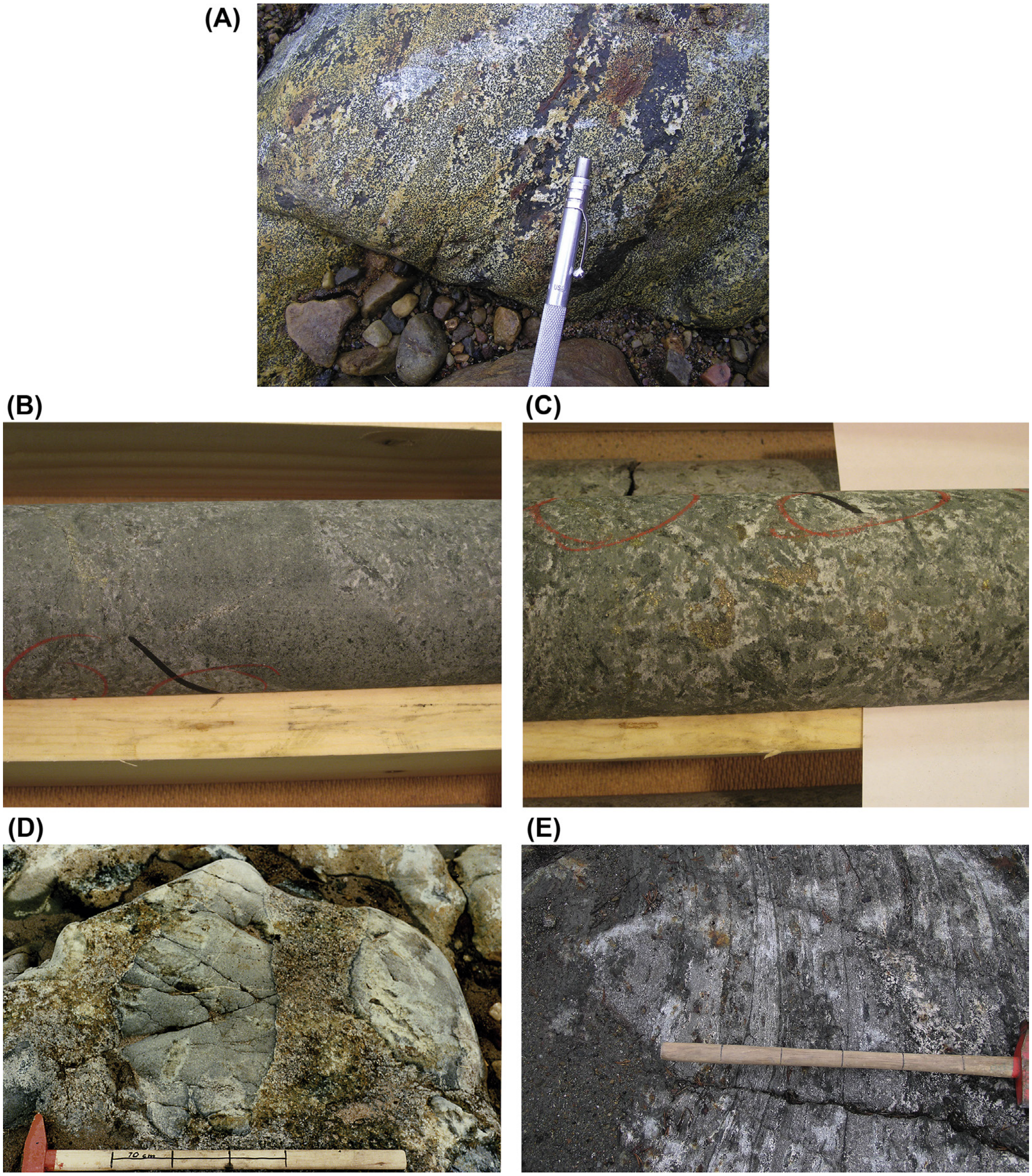

FIGURE 3.3.4 (A) Varitextured gabbro at Konttijärvi. (B) Fine-grained and sharp-edged chilled margin fragments in the Ahmavaara drill core. For the structural position, see Fig. 3.3.5. (C) Cresscumulate with sulfides in the lower part of the Ahmavaara marginal series. (D) Large blocks of the Portimo dikes in the olivine cumulate (darker) of the Konttijärvi marginal series. (E) Banded gabbro, varitextured zone, Konttijärvi.

Source: *Photos by M. Iljina.*

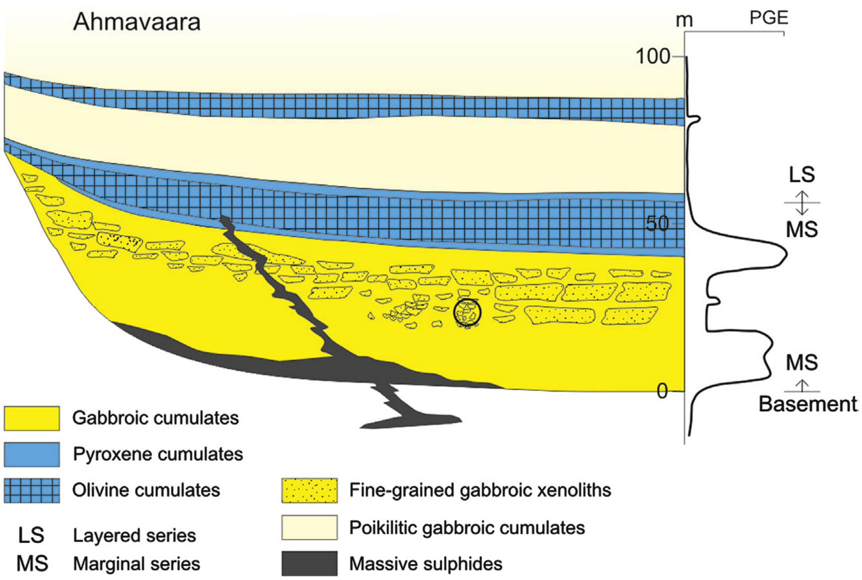

FIGURE 3.3.5 Schematic cross section of the Ahmavaara marginal series and lowermost layered series (Suhanko intrusion).

The circle shows the location of the photograph in Fig. 3.3.4B.

derived from the footwall rocks. These rocks are referred to as *hybrid gabbro* and *banded gabbro* (Figs. 3.3.4, 3.3.6, and 3.3.8). The hybrid gabbro is characterized by fine- to medium-grained rocks but also contains partially digested felsic fragments derived from the footwall. Further away from the intrusion, the hybrid gabbro turns into banded gabbro (Fig. 3.3.4E). This banding is probably due to flow of a heterogeneous mixture of mafic magma and anatectic felsic melts. Contacts between the homogenous gabbro, hybrid gabbro, and banded gabbro are diffuse, but the hybrid and banded gabbros together form a distinct mappable unit that also contains nonassimilated basement gneiss blocks up to several tens of meters in size. The varitextured gabbro zone appears to be a result of the mechanical and metasomatic mixing of melted Archean gneiss and mafic magma, indicating dynamic intrusion of the mafic magma.

The cumulus sequences of the lower layered series of the Konttijärvi and Ahmavaara areas bear a strong resemblance. The pyroxenite occurring between the lowermost poikilitic gabbronorite of the layered series and the overlying gabbronoritic adcumulate attains a thickness of several tens of meters in both sections. It measures only a tenth of the thickness elsewhere in the Suhanko intrusion.

THREE-DIMENSIONAL STRUCTURE OF THE PORTIMO COMPLEX

The surface exposure and geological cross sections of the Narkaus intrusion indicate a sill-like body (Iljina, 1994; Iljina and Salmirinne, 2011) dipping at a moderate angle beneath the sedimentary roof rocks, down to a depth of ~700 m, in a similar way as the Penikat intrusion does (Lerssi, 1990). In contrast, the Suhanko intrusion has a more lopolithic shape, which is also reflected in the variability of the stratigraphic sequences along surface profiles and the location of mineral deposits. Interpretations of

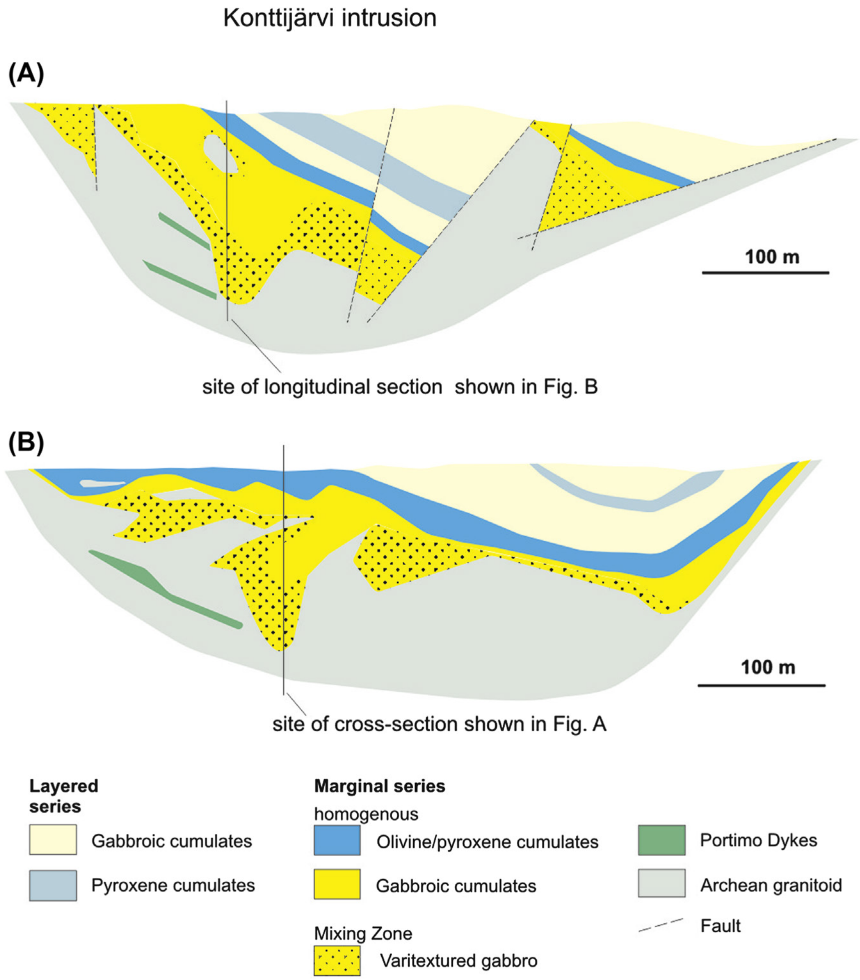

FIGURE 3.3.6 Cross section (A) and longitudinal section (B) of the Konttijärvi intrusion.

Source: *Modified after Iljina and Hanski (2005).*

gravimetric measurements (Pernu et al., 1986) and seismic reflection surveys (Iljina and Salmirinne, 2011) have revealed the three-dimensional structure of the Suhanko intrusion. The magmatic body has an estimated present-day volume of about 13.9 km^3. Figure 3.3.7 presents horizontal sections through the intrusion at variable depths. The most significant feature is that the central and northern parts of the Suhanko intrusion plunge to the northwest at a low angle, reaching a depth of about 1 km. The lower contact of the intrusion is *transgressive*; that is, the base of the southeastern tip is in contact with relatively higher levels of the Archean basement complex than the remainder of the intrusion. In view of its cumulus stratigraphy and chemistry, the Ahmavaara section is interpreted to represent the stratigraphically lowest part of the Suhanko intrusion, partly because it contains the highest proportion of ultramafic cumulates. In contrast, the southeastern tip of the intrusion represents a relatively elevated stratigraphic level.

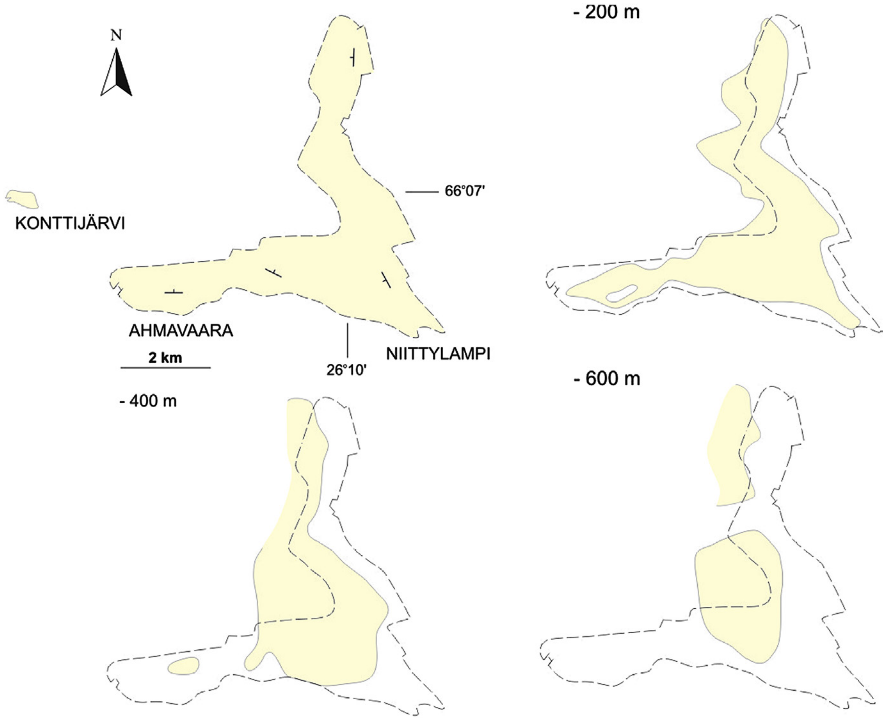

FIGURE 3.3.7 Suhanko intrusion: plan view and horizontal cross sections at depths of 200, 400, and 600 m.

Source: *Modified after Pernu et al. (1986).*

CU-NI-PGE MINERALIZATION IN THE PORTIMO COMPLEX

Of the Finnish layered intrusions, the Portimo complex contains the most diverse types of PGE mineralization, including internal PGE reefs, contact-type PGE reefs, and so-called offset deposits (refer to Figs. 3.3.8–3.3.11). Based on Iljina (1994), the following are the principal mineralization types.

Contact-type deposits:

- PGE-bearing Cu-Ni-PGE sulfide disseminations in the marginal series of the Konttijärvi and Suhanko intrusions (see Figs. 3.3.8 and 3.3.9).
- Predominantly massive pyrrhotite deposits located close to the basal contact of the Suhanko and Narkaus intrusions (Fig. 3.3.2).
- Offset-type Cu-PGE mineralization below the Narkaus intrusion (Fig. 3.3.10).

Reef-type deposits:

- The Rytikangas PGE Reef in the layered series of the Suhanko intrusion (Figs. 3.3.11 and 3.3.20).
- The Siika-Kämä PGE Reef in the layered series of the Narkaus intrusion (Figs. 3.3.11 and 3.3.20).

Four other PGE enrichment types are depicted in Fig. 3.3.11: (1) PGE enrichment in the Portimo dikes below the Konttijärvi and Ahmavaara marginal series, (2) PGE enrichment near the roof of the Suhanko intrusion, mostly associated with pegmatites, (3) a Pt-enriched clinopyroxenitic pegmatite

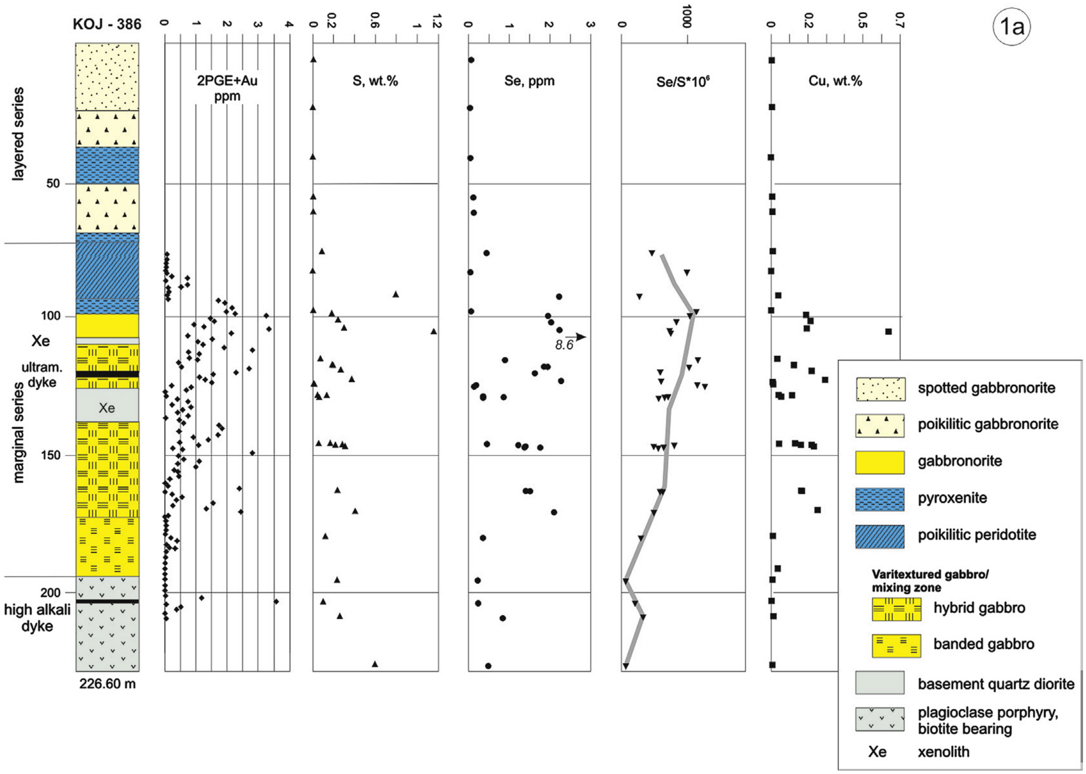

FIGURE 3.3.8 Stratigraphic sequence of the Konttijärvi marginal series.

This shows variations in bulk Pt + Pd + Au, S, Se, Se/S, and Cu. For structural position, see circle 1a in Fig. 3.3.11.

Source: *Modified after Iljina (2005).*

pipe in the western limb of the Suhanko intrusion, and (4) chromite and silicate-associated PGE enrichments in the lower parts of the Narkaus intrusion and MCU II. Fig. 3.3.11 shows the structural model for the Portimo complex and the positions of the deposits referred to earlier. Table 3.3.4 shows grade and tonnage information of various deposits in the Portimo complex.

Disseminated contact-type Cu-Ni-PGE mineralization in the Suhanko and Konttijärvi intrusions

Disseminated PGE-bearing base-metal-sulfide mineralized zones, normally 10–30 m thick, occur practically throughout the marginal series of the Suhanko and Konttijärvi intrusions (Figs. 3.3.8, 3.3.9, and 3.3.11 later). The distribution of the mineralization is erratic; it generally extends from the peridotitic layer of the marginal series downward for some 30 m into the granitic basement. The PGE contents vary from only weakly anomalous values (100 s of ppb) to 2 ppm in much of the marginal series of the Suhanko intrusion, but rise to >10 ppm in several, ~1-m-long drill core intervals in the Konttijärvi and Ahmavaara areas.

Fig. 3.3.8 depicts the variation in the copper and precious metal contents and Se/S ratio in one drill hole across the Konttijärvi marginal series. The whole-rock PGE contents show a good positive

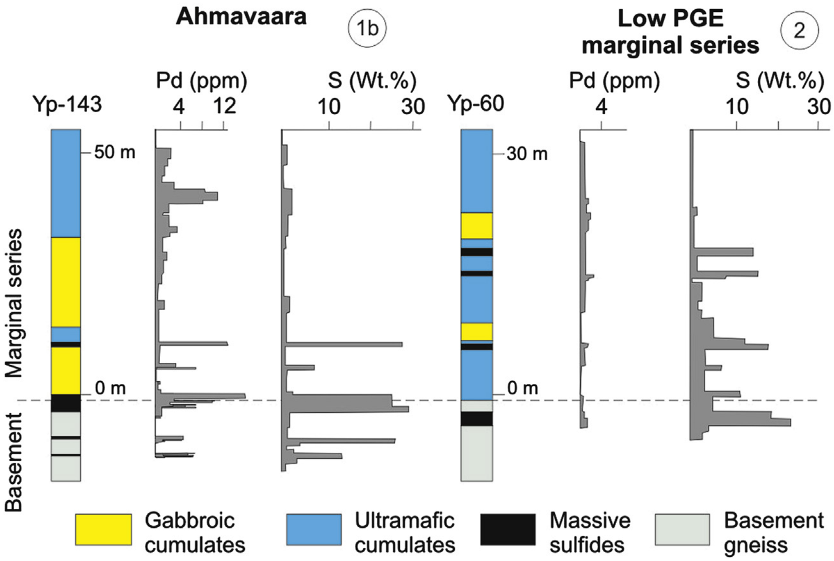

FIGURE 3.3.9 Comparison of the Ahmavaara deposit and one low-grade (Suhanko proper, Fig. 3.3.2), disseminated and massive sulfide deposit of the Suhanko intrusion (Fig. 3.3.2).

For the structural position, see circles 1b and 2 in Fig. 3.3.11.

Source: *Modified after Iljina et al. (1992).*

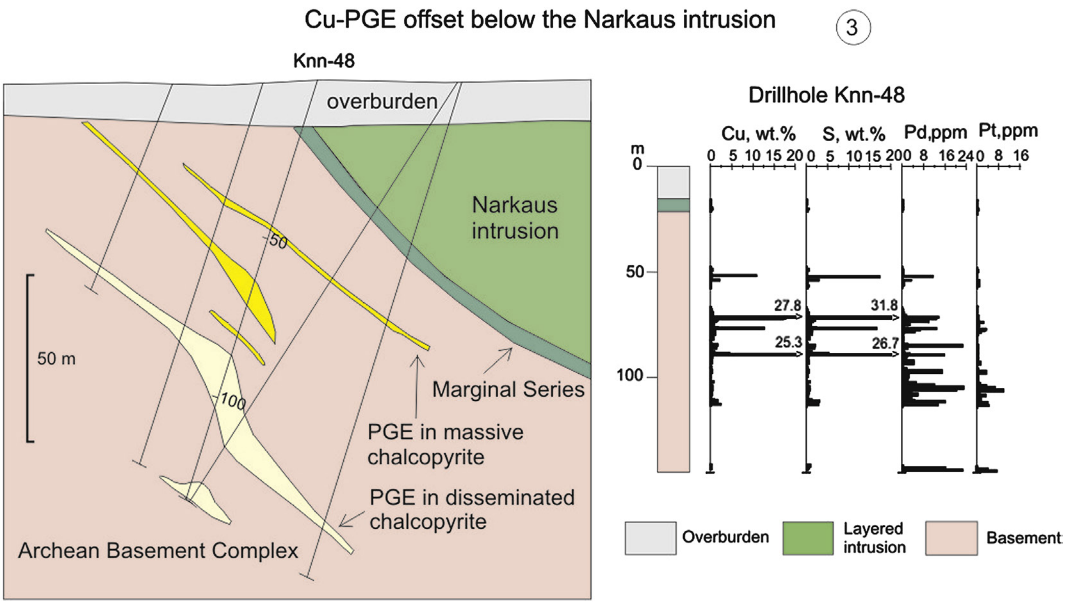

FIGURE 3.3.10 Offset Cu-Pd deposit at Kilvenjärvi below the Narkaus intrusion.

For the structural position, see circle 3 in Fig. 3.3.11.

Source: *Metal data from Huhtelin et al., 1989.*

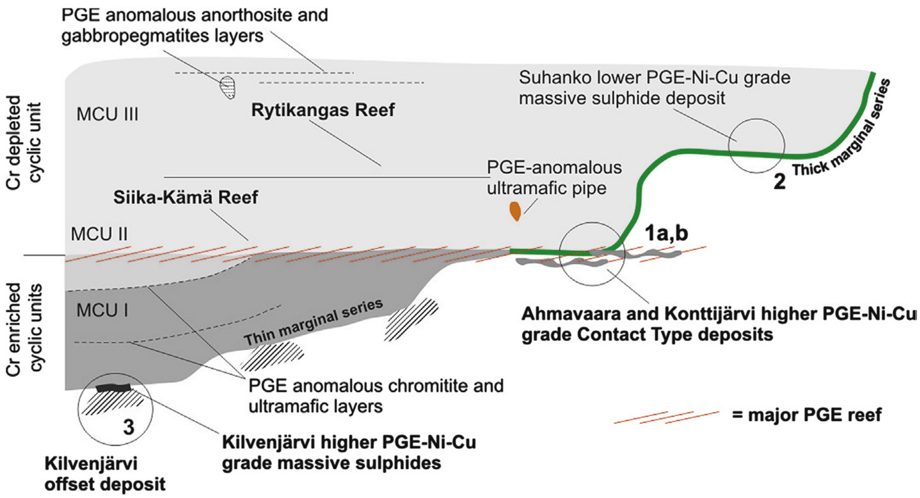

FIGURE 3.3.11 Schematic presentation of the locations of the various PGE enrichments encountered in the Portimo complex.

The circled numbers refer to Figs. 3.3.8–3.3.10 in this chapter.

Source: *Modified after Iljina (1994).*

correlation with Cu, Se, and Se/S. As a whole, half of the metal content of the entire Konttijärvi deposit is hosted by varitextured gabbro and basement rocks located below the homogenous marginal series proper.

Massive sulfide mineralization

Massive sulfide mineralization is characteristic for the marginal series of the Suhanko intrusion (Fig. 3.3.2). The mineralization occurs in the form of dikes and also plate-like bodies conformable to the layering, and generally varies in thickness from 20 cm to 20 m. The massive sulfide bodies may be located within felsic basement gneiss up to 30 m below the basal contact of the intrusion, or within the intrusion, up to 20 m above the basal contact (Figs. 3.3.5 and 3.3.9). They range in size from about 1 million tons to more than 10 million tons. The sulfide minerals are almost exclusively composed of pyrrhotite, except in the Ahmavaara deposit, which also contains chalcopyrite and pentlandite. The massive pyrrhotite deposits show relatively low PGE values with the maximum Pt + Pd content normally reaching a few ppm (exemplified by circle 2, Figs. 3.3.9 and 3.3.11). However, analogous to the disseminated sulfide mineralization in the marginal series of Ahmavaara, the PGE concentrations in the Ahmavaara massive sulfides are generally much higher than elsewhere in the Suhanko intrusion, attaining a level of 20 ppm (exemplified by circle 1b, Figs. 3.3.9 and 3.3.11). Drilling also shows that the relatively PGE-poor Suhanko (proper) massive sulfide deposit is located physically above the Rytikangas Reef due to the transgressive nature of the Suhanko marginal series (refer Fig. 3.3.12 later).

A less well-known massive sulfide deposit is located at the base of the Kilvenjärvi block of the Narkaus intrusion, above the Kilvenjärvi offset deposit. The base and precious metal tenors of this deposit resemble those of the Ahmavaara deposit in being distinctly higher than in the low-PGE grade deposits of the Suhanko intrusion.

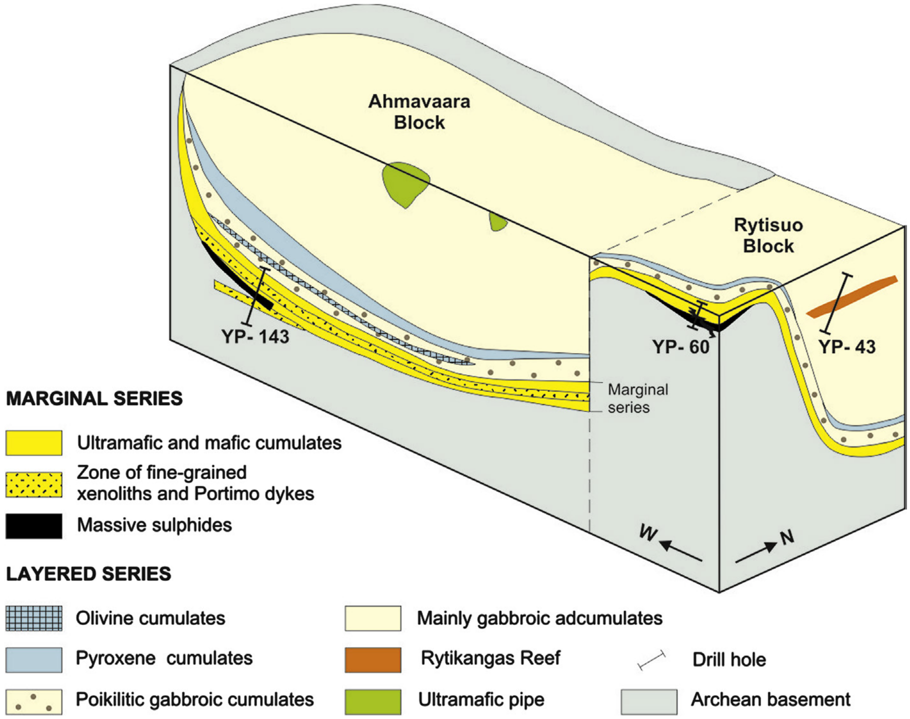

FIGURE 3.3.12 Perspective section from the western lobe of the Suhanko intrusion, showing the structural relationships between the Portimo dikes, Ahmavaara, and Suhanko proper massive sulfide deposits and Rytikangas Reef.

Drill hole sections YP-60 and YP-143 refer to Fig. 3.3.9.

Modified after Iljina et al. (1992).

Offset-type Cu-Pd mineralization

Copper-Pd mineralization is sporadically distributed in the basement gneisses and granites below the entire length of the Narkaus intrusion. It is usually referred to as *offset-type* mineralization (Huhtelin et al., 1989; Iljina, 1994; Andersen et al., 2006). The largest and best-known deposit is situated below the Kilvenjärvi block (Figs. 3.3.2, 3.3.10, and 3.3.11). This deposit is composed of a cluster of closely grouped ore bodies and is located in and near an N-trending major fault zone, some tens of meters wide, against which the Kilvenjärvi block terminates. The offset mineralization represents the richest PGE deposit type in the Portimo area, with whole-rock Pt + Pd contents reaching 100 ppm. The offset mineralization is predominantly a Pd deposit, as it has a much higher Pd/Pt ratio than the other Portimo deposits (or any other PGE deposit in the Tornio-Näränkävaara belt), whereas the Os, ir, Ru, and Rh concentrations are extremely low. The mineralization may comprise disseminated "clouds" of sulfide and PGM, massive sulfide veins or bodies, and sulfide-bearing granite breccias. The proportions of base metal sulfides and PGM are highly variable. The massive sulfide bodies are always rich in PGE, but some samples containing almost no visible sulfides can also carry several tens of ppm of Pd. In general terms, the more sulfide-rich occurrences are situated closer to the basal contact of the intrusion and those poorer in sulfides are encountered a greater distance below the intrusion (Fig. 3.3.10).

Siika-Kämä PGE Reef

The laterally persistent Siika-Kämä (SK) PGE Reef of the Narkaus intrusion is most commonly located at the base of MCU III (Figs. 3.3.2, 3.3.3, 3.3.11, and 3.3.20), but in some cases, it may occur somewhat below the basal contact of MCU III, or in the middle of the basal olivine cumulate layer (peridotite) of MCU III. The reef is normally hosted by chlorite-amphibole schist, similarly to the Sompujärvi PGE Reef in the Penikat intrusion. In some locations, the PGE mineralization is associated with thin chromite seams or chromite disseminations. The thickness of the reef varies from <1 m to several meters, and in many drill holes it consists of a number of mineralized layers separated by PGE-poor layers, which can be several meters thick. The PGE concentration varies from several hundred ppb to tens of ppm. Gabbroic pegmatites, abundant in the uppermost gabbroic, adcumulate tens of meters below MCU III, can sometimes also be mineralized, and contain several ppm of Pd and Pt. The Siika-Kämä mineralization is one of the most sulfide-deficient PGE mineralizations in the Portimo complex, in some places containing no visible sulfides and rarely having a whole-rock sulfur content of higher than 1 wt%.

Rytikangas PGE Reef

The Rytikangas PGE Reef represents the main PGE occurrence in the layered series of the Suhanko intrusion (Figs. 3.3.3, 3.3.11, and 3.3.12). It is located in the central portion of the cumulate sequence, about 170 m above the base of the western limb of the intrusion. The reef is verified by drilling to be continuous over the strike length of 1.5 km. It is hosted by anorthosites and gabbronorites (plagioclase-bronzite-augite orthocumulates with poikilitic augite). This cumulate series overlies a 70-m sequence of monotonous gabbronorite adcumulates and underlies 10 m of homogenous gabbronorite mesocumulates, in which augite has a nonpoikilitic intercumulus habit. The orthocumulate layer hosting the reef varies in thickness from 30 cm to 10 m. The thickness of the reef itself is 30–50 cm, and it typically occurs in the uppermost part of the poikilitic orthocumulate layer. The cumulus stratigraphy and compositional variation in major and trace elements across the Rytikangas Reef resembles those of the Ala-Penikka Reef in the Penikat intrusion.

Composition of the sulfide fraction and PGE characteristics

The concentrations of sulfur and base and noble metals in representative samples, and their values as recalculated to 100% sulfides, are presented in Table 3.3.1. Average concentrations for a large number of samples from each deposit, also recalculated to 100% sulfides, are also given in Table 3.3.1. A graphical presentation of the base and precious metal concentrations in 100% sulfides for massive sulfide deposits is shown in Fig. 3.3.13.

The massive sulfide deposits at the base of the Suhanko intrusion, with the exception of Ahmavaara, proved to be poor in nickel and copper, having Ni and Cu tenors from 0.48–2.2 wt% and from 0.37–2.4 wt%, respectively. Conversely, the Ahmavaara massive sulfide deposit has a markedly higher nickel content, with 2.7 wt% Ni in the sulfide fraction (Table 3.3.1).

Pd/Pt, Pd/Ir, and (Pt + Pd)/(Os + Ir + Ru) ratios of the deposit types are presented in Table 3.3.2. Most deposit types are characterized by a predominance of palladium over platinum, with only the Siika-Kämä Reef and the chromite and silicate-associated PGE enrichments of MCU II locally showing Pt/Pd ratios above unity. The Konttijärvi PGE-rich marginal series, the Ahmavaara massive sulfide deposit, and the Rytikangas and Siika-Kämä PGE Reefs have similar Pd/Ir and (Pt + Pd)/(Os + Ir + Ru) ratios.

Table 3.3.1 A: Average whole-rock Ni, Cu, S, PGE, and Au concentrations for selected type samples
B: Concentrations in the type samples, recalculated to 100% sulfide
C: Metal concentrations in a large number of samples, recalculated to 100% sulfide

		Ni(wt%)	Cu	S	Os-(ppb)	Ir	Ru	Rh	Pt	Pd	Au
Portimo dikes and sulfide disseminated marginal series											
Portimo dikes	A	0.025	0.093	0.183	3.0	0.5	-	2.0	510	2200	47
n = 1	B	5.0	18.5	36.5	598	99.7		399	101 700	438 700	9370
Konttijärvi	A	0.056	0.239	0.323	8.6	19.0	14.2	92	1 300	4 070	240
marginal series	B	6.1	25.9	35.0	930	2 060	1 540	9 970	140 800	440 900	26 000
n = 5	C	5.4	14.4	36.7							
Massive sulfide deposits of marginal series											
Ahmavaara	A	2.00	0.719	25.8	20	50	44	357	1 510	11 030	104
n = 3	B	3.0	1.1	39	30	76	67	540	2 280	16 700	160
	C	2.7	2.4	37					2 120	15 200	
Suhanko	A	0.919	0.807	20.7	30	64	64	222	207	1 230	7.3
n = 3	B	1.7	1.5	39.1	57	120	120	420	390	2 320	14
	C	1.5	2.4	37							
Vaaralampi	A	0.284	0.143	23.3	25	8.5	89	24		485	5.0
n = 2	B	0.48	0.24	39.5	42	14	151	41		820	8.5
	C	0.94	0.63	37							
Niittylampi,	A	1.67	0.305	32.7	23	79	36	550	136	835	19
n = 2	B	2.0	0.37	39.2	28	95	43	660	160	1 000	23
	C	2.2	1.6	37					870	2 190	
Yli-Portimojärvi	A	0.456	0.575	24.9		111		199	171	930	7.0
n = 2	B	0.72	0.91	39.4		180		310	270	1 470	11
Kilvenjärvi	A	2.92	0.6	20.1	15	27	60	207	625	3 800	85
n = 2	B	5.6	1.15	38.6	29	52	115	397	1 200	7 280	163
Layered series											
Rytikangas reef	A	0.063	0.249	0.291	28	32	24	171	1 630	7 240	207
n = 5	B	7.4	29.3	34.2	3 290	3 760	2 820	20 100	191 600	850 900	24 300
	C	6.4	38.7	33.0							
Siika-Kämä reef	A	0.080	0.360	0.454	32	65	47	330	2 850	9 980	337
n = 4	B	6.2	27.7	34.9	2 460	5 000	3 610	25 370	219 000	766 900	25 910
Mineralized upper	A	0.035	0.231	0.492	23	27	76	53	605	1270	40
Suhanko layered series	B	2.7	17.9	38.2	1 790	2 100	5 900	4 120	47 000	98 600	3 100
n = 2											

n = number of samples
Source: *Data from Iljina (1994) and references therein.*

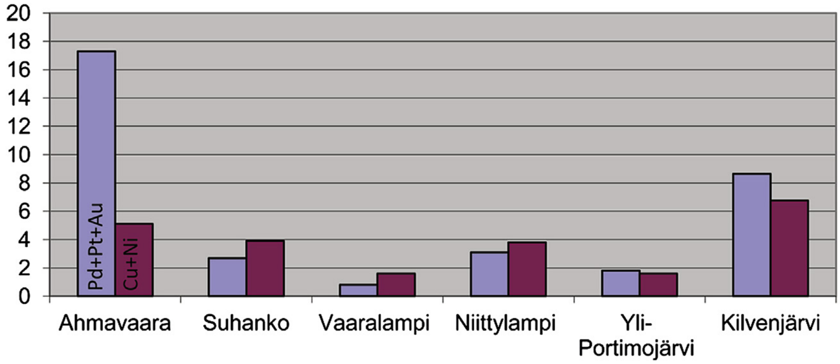

FIGURE 3.3.13 Nickel, copper, and precious metal concentrations recalculated in 100% in various massive sulfide deposits of the Portimo complex.

Base metals in wt% and precious metals in ppm.

The Portimo dikes have markedly higher Pd/Ir of ~3840 and (Pt + Pd)/(Os + Ir + Ru) of >267, respectively, whereas the PGE-poor massive sulfide deposits have lower Pd/Ir and (Pt + Pd)/(Os + Ir + Ru).

Chondrite-normalized metal patterns are presented in Fig. 3.3.14. The Konttijärvi and Ahmavaara disseminated, PGE-rich marginal series, the Ahmavaara and Kilvenjärvi massive sulfides, and the Rytikangas and Siika-Kämä Reefs have very similar metal patterns, all showing a steep positive slope and a negative Ru anomaly. In contrast, the PGE-poor massive pyrrhotite deposits have flatter metal patterns, with negative Pt anomalies instead of negative Ru anomalies (Fig. 3.3.14). The Kilvenjärvi offset deposit shows the most fractionated pattern with a strong relative depletion in Os, Ir, Ru, and Rh.

Mineralogy of base metal sulfides

The most common base metal sulfides are pyrrhotite, chalcopyrite, and pentlandite, occurring in variable proportions. The massive sulfide deposits at the base of the Suhanko and Narkaus intrusions are deficient in pentlandite and chalcopyrite, except in the Ahmavaara and Kilvenjärvi deposits. In the Rytikangas PGE Reef, Fe-deficient copper sulfides, (i.e., bornite and chalcocite), dominate over chalcopyrite and Fe(-Ni) sulfides. Among the nickel-bearing sulfides, millerite (NiS) is estimated to contain half of the sulfidic nickel in the Rytikangas Reef.

An indication of low-temperature sulfide mineralization is noted in the basement granitoids below the Konttijärvi marginal series, where pyrite grains were found to contain polymineralic chalcopyrite, pyrrhotite, and pentlandite inclusions. A peculiar sulfide aggregate composed almost in equal proportions of pentlandite, galena, sphalerite, and pyrite is also common in the mineralized basement below the Konttijärvi marginal series.

Even a lower crystallization temperature is indicated by the secondary sulfide assemblage of the offset mineralization, which is composed of chalcopyrite, polydymite ($NiNi_2S_4$), melnikovite-pyrite, and bravoite. Bravoite is an intermediate member (6.8–19.8 atomic % Ni) of the solid-solution series of vaesite (NiS_2) and pyrite (FeS_2). This atypical sulfide mineralogy of the Kilvenjärvi offset deposit occurs in deep drill holes, suggesting that surface alteration played no role in mineralization.

Table 3.3.2 Average Pd/Pt, Pd/Ir, and (Pt + Pd)/(Os + Ir + Ru) ratios in the mineralized zones (range in parenthesis)

	N	Pd/Pt	Pd/Ir	(Pt+Pd)/ (Os+Ir+Ru)
Offset, Portimo dikes, and Konttijärvi marginal series				
Offset	1	6.7	>12 900	>687
Portimo dikes	2	3.4	3 840	>267
		(2.6–4.3)	(3 270–4 400)	
Konttijärvi marginal series	5	3.0	212	141
		(1.4–4.0)	(138–429)	(67–300)
Massive sulfide deposits				
Ahmavaara	3	8.0	243	116
		(6.2–10.3)	(114–335)	(64–175)
Suhanko	3	6.6	20.6	10.5
		(4.5–9.3)	(15.2–24.3)	(6.6–14.2)
Vaaralampi	1	3.6	42.7	4.2
Niittylampi	2	7.6	10.7	7.1
		(4.3–10.9)	(9.7–11.7)	(6.8–7.3)
Yli-Portimojärvi	1	5.3	6.3	2.3
Kilvenjärvi	2	6.1	146	43.8
		(5.6–6.6)	(123–170)	(42.7–44.9)
Layered series				
Rytikangas reef	5	4.4	270	132
		(3.7–5.1)	(147–382)	(77–184)
Siika-Kämä reef	8	1.7	83.6	62.2
		(0.8–3.0)	(32.1–132)	(41.7–93.3)
Mineralized upper	2	2.1	46.6	14.9
Suhanko layered series		(2.0–2.2)	(44.5–48.6)	(14.4–15.4)
Chromitite layer, MCU I	1	3.8	17.1	5.6
Chromite and silicate-associated MCU II	3	0.9	49.8	43.1

N = number of samples
Source: *Data from Iljina (1994) and references therein.*

Platinum-group minerals

The platinum-group mineralogy is dominated by sperrylite ($PtAs_2$) and various Pd-Sb-As and Pd-Te-Bi phases, while PGE sulfides are rare and alloys are absent. The platinum-group sulfarsenides are represented by hollingworthite (RhAsS) and platarsite (PtAsS), which were also found to be the only carriers of osmium, iridium, ruthenium, and rhodium. Sn-bearing Pd minerals and pure Pd-Sn minerals have been identified in the Konttijärvi and Ahmavaara marginal series, while the high whole-rock Se/S ratio of the Portimo dikes is reflected also by the presence of PGE-Se mineral phases. Other rare PGM phases include a Pd-Ni-As mineral and Pd-Ag-Te phases found in the Rytikangas Reef.

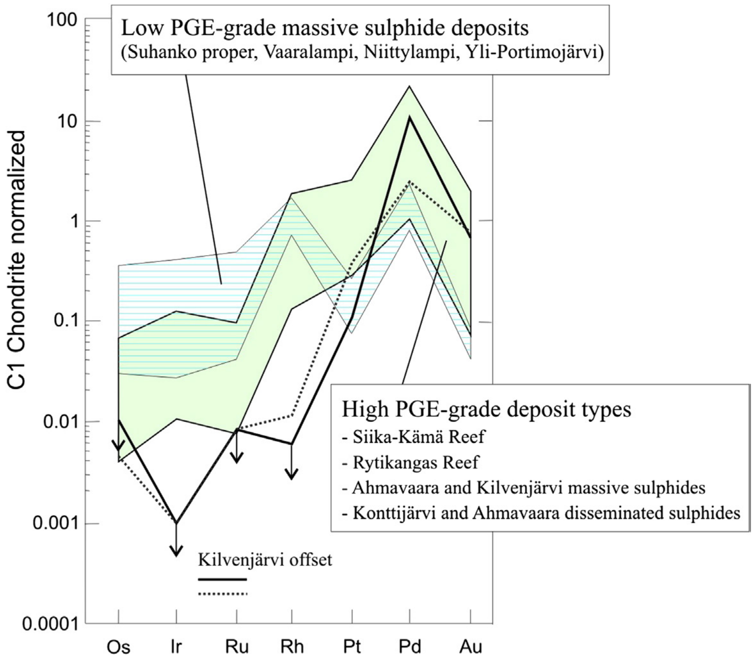

FIGURE 3.3.14 Chondrite-normalized PGE and Au patterns of the Kilvenjärvi offset mineralization, the Siika-Kämä and Rytikangas PGE Reefs, Konttijärvi and Ahmavaara high-grade disseminated and massive sulfide PGE deposits, and lower-grade massive sulfide PGE deposits of the Suhanko marginal series.

Sources: *Chondrite values are from Naldrett (1981). Modified after Iljina (1994).*

An atypical platinum-group mineralogy is observed locally in the Kilvenjärvi offset deposit. In view of the very high whole-rock PGE contents (up to several tens of ppm), large PGM grains are scarcer than expected. Instead, polydymite grains are found to host a large number of tiny (≤1 μm) Pd mineral grains containing the bulk of the Pd in the rock.

Mineral resources of contact-type deposits

Classified mineral resources of the Portimo contact type deposits are presented in Table 3.3.3. The total resources (Puritch et al., 2007) are ~263 million tons including measured, indicated, and inferred resources. These resources result in about 10 million ounces of platinum, palladium, and gold combined.

CONCLUDING REMARKS

- Of the Finnish layered intrusions, the Portimo complex is exceptional in hosting a variety of PGE mineralization types.
- The lower contact of the Suhanko intrusion is *transgressive* relative to the Archean basement; the southeastern tip of the intrusion is in contact with stratigraphically higher levels of the Archean basement complex than the remainder of the intrusion.
- In the contact-type deposits of the Portimo complex, the Cu, Ni, and precious metal concentrations in the whole-rock samples and the sulfide fraction are highest in the western portion of the complex (Konttijärvi and Ahmavaara areas).

Table 3.3.3 Classified mineral resources and metal grade information for contact-type PGE deposits

Intrusion/ complex	Tons (Mt)	Pd (ppm)	Pt (ppm)	Au (ppm)	Ni (wt%)	Cu (wt%)
Portimo Ahmavaara						
Measured	38.197	0.707	0.141	0.086	0.061	0.161
Indicated	114.816	0.851	0.175	0.104	0.071	0.181
Inferred	34.757	0.867	0.187	0.103	0.070	0.170
Total	**187.770**					
Konttijärvi						
Measured	26.031	1.064	0.307	0.081	0.059	0.100
Indicated	37.571	0.902	0.255	0.071	0.043	0.095
Inferred	11.638	0.867	0.241	0.062	0.027	0.097
Total	**75.240**					
Koillismaa Kaukua						
Indicated	10.4	0.73	0.26	0.08	0.1	0.15
Inferred	13.2	0.63	0.22	0.06	0.1	0.13
Total	**23.6**					
Haukiaho						
Inferred	23.2	0.31	0.12	0.10	0.14	0.21
Total	**23.2**					

Note: *Calculated using cutoff grades of 1.0 g/t* Pd_{Eq} *for Portimo deposits and 0.1 g/t Pd for Koillismaa deposits.*
Sources: *Portimo deposits from Puritch et al. (2007), and Koillismaa deposits from the Finore Mining Inc. press release of September 19, 2013.*

- The relative proportion of ultramafic cumulates within the Portimo complex is highest at Konttijärvi.
- Based on its cumulus stratigraphy and chemistry, the Ahmavaara section is interpreted to represent the stratigraphically lowest part of the Suhanko intrusion.
- Megacyclic units form two groups in terms of their chromium content, one being relatively rich and the other relatively depleted. The former is represented by MCU I and II of the Narkaus intrusion, as well as the Portimo dikes, and the latter is represented by MCU III and the Suhanko and Konttijärvi intrusive bodies.
- The Portimo dikes have so far only been identified below the Konttijärvi and Ahmavaara marginal series.
- Autoliths interpreted to represent the chilled margin of the intrusion become less Cr- and MgO-rich from the west (Ahmavaara) to the east (Niittylampi) within the Suhanko intrusion, representing stratigraphically progressively higher levels. This trend is reminiscent of the change from B1 to B3 type sills in the floor rocks of the lower to main zone of the Bushveld complex.

REEF-TYPE PGE MINERALIZATION IN THE PENIKAT INTRUSION

The Penikat intrusion is located approximately 30 km to the northeast of the town of Kemi and 30 km to the southwest of the Portimo complex. It is 23 km long and 1.5–3.5 km wide (Halkoaho, 1993; Iljina and Hanski, 2005). The magmatic body has an intrusive contact to K-rich granite in its footwall, but the uppermost rocks were eroded away before the deposition of the overlying sedimentary rocks.

The basal contact of the intrusion is sharp, defined by a chilled margin, which is relatively biotite-rich and thus believed to be contaminated. This model is consistent with the relatively evolved composition of the rocks. Two samples analyzed by Halkoaho (1993) gave 6.5–8 wt% MgO, 0.3–0.6 wt% TiO_2, 440–470 ppm Cr, 90–100 ppm Ni, and 12–14 ppb Pd. The chilled margin is overlain by approximately 10–20 m of marginal series rocks consisting of subophiticgabbro (18 wt% MgO; Halkoaho, 1993), as well as gabbronoritic and orthopyroxenitic cumulates, which may be injected by rheomorphic granite veins.

The layered series is close to 3000 m thick and can be subdivided into five megacyclic units (MCU I–V). MCU I is between 270 and 410 m thick and contains a thin basal chromitite overlain by chromite-bearing orthopyroxenite and then gabbronorite. MCU II is 160–230 m in thickness and shows more variability than MCU I. It consists of basal websterite, overlain by lherzolite with thin chromitite stringers; websterite containing interlayers of gabbronorite and lherzolite; and finally, two chromite-bearing gabbronorite layers separated by websterite. MCU III is 75–330 m thick and consists of basal chromite-bearing websterite that may host a lherzolite layer. This is overlain by gabbronorite adcumulates and, locally, by poikilitic gabbronorite associated with gabbronoritic pegmatoids and disseminations, schlieren, and layers of chromite. MCU IV is 760–1110 m thick and hosts the bulk of the PGE mineralization in the form of three reefs. The first one, named the Sompujärvi or SJ Reef, occurs near the base of the unit. The second reef is termed the Ala-Penikka or AP Reef and occurs in the center of the unit, whereas the third reef, termed the Pasivaara or PV Reef, is located at the top of the unit. The base of MCU IV is transgressive and shows a 10–20-m-thick ultramafic layer consisting of a thin basal chlorite schist that can be highly enriched in chromite. This is overlain by a 1-m-thick layer of orthopyroxenite, a thick olivine cumulate layer containing intercumulus ortho- and clinopyroxene, and finally, a further orthopyroxenite. Next follow gabbronoritic cumulates, in which clinopyroxene has a poikilitic intercumulus status, followed by gabbronorite where clinopyroxene has a cumulus habit. In places, pronounced rhythmic layering is seen, including horizons of orthopyroxenite, gabbronorite, and anorthosite. Some 200–300 m above the base of the MCU IV is the AP Reef, hosted by mottled anorthosite and gabbronorite. At the top of MCU IV is a 40–60 m thick, highly complex zone consisting of gabbronorite, anorthosite, pegmatoid, and what could represent a magmatic breccia of anorthosite and gabbronorite (Huhtelin et al., 1990). This zone hosts the PV Reef. MCU V has a highly variable thickness (0–900 m), likely due to erosion. At its base is an orthopyroxenite overlain by norite. Toward the top, there also occurs some gabbro and magnetite-bearing leucogabbro, anorthosite, and plagioclase-quartz-biotite rock resembling the granophyre in the roof of the Koillismaa intrusion (Iljina and Hanski, 2005).

The compositional variation through the intrusions is summarized in Fig. 3.3.15. As a whole, the intrusion is relatively mafic, with ultramafic rocks making up <10% of the stratigraphy. This is a major difference compared to the Kemi intrusion, located immediately to the southwest, together with a relatively lower proportion of chromite, but much higher PGE grades at Penikat. The Penikat megacyclic units are well delineated by a progressive decrease in Cr/V from the base to the top. The

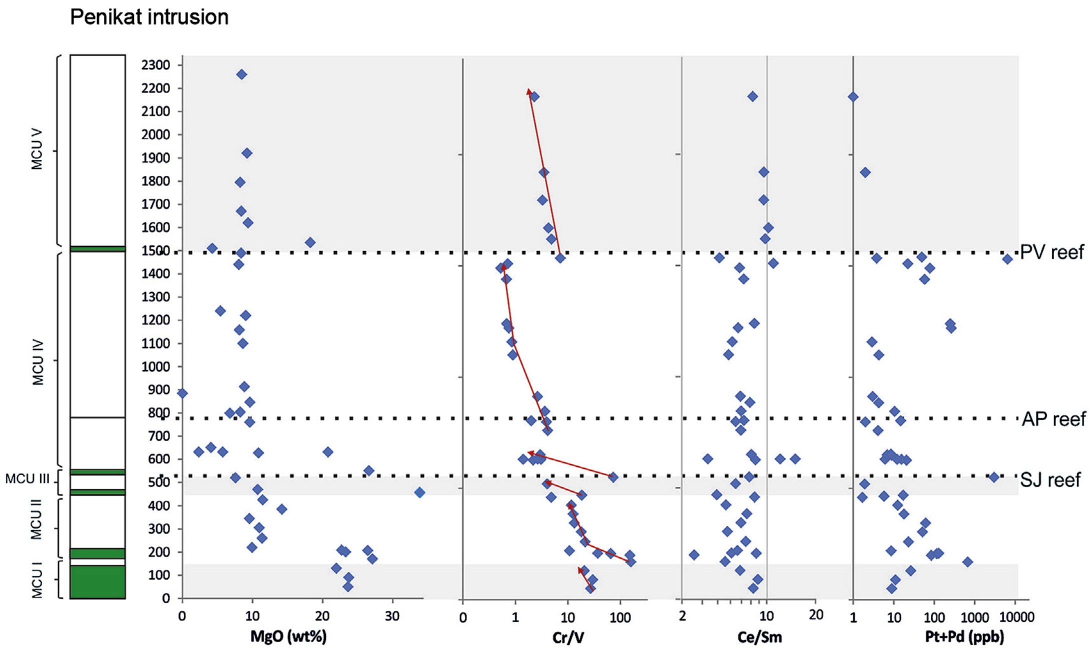

FIGURE 3.3.15 Litho- and chemostratigraphy of the Penikat intrusion.

Source: *Based on Halkoaho, 1993, and unpublished data of W.D. Maier.*

PGE-enriched zones of the SJ and PV Reefs are located at compositional and lithological reversals, represented by high Cr/V and the reappearance of orthopyroxene in the liquidus, analogously to many other PGE mineralized layered intrusions. However, in contrast to the Bushveld complex, for example, incompatible trace element ratios give no strong evidence for mixing between compositionally distinct magma pulses at Penikat, except for an increase in Ce/Sm above the SJ Reef, and a minor increase in Ce/Sm at the level of the PV Reef. Thus, if there was significant magma replenishment in the Penikat intrusion, the involved magma had a broadly similar chemical character in terms of elements discussed above. The compositional and lithological variation across the reefs is described in detail in Halkoaho (1993) and Halkoaho et al. (1990a,b).

PGE REEFS

The PGE in the SJ Reef are mostly concentrated in the basal portion of MCU IV, but can locally occur in the overlying peridotite or the underlying gabbronorite (see Halkoaho, 1990a). The PGE can be associated with sulfide enrichments of up to ~1 wt% (base metal-type) or with S-poor silicate rocks and chromitites, to the effect that the mineralization is invisible to the naked eye. The SJ Reef has been correlated with the Siika-Kämä Reef of the Portimo complex (see earlier and Iljina and Hanski, 2005). It locally contains grades of up to >100 ppm PGE over several dm. However, the average grade is much lower, and the thickness is usually ~1 m. In general, all three Penikat reefs show much more variation in thickness and lateral consistency than the Bushveld reefs.

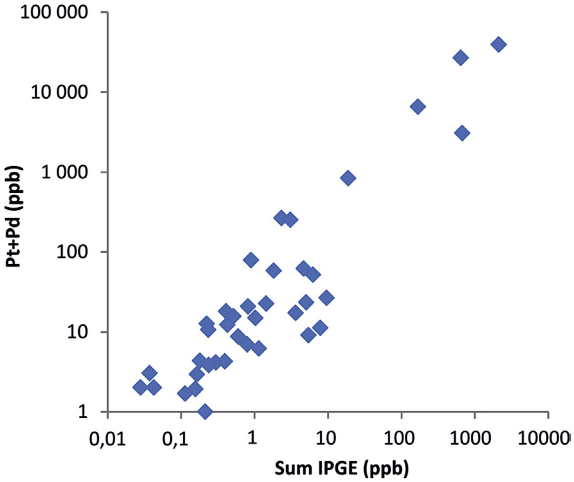

FIGURE 3.3.16 Pt + Pd vs. total IPGE + Rh diagram for SJ, AP, and PV Reefs.

The Ala-Penikka (AP) PGE Reefs (Halkoaho et al., 1990b) are located 250–450 m above the base of MCU IV. They are developed along most of the strike length of the intrusion and have been correlated with the Rytikangas Reef of the Portimo intrusion (Iljina and Hanski, 2005). The API Reef is normally 20–40 cm thick and contains erratic PGE mineralization hosted by gabbronorite and anorthosite. In the so-called depression structures (which are likely equivalents to the Bushveld potholes), the reef can be up to 20 m thick. Laterally less continuous APII Reef, some tens of meters above API, strongly resembles the API Reef in terms of host rock types, but contains less base metal sulfides. PGE grades in API may locally reach several tens of ppm, but are mostly much lower. The sulfide fraction shows the following element ratios: Cu/Ni 1.4–2.7, Pd/Pt 3.7, and Pd/Ir 170–240. Primitive mantle-normalized metal patterns of the AP reefs are more fractionated than those of the SJ Reef.

The Pasivaara (PV) Reef (Huhtelin et al., 1990) is located ~700–1000 m above the AP Reefs. Like the other reefs, it is broadly continuous along the entire strike of the intrusion, with the exception of the Keski-Penikka block where it has been eroded away. The PGE mineralization is erratically distributed within the reef. The best grades are usually found within the anorthosite near the top of MCU IV, or up to 30 m below the peak mineralization. The average thickness of the reef is 1 m with element ratios Cu/Ni 1, Pt/Pd 2 (the highest in the Penikat intrusion), and Pd/Ir 28. The primitive mantle-normalized metal patterns resemble those of the SJ base metal-type mineralization and the Merensky Reef, and are less fractionated than those of the AP Reefs.

There is generally a good correlation between PPGE and IPGE contents in the Penikat intrusion (Fig. 3.3.16), suggesting that the original PGE concentration mechanism was magmatic, possibly followed by some mobility of S.

PLATINUM-GROUP MINERALS

The platinum-group mineralogy of the SJ Reef is characterized by Pt-As, Pd-Sb-As, Pd-Te-Bi, and Rh-As-S phases resembling the mineralogy of various Portimo PGE enrichments. In chromite-bearing samples, platinum and palladium sulfides are relatively abundant. Alloys are exclusively found in chromite-bearing samples of the SJ Reef (Halkoaho et al., 1990b). The mineralogy of the AP and PV Reefs resembles that of the SJ Reef (Huhtelin et al., 1990).

PARENTAL MAGMA

The parental magma composition may be represented by the Loljunmaa dike, to the east of the Penikat intrusion (Alapieti et al., 1990). The dike has 11.2 wt% MgO, 0.86 wt% TiO_2, 990 ppm Cr, 350 ppm Ni, and 420 ppm S, showing a composition that is broadly similar to that of the Bushveld B1 type magma (Table 3.3.4). However, it is less enriched in incompatible trace elements and has half the PGE contents of Bushveld B1 (9 ppb Pt and 6 Pd vs. 20 ppb Pt and 13 ppb Pd; Barnes et al., 2010). Notably, the Loljunmaa dike has Ce/Sm identical to the ratio in Penikat cumulates, which is consistent with it being parental to the intrusion. The average composition of 2.45 Ga siliceous high-magnesium basalt dikes in northern Finland (Guo and Maier, 2013) is 11.21 wt% MgO, 0.62 wt% TiO_2, 960 ppm Cr, 297 ppm Ni, 6.8 ppb Pd, 6.9 ppb Pt, and Ce/Sm 8, showing an overlap with the Loljunmaa dike composition.

CONCLUDING REMARKS

The Penikat intrusion contains several PGE-enriched zones or reefs, analogously to many other PGE mineralized layered intrusions. However, the Penikat reefs are of a lower lateral persistence than, for example, those in the Bushveld complex or the Stillwater complex. It is possible that this reflects a faster cooling rate of the relatively small Penikat intrusion. A notable difference between the Bushveld and Portimo complexes is the absence of a mineralized marginal zone at Penikat. In the Bushveld and Portimo complexes, it has been proposed that the best contact-type deposits are developed where the internal reefs abut against the floor (Iljina, 1994; Iljina and Lee, 2005; Maier et al., 2013). Such structural sections are absent at the present erosional level of the Penikat intrusion.

CONTACT-TYPE CU-NI-PGE MINERALIZATION OF THE KOILLISMAA INTRUSION

The Koillismaa intrusion of the Koillismaa-Näränkävaara complex hosts two principal types of orthomagmatic metallic mineralization: Cu-Ni-PGE-bearing sulfide occurrences and a vanadium deposit hosted by magnetite gabbro (Karinen et al., 2015).

The marginal series of the Koillismaa intrusion is mineralized with Cu, Ni, and PGE along its entire strike length of approximately 100 km. Here we focus on two sections that have been investigated in detail (i.e., Kaukua and Haukiaho). On average, the chalcophile element contents of the Koillismaa marginal series are low, reaching 0.2–0.4 wt% Cu and 0.2–0.3 wt% Ni in 1-m-long drill core samples, but may occasionally exceed 1.0 wt% in both elements. The principal sulfide minerals are pyrrhotite, chalcopyrite, pentlandite, and, in places, pyrite. Variations in precious metal content broadly correlate with those of the base metal sulfides and in many samples, the grade is on the order of 0.5–1.0 ppm of combined Pt + Pd + Au. Tellurides, bismuthides, and antimonides dominate the Pd mineralogy, while sperrylite is the dominant Pt mineral (Alapieti, 1982; Kojonen and Iljina, 2001; Iljina and Hanski, 2005; Karinen 2010).

Table 3.3.4 Chemical compositions for the evaluation of the parental magmas

wt%	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	54.0	51.4	52.0	53.5	53.4	53.4	50.7	52.7	52.2	51.3	56.1	51.7
TiO_2	0.16	0.40	0.68	0.21	0.24	0.30	0.22	0.33	0.15	0.12	0.34	0.19
Al_2O_3	3.2	8.0	12.3	13.4	12.2	9.8	14.2	16.9	16.1	17.1	11.5	16.8
FeO_{tot}	7.9	12.0	10.2	9.7	9.9	10.5	7.1	7.3	7.4	5.9	9.5	7.1
MnO	0.2	0.3	0.18	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.2
MgO	23.3	13.8	13.0	12.6	13.7	15.1	14.7	9.0	9.8	10.6	13.0	7.9
CaO	9.9	11.0	9.26	8.0	8.0	9.2	11.6	10.7	10.9	12.2	6.7	11.8
Na_2O	0.11	0.62	1.74	2.14	2.05	1.29	1.22	2.38	2.84	2.26	1.68	2.31
K_2O	0.01	0.45	0.71	0.10	0.19	0.11	0.22	0.57	0.42	0.18	0.80	0.24
P_2O_5	0.03	0.07	0.10	0.01	0.01	0.02	0.02	0.04	0.01	0.01	0.07	0.02
ppm												
V	50	230		127	126	157			150	150	167	130
Cr	1800	2300	1180	1137	951	1000	3330	280	290	380	1240	550
Ni	610	250	362	375	440	318	270	280	160	190	295	130
Zn	85	160		83	81	79			60	58	78	56
Sc	23	37		28	29	30			33	35		31
Sr	10	20	200	382	308	157	150	210	340	500	160	330
Y	4.8	7.0		4.1	4.9	6.2			2.5	1.0	13	11
Zr	20	40	70	10	10	15	25	47	30	1.0	77	26
Nb	1.9	2.0		<0.2	0.34	0.22			2.7	1.9	3.6	
Ba	53	47	210	68	108	63	75	180	110	52		
La		10.9		1.83	3.81	2.51			2.50	1.10	14.8	3.80
Ce		25.0		3.37	7.44	5.83			7.00	2.00	29.5	8.30
Nd		12.0		1.76	3.95	4.04			4.00	1.00	12.1	
Sm		2.50		0.26	0.53	0.77			0.75	0.37	2.70	0.86
Eu		0.61		0.37	0.52	0.38			0.32	0.26	0.72	0.52

Continued

Table 3.3.4 Chemical compositions for the evaluation of the parental magmas—cont'd

wt%	1	2	3	4	5	6	7	8	9	10	11	12
Tb		0.30		<0.1	0.13	0.19			0.20	<0.10	0.30	
Yb		1.08		0.58	0.55	0.48			0.59	0.30	1.16	0.64
Lu		0.16		0.10	0.1	<0.10			0.09	0.04	0.15	0.07
U	0.80	1.20		<0.2	<0.2	<0.2			<0.10	<0.10		

Cr-richer group
1. Westerite Portimo dike, Konttijärvi. Iljina (1994).
2. Westerite Portimo dike, Ahmavaara. Iljina (1994).
3. Loljunmaa dike. (Alapieti et al., 1990). Iljina (2005).
4. Ahmavaara autolith, YP-517/109.9 m. Iljina (2005).
5. Ahmavaara autolith, YP-517/115.5 m. Iljina (2005).
6. Ahmavaara autolith, YP-517/126.4 m. Iljina (2005).
7. Weighted average of Narkaus MCU I. Alapieti et al. (1990).
Cr-poorer group
8. Weighted average of the Suhanko intrusion (MCU III), Alapieti et al., (1990).
9. Niittylampi autolith. Iljina (1994).
10. Niittylampi autolith. Iljina (1994).
Bushveld
11. Bushveld B1 Sill. Sharpe and Hulbert (1985).
12. Fine-grained marginal rock adjacent to the Main Zone/Bushveld complex. Hatton and Sharpe (1989).

HAUKIAHO AND KAUKUA DEPOSITS

Figure 3.3.17 depicts a typical cross section from Haukiaho. The sulfide-bearing gabbroic zone, about 30 m in thickness, is heterogeneous and contains albite-quartz veins and basement inclusions. The dip of the magmatic layering in the deposit is 55–85° to the north. Sulfides comprise 1–5 vol% of the rock and occur mostly as a blebby dissemination in the interstices of silicate grains. The lowermost part of the marginal series includes a light-colored albite and quartz-rich rock, which grades into granitoidal rock of the basement complex. The albite and quartz-rich rock is considered to represent metasomatically altered portions of the basement complex.

The mineralized Kaukua marginal series, which dips ~35° to the south, represents the thickest part of the Koillismaa marginal series (Fig. 3.3.18), but it is possible that layer-parallel shearing has duplicated the mineralization. In addition to the contact-type mineralization, a low-grade reef-type mineralization is found just above the marginal series. Locally these two mineralization types merge together. Relatively feldspathic cumulates are found near the basal contact of the intrusion, whereas the upper part of the marginal series is composed exclusively of ultramafic cumulates.

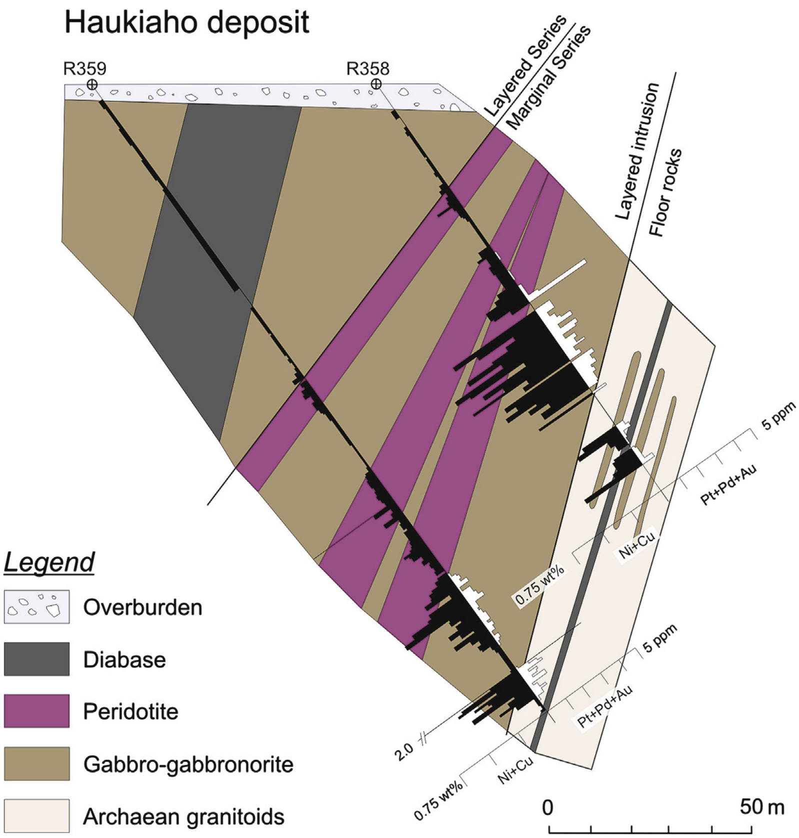

FIGURE 3.3.17 Cross section of the Haukiaho deposit along drill hole profile R358-R359, as seen from the west.

Source: *Modified from Iljina and Hanski (2005).*

In general, the Kaukua marginal series is more heterogeneous than that at Haukiaho. The sequence includes multiple thin layers of more magnesian cumulates and zones of gabbroic rocks containing mafic autoliths and minor amounts of felsic xenoliths derived from the basement. It is therefore difficult to map coherent units of mafic and ultramafic cumulates in the Kaukua deposit, and only the stratigraphically highest layer of peridotite is marked in Fig. 3.3.18. In contrast to Haukiaho, the marginal series in the Kaukua area is mineralized throughout, comprising 1–5 vol% of finely disseminated sulfides. The bottom part of the Kaukua section contains the so-called mixed zone, which is composed of basement rocks with thin mafic cumulate intercalations or xenoliths. The abundance of the mafic layers or fragments decreases downward until the rock consists entirely of basement granitoid.

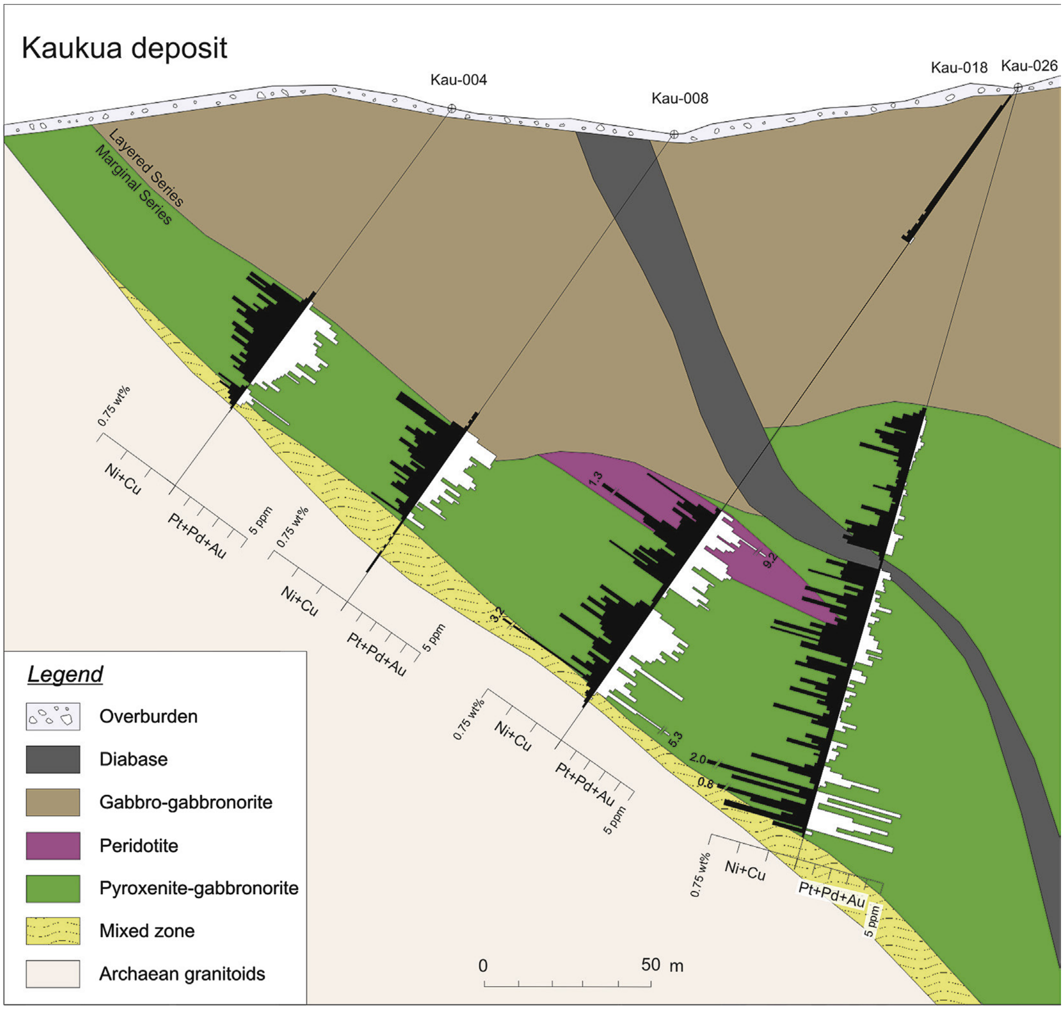

FIGURE 3.3.18 Cross section of the Kaukua deposit along Section 3553700E, as seen from the west.

Figure provided by Finore Mining Inc.

The current mineral resources for Kaukua are 23.6 Mt (refer to Table 3.3.4) of ore containing 1.07 ppm and 0.91 ppm Pd + Pt + Au in indicated and inferred categories, respectively. For the Haukiaho deposit, the inferred mineral resources are 23.2 Mt ore grading 0.53 ppm of combined Pt + Pd + Au, 0.21 wt% Cu, and 0.14 wt% Ni.

Both the Kaukua and Haukiaho deposits show similar Cu/Ni (~2.0) and Pd/Pt (~2.8), but it is noteworthy that Kaukua has higher values of PGE + Au whereas Haukiaho is relatively more enriched in base metals (Figs. 3.3.19A and B and Table 3.3.3). Based on sulfide-specific assays, the sulfide fraction from Kaukua contains 4–6 wt% Ni, 7–17 wt% Cu, and 80–100 ppm combined Au + Pd + Pt. At Haukiaho, the sulfide fraction contains 4–8 wt% Ni, 12–35 wt% Cu, and 40 ppm combined Au + Pd + Pt (Iljina et al., 2012). Both deposits display similar chondrite-normalized chalcophile element patterns (Fig. 3.3.19C). This indicates a similar parental magma, and thus the higher PGE + Au grades at Kaukua may be related to a higher R factor, reflecting more dynamic magma emplacement conditions as also evidenced by repeated ultramafic and mafic layers and higher abundance of rock fragments.

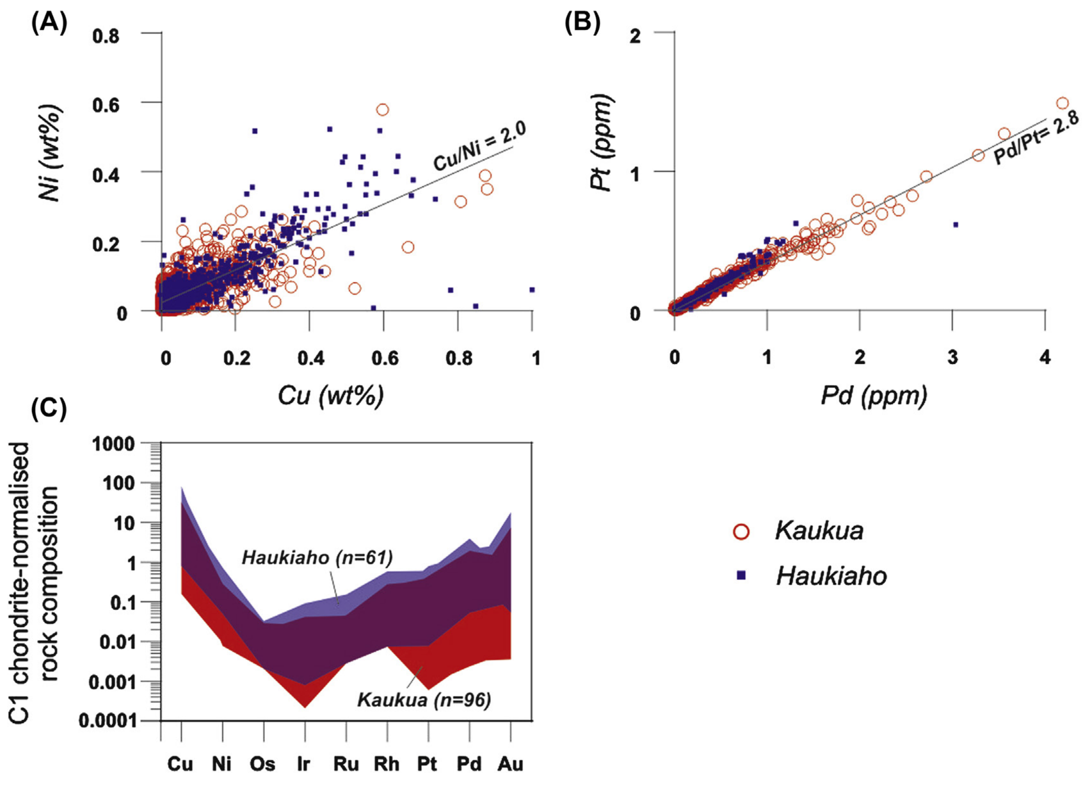

FIGURE 3.3.19 Chalcophile element abundances in rocks from the Kaukua and Haukiaho deposits.

(A) Ni versus Cu plot, with samples analyzed by ICP-AES after aqua regia leaching; thus compositions contain sulfidic and some silicate nickel. (B) Pt versus Pd plot with metals measured by ICP-AES after fire-assays preconcentration. (C) Chondrite-normalized metal patterns for rocks from the two deposits (samples analyzed by ICP-MS).

Sources: *Chondrite values are from Barnes and Maier (1999). Data provide by Finore Mining Inc., 2013.*

COMPOSITIONAL DIFFERENCES BETWEEN CYCLIC UNITS AND IMPLICATIONS FOR EXPLORATION

During the PGE exploration in the Portimo and Penikat intrusions during the 1980s, it was recognized that the cumulates of various megacyclic units formed two contrasting groups in terms of their Cr contents (Table 3.3.4). The lower portions of the intrusions were found to be composed of relatively Cr-enriched cyclic units, whereas the upper portions are composed of relatively Cr-depleted units. This was attributed to differences in the parental magma composition of the cyclic units (Lahtinen et al., 1989; Alapieti et al., 1990; Saini-Eidukat et al., 1997).

The stratigraphically lowermost significant PGE reef (the SJ Reef in the Penikat intrusion and the SK Reef in the Portimo intrusion) was found to be located in the transition zone between the uppermost Cr-enriched and the lowermost Cr-depleted cyclic unit (Fig. 3.3.20). Similarly, the Konttijärvi and Ahmavaara PGE-enriched marginal series are located in the same transitional interval, as indicated by the observation that the immediately underlying Portimo dikes belong to the relatively Cr-enriched group. The Rytikangas (RK) and Ala-Penikka (AP) Reefs are found stratigraphically above the transition level. This model, as first published by Lahtinen et al. (1989), was developed in a collaborative research project between the Oulu University and the exploration department of Outokumpu Oy and was successfully applied to PGE exploration in the 1980s when PGE enrichments in the Portimo and Penikat areas were discovered.

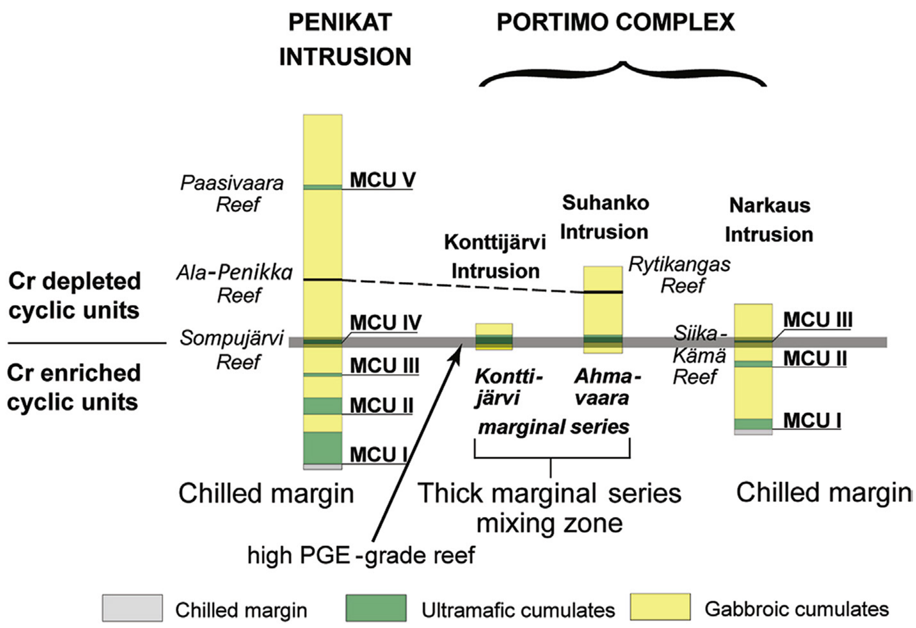

FIGURE 3.3.20 Stratigraphical correlation of the Portimo and Penikat complexes.

For discussion, see text.

Source: *Modified after Lahtinen et al. (1989).*

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