CHAPTER

THE KEVITSA NI-CU-PGE DEPOSIT IN THE CENTRAL LAPLAND GREENSTONE BELT IN FINLAND

3.6

F. Santaguida, K. Luolavirta, M. Lappalainen, J. Ylinen, T. Voipio, S. Jones

ABSTRACT

The Kevitsa Mine is a Ni-Cu-PGE magmatic-type deposit hosted within a composite ultramafic intrusion within the Lapland Greenstone Belt. Discovered in 1987 by GTK, mine production began in 2012 with an expected life of over 20 years. Mineralization is predominantly disseminated pyrrhotite, pentlandite, and chalcopyrite with an irregular shape that roughly conforms to magmatic layering within the deposit area. The host rock is an olivine-pyroxenite containing both clinopyroxene and orthopyroxene. Amphibole and serpentine-chlorite alteration is prevalent throughout the intrusion and obscures primary relationships, but overall does not impact the distribution of metals at the deposit-scale. The disseminated style, high metal tenor, and Cu endowment over Ni is unique compared other magmatic deposits globally.

Keywords: magmatic; nickel; copper; Kevitsa; Lapland; olivine pyroxenite; disseminated.

INTRODUCTION

The Kevitsa mine is Europe's most recent nickel mine. Production commenced in 2012, with annual output in the range of 17,000–19,000 t of copper, 9000–10,000 t of nickel, 12,000–13,000 oz of gold, and 22,000–24,000 oz each of platinum and palladium. Plans for expansion will accelerate mining, but the approximate life of the mine will be more than 20 years.

Compared to most other magmatic Ni-Cu-PGE deposits globally, the Kevitsa deposit is unique. The sulfide mineralization is mostly disseminated, the ore is enriched in Cu relative to Ni, and the tenor is consistently high. While previous work (Hanski et al., 1997; Mutanen, 1997; Gervilla and Kojonen, 2002) laid the foundation to the present petrogenetic model for Kevitsa, this chapter presents a description of the deposit and its host rocks based on drill core analysis, lithogeochemical interpretation, and several geophysical surveys conducted over the last decade. Understanding of ore formation and intrusion architecture has advanced most recently from pit mapping and modeling grade control data during mining. Further insight is expected from two Ph.D. dissertations, by K. Luolavirta at Oulu University in Finland and M. LeVaillant at the University of Western Australia, that are in progress at the time of writing this chapter.

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REGIONAL GEOLOGY

The Kevitsa deposit is located within the Central Lapland Greenstone Belt (CLGB), a Paleoproterozoic volcano-sedimentary sequence. Ultramafic intrusive and volcanic rocks are widespread and occur at several stratigraphic levels within the CLGB (Hanski et al., 2001; Hanski and Huhma, 2005). The ultramafic intrusion hosting the Kevitsa deposit is a composite olivine pyroxenite to gabbro complex dated at 2058 ± 4 Ma (Mutanen and Huhma, 2001). At the surface, the intrusion has an arcuate shape (Fig. 3.6.1). Drilling has established a thickness of more than 1.5 km, with an increasingly complex geometry at depth that in part reflects regional deformation effects as well as the original magmatic emplacement relationships.

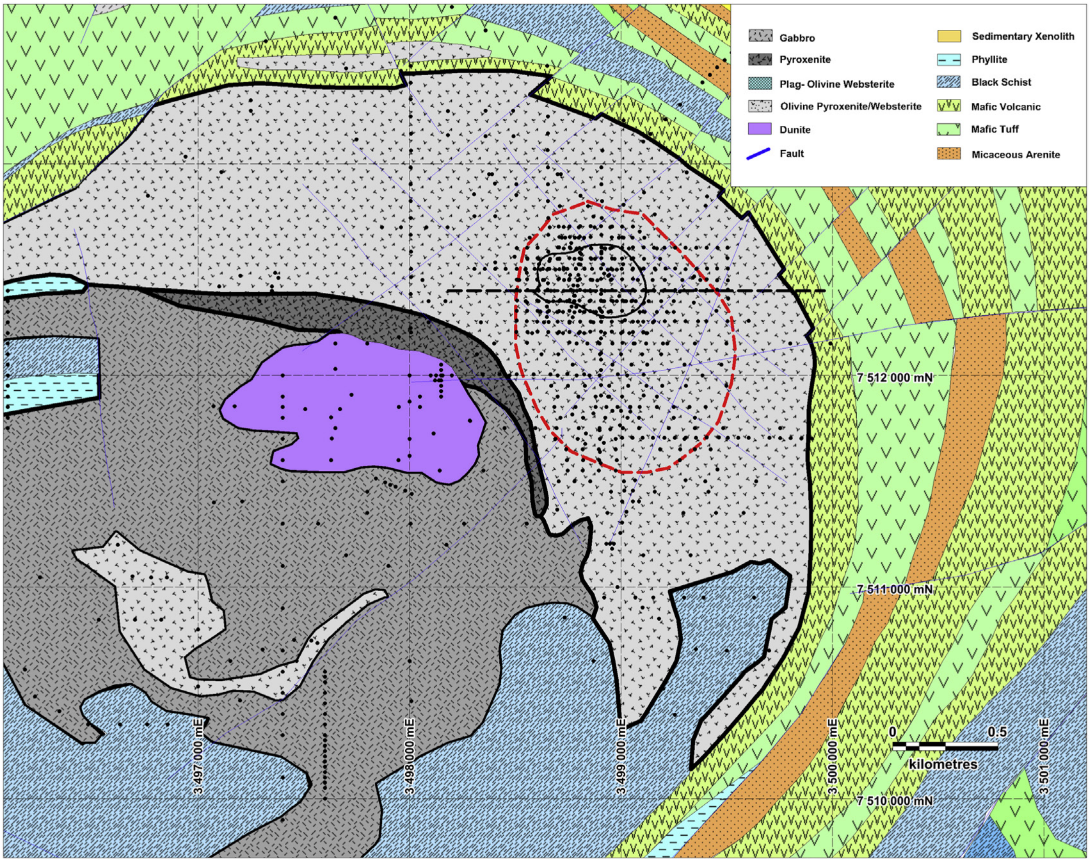

FIGURE 3.6.1 Bedrock geology of the Kevitsa intrusion and surrounding area.

This is based on surface mapping, diamond drill holes, and geophysical interpretation. The outline of the final open pit is indicated by the red line and roughly shows the location and extent of Ni-Cu mineralization. Diamond drill holes are shown by the black dots. Coordinate numbers are Finnish KKJ projection (Zone 3). The black dashed line shows the location of the east–west section shown in Fig. 3.6.7.

EXPLORATION AND DEVELOPMENT HISTORY

The Kevitsa Ni-Cu-PGE deposit was discovered in 1987 by the Geological Survey of Finland (Table 3.6.1) by drilling a glacial till geochemical anomaly following previous findings of disseminated pyrrhotite in outcropping peridotite. Early metallurgical tests returned uneconomic recoveries of Ni and Cu. Several subsequent iterations of mineral resource modeling did not improve the economic outlook of Kevitsa. Prior to the mine development decision in 2009, First Quantum Minerals Ltd. (FQML) initiated a comprehensive drilling campaign to confirm previous results and to increase the confidence level of the previous resource model, which was calculated in September 2008. In late 2009, FQML released its first NI 43-101 compliant report regarding the Kevitsa Ni-Cu-PGE project. On the basis of the 2009 mineral resources, an updated mineral reserve for Kevitsa was disclosed. The new reserve, together with improved metal prices, plus other technical factors, encouraged a board decision to start development of the Kevitsa Ni-Cu-PGE project.

Between October 2009 and August 2010, FQML completed a second major resource definition drilling campaign following a successful near-mine exploration program. The exploration program resulted in a new geological and structural model that led to drilling of geophysical and conceptual targets. The second definition drilling campaign focused on the previously unknown southern extensions of the Kevitsa deposit as well as upgrading the inferred resources from 2009 modeling to measured and indicated classes. In March 2011, FQML published its second NI 43-101 compliant technical report showing a significant increase in the mineral resource and reserves compared to the 2009 calculations (Lappalainen and White, 2010). As a positive consequence, FQML is actively looking for possibilities to expand the planned annual production. The current measured and indicated mineral resource for the Kevitsa Ni-Cu-PGE deposit is 240 Mt at 0.30% Ni, 0.41% Cu, 0.21 gpt Pt, 0.15 gpt Pd, and 0.11 gpt Au. Additionally, an inferred resource of 34.7 Mt with comparable grade is calculated.

Table 3.6.1 Summary of the exploration history of the Kevitsa Ni-Cu-PGE deposit

Years	Owner	Description
1960s	GTK	Mapping of outcrops and river boulders
1970s	Outokumpu Ltd.	Reconnaissance regional exploration
1984	GTK	Initial diamond drilling; discovery of “false ores”
1984–1987	GTK	Basal till geochemistry and ground geophysical surveys (magnetic, gravity, electromagnetic)
1987	GTK	Diamond drilling and discovery of Ni-Cu mineralization
1990	GTK	Diamond drilling (exploration)
1992–1993	GTK	Resource definition drilling and trenching program, resource modeling
1994	GTK	Airborne geophysical survey
1997	GTK	Publication of Mutanen Ph.D. thesis
1996–1998	Outokumpu Ltd.	Till geochemistry, diamond drilling, and metallurgical test work
2000–2008	Scandinavian Minerals	Acquisition; resource and exploration diamond drilling
2008	First Quantum Minerals Ltd.	Acquisition
2008–present	First Quantum Minerals Ltd. (Kevitsa Mining Oy)	Resource and exploration diamond drilling; 3D seismic and magnetotelluric geophysical surveys

MINE GEOLOGY

MINERALIZATION

Due to the disseminated style of the sulfide mineralization, the ore body has an irregular shape. For reserve and resource estimation, several distinct ore domains were defined to coincide with general lithological layering in the deposit area (Fig. 3.6.2). Mineralization is concentrated in the center of the intrusion and not along the basal contact, unlike many other Ni-Cu magmatic ore bodies.

Pentlandite and chalcopyrite are the dominant ore minerals occurring together with pyrrhotite and magnetite (Fig. 3.6.3). Magmatic textures are commonly preserved, with sulfides and magnetite occurring between cumulate olivine and pyroxene grains. In places, the sulfide mineralization is net-textured, but such zones cannot be defined beyond one or two diamond drill holes. In the net-textured zones, pyrrhotite is relatively abundant, thus tenor tends to be relatively low. Mutanen (1997) identified four ore types based largely on Ni tenor: *regular ore*, *transitional ore*, *Ni-PGE ore*, and *false ore*. Subsequent drilling and ore resource modeling demonstrated that transitional ore was not truly a distinct type, but represents a lower grade of Ni-PGE ore (Lappalainen and White, 2010).

In the ore reserves and resources, regular ore has an Ni tenor of 4–7% and combined PGE contents of less than 1 g/t. The regular ore constitutes approximately 95% of the resource, although mining has exposed small pods of Ni-PGE ore not known from the resource drilling.

Ni-PGE ore is distinguished by high Ni tenor of greater than 10 and the presence of millerite and heazlewoodite as additional Ni mineral phases. Pyrite is also present and appears contemporaneous with millerite. The host rocks to the Ni-PGE ore are similar to regular ore, but generally contain more clinopyroxene than orthopyroxene. The Ni content within olivine is unusually high, up to 14,000 ppm (Hanski et al., 1997; Määttä, 2012; Yang et al., 2013). The Ni-PGE ore zones are discordant to the regular ore (see Fig. 3.6.3); thus, they are generally considered to have formed separately, but their origin remains debated (Mutanen, 1997; Hanski et al., 1997; Yang et al., 2013).

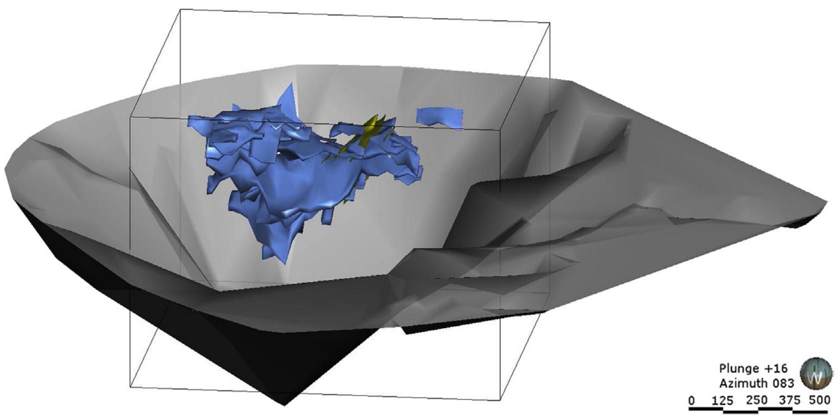

FIGURE 3.6.2 3D model of the Ni-Cu-Pt-Pd ore domains at Kevitsa.

Regular ore type is in blue and Ni-PGE ore type is in yellow. The basal intrusive contact with the country rocks is shown in gray. The view is looking eastward from above. Ore domains in the southern portion of the deposit appear to abruptly terminate, but this is due to a lack of drilling in this area.

Source: *Ore domain solids as published in the NI43-101 report (2011).*

The variability between Ni, Cu, Co, Pt, Pd, and Au within the regular ore is relatively low, with copper contents generally twice as high as Ni (Fig. 3.6.4). Cobalt typically correlates well with Ni and is hosted within pentlandite and pyrrhotite, rather than as a discrete sulfide mineral phase. Elevated Pt-Pd-Au occurs with both Cu-rich and Ni-rich mineralization, but the highest grades occur in Ni-PGE ore. In general, Pt:Pd ratios throughout the deposit are quite consistent at around 4:3, but approach 1:1 in Ni-rich domains and specifically within the Ni-PGE ore. High Au values, greater than 0.2 g/t, occur locally and coincide with Cu-rich ores.

Aside from the different types of ore, Ni-Cu variability can be high at the local scale (20 m × 20 m), but general zoning is also apparent at the deposit-scale (Fig. 3.6.5). Both Ni-rich and Cu-rich types of mineralization occur as discrete zones. Nickel-rich mineralization is particularly prominent at depth and in the southern portion of the ore body. Copper-rich zones typically occur in the central part of the ore body.

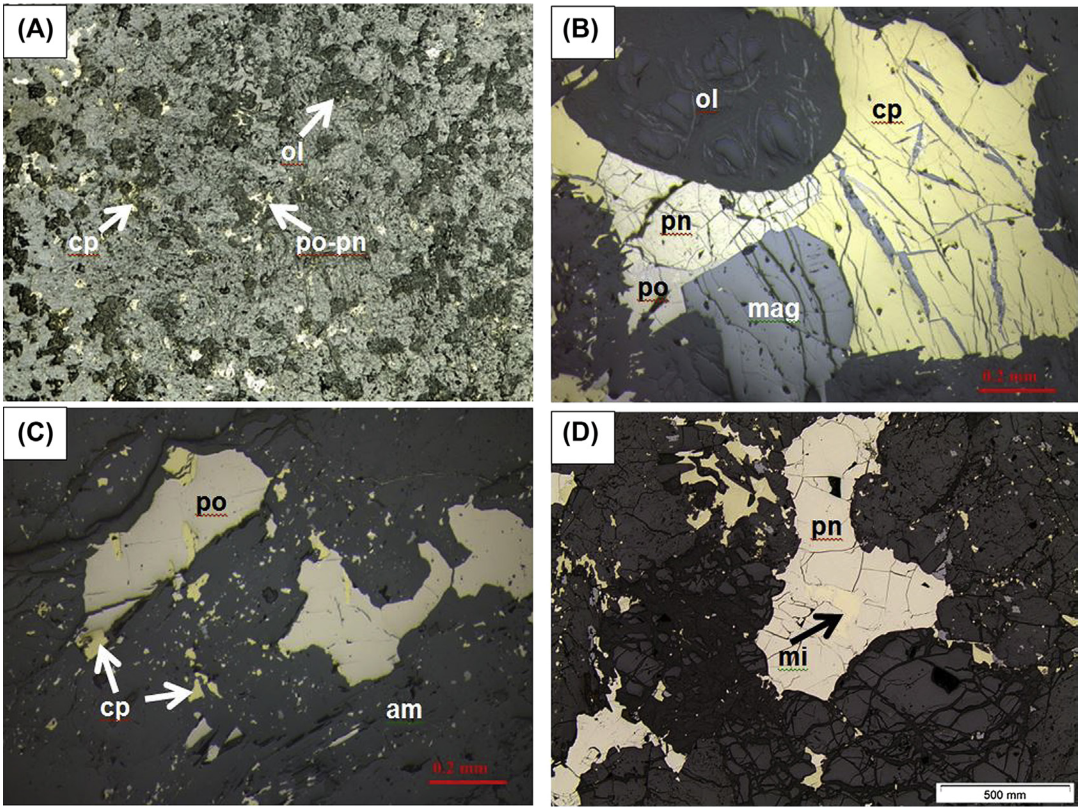

FIGURE 3.6.3 Typical textures of Kevitsa Ni-Cu-PGE mineralization.

(A) Polished hand specimen of disseminated mineralization (width of photo is 3 cm). (B) Interstitial texture of ore minerals in relatively fresh olivine pyroxenite. (C) Ore minerals in intensely amphibole-altered rock. Fine sulfide grains are hosted within tremolite. (D) Millerite within core of pentlandite grain in Ni-PGE ore. Abbreviations: po = pyrrhotite, cp = chalcopyrite, pn = pentlandite, mag = magnetite, mi = millerite, ol = olivine, am = amphibole.

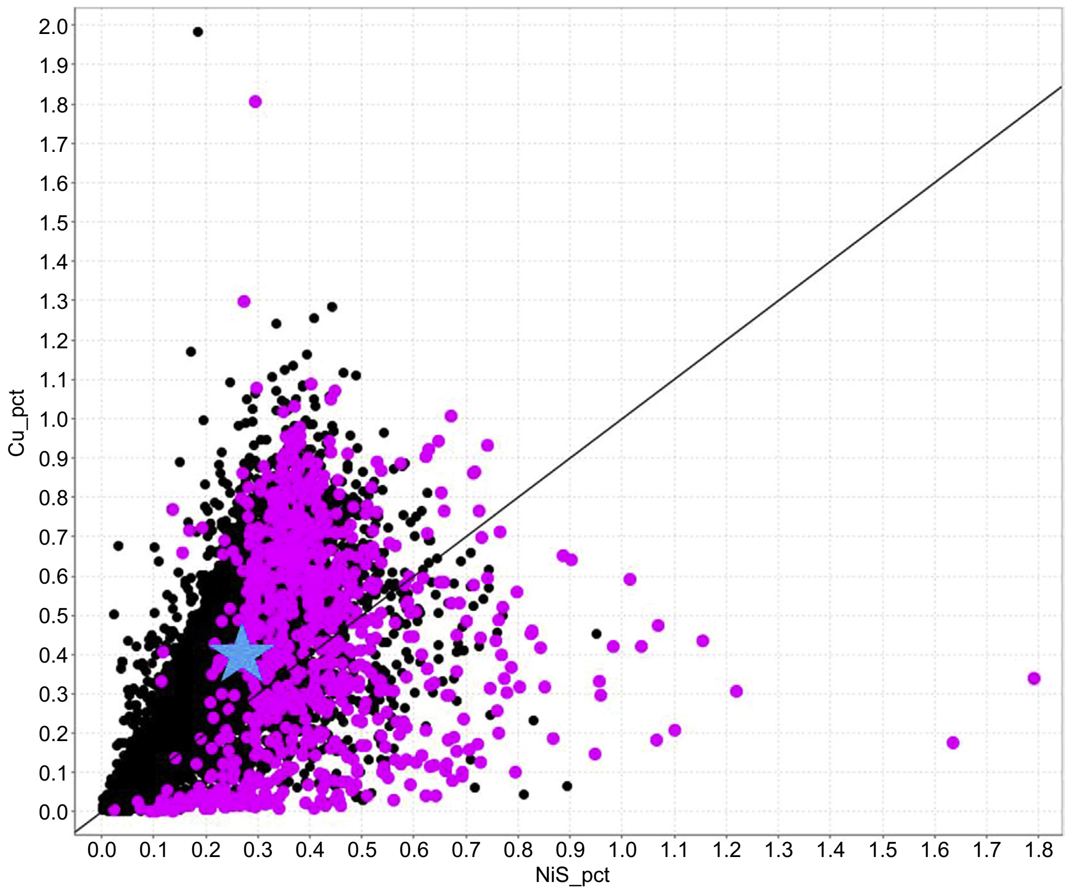

FIGURE 3.6.4 Grade distribution of metals shown by assay data contained in the resource model.

For this, more than 15,400 metals were analyzed. The blue star indicates the mean for this dataset. The 1:1 line cuts Cu-rich from Ni-rich ore. Nickel represents Ni in sulfide from ammonium citrate digestion that does not dissolve silicate minerals (see Lappalainen and White, 2010, for a description of the method and data quality assurance and control). Samples with Pt + Pd + Au > 600 ppm are highlighted by cyan color representing "high grade."

Small pods of Ni-Cu-PGE disseminated mineralization also occur outside of the Kevitsa deposit, but within the intrusion. These have not yet been fully defined or well understood, but their existence suggests that there is potential for economic mineralization beyond the presently identified deposit.

As in the case of many other magmatic Ni-Cu-PGE deposits, the number of platinum-group minerals (PGM) is extensive. They range in size from 100 to a few microns (Gervilla and Kojonen, 2002). The dominant minerals are Pt-Pd bismuth tellurides and sperrylite ($PtAs_2$). Braggite (Pt-PdS) is also common, but typically small in size and not as volumetrically significant. The proportions of the PGMs and their grain size vary at the meter scale within single drill holes, but mineral zoning is

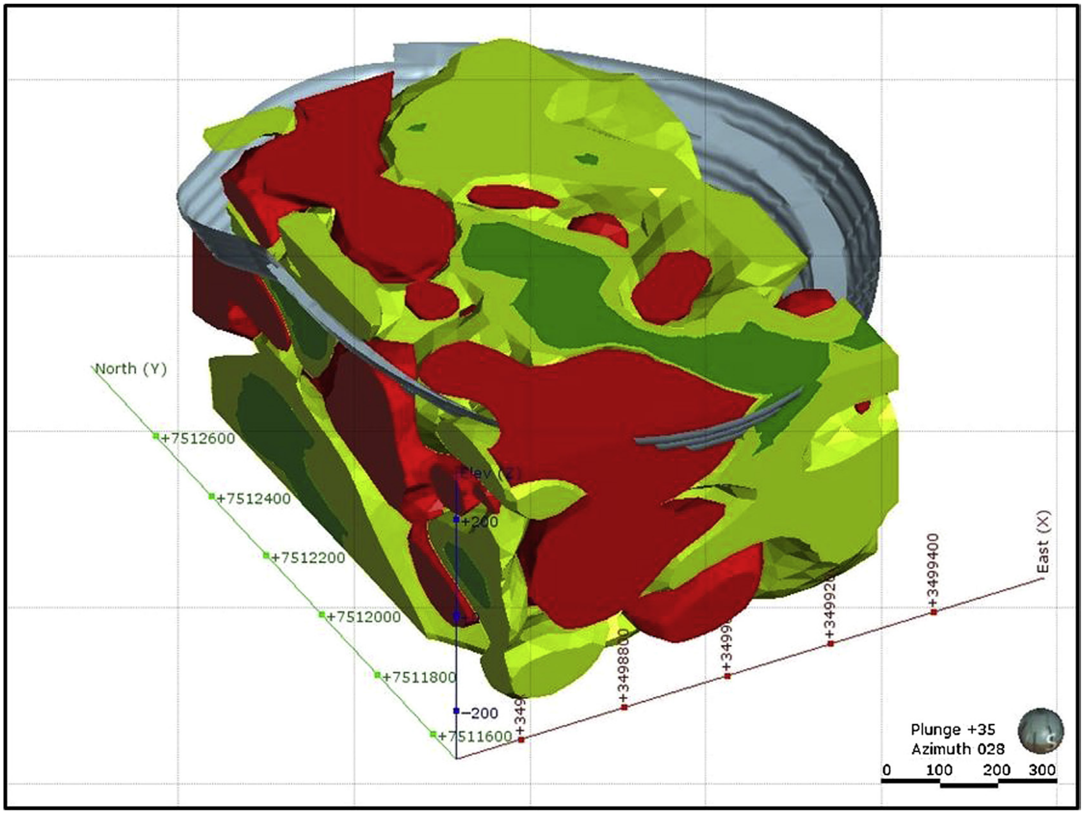

FIGURE 3.6.5 Ni and Cu variability in the deposit area.

View toward northwest. Modeling is done using the diamond drill hole assay database. Ni:Cu ratios represented by solid colors: red is >1.5; light green is 1.5–0.5 and dark green is <0.5. Gaps in the model indicate waste. Large, broad solids at depth and in the western part of the deposit are considered interpretive (inferred) due to the wide drill hole spacing lying outside of the resource area. The planned final open pit is shown in gray. The elongated Ni-rich and Cu-rich zones in the central part of the deposit reflect, in part, sulfides concentrated within veins.

not apparent at the deposit scale. The size distribution of the PGM is currently not well constrained. Silver and Au tellurides are both present, and rare native gold also occurs.

False ore consists entirely of pyrrhotite, with only rare chalcopyrite and pentlandite; it is defined by relatively low Ni tenor of 2–3%. False ore is easily recognized as it forms good electromagnetic conductors due to the high interconnection of the disseminated sulfides, thus it is well mapped by geophysical methods. South of the deposit, but still within the Kevitsa intrusion, a horizon of false ore contains net textured sulfides with >10 pyrrhotite over a width of several tens of meters and >200 m strike length. To the west of the deposit area, intersections of Ni-poor semimassive sulfides have been drilled at depth (>1000 m), immediately above the base of the intrusion. These are called *contact ore*. Despite the low tenor, both pentlandite and chalcopyrite are present.

Sulfides also occur within veins crosscutting the ore body. These have previously been considered unimportant, but mining has exposed several quartz-carbonate veins with a width of more than 1 m that have massive sulfide selvages enriched in Cu and locally Ni. The Ni-Cu-PGE content in the veins does not greatly impact the resource at Kevitsa, but the presence of vein sulfides does indicate that metal mobilization has occurred.

ROCK TYPES AND STRATIGRAPHY

The Kevitsa intrusion consists of an ultramafic lower part (approximately 1 km thick) overlain by gabbroic rocks. A large lherzolite body occurs in the central part of the intrusion (see Fig. 3.6.1), but is not spatially associated with the ore deposit. Compositional variations within the lower ultramafic portion are minor, but discrete lithological units can nevertheless be mapped. Layering is locally developed, particularly within the deposit, but in general, the contacts between rock types are diffuse. Alteration of pyroxene and olivine is intense in places, making primary rock types difficult to recognize and further complicating stratigraphic correlation. Images of the main rock types are shown in Fig. 3.6.6. The distribution and stratigraphic sequence of the rock types described here are shown in Fig. 3.6.7.

Olivine websterite is the dominant rock type and host rock for the sulfide mineralization, defined locally as containing more than 5% orthopyroxene. Olivine occurs as discrete grains or clusters a few millimeters in size. The rock has a poikilitic (heteradcumulate) texture, with orthopyroxene-forming oikocrysts. Typical accessory minerals include plagioclase, magnetite, sulfides, and apatite. Hornblende and phlogopite also occur locally.

Olivine pyroxenite resembles the olivine websterite in terms of texture, but is devoid of orthopyroxene (<5%). Because pyroxene is susceptible to overprinting by amphibole, it is difficult to distinguish these two rock types; however, the olivine clinopyroxenites can be clearly identified in thin section and, in general, are more prevalent outside of the ore body.

Plagioclase-bearing (olivine) websterite occurs as discontinuous zones within the olivine websterite/clinopyroxenite. The plagioclase-bearing (ol) websterites show orthocumulate textures and contain visible plagioclase (>10%) as an intercumulus phase. Orthopyroxene oikocrysts are also more abundant (15–25%) than in typical olivine websterite. Olivine is absent or rare (<15%). Contacts with the olivine websterite/clinopyroxenite are mainly diffuse, but can be locally quite sharp. In places, the plagioclase-bearing (olivine) websterite forms marker horizons characterized by magmatic layering, but in most cases, the layers are discontinuous and cannot be traced beyond a few hundred meters (see Fig. 3.6.7). Overall, these rocks are weakly mineralized and not found outside of the mineralized area.

Pyroxenite, with <5% olivine, forms the uppermost ultramafic cumulate unit below the gabbroic rocks, outside the mineralized area. The transition between olivine websterite and pyroxenite is highly gradational.

The marginal rocks of the intrusion are composed of pyroxenite (± minor olivine) and gabbro. Mutanen (1997) considered these rocks to be "microgabbros." The contact between olivine websterite and the marginal rocks is gradational. In places, distinct layering or banding between pyroxene-rich and plagioclase-rich rocks is seen, but most commonly the marginal rocks are varitextured. The marginal rocks vary in thickness from a few meters to more than 50 m. In places, the marginal rocks are absent and faulting is inferred. Where the marginal rocks are sulfide mineralized, they form so-called contact ore, dominated by pyrrhotite, and thus are uneconomic. Fragments of country rock are

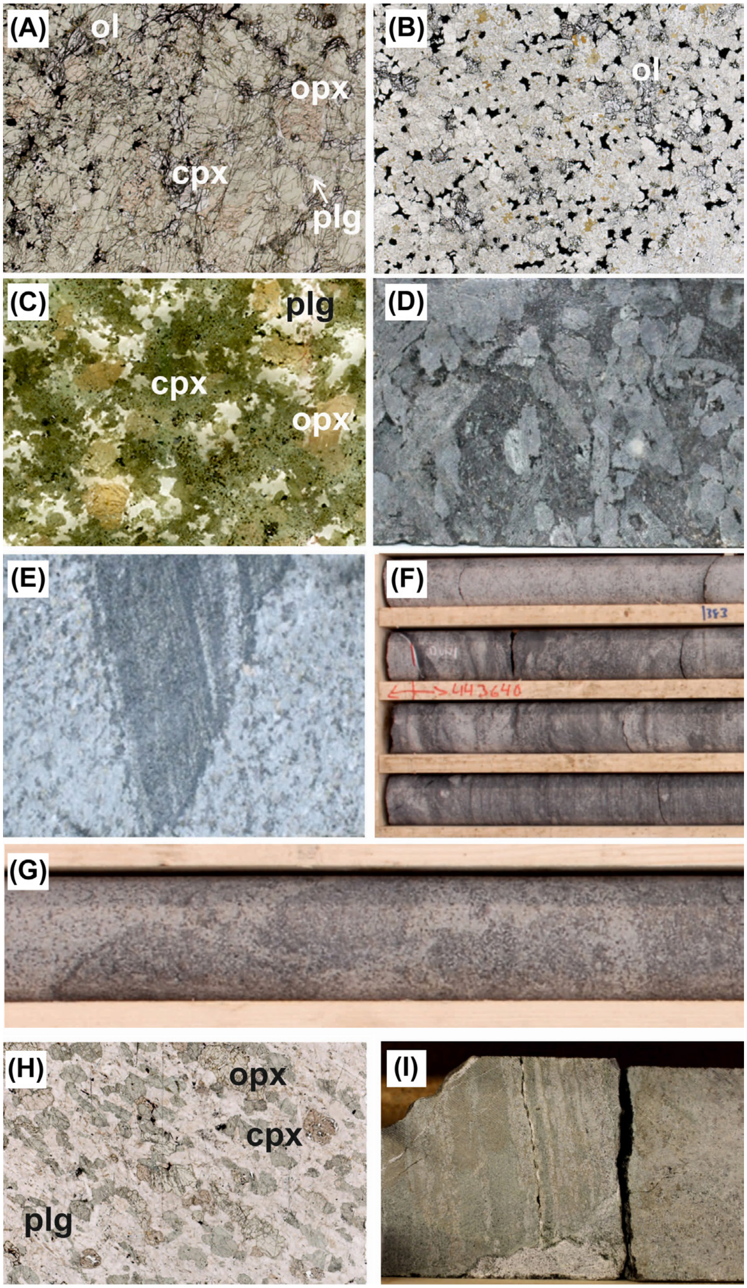

FIGURE 3.6.6 Kevitsa rock types.

(A) Unaltered olivine websterite. Orthopyroxene (opx) stands out as brownish oikocrysts. Plagioclase (pla) is interstitial to olivine (ol) and clinopyroxene (cpx). Opaque minerals are magnetite and sulfides. Scanned thin section image, width of the photo ~1.5 cm. (B) Ore-bearing (opaque intercumulus sulfides + magnetite) olivine clinopyroxenite, with clinopyroxene altered to amphibole; olivine (ol) is preserved. Scanned thin section image, width of the photo ~1.5 cm. (C) Plagioclase-bearing, olivine websterite. Clinopyroxene replaced by amphibole and magnetite. Scanned thick section image, width of the photo ~1.5 cm. (D) Varitextured pyroxenite of the marginal zone, weakly altered by amphibole, width of photo is 5 cm. (E) Lherzolite-occurring as an angular fragment in olivine websterite (F) Mixed olivine websterite (light coloured) and lherzolite (dark coloured). (G) Magmatic breccia of lherzolite fragments in olivine websterite (autolith?). (H) Gabbro containing intercumulus orthopyroxene (op) and plagioclase (pla). Clinopyroxene (cpx) occur as phenocrysts. (width of photo is 2 cm). (I) Banded metasedimentary xenolith (width of photo is 5 cm).

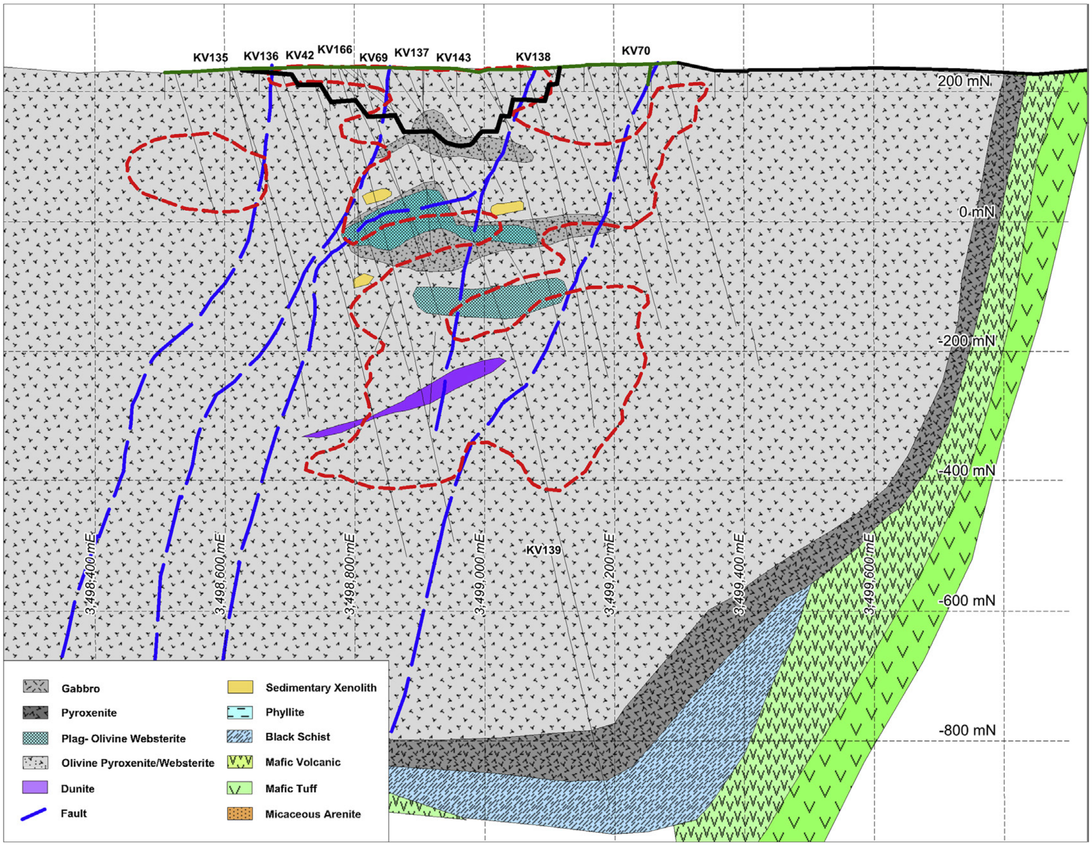

FIGURE 3.6.7 East–west section through the Kevitsa intrusion defined by drilling and geophysical data interpretation.

Deep diamond drill holes are labeled (KV series). The thick black line indicates the Stage 1 pit outline. The shape of the Ni-Cu-PGE mineralization is shown by the red dashed line and in part reflects the lateral variation of pyroxene-rich to olivine-rich layering within the immediate host rocks. This layering is not continuous outside of the mineralized zone.

also common within the marginal sequence. The immediate country rocks to the intrusion consist of mafic volcanic flows and epiclastic rocks, as well as micaceous phyllites and carbonaceous schists. In many places, the contact is sharp and intact, although faulting is prevalent at the southern margin of the intrusion.

The intrusion contains a number of distinct olivine-rich bodies and lenses that contain >50% olivine. They are of lherzolitic to wehrlitic composition, but have been collectively termed *dunite* in Kevitsa mine terminology. The rocks are intensely serpentinized, particularly near the surface. A large lherzolite body occurs in the central portion of the intrusion, but shows no spatial relationship with the mineralization (refer to Fig. 3.6.1). Lherzolite has also been intersected by drilling below the deposit; whether this lherzolite is related to the previously mentioned lherzolite body is currently unknown. Lherzolite clasts occur throughout the mineralized zone, but their origin remains contentious (Mutanen, 1997; Yang et al., 2013). The clasts are highly variable in size, ranging from centimeters to traceable zones roughly tens of meters in thickness (see Fig. 3.6.7). Cumulate texture of olivine is locally preserved, although most clasts are foliated along serpentinized planes. The clasts may occur as discrete, rounded fragments, or, in places, lherzolite is intermingled with olivine websterite. Pyrrhotite is common within lherzolite, whereas pentlandite and chalcopyrite only occur locally. In general, the lherzolite clasts host the same sulfide assemblage as their surrounding olivine websterite/pyroxenite.

Gabbroic rocks occur on top of the ultramafic cumulates. They are particularly prominent in the southwestern portion of the intrusion (see Fig. 3.6.1). Plagioclase is the dominant mineral along with clinopyroxene and accessory olivine. Modally, the rocks are gabbros, olivine gabbros, and gabbronorites. Apatite, magnetite, and ilmenite are common accessory phases. Magnetite-rich hornblende gabbro is prominent along the southern portion of the intrusion. Drilling has shown that the gabbroic rocks form a relatively thin unit (<500 m) overlying the thick ultramafic portion of the intrusion. Copper-Au mineralization occurs at two prospects along the gabbroic margins of the intrusion, but overall, sulfide minerals are rare and consist mostly of pyrite.

Xenoliths of hornfelsed pelitic sediments and mafic volcanics are common throughout the intrusion, but are particularly concentrated within the deposit area where they are spatially associated with lherzolite clasts. Xenoliths are concentrated in discrete zones that measure several meters in thickness and extend for several hundreds of meters in a north–south direction. Most xenoliths are pervasively altered to phlogopite.

Numerous dikes crosscut the intrusion and the mineralization. Most are olivine gabbroic in composition. The coarse-grained dikes rarely contain sulfide minerals, although veins containing pyrrhotite-chalcopyrite ± pentlandite may form locally along the margins. Fine-grained gabbroic dikes cut the mineralized ultramafic rocks and often contain pyrrhotite-chalcopyrite ± pentlandite. These are altered to a chlorite-actinolite-magnetite assemblage. Felsic dikes consisting of feldspar, quartz, and minor amounts of mafic minerals also occur. Dikes are rarely traceable beyond a single drill hole, thus their orientations are not established.

Granophyre occurring along the southern margin of the intrusion has been described by Mutanen (1997). Despite extensive drilling, these rocks have not been encountered in the present exploration and mining operation. Instead, several tens of meters of albitized gabbroic rocks and dikes have been intersected in some drill holes along the southern margin of the intrusion. These rocks do not host mineralization, thus they have not been intensely studied nor are they shown on the most current geological maps (see Fig. 3.6.1).

Lithogeochemistry has been useful for discriminating between rock types in the Kevitsa intrusion (Fig. 3.6.8). Multielement ICP analyses have been done on selected drill holes to improve correlation within the lithological units. Specifically, Al/Cr ratios have been found to be reliable proxies to the presence of plagioclase even where alteration is prominent, allowing plagioclase-bearing (ol) websterites to be more confidently recognized. Olivine-rich rocks have an inherently low Al/Cr ratio compared to pyroxenite. Notably, high Cr typically reflects the presence of clinopyroxene, although Cr may locally be hosted by magnetite. High Al/Cr is characteristic of fine-grained gabbroic dikes, and these are easily recognized during logging. Magnesium correlates well with Cr and is low within the plagioclase-bearing rocks, corresponding to reduced olivine content rather than alteration.

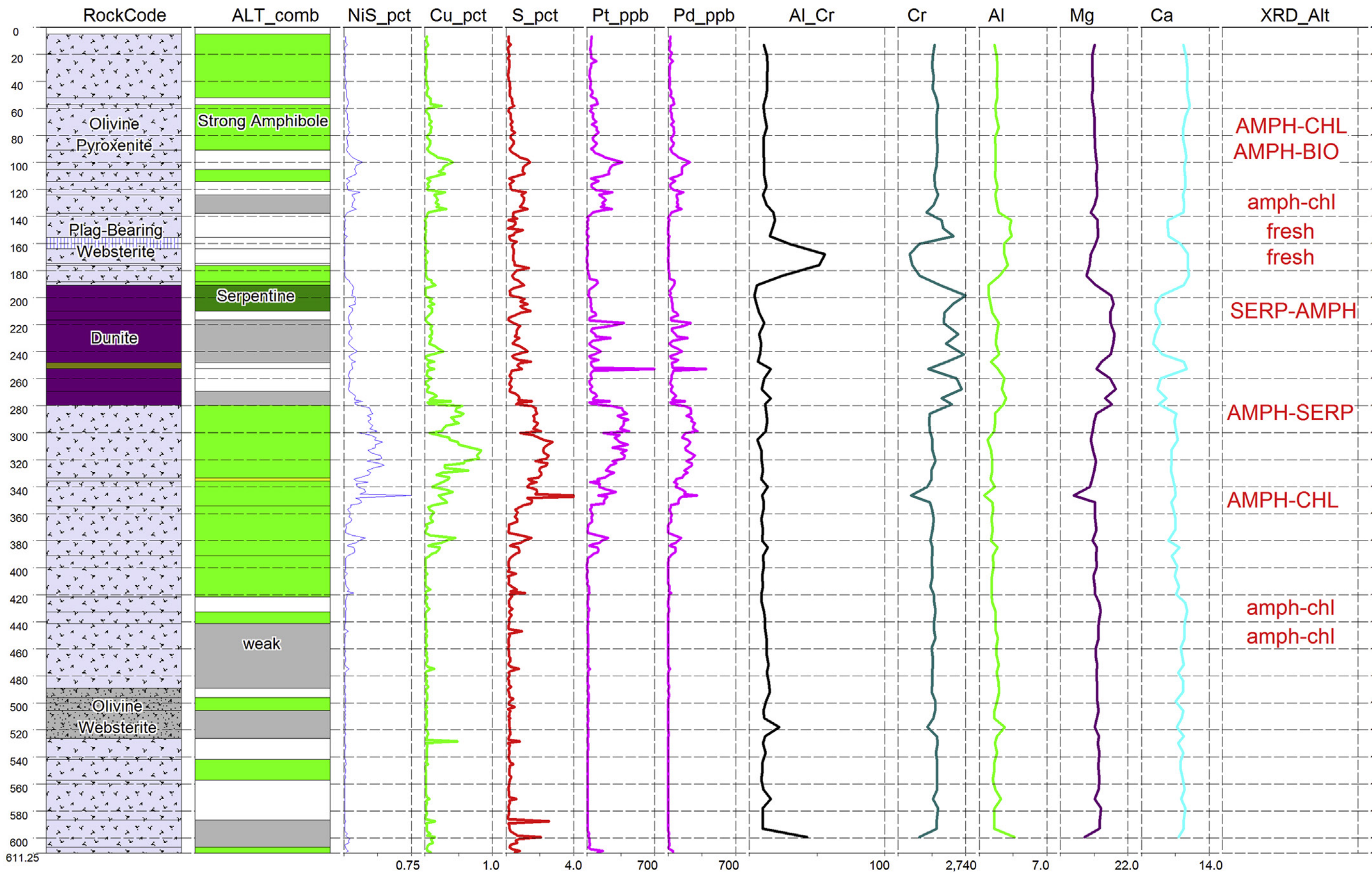

FIGURE 3.6.8 Representative diamond drill hole (KV157) through the Kevitsa deposit showing relationships of lithology, alteration mineral assemblages, and lithogeochemical data.

The rock code legend is the same as in Fig. 3.6.1. Alteration column abbreviations: AMPH = amphibole-chlorite-serpentine assemblage, CARB = carbonate mineral assemblage. XRD_Alt column abbreviations: AMPH = amphibole, SERP = serpentine, CHL = chlorite, BIO = biotite/phlogopite. Capital letters denote abundances >30%. Lowercase letters denote abundances >15%. Rock is considered unaltered where alteration minerals <15%.

HYDROTHERMAL ALTERATION

Hydrothermal alteration is notable throughout the Kevitsa deposit and its host intrusion (Fig. 3.6.9). Many of the rocks hosting mineralization have been overprinted by amphibole. Clinopyroxene is most susceptible to replacement, but, in places, olivine and orthopyroxene have also been completely altered to amphibole, chlorite, and serpentine. The distribution of the alteration is difficult to assess, but the most intense zones appear to be directly associated with relatively late mafic dikes and veins. A systematic study of the amphibole minerals has not been done, but microprobe analyses have typically returned tremolite-actinolite compositions. In general, the amphibole overprint does not affect Ni-Cu-PGE grades, but individual platinum-group minerals have been found enclosed in tremolite, and textures of sulfides reflect remobilization at a microscale. X-ray diffraction analyses have been done in places to

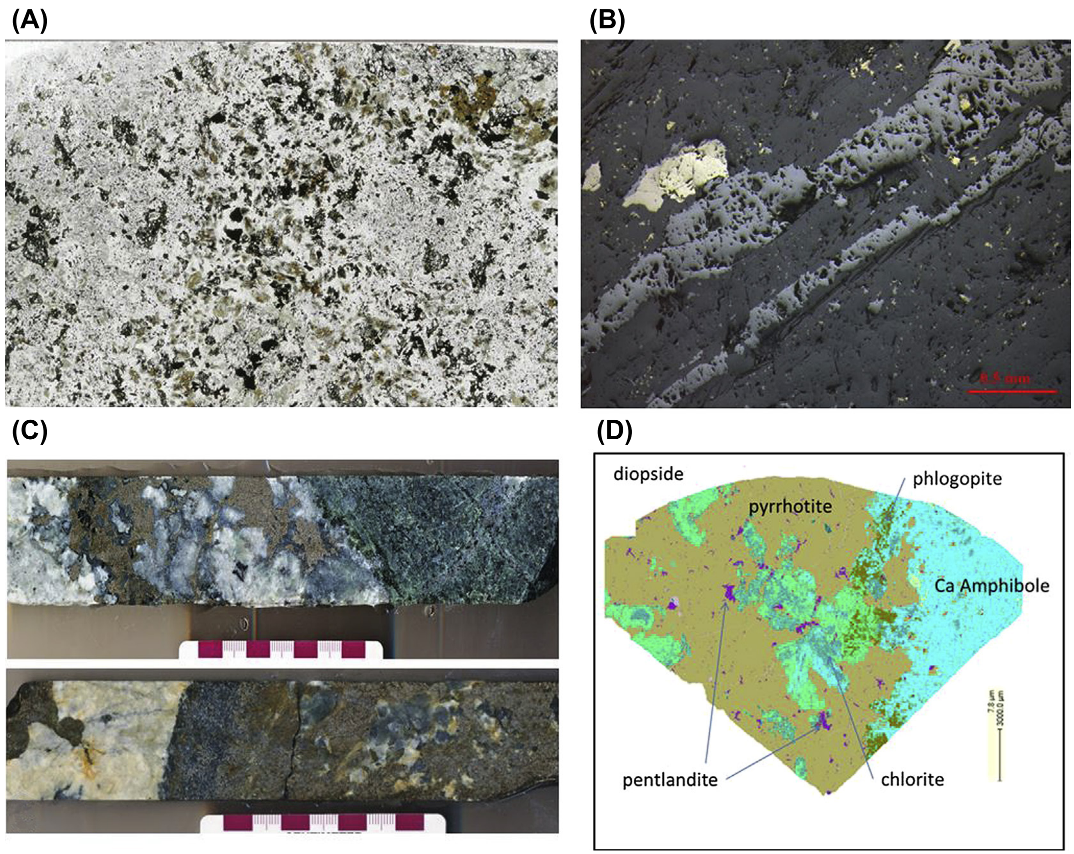

FIGURE 3.6.9 Alteration textures and minerals.

(A) Thin section scan of amphibole-altered olivine pyroxenite. Light to dark gray areas consist entirely of amphibole. Dark brown mineral is hornblende. Olivine is locally preserved. (B) Magnetite veins crosscutting amphibole and sulfide minerals. (C) Veins with massive sulfide (core from separate drill holes). (D) Falso colour Scanning Electron Microprobe image of vein mineralization.

further characterize the amphibole alteration (see Fig. 3.6.8). The Al/Cr ratios are not affected by intense amphibole alteration and confirm previous assessments that the hydrothermal overprint is generally isochemical.

Magnetite also occurs as a secondary mineral, clearly seen as thin, millimeter-sized veins throughout the deposit area. An association to the amphibole alteration is evident in places where anomalous down-hole magnetic susceptibility readings have been logged within intense alteration zones, but this relationship is not consistent and requires more investigation. Chlorite and serpentine replace amphibole and olivine, respectively. This is largely attributed to regional metamorphism. Neither mineral is ubiquitous, but is locally concentrated where gabbroic dikes are present, suggesting an association with permeable structures.

Veining occurs throughout the deposit. Most commonly, veins consist of dolomite, actinolite, biotite, serpentine, talc, and, locally, quartz. Pyrrhotite is ubiquitous within veins, but chalcopyrite and pentlandite can also occur locally. The veins range in thickness from less than 1 cm to more than 1 m. In the open pit, individual veins have been traced for more than 100 m. Some sulfide-bearing veins are enriched in Ni, Cu, Pt, and Pd, suggesting a magmatic origin, but more detailed studies are required to investigate this.

STRUCTURE

Overall, faulting does not offset the ore body over significant distances (Standing et al., 2009). Most faults and fractures are steeply dipping and displacement is typically <10 m; however due to the lack of many stratigraphic marker horizons, exact displacement is not well constrained. Fractures have been developed close to the surface (<50 m below the bedrock interface), enhancing weathering and causing minor oxidation of the sulfide minerals. Regional northeast–southwest trending structures that transect the intrusion and offset the country rocks are indicated in magnetic surveys (see Fig. 3.6.1).

Steeply dipping, north–south trending faults are exposed in the open pit. Veins containing massive pyrrhotite, chalcopyrite, and, locally, pentlandite are concentrated along one single fault zone in the central part of the mine, resulting in increased Ni-Cu grades (refer to Fig. 3.6.5). Based on the orientation of the ore body, these north–south trending structures appear to dip westward, but do not demonstrate significant offset. Other east–west trending structures are also exposed in the open pit where they are defined by calcite veining. Because they do not contain sulfides, these structures may be part of the fault set developed during later regional deformation.

COMPARISON TO OTHER MAGMATIC NI-CU-PGE DEPOSITS

Most magmatic sulfide deposits in northern Finland are considered to be “reef-type” (Eckstrand and Hulbert, 2007) or “PGE-type” deposits (Naldrett et al., 2011). Examples are Ahmavaara and Suhanko in the Portimo complex (Lahtinen et al., 1989; Iljina et al., 2015) and Haukiaho in the Koillismaa complex (Iljina et al., 2015). The Ni-Cu sulfide deposits within the 1.89–1.87 Ga Svecofennian mafic–ultramafic intrusions in southern and central Finland show certain petrogenetic commonalities to Kevitsa, but their tectonic setting is very different, with Kevitsa being emplaced during rifting in an intracontinental setting, whereas the Svecofennian deposits have been ascribed to arc magmatism (Peltonen, 2005).

Among Ni-Cu sulfide deposits globally, Kevitsa has relatively high Cu/Ni ratios above unity. Few other major deposits are Cu-enriched, however, some of the most notable are the deposits in the Noril'sk district Russia (Naldrett et al., 2011) and Okiep South Africa (Maier et al., 2013). Many magmatic systems contain Cu-rich portions and several of these have been shown to be influenced by Cl-rich hydromagmatic fluids, for example, the Sudbury Canada footwall deposits (Farrow and Watkinson, 1997). While Cl-bearing minerals such as hornblende, biotite, and apatite are present at Kevitsa, their paucity suggests that the Cu enrichment is of magmatic origin.

Burrows and Lesher (2012) provide a review of Cu-rich magmatic Ni-Cu-PGE deposits highlighting a number of processes as part of intrusion emplacement to generate this style of mineralization. Distinct Ni and Cu rich portions in magmatic ore deposits can be generated by fractionation of sulfide melt during magma emplacement (Naldrett, 2004; Naldrett et al., 2011). Conspicuously, the Sakatti deposit near Kevitsa also contains Cu-enriched mineralization in addition to Ni-rich ores considered to be generated by this process (Coppard, 2011; Brownscombe et al., 2015). This model could suggest some potential for discovery of Ni-rich sulfides in the Kevitsa intrusion. A better understanding of the magmatic architecture and the emplacement history of the Kevitsa intrusion would clearly be beneficial to define further exploration targets.

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