



Magmatic Sulfide-Rich Nickel-Copper Deposits Related to Picrite and (or) Tholeiitic Basalt Dike-Sill Complexes: A Preliminary Deposit Model

By Klaus J. Schulz, Val W. Chandler, Suzanne W. Nicholson, Nadine Piatak, Robert R. Seal, II, Laurel G. Woodruff, and Michael L. Zientek

Open-File Report 2010–1179

U.S. Department of the Interior
U.S. Geological Survey

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U.S. Geological Survey, Reston, Virginia: 2010

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Suggested citation:
Schulz, K.J., Chandler, V.W., Nicholson, S.W., Piatak, Nadine, Seall, II, R.R., Woodruff, L.G., and Zientek, M.L., 2010, Mamatic sulfide-rich nickel-copper deposits related to picrite and (or) tholeiitic basalt dike-sill complexes—A preliminary deposit model: U.S. Geological Survey Open-File Report 2010–1179, 25 p. (available at <http://pubs.usgs.gov/of/2010/1179/>).

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
Length		
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
Area		
square kilometer (km ²)	247.1	acre
square kilometer (km ²)	0.3861	square mile (mi ²)
Volume		
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
cubic kilometer (km ³)	0.2399	cubic mile (mi ³)
Mass		
gram (g)	0.03527	ounce, avoirdupois (oz)
milligram (mg)	3.527×10^{-5}	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)

Symbols and Abbreviations

~	approximately
>	greater than
≥	greater than or equal to
<	less than
≤	less than or equal to
g/L	gram per liter
µg/L	microgram per liter
mg/L	milligram per liter
mg/kg	milligrams per kilogram
%	percent
‰	permille
ϵ_{Nd}	epsilon neodymium
$\delta^{18}O$	delta O-18
$\delta^{34}S$	delta S-34
γ_{Os}	gamma Os
Al	aluminum
Au	gold
Ba	barium
Bi	bismuth
Cd	cadmium
Co	cobalt
Cr	chromium
Cu	copper
Fe	iron
Ga	gigayears
Ir	iridium
K	potassium
La	lanthanum
LIP	large igneous provinces
MgO	magnesium oxide
MORB	Mid-Ocean Ridge Basalt
Myr	million years
Nb	niobium
Nd	neodymium
Ni	nickel
NNP	net-neutralizing potential
O	oxygen
Os	osmium
P	phosphorus
Pb	lead
Pd	palladium
Pt	platinum
PGE	platinum-group elements
ppb	parts per billion
Re	rhenium
REE	rare earth elements
Rh	rhodium
Ru	ruthenium
S	sulfur
Sm	samarium
Sr	strontium
Th	thorium
Ti	titanium
V	vanadium
Zn	zinc

Magmatic Sulfide-Rich Nickel-Copper Deposits Related to Picrite and (or) Tholeiitic Basalt Dike-Sill Complexes: A Preliminary Deposit Model

By Klaus J. Schulz,¹ Val W. Chandler,² Suzanne W. Nicholson,¹ Nadine Piatak,¹ Robert R. Seal, II,¹ Laurel G. Woodruff,³ and Michael L. Zientek⁴

Introduction

Magmatic sulfide deposits containing nickel (Ni) and copper (Cu), with or without (\pm) platinum-group elements (PGEs), account for approximately 60 percent of the world's Ni production and are active exploration targets in the United States and elsewhere. On the basis of their principal metal production, magmatic sulfide deposits in mafic rocks can be divided into two major types (Naldrett, 2004): those that are sulfide-rich, typically with 10 to 90 percent sulfide minerals, and have economic value primarily because of their Ni and Cu contents; and those that are sulfide-poor, typically with 0.5 to 5 percent sulfide minerals, and are exploited principally for PGE. Because the purpose of this deposit model is to facilitate the assessment for undiscovered, potentially economic magmatic Ni-Cu \pm PGE sulfide deposits in the United States, it addresses only those deposits of economic significance that are likely to occur in the United States on the basis of known geology. Thus, this model focuses on deposits hosted by small- to medium-sized mafic and (or) ultramafic dikes and sills that are related to picrite and tholeiitic basalt magmatic systems generally emplaced in continental settings as a component of large igneous provinces (LIPs). World-class examples (those containing greater than 1 million tons Ni) of this deposit type include deposits at Noril'sk-Talnakh (Russia), Jinchuan (China), Pechenga (Russia), Voisey's Bay (Canada), and Kabanga (Tanzania) (fig. 1). In the United States, this deposit type is represented by the Eagle deposit in northern Michigan, currently under development by Kennecott Minerals. Descriptions of other magmatic Ni-Cu \pm PGE sulfide deposit types are given in Naldrett (2004), Barnes and Lightfoot (2005), and Eckstrand and Hulbert (2007).

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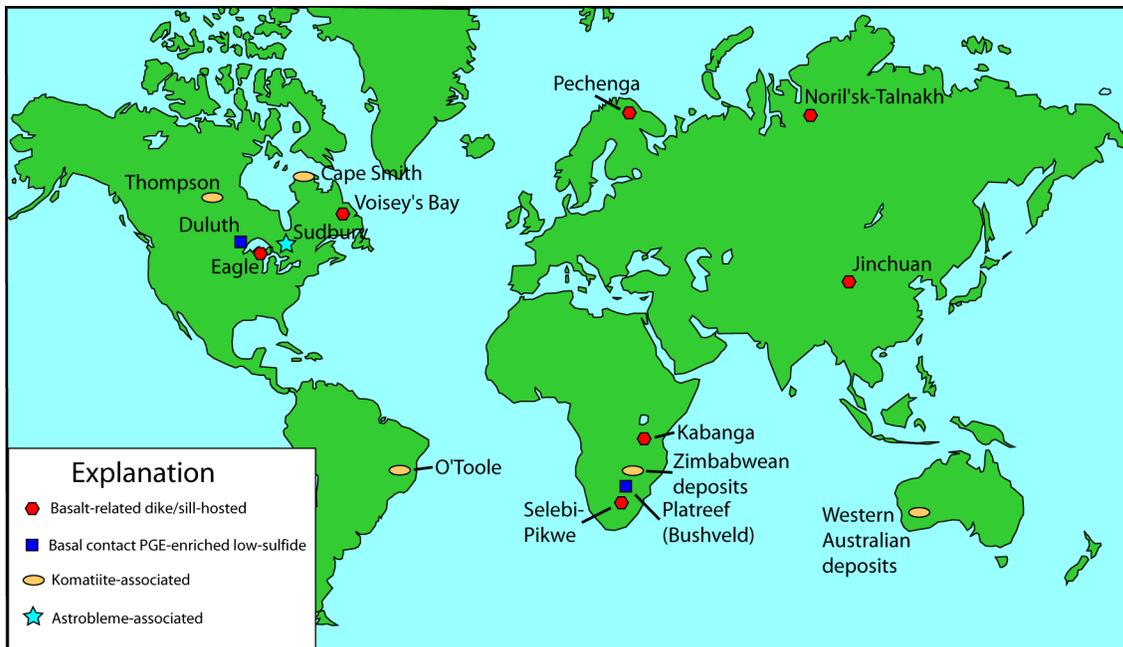


Figure 1. Location of some of the world's major nickel mining camps and types of deposits.

The deposits in the Sudbury district of Ontario, Canada, are not included here because they are associated with a unique meteorite impact-related melt sheet (see Naldrett, 2004, and Ames and Farrow, 2007, for reviews of Sudbury deposits). There is no evidence for similar sulfide deposits being associated with any other known impact structure elsewhere in the world. Also not included are the deposits associated with komatiitic lava flows and sills (see Leshner and Keays, 2002, for a review of komatiite-associated deposits). Although these deposits are an important source for Ni, particularly in Australia, Canada, and Zimbabwe, komatiite deposits are rare in the United States and have not proven to be prospective for significant Ni sulfide mineralization.¹

This deposit model is intended to provide the basis for assessing the occurrence of undiscovered, potentially economic magmatic Ni-Cu±PGE sulfide deposits in the United States as part of the next National Mineral Resource Assessment by the U.S. Geological Survey (USGS). The strategy employed by the USGS in quantitative mineral resource assessments (Singer, 1993; 2007) includes: (1) delineating tracts permissive for the occurrence of undiscovered magmatic Ni- and Cu-bearing sulfide deposits, (2) estimating the amount of metal and some ore characteristics by means of appropriately selected grade and tonnage models, and (3) estimating the number of undiscovered deposits by deposit type. Thus, it is critical to the assessment methodology to have accurate and reliable data on the major characteristics of the Ni-Cu sulfide deposits, particularly features such as host lithology, tectonic setting, structure, ore-gangue-alteration mineralogy, geochemical and geophysical signatures, theory of deposit formation, and geoenvironmental characteristics.

¹ Although this report does not focus on the magmatic Ni-Cu sulfide deposits at Sudbury or those related to komatiites, these sulfide deposits have been studied extensively and share many similarities with the deposits related to picrite and tholeiitic basalt dike-sill complexes. Therefore, reference to the Sudbury and komatiite-related deposits is occasionally made where appropriate.

Deposit Type and Related Deposits

The deposits described in this model are referred to here as magmatic sulfide-rich Ni-Cu±PGE deposits related to picritic or tholeiitic basalt dike-sill complexes. The name emphasizes the relationship of these Ni-Cu deposits to picrite and tholeiitic basalt magmas and to mostly small- to medium-sized dikes and sills in comparison to the generally much larger layered mafic-ultramafic intrusive complexes that typically host sulfide-poor PGE-enriched deposits. A variety of other names has been applied to these deposits in the literature that generally emphasize aspects of mineralization style, tectonic setting, and (or) lithology of the host rocks. Names include tholeiitic basal segregation type, gabbroid-associated layered intrusive type, mafic-ultramafic intrusion-hosted type, flood basalt-related type, and feeder/conduit type deposits. In addition, deposits have been named after giant deposits of that type, such as Noril'sk type or Voisey's Bay type.

Magmatic sulfide deposits form when mantle-derived, sulfur undersaturated picritic or tholeiitic basalt magmas become sulfide saturated, commonly following interaction with crustal rocks. Sulfur saturation results in the formation of an immiscible sulfide liquid; the sulfide liquid tends to segregate into physical depressions or other areas in the lower parts of dike- and (or) sill-like intrusions because of changes in magma flow dynamics. Economic deposits develop almost exclusively within dynamic magmatic systems that experience repeated surges of magma. Such dynamic systems promote the interaction of a sulfide liquid with a sufficiently large amount of silicate magma to concentrate chalcophile elements to economic levels. The principal sulfide minerals generally consist of intergrown pyrrhotite, pentlandite, and chalcopyrite. Cobalt (Co) is found in pentlandite, and PGEs are generally present as small grains of PGE-bearing sulfides, arsenides, antimonides, bismuthinides, and tellurides. Most deposits also contain 1- to 15-percent magnetite.

The tectonic setting of these magmatic sulfide deposits is principally flood basalt-dominated LIPs, which are generally attributed to the upwelling and melting of buoyant mantle as a plume beneath crustal lithosphere (Condie, 2001). The sulfide deposits and their host intrusions range in age from Archean to Middle Jurassic. They are generally found close to deeply penetrating structures that allow for the efficient transport of sulfur-undersaturated mantle magma to relatively shallow crustal depths. Although sulfur-bearing crustal rocks such as black shales, evaporates, or paragneisses are proximal to many deposits, they may not be the primary source of sulfur (Hoatson and others, 2006). Deposits are hosted by a wide range of olivine-bearing mantle-derived rocks; these rocks and example locations include ferropicrite (Pechenga, Russia), tholeiitic picrite (Noril'sk-Talnakh, Russia), and high aluminum basalt (Voisey's Bay, Canada). No known economic deposits are associated with mid-ocean ridge basalts (MORB), ophiolites, or alkaline rocks.

Magmatic Ni-Cu±PGE sulfide deposits can occur with a number of other magmatic ore deposits. These include low-sulfide, contact-type, and reef-type PGE deposits, chromite deposits, and Fe-Ti-V deposits. In addition, secondary processes can produce associated asbestos, soapstone, and native copper deposits.

Regional Environment

Magmatic sulfide-rich Ni-Cu±PGE deposits typically occur in continental geologic settings where a large volume of mostly tholeiitic mafic-ultramafic magma has been emplaced in the crust and erupted on the surface by processes not associated with "normal" spreading ridge or

subduction environments. These intraplate LIPs (and example locations) include continental flood basalts (Deccan, Karoo, Siberian Traps, Columbia River) and volcanic rifted margins (North Atlantic Igneous Province), along with their plumbing system components (dikes, sills, and layered intrusions) (Coffin and Eldholm, 1994). The LIPs also are represented by oceanic plateaus (Ontong-Java) and ocean basin flood basalts (the Caribbean Flood Basalts) (Coffin and Eldholm, 1994). Many LIPs have areal extents of greater than 1 million km² and volumes greater than 1 million km³ (Courtilot and Renne, 2003). The largest continental LIP, the Siberian Traps, which hosts the Noril'sk-Talnakh deposits, is estimated to have a minimum size of 4 million km³ (Ivanov, 2007). Although magmatic activity in LIPs can have lifespans of 50 million years (Myr) or more, the largest proportion (greater than 75 percent) of the total igneous volume is generally emplaced during a short duration pulse(s) of approximately 1 to 5 Myr (Courtilot and Renne, 2003; Bryan and Ernst, 2008). The emplacement of such large volumes of mafic and ultramafic magma is attributed to the rise and impingement of mantle plumes on continental and oceanic lithospheric plates (Condie, 2001; Pirajno, 2007).

Plume-related magmatism and LIPs extend from the present to at least 2.7 gigayears (Ga) (Ernst, 2007). Mesozoic-Cenozoic continental LIPs are typically the best preserved, with extensive flood basalt sections as much as several kilometers thick that consist of large tabular lava flow units typically without significant interlayered sedimentary rocks. In contrast, older (Precambrian to Paleozoic) LIPs are commonly more deeply eroded, with only flood basalt remnants preserved but with their plumbing system exposed as giant dike swarms, sill complexes, and layered intrusions. Recognition of LIPs in the Archean is more uncertain because most volcanic rocks and associated intrusions occur in deformed and fault-segmented greenstone belts (de Wit and Ashwal, 1997) and generally cannot be traced over LIP-scale areas.

Economic magmatic Ni-Cu±PGE sulfide deposits in LIP settings range in age from Archean to Middle Jurassic and are almost exclusively associated with dynamic (replenished) magmatic systems, including periodically replenished subvolcanic feeder sills, feeder dikes, and volcanic vents (Leshner, 2004). Less dynamic (unreplenished) systems such as sheeted sills and larger layered intrusions are normally barren of sulfide-rich Ni-Cu±PGE mineralization unless they are a lateral component in a dynamic magma system. The apparent restriction of economic sulfide-rich Ni-Cu±PGE deposits to Jurassic and older magmatic systems is probably a reflection of the more deeply eroded nature of older LIPs, which exposes more of the plumbing system present below the extensive and barren flood basalt sections that are still preserved in younger LIPs.

Extension, rifting, and development or reactivation of deeply penetrating faults typically accompany development of LIPs and play an important role in providing zones of weakness and dilation along which magma may ascend into the crust (Pirajno, 2007). These magma-focusing structures facilitate development of dynamic subvolcanic feeder systems that typically host sulfide-rich Ni-Cu±PGE deposits (Arndt, 2005). The resulting intrusions are generally small to medium sized (less than 3-km thick and hundreds of meters to tens of kilometers long) and range from oblate circular through sheet shaped to rod shaped.

The formation of Ni-Cu±PGE sulfide minerals is a direct result of the evolution of the dynamic magmatic system that hosts the deposits. However, country rocks, including basement metamorphic rocks and upper crustal sedimentary rocks, play two important roles in the formation of these deposits. First, crustal structure helps control the formation of magma chambers, defining sites where ascending magmas can be trapped at density discontinuities in the crust (Arndt, 2005). Second, a common trigger for sulfur saturation and segregation of an

immiscible sulfide liquid is interaction between the sulfur undersaturated magma and crustal rocks. This interaction either changes the temperature and composition of the magma so as to decrease the sulfur solubility and (or) adds sulfur to the magma. Horizontal flow through upper crustal dike-sill complexes can augment the period of interaction between magma and wall-rocks, thereby increasing the extent of contamination (Arndt, 2005). Although sulfide- and (or) sulfate-bearing rocks are commonly present in the country rocks near intrusions, the rocks that the magma(s) interacted with during their ascent through the crust appear to be more important than the country rocks at the final level of emplacement (Hoatson and others, 2006).

Physical Description of Deposit

Magmatic sulfide-rich Ni-Cu±PGE deposits typically occur in clusters, and many deposits contain multiple mineralized zones. Sulfide ores occur within host intrusions and country rocks in a variety of forms (table 1), depending on the timing of sulfide segregation relative to the emplacement and crystallization history of the host rock and the degree of subsequent magmatic, hydrothermal, and (or) tectonic mobilization (Leshner, 2004). In general, three distinct types of Ni-Cu±PGE sulfide mineralization occur in stratiform or stratabound deposits:

1. Massive sulfide (greater than about 66 percent sulfide minerals) and matrix or net-textured (about 33 to 66 percent sulfide minerals) ores tend to form dikes and flat-lying sheets and lenses at the bottom of intrusions, in some cases also protruding downward into the footwall rocks. At Noril'sk, massive ores can extend for several kilometers along the long axis of the host intrusion with thicknesses as much as 50 m and widths as much as 1 km (Diakov and others, 2002). Massive ores typically occur in physical depressions or where changes in the geometry or topography of the footwall occur. The thickness of the massive ores correlates with the thickness of the intrusion, generally pinching out where the intrusion thickness decreases (Diakov and others, 2002). Massive ores can show distinct sulfide mineral zonation, ranging from pyrrhotite-dominated, chalcopyrite-pentlandite assemblages in the outermost and lower parts, through progressively more Cu-rich zones, to mainly Cu-rich sulfides that are commonly enriched in PGE in the middle or upper parts. This zonation of sulfides is attributed to *in situ* fractionation of the original sulfide liquid (Naldrett, 2004).
2. Breccia ores can form semi-conformable, sheet-like zones along both the lower and the upper contacts of the intrusions and may enclose massive ore. The breccias comprise fragments of both the intrusion and the wall-rocks in a matrix of mainly massive sulfide. Sulfide stringers and disseminations may accompany the breccias.
3. Disseminated sulfides (about 1 to 33 percent sulfides) form lenticular to tabular layers within the middle and lower parts of intrusions. In most cases, they occur as irregular 1-mm- to 1-cm-diameter patches interstitial to the silicate and oxide minerals. However, at some localities (for example, Noril'sk-Talnakh, Pechenga, and Insizwa in South Africa), disseminated sulfides can occur as 1- to 10-cm-sized spheres or globules of chalcopyrite, pentlandite, and pyrrhotite dispersed through the host rock and can be zoned in the manner of the massive ores (pyrrhotite-rich base and chalcopyrite-rich top). In the Talnakh intrusion, the thickness of the disseminated ore zone tends to follow the outline of the footwall of the intrusion; however, whereas massive ore pinches out along strike,

disseminated ore is nearly continuous along the strike axis of the intrusion (Diakov and others, 2002).

Table 1. Form, distribution, textures, and timing of segregation of types of Ni-Cu±PGE sulfide ores (from Lesher, 2004).

Ore Type	Form/Distribution	Texture	Timing
I	Stratiform or stratabound, at or near the base of host unit	Massive, net-textured, disseminated	Early magmatic segregation
II	Stratabound to podiform, internal to host unit	a. Massive, net-textured, or heavy disseminated b. Blebby disseminated c. Fine disseminated	Early magmatic segregation Early or intermediate magmatic segregation Late magmatic segregation
III	Stratiform or stratabound in country rocks adjacent to Type I ores	d. Mineralized metasedimentary rocks e. Interbreccia, interpillow, veins in footwall rocks	Early magmatic and (or) metamorphic diffusion Early magmatic percolation
IV	Veins in country rocks associated with Type I ores	Massive or semi-massive veins, often with only very narrow alteration selvages	a. Magmatic-hydrothermal b. Metamorphic-hydrothermal
V	Massive to semi-massive within shears and fault zones mainly associated with Type I ores	Normally foliated, normally inclusion-bearing	Tectonically mobilized

Geophysical Characteristics

Magmatic sulfide-rich Ni-Cu±PGE deposits hosted in picritic and tholeiitic dikes and sills present some unique and challenging targets for geophysical exploration. Because these sulfide deposits involve some combination of pyrrhotite, pentlandite, and chalcopyrite, they typically are characterized by highly anomalous physical properties, including density, magnetization, electrical conductivity, electrical chargeability, and acoustic velocity (King, 2007). As a result, geophysical methods can be very useful in detecting and characterizing such deposits (Ford and others, 2007). Unfortunately, the intrusive host rocks, as well as the wall-rocks themselves, can also have anomalous physical properties, and their geophysical signatures can obscure those of the Ni-Cu sulfide minerals. Furthermore, the geophysical signatures of the sulfide deposits, as well as the host intrusions, may vary widely, owing to a variety of geometric and geologic factors, and a geophysical method that works effectively in one region may not work at all in another (King, 2007). Finally, the Ni-Cu±PGE sulfide deposits, as well as their host intrusions, are small, commonly only tens or hundreds of meters in length, and thus represent the proverbial “needle in a haystack” for any regional-scale exploration program. Overall, a successful geophysical program for these types of deposits requires a creative and highly flexible strategy.

In most situations, the aeromagnetic survey method is the most effective tool for reconnaissance-scale exploration of dike- and sill-hosted Ni-Cu±PGE sulfide deposits. In addition to the relatively low cost, the aeromagnetic survey method is particularly effective in

detecting the pronounced anomalies that commonly arise from either the host intrusions or the pyrrhotite component of the sulfide deposits. Wherever they are available, regional surveys (400-m line spacing or wider) are used for broad reconnaissance, after which detailed surveying, with line spacing on the order of 100 m or less, are flown in selected target areas. Ground-based magnetic surveying may subsequently follow up on specific targets. In spite of the general utility of magnetic methods for these types of deposits, not all applications are successful. At Voisey's Bay, for example, neither the pyrrhotite-dominated sulfide assemblage, nor the host intrusions are magnetic, and the observed magnetic signature primarily reflects pre-intrusion features in the wall rock (King, 2007). In these situations, other geophysical methods, such as electromagnetic (EM) surveying, may have to be used.

These sulfide-rich deposits are usually excellent conductors of electricity and are, therefore, detectable by EM surveying (King, 2007). Similar to magnetic surveying, most EM methods can be readily applied from airborne platforms, allowing rapid and efficient acquisition over large areas. However, most airborne EM methods are considerably more expensive than aeromagnetic surveying, and they are consequently applied during late- or post-reconnaissance stages of exploration, once several targets or target areas have been identified based on other geophysical, geochemical, or geologic data. Following airborne applications, a variety of ground-based EM methods may be applied to selected targets. The interpreter must always be mindful that these sulfide deposits are usually small and their EM signature can be easily obscured by a variety of factors, including depth of burial, conductive overburden, and the presence of graphitic conductors in the wall rock.

In addition to ground-based magnetic and EM surveying, other ground-based geophysical methods have been applied to Ni-Cu±PGE sulfide deposits, usually to specific targets. Electrode-based methods, including resistivity, induced polarization, and spontaneous potential, have been used in some areas to help locate and characterize sulfide deposits (Guo and Dentith, 1997; King, 2007). Both the host intrusions and the sulfide bodies usually have much higher densities than those of the surrounding rocks, and the resulting gravity anomalies are useful in interpreting the subsurface geometries of these bodies (Ford and others, 2007; King, 2007). Seismic reflection profiling has recently emerged as a potentially powerful tool for magmatic sulfide exploration. For example, profiling at Sudbury has clearly demonstrated that the igneous host rocks, as well as the sulfide masses, produce detectable reflection and diffraction signatures (Salisbury and Snyder, 2007). Although far too expensive to use as a reconnaissance tool, 3-D seismic reflection profiling may serve as a useful guide for test drilling once a highly favorable target has been located.

In summary, geophysical methods have proven useful for exploration of dike- and sill-hosted sulfide-rich Ni-Cu±PGE deposits, and their use is likely to continue and improve. Particularly promising frontiers may exist for 3-D seismic profiling of specific targets and for airborne gravity surveying. The latter method has been used rather sparingly to date (King, 2007), but improvements in technology and lower costs are likely to continue, resulting in much broader usage.

Hypogene and Supergene Ore Characteristics

The hypogene ore minerals for magmatic Ni-Cu±PGE sulfide deposits are lower temperature assemblages of high-temperature sulfide liquids that have undergone fractionation, physical redistribution and separation, recrystallization with cooling, possible reheating and remelting by recurring igneous injections, and potential remobilization by both magmatic and

nonmagmatic hydrothermal fluids. The dominant minerals in these deposits are mainly variants of Fe-, Cu-, and Ni-bearing sulfide minerals, typically pyrrhotite, pentlandite, and chalcopyrite, with or without lesser cubanite and troilite; a number of other minerals are found in trace amounts. The occurrence of platinum group minerals (PGMs) in these deposits is of critical economic interest because PGE, typically present only in trace amounts, may make a deposit economic.

The mineralogy and distribution of elements and minerals within major deposits have distinct zoning patterns that reflect the fractionation path of an immiscible sulfide liquid. Many deposits have basal zones of massive sulfide interpreted to have crystallized from the base upward, with a fractional, residual liquid enriched in Cu, Au, Pd, and Pt becoming concentrated near the top. At the Oktyabr'sky deposit at Noril'sk, lower and marginal ores are mainly Fe-Os-Ir-Ru-Rh-rich pyrrhotite, whereas the central overlying ores are Cu-Pd-Pt-Au-rich chalcopyrite and mooihoekite (Distler, 1994; Barnes and Lightfoot, 2005; Gorbachev, 2006).

Sulfides in magmatic deposits may be divided into disseminated sulfides (sulfides not connected to one another), matrix- or net-textured sulfides (sulfides in an interconnected matrix with silicate minerals), and massive sulfide (concentration of sulfide exceeding 66 percent of the rock volume). Sulfides can occur as coarse crystals as much as 2 cm in diameter or as fine exsolution lamellae. Where present, PGMs are typically small euhedral crystals occurring at the boundary of Ni-Cu sulfide minerals.

The most complete information on supergene development for magmatic Ni-Cu±PGE deposits is in the voluminous literature describing the numerous Ni deposits of Western Australia. Although this specific type of komatiite-related Ni mineralization is not considered for this report, commonalities of hypogene ores among magmatic-hosted Ni-Cu±PGE deposits and similar ultramafic-hosted Ni deposits suggest that the supergene mineral reactions described for the deposits in Western Australia would be typical of supergene reactions for many magmatic Ni-Cu±PGE sulfide deposits. In general, whereas supergene enrichment is recognized in many weathered profiles developed on Ni deposits, such enrichment does not have a significant role in upgrading the metal tenor of magmatic Ni-Cu±PGE deposits.

Consistent mineral assemblages are reported for most magmatic Ni deposits that have undergone supergene alteration. In deeply weathered terranes, supergene sulfide minerals have lost sulfur and base metals, and the new mineralogy includes bravorite, violarite, pyrite, millerite, marcasite, and native copper or copper-oxides (Barnes and Lightfoot, 2005).

When exposed to supergene alteration, most Ni-Cu±PGE sulfides tend to develop distinct mineral zones that reflect increasing degrees of oxidation towards the surface. The first indication of the initiation of sulfide oxidation of primary pyrrhotite-pentlandite is the appearance of violarite-bravoite/pyrite-marcasite. With decreasing depth, conversion of pyrrhotite-pentlandite continues, although primary chalcopyrite and pyrite persist. Above the water table, sulfide minerals are replaced by a weathered gossan of hydrated ferric oxides, various carbonate, and silica minerals. Gossans developed from the weathering of magmatic Ni-Cu±PGE hypogene minerals typically will retain immobile PGE.

Hypogene and Supergene Gangue Characteristics

Gangue mineralogy for magmatic Ni-Cu±PGE deposits can be divided into three categories: (1) magmatic silicates and oxide minerals of the ore-hosting mafic to ultramafic intrusions; (2) metamorphic minerals resulting from contact and post-depositional regional

metamorphic events; and (3) minerals in partially ingested xenoliths and hornfelsed country rock.

Magmatic gangue minerals for most deposits are the minerals of the host mafic and ultramafic silicate rocks. Typical minerals are olivine, orthopyroxene, clinopyroxene, plagioclase, magnetite, ilmenite, and Cr-spinel. Gangue minerals at deposits that have undergone magmatic and post-depositional alteration typically reflect the original mineralogy. Minerals formed by reactions with country rock, either by contact metamorphism or by ingestion of xenoliths, are much more complex because of the wide range of lithologies in contact with mineralized host rocks. Xenoliths may be incorporated into magma by thermal erosion of conduit walls. At Voisey's Bay, near total fusion of gneissic xenoliths in magma produced immiscible aluminous liquids—garnet oxidized to form hercynite and magnetite, hypersthene and potassium feldspar reacted together to also produce hercynite, and plagioclase broke down to produce corundum (Li and Naldrett, 2000). At Noril'sk, metamorphism of sedimentary country rock, which includes dolomite, argillite, evaporates, and terrigenous coal measures, involved prograde development of hornfels and marble and retrograde development of calc-silicates/skarn (Likhachev, 1994). Evidence of reaction with country rock, particularly one with potentially readily available sulfur (pyrite), is a favorable indicator when evaluating an intrusion as a potential exploration target (Naldrett, 2004).

Supergene gangue characteristics are complex because of the variable rock types that host magmatic sulfide ore bodies. The nature of gangue minerals enclosing sulfide minerals can exert a strong influence on weathering reactions, solution pH, and resulting precipitates. Weathering of gangue minerals such as feldspars, amphiboles, and pyroxenes releases alkali metals, as well as aluminum. In solutions with very low pH, relatively insoluble sulfate minerals, such as alunite $[KAl_3(SO_4)_2(OH)_6]$ and jarosite $[KFe^{3+}_3(OH)_6(SO_4)_2]$ precipitate (Thorner, 1985; Burns, 1988). At deposits where country rocks have a buffering effect on pH, acid produced by oxidation is neutralized by interaction with nearby silicate and carbonate minerals. At higher pH, ferric ions precipitate as poorly crystalline iron hydroxides, such as goethite; secondary carbonates may form; silica will reprecipitate as quartz, jasper, or opal; and if sufficient aluminum is present, clay minerals or aluminum hydroxides are formed.

Weathering – Supergene Processes

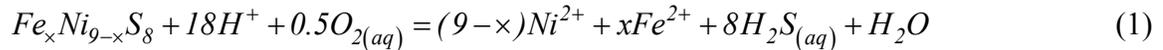
Sulfide minerals are unstable in the presence of oxidized aqueous solutions in the unsaturated vadose zone located between the land surface and the groundwater table. In this zone, chemical weathering reactions convert primary sulfide minerals to secondary sulfide, sulfate, and oxide mineral assemblages. Below the groundwater table, deep weathering of primary magmatic Ni-Cu-sulfide minerals is initiated by dissolved ferric iron (Fe^{3+}) ions in percolating groundwater (Burns, 1988). The role for dissolved oxygen is to produce Fe^{3+} in the near surface environment and it is not essential for the formation of secondary sulfides in Ni-Cu±PGE deposits, such as violarite, pyrite, and covellite.

Most sulfide minerals are coherent electronic conductors, and thus sulfide weathering proceeds by electrochemical reactions involving coupled half-cell reactions. Oxidation involves the loss of electrons. In weathering reactions, sulfide minerals act as an anode and electrons are conducted away from a sulfide through the groundwater electrolyte to cathode reaction sites. In ore-bodies, these reactions may act on the scale of an individual mineral (for example, disseminated sulfides) or over hundreds of meters in massive ore (Thorner, 1975). The general

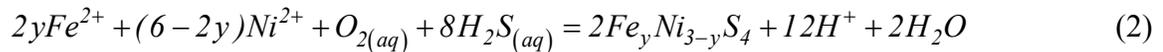
weathering processes involve conversion of magmatic massive sulfide, made up of pyrrhotite and pentlandite with minor chalcopyrite and pyrite, to violarite and secondary pyrite, with further conversion of all sulfide minerals to gossanous materials above the water table.

Magmatic sulfide ore-bodies may act as giant corrosion cells, with electrochemical processes driving metal diffusion (Thornber, 1975). By this process the oxidative power of atmospheric oxygen is the driving force for the weathering of sulfides in the absence of bacterial activity. The rate at which atmospheric oxygen dissolves in groundwater and is transported to the reactive sulfide, where it is reduced, may be the rate-limiting step in the weathering process. Groundwater movement will result in some transport of oxygen, but close to the sulfide surface, diffusion will be the rate-limiting step.

Although this basic model remains valid, recent experimental work (Xia and others, 2009) demonstrates that the replacement of pentlandite by violarite, the principal reaction in supergene alteration of nickel sulfide ore, is an example of a pseudomorphic coupled dissolution-reprecipitation reaction. Thus, the replacement of pentlandite proceeds by dissolution (reaction 1) followed by violarite precipitation (reaction 2), rather than by solid state diffusion.



pentlandite



violarite

Xia and others (2009) argued that the slowest among the three critical steps in this process may be transport of solute to and from the reaction front, pentlandite dissolution, or violarite precipitation. Kinetic results from Xia and others (2009) demonstrate that, in mildly acidic conditions ($1 < \text{pH} < 6$), the rate-limiting step is pentlandite dissolution. However, under strongly acidic conditions ($\text{pH} = 1$), the rate-limiting step is violarite precipitation.

The ultimate development and preservation of a supergene enrichment/weathering zone above an ore-body are achieved only through an intricate combination of highly favorable climate, geology, topography, and preservation factors. For example, the convoluted geological and climatic paths that resulted in formation and exposure of Archean sulfide mineralization in Western Australia involved a long history of uplift, glaciation, peneplanation, and erosion combined with swings in climate from cold to warm, and from arid to humid, ending with a final fortuitous configuration that resulted in the recognition of more than 20 major nickel sulfide deposits in the Yilgarn Shield, virtually all discovered by “gossan hunting” (Smith, 1984).

Geochemical Characteristics of Ores

Metal contents and ratios such as Ni/Cu, Ni/Co, and PGE/Ni+Cu can be used to distinguish dike/sill tholeiitic magmatic sulfide deposits from other types of Ni-Cu±PGE magmatic sulfide deposits (table 2). Tholeiitic dike/sill-related deposits typically have somewhat lower Ni/Cu ratios than reef-type and komatiitic-hosted deposits and much lower PGE/Ni+Cu ratios than reef-type deposits.

Without the influence of external factors, sulfide minerals typically will not form early in the magmatic crystallization process. Modeling suggests that large volumes of sulfide melt,

typically rich in Ni, Cu, and Co but relatively poor in PGE, can be produced by assimilation of sulfide-rich country rock (Mungall, 2007). If sulfur saturation of the magma is reached early before much olivine crystallization has occurred, then Ni will not yet have been removed by olivine and thus the resulting sulfide mineral assemblage will have a high Ni/Cu ratio. If sulfide saturation occurs after significant olivine crystallization, then the resulting sulfide assemblage will have a much lower Ni/Cu ratio (Mungall, 2007). These ratios can be used to evaluate the degree to which magmas have previously segregated sulfides and (or) been affected by crustal contamination (Naldrett and others, 1992).

Table 2. Sulfide geochemistry of magmatic Ni-Cu (\pm PGE) deposits (from Naldrett, 2004).

[---, data not available]

Deposits	Ni/Cu	Ni/Co	Pd/Pt	Pd/Ir	(Pt+Pd)/(Ni+Cu)
Tholeiitic sill/dike deposits					
Eagle (United States)	1.23	35.7	0.64	-	0.2
Insizwa (Karoo) (South Africa)	0.91	-	2.40	18.12	0.73
Jinchuan (China)	1.76	56.0	1.00	14.37	0.04 to 0.45
Kabanga (Tanzania)	5 to 10	10 to 15	0.3 to 2.0	2 to 20	0.06 to 0.4 (+1.6)
Noril'sk-Talnakh (Russia)	0.58	58.0	3.43	217.34	1.1 to 4.8
Pechenga (Russia)	1.86	26.0	1.33	9.7	0.05 to 0.26
Voisey's Bay (Canada)	1.87	18.0	1.29	59.98	0.05
Reef-type deposits					
Duluth (United States)	0.33	10.50	3.35	184.17	2.9 to 4.8
Platreef (South Africa)	1.27	-	1.5	88 to 166	2.1 to 4.4
Merensky reef (South Africa)	2.6	-	0.54	14.69	17.4 (+112.6)
J-M reef (United States)	2.03	-	3.47	901.7	353.99
Komatiitic Ni-Cu deposits					
Kambalda (Australia)	13.5	0.07	1.39	8.87	0.19 to 0.26
Meteoritic impact-related deposits					
Sudbury (Canada)	1.11	32.00	1.26	30.65	0.06 to 1.37

Sulfur and oxygen isotopes can be used to assess the origin of sulfur and metal-carrying fluids, whereas other isotopic systems (Re-Os, Sm-Nd, Pb) can be used to evaluate the source of the metals and degree of assimilation of country rocks. Stable isotope data and resulting interpretations of these data are very variable between deposits. Xenoliths of country rocks were entrained in magmas at the Voisey's Bay, Kabanga, and some of the Noril'sk deposits. In most cases, xenoliths and their host rocks have sulfur and oxygen isotope values that demonstrate significant country rock sulfur contributions (Grinenko, 1985; Ripley and others, 1999, 2002, 2003; Mariga and others, 2006) (fig. 2). In contrast, $\delta^{18}O$ values of silicate minerals at the Uitkomst deposit in South Africa are consistent with magmatic values, but heavy $\delta^{34}S$ values for sulfide minerals from the same horizons indicate that sulfur was added to magmas as a hydrothermal fluid rather than through bulk assimilation of country rocks (Sarkar and others, 2008). Likewise, at the Jinchuan deposit, hydrothermal fluids, likely derived from evolved seawater or a metamorphic fluid, appear to have altered the $\delta^{18}O$ values in silicates in the early stages of alteration (Ripley and others, 2005). In contrast, sulfides have $\delta^{34}S$ values near 0‰, which is consistent with magmatic values, or possibly unexposed country rocks with mantle-like

values (Ripley and others, 2005). At the Nebo-Babel deposit in Western Australia and at some of the Noril'sk deposits, sulfur saturation is inferred to have occurred due to assimilation of orthogneisses at depth and not as a result of the addition of external sulfur (Seat and others, 2009; Keays and Lightfoot, 2010).

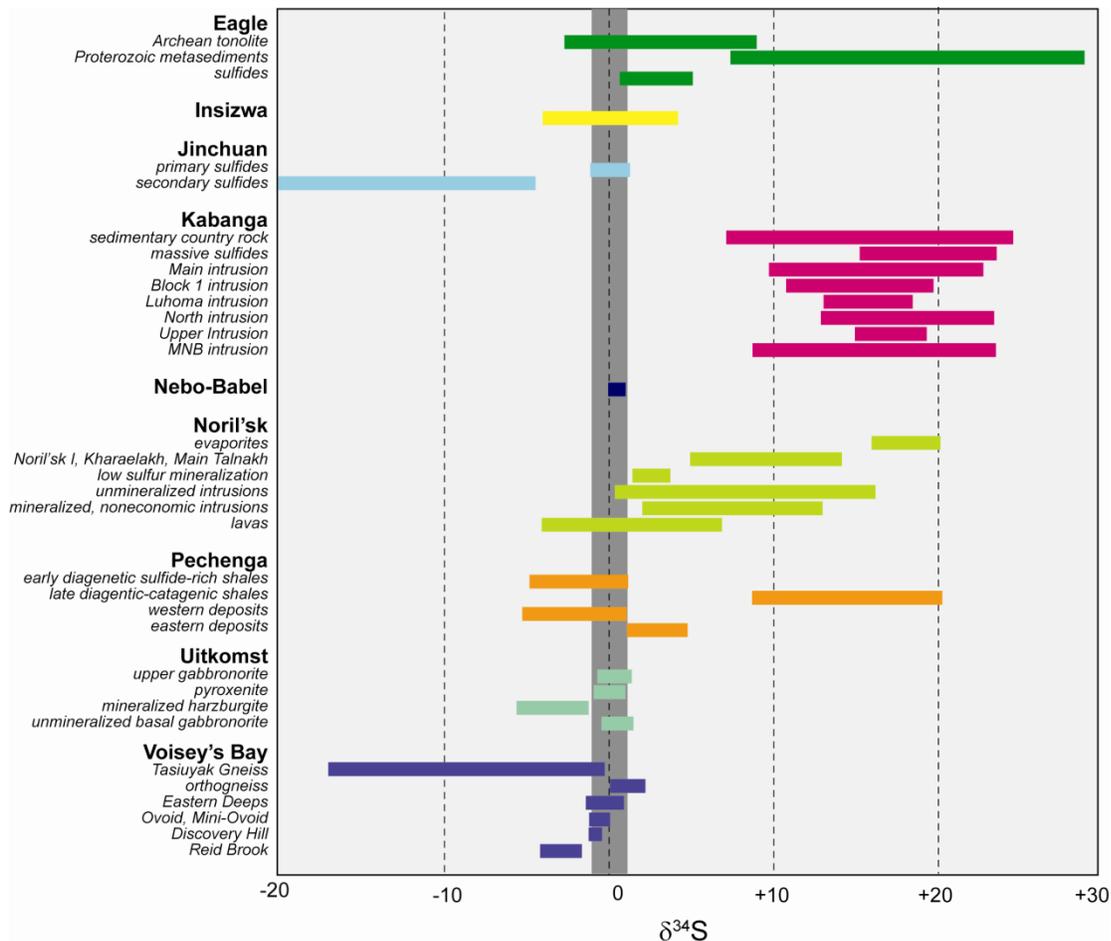


Figure 2. Comparison of sulfur isotope variations in magmatic Ni-Cu±PGE deposits (modified from Maier and others, 2010). Sources for data are: Eagle (Ding and others, 2009), Insizwa (Lightfoot and others, 1984), Jinchuan (Ripley and others, 1999), Kabanga (Maier and others, 2010), Nebo-Babel (Seat and others, 2009), Noril'sk (Grinenko, 1985; Li and others, 2003; Ripley and others, 2003), Pechenga (Abzalov and Both, 1997; Barnes and others, 2001), Uitkomst (Li and others, 2002), and Voisey's Bay (Ripley and others, 1999, 2002). The shaded area indicates the spread of sulfur isotope values typical of mantle-derived sulfide minerals.

The Re-Os isotopic system is an ideal tracer for determining the origin of metals and the extent of crustal contamination in magmatic Ni-Cu±PGE deposits because the large partitioning coefficients for these chalcophile elements mean that the metals are strongly concentrated in immiscible sulfide liquids compared to silicate melts (Lambert and others, 1998; 1999a, 1999b, 2000). The Re-Os isotopes, when coupled with other isotopic systems such as Sm-Nd and Pb, can constrain the magmatic and assimilation/fractionation histories of magmas (Lightfoot and others, 1993; Horan and others, 1995).

At Voisey's Bay, very high initial Y_{Os} values for the ores suggest a significant contribution from old adjacent gneisses (Lambert and others, 1999b). Complex magmatic histories can be defined using Nd, Os, and Sr isotopic analyses of sulfide ores. For example, at Noril'sk, Arndt and others (2003) found isotopic evidence of strong contamination of some magmas at depth, but the major ore bodies appear to be derived from the interaction of chemically distinct, less contaminated mafic magmas that reached sulfur saturation when in contact with crustal anhydrite. Post-ore metamorphism commonly affects the Os, Pb, and Sr isotopic systems, preferentially causing disruptions in isotopic signatures of disseminated ores rather than massive ores; for example, Jinchuan (Yang and others, 2008).

Petrology of Related Igneous Rocks

Magmatic sulfide-rich Ni-Cu±PGE deposits are consistently found with small- to medium-sized differentiated mafic and (or) ultramafic dikes, sills, chonoliths (tens to a few hundreds of meters in thickness, ≤ 100 - to $\geq 2,000$ -m-wide, and hundreds of meters to several kilometers in length), and plug-like intrusions (generally <10 km in diameter). The dike- and sill-like intrusions may show significant changes in dip and width along their strike length and may be surrounded by intense metamorphic and metasomatic aureoles that can extend outwards into the country rocks for considerable distances—for example, as much as 400 m at Noril'sk. Intrusions generally appear to have formed as the plumbing system to the emplacement of mafic magmas in LIPs.

Intrusions hosting sulfide-rich Ni-Cu±PGE deposits are related to a range of generally olivine-bearing, mantle-derived magmas including ferropicrite (Pechnega; Eagle), tholeiitic picrite (Noril'sk-Talnakh), high-aluminum basalt (Voisey's Bay), and siliceous high-magnesium basalt (Uitkomst). These diverse magma types produce a variety of igneous lithologies depending on composition, depth of emplacement, and the rate of cooling, ranging from fine-grained basalt and diabase to medium- and coarse-grained gabbro, pegmatite, and breccia. Cumulate rocks are common in some intrusions and are generally composed of varying proportions of olivine, orthopyroxene, clinopyroxene, and plagioclase. Chromite, iron-titanium oxides, and apatite may be present as accessory minerals and biotite may occur near interstitial sulfide minerals. Sulfide-hosting intrusions are typically texturally and lithologically heterogeneous, exhibiting changes in texture and mineralogy on a variety of scales, from centimeters to tens of meters. Textures indicative of chilling and unidirectional growth may be present. Typically, the sequence of layers, if present, and changes in mineral composition can be used to define igneous stratigraphy within an intrusion and may provide evidence for recharge and open system behavior.

Magmas parental to intrusions that host magmatic sulfide-rich Ni-Cu±PGE deposits, although diverse in major element composition, are generally characterized as olivine-bearing, high-degree mantle partial melts, which are undersaturated in sulfur and relatively enriched in Ni, Cu, and PGE (Keays, 1995; Arndt and others, 2005). In addition, the silicate melts are enriched in most of the strongly incompatible elements, such as K, P, Ba, Sr, Pb, Th, Nb, and light REE (Zhang and others, 2008). They also tend to have relatively high Os contents (≥ 0.03 to 10 ppb), and low Re/Os (< 10) and display trends of Sr-Nd-Pb isotopes that suggest interaction between plume-related magmas and ancient cratonic subcontinental lithospheric mantle (Zhang and others, 2008). Evidence for local crustal contamination can include high Th/Nb and La/Nb ratios, crustal $\delta^{34}\text{S}$, high $^{87}\text{Sr}/^{86}\text{Sr}$, strongly negative ϵ_{Nd} , and elevated Pb

isotope ratios. Depletion in chalcophile elements (for example, high Cu/Pd, low PGE contents) characterizes silicate magmas that have experienced sulfur saturation and separation of an immiscible sulfide liquid.

Petrology of Related Sedimentary and Metamorphic Country Rocks

Magmatic sulfide-rich Ni-Cu±PGE deposits range in age from Archean to Mesozoic and have been emplaced into a broad spectrum of country rock and basement terranes (table 3). However, as noted by Hoatson and others (2006), the presence of Ni-Cu±PGE mineralization shows no obvious correlation with the composition or metamorphic grade of basement rock lithologies. Thus, the importance of the country rocks that host magmatic Ni-Cu±PGE deposits lies not in their chemical composition but in whether the rocks may contribute to sulfur saturation of magma and to the physical controls that country rocks may exert on intrusion dynamics.

Table 3. Comparison of exposed sedimentary and metamorphic country rocks associated with magmatic Ni-Cu±PGE sulfide deposits.

Deposit/Age	Related Sedimentary Rocks	Related Metamorphic Rocks	Metamorphic Grade
Insizwa (South Africa) (183 Ma)	Black shales, calcareous nodules	Hornfels (0.5 m thick)	Contact metamorphism
Wellgreen (Canada) (232 Ma)	Carbonates, volcanoclastics, clastic sedimentary rocks	None	Unmetamorphosed
Noril'sk – Talnakh (Russia) (251 Ma)	Dolomites, limestones, argillites, evaporites, coal seams	Hornfels (100–400 m thick)	Contact metamorphism
Jinchuan (China) (827 Ma)	Shales, limestones	Marbles, gneisses, schists	Upper amphibolite facies (basement rocks) greenschist facies (cover rocks)
Nebo-Babel (Australia) (1,078 Ma)	None	Orthogneisses	Amphibolite to granulite facies
Eagle (United States) (1,109 Ma)	Quartzites, cherts, graywackes, slates	Gneisses, metasediments	Regional greenschist facies
Kabanga (Tanzania) (1,275 Ma)	Sulfide-bearing pelitic rocks (footwall); quartzites, immature clastic rocks, shales (hanging wall)	Muscovite-stauralite-biotite ± garnet schists	Contact metamorphism; country rocks are mid-amphibolite facies
Voisey's Bay (Canada) (1,334 Ma)	None	Orthogneisses, paragneisses	Amphibolite-granulite facies
Pechenga (Russia) (1,977 Ma)	Sandstones, siltstones, tuffs	Phyllites	Greenschist to amphibolites facies

Table 3. Comparison of exposed sedimentary and metamorphic country rocks associated with magmatic Ni-Cu±PGE sulfide deposits.—Continued

Uitkomst (South Africa) (1,977 Ma)	Shales, quartzites, dolomites, chert-conglomerates	Archean granitic gneisses, quartzites	Contact metamorphism, skarn near dolomites
Radio Hill (Australia) (2,892 Ma)	None	Metavolcanic rocks, gneisses, migmatites	Variable, mostly high

In a closed system, fractional crystallization of magma with low sulfur contents will produce only a small volume of sulfide minerals late in a crystallization sequence. To produce sufficient sulfide to form a deposit, an external mechanism is needed to induce sulfur saturation early in the crystallization process (Lightfoot and others, 1984; Arndt, 2005). Two possible external mechanisms have been identified: (1) addition of sulfur to a magma either by bulk assimilation of sulfide- or sulfate-bearing country rocks or by selective uptake by magma of externally derived sulfur as a vapor or fluid phase from surrounding country rocks; or (2) assimilation of felsic wall-rocks during magma ascent, thus increasing the silica content of the magma and thereby reducing sulfur solubility and inducing sulfur saturation (Lightfoot and others, 1984; Hoatson and others, 2006). For some deposits, both mechanisms may have played a role. Li and others (2009) suggested that addition of external sulfur, as well as addition of siliceous material to drive sulfur saturation, were crucial for the development of the sulfide deposits at Noril'sk. Horizontal flow through upper crustal sill complexes can augment the period of interaction between magma and wall-rocks, thereby increasing the extent of contamination and the likelihood of sulfur saturation (Arndt, 2005).

The effect of metamorphism and deformation on magmatic sulfide deposits can be manifested in several ways. First, metamorphism of the country rocks due to emplacement of intrusions may result in the development of skarns and contact aureoles (for example, Noril'sk, Uitkomst). Also, post-emplacement cataclastic metamorphism may remobilize, and possibly disperse, sulfide ores, as in the development of matrix-brecciated sulfides at Pechanga (Naldrett, 2004) or the remobilization of sulfides along shear zones as at the Kabanga deposit (Maier and others, 2010). Finally, deformation may alter the orientation of a deposit.

The physical nature of country rocks may also influence intrusion emplacement styles (Naldrett, 2004). Continental crust is typically stratified with a lower layer of dense granulite-facies rocks, an intermediate layer of lower density granitoid and metamorphic rocks and, in many cases, an upper layer of still less dense sedimentary rocks. This crustal structure helps control the formation of magma chambers as ascending magma tends to become trapped at each density discontinuity (Arndt, 2005). For example, differences in metamorphic grade between packages of rocks may provide a structural contrast or weakness that can allow for emplacement of an intrusion along those structural breaks. One example would be emplacement of intrusions at Jinchuan along a marble/gneiss boundary. In addition, when magma reaches horizontally bedded sedimentary strata in the upper crust, horizontal intrusions and sills tend to form, such as at Noril'sk (Naldrett, 2004).

Theory of Deposit Formation

The formation of magmatic Ni-Cu±PGE sulfide deposits is a consequence of normal crystallization of mafic and ultramafic magmas. However, although separation of an immiscible sulfide liquid is a normal product in the crystallization of most mafic-ultramafic systems, usually only a small quantity of sulfide is found. This is because of limitations on the abundance of sulfur in most magmas and because separation of a sulfide liquid usually is late in the crystallization history when silicate minerals are abundant. The typical result is a small amount of disseminated sulfide minerals among silicate minerals, generally insufficient in quantity and metal tenor to be economic.

There are four critical aspects to the formation of magmatic Ni-Cu±PGE sulfide deposits (Naldrett, 2004):

1. Generation of a metal-bearing mafic or ultramafic parental magma through partial melting in hotter-than-normal parts of the mantle. These magmas generally represent high degrees of partial melting (> 25%), have relatively high MgO contents, and are sulfur-undersaturated during their rise from the mantle and emplacement into the crust (Keays, 1995). Such magmas are a common component in LIPs where picrites and high-MgO basalts are generally present particularly early in the magmatic history.
2. The magma interacts with its crustal wall-rocks during ascent and staging in subcrustal magma chambers. Such interaction can form hybrid or contaminated magma and commonly results in incorporation of crustal sulfur. Both processes can result in driving the magma to sulfur saturation and the generation or segregation of an immiscible sulfide liquid (Li and others, 2001). For the efficient accumulation of massive sulfide, it is important that sulfide saturation and sulfide liquid segregation occur early in the crystallization sequence before abundant silicate minerals crystallize and trap the sulfides. In addition, early sulfide saturation is necessary to form typical nickel sulfide ore. This is because significant olivine crystallization prior to formation of an immiscible sulfide liquid will deplete a silicate liquid in Ni, thus limiting the quantity of Ni available to a sulfide liquid (Naldrett, 2004).
3. The resulting immiscible sulfide liquid has an opportunity to interact dynamically with a much larger mass of silicate magma, thereby increasing the tenors of the ore metals, particularly for the strongly chalcophile elements that have very large partition coefficients between sulfide liquid and silicate magmas (Mungall, 2005). The Ni, Cu, and PGE contents of many ores are much higher than would be expected of sulfide that had separated from the relatively small quantity of magma represented by their host intrusions (Campbell and Naldrett, 1979). Therefore, sulfide liquid must have interacted with, and extracted ore metals from, a much larger volume of silicate magma. Such upgrading is enhanced in magma conduit systems where sulfide can interact with new pulses of undepleted magma (Maier and others, 2001). However, exactly how sulfide liquid and new pulses of magma interact is not clear and may vary from deposit to deposit.
4. Finally, metal-rich sulfide liquid becomes concentrated in a restricted locality in a quantity sufficient to form an economic deposit (Maier and others, 2001). Structural traps, where the flow velocity of magma is reduced, appear to be important sites for the collection of sulfides. This includes embayments in the footwall, where dense sulfide liquid can migrate downward along the axis of the embayment and down the flanking

sides (Noril'sk-Talnakh; Diakov and others, 2002) and where a narrow feeder conduit enters a larger intrusion, resulting in a decrease in flow velocity and the preferential concentration of sulfide droplets (Voisey's Bay; Li and others, 2000).

Exploration and Resource Assessment Guides

Regional geological guides

1. An LIP with evidence of primitive Mg-rich melts and large volumes of tholeiitic magmatic rocks occurring on or near the edges of ancient cratons.
2. Province boundaries, rifts, and deeply penetrating faults that can allow for efficient transport of magma through the crust.
3. Small- to medium-sized differentiated mafic and (or) ultramafic dikes, sills, chonoliths and plug-like intrusions. Deposits are generally not hosted in thick, large-layered intrusions.
4. Sulfur-bearing (sulfide and (or) sulfate) crustal rocks.

Local geological guides

1. Clusters of small- to medium-sized, generally mafic-dominated tholeiitic intrusions with ultramafic rocks, if present, generally concentrated in the lower parts of the intrusion. However, intrusions related to picrites may be wholly or dominantly ultramafic.
2. Massive or layered intrusions with variably textured rocks and (or) magmatic breccias. Intrusions can exhibit changes in texture and mineralogy on a variety of scales (a few centimeters to tens of meters) with cumulus-, equigranular-, intergranular-, and (or) subophitic-textured rocks.
3. Laterally extensive contact metamorphism and (or) metasomatism of country rocks near intrusions.
4. Local evidence of crustal contamination and (or) chalcophile element depletion in intrusions and (or) related volcanic rocks. Widespread evidence of contamination and (or) chalcophile element depletion may reflect source characteristics or magma contamination in the lower crust.
5. Significant changes in dip and width along the strike of an intrusion, indicating sites of possible changes in magma flow dynamics. Changes in the dynamics of magma flow (slow, fast, or turbulent flow) and conduit geometry (changes from narrow vertical conduits to subhorizontal broad magma chamber; physical traps) are important factors for the precipitation and accumulation of massive sulfide.
6. Evidence for a dynamic, open, periodically replenished magmatic system, such as magmatic breccias, reversals in fractionation indicators, and changes in chalcophile element contents.
7. Presence of massive, matrix, and disseminated Fe-Ni-Cu-Co-bearing sulfide minerals in the lower parts of intrusions and Cu-Pd-Pt-Au-enriched sulfide minerals either stratigraphically above Cu-poor sulfides or as footwall dikes and veins that provide evidence of remobilized and fractionated sulfide liquid. Massive sulfides typically are confined to structural embayments and depressions along the basal contacts of intrusions

or in feeder conduits. Therefore, determination of the base of a given intrusion is an important criterion in exploration targeting, particularly in deformed terranes.

8. Because massive sulfides are incompetent and concentrate stress during deformation, they may be displaced significant distances (≥ 1 km) from their host intrusions. Therefore, country rocks surrounding sulfide-bearing intrusions should also be investigated in strongly deformed terranes.

Exploration methods

1. Exploration using geophysics must be tailored to a study area on the basis of factors such as the maximum depth of detection and physical properties of the overburden, intrusions, host lithologies, and mineralization. Regional aerial magnetic and gravity surveys are used to identify prospective areas of LIPs showing the regional characteristics noted above and to determine the extent, geometry, and basal contacts of intrusions. At district to local scales, ground magnetics are used to delineate lithologic layering and identify small-scale structural embayments and depressions along the basal contact of intrusions. Airborne and ground electromagnetics and induced polarization are used to identify and delineate conductive sulfides.
2. Stream sediment and soil geochemistry can be useful if intrusions are exposed or are in subcrop. Lithochemical study of prospective intrusions for S, Cu, Ni, PGE contents, as well as Cu/Pd ratio and Mg-number helps to determine stratigraphic variations and the occurrence of sulfur-saturation events.
3. Composition of olivine (Ni content versus Mg-number) can be used as an indicator of nickel depletion in magmas from which the olivine has crystallized.
4. Evidence for crustal contamination and (or) sulfur addition can be determined from S, O, Sr, Nd, Pb, and Os isotopes; high Th/Nb, and La/Nb ratios, and enriched light REE and alkali contents; hybrid rocks; and xenoliths of country rock and (or) xenocrysts.
5. Unusual gossan chemistry and mineralogy, such as high Bi, Pt, Pd, and Ir or the presence of chalcopyrite stringers and Ni-carbonates, can distinguish unmineralized pyritic gossans from gossans developed on Ni-Cu±PGE deposits.
6. Closely spaced drilling, particularly of basal contacts and feeder conduits, as well as down-hole geophysics, such as time-domain electromagnetics, mise-a-la-masse methods, and radio imaging methods can help direct exploration toward the most mineralized parts of the intrusion (Diavok and others, 2002).

Geoenvironmental Features

The geoenvironmental features of magmatic Ni-Cu±PGE sulfide deposits arise from the mineralogy of the ore deposits and their mine wastes, the mining and ore-processing methods used to exploit them, and the local hydrologic and climatic characteristics of individual deposits. Common gangue minerals associated with mine waste from magmatic Ni-Cu deposits include olivine, orthopyroxene, clinopyroxene, plagioclase, magnetite, ilmenite, quartz, chlorite, and minor amounts of calcite or dolomite. Common sulfide minerals include pyrrhotite, pyrite, chalcopyrite, and pentlandite. The environmental characteristics of these deposits are dominated by their significant acid-generating potential, due to the abundance of pyrrhotite, and their limited acid-neutralizing potential due to the general absence of carbonate minerals in their

mineralization, alteration, and host rock assemblages. Acid generated by the oxidative weathering of pyrrhotite can attack associated ore sulfide minerals and gangue silicate minerals, releasing a variety of potentially toxic elements, particularly Fe, Cu, Ni, Co, and Mn, and to a lesser extent Al, Cd, Zn, Cr, and Pb, to solution or to secondary solid phases (McGregor and others, 1998; Johnson and others, 2000).

In terms of pre-mining geochemical baselines, magmatic Ni-Cu±PGE sulfide deposits are geochemical anomalies that can express themselves in groundwater, surface water, and soil. Near the buried Eagle deposit, northern Michigan, maximum concentrations of Fe (190 µg/L), Ni (59 µg/L), and Zn (88 µg/L) in groundwater near the deposit reflect the presence of the ore body, whereas all concentrations of Cu (<5 µg/L) and Co (<10 µg/L) are below detection limits. In contrast, the concentrations of Cu, Ni, and other trace elements in surface waters are indistinguishable from background due to the buried nature of the deposit (Kennecott Eagle Minerals, 2006). The concentrations of various metals, such as Cu and Ni, in soils are also indistinguishable from regional background. In contrast, the geochemical signatures in deflation lag and soil samples in the vicinity of the outcropping Babel and Nebo deposits, central Australia, have anomalous concentrations of Ni, Cu, Pt, Pd, and Au (Baker and Waugh, 2005).

The dominance of pyrrhotite in mine tailings results in waste material with a high acid-generating potential. The minor presence of carbonate minerals in the ore assemblage and the lower reactivity of neutralizing minerals such as olivine or pyroxene offer minimal short-term acid neutralizing potential, although some may be realized over longer timeframes from olivine and pyroxene. Massive sulfide ore from the Eagle deposit is typified by a mean acidic net-neutralizing potential (NNP) of -1111 kilograms (kg) CaCO₃ per tonne (t) of waste; the mean NNP of semi-massive sulfide ore at Eagle is -378 kg CaCO₃/t (Kennecott Eagle Minerals, 2006). The NNP of mineralogically similar tailings from Sudbury is similar (McGregor and others, 1998; Johnson and others, 2000).

Mine drainage from abandoned and active mines shows a strong link with the underlying geology of the mineral deposits. Johnson and others (2000) documented the generation of low pH (as low as 3.0) waters with dissolved concentrations of as much as 9.8 g/L Fe, 24 g/L SO₄²⁻, 1,130 mg/L Al, and 698 mg/L Ni in groundwater in the tailings pile at the Nickel Rim mine, Sudbury. As much as 3.5 mg/L Cu and 2.5 mg/L Co were also measured. Similarly, for groundwater and surface water in the vicinity of the Hitura mine, western Finland, Heikkinen and others (2002) found variable pH waters (2.8 to 8.7), with a range of dissolved Fe (< 0.02 to 330 mg/L), Al (< 0.01 to 20.4 mg/L), Mn (< 0.01 to 19.5 mg/L), Cd (< 0.2 to 1,120 µg/L), Co (< 0.03 to 2,610 mg/L), Cu (< 0.01 to 7.51 mg/L), Ni (< 0.02 to 2,860 mg/L), Pb (< 0.05 to 0.11 mg/L), Zn (< 0.05 to 760 mg/L), and sulfate (< 1 to 17,250 mg/L) concentrations.

The geochemistry of soils near developed magmatic Ni-Cu±PGE sulfide deposits can reflect the combined influences of mining and smelting activities. Surrounding the extensive mining district at Sudbury, elevated concentrations of Cd (< 0.06 to 10.1 mg/kg), Co (0.9 to 113.3 mg/kg), Cu (11.4 to 1,891 mg/kg), Ni (5.3 to 2,149 mg/kg), and Zn (1.5 to 336 mg/kg) have been documented in soils (Dudka and others, 1995). Likewise, residential soils in the Noril'sk mining district have significant maximum concentrations of Co (1,229 mg/kg), Cu (16,000 mg/kg), Ni (2,915 mg/kg), and Zn (172.4 mg/kg) (Yakovlev and others, 2008).

Ecosystem risks associated with magmatic Ni-Cu±PGE sulfide deposits center around acid-mine drainage and the associated leaching of metals. Metal concentrations described above all exceed aquatic ecosystem guidelines. Human-health risks include drinking water and soils. The maximum concentrations in surface water and groundwater for Ni, Cu, Pb, and Zn all

exceed drinking water guidelines. Likewise, the maximum concentrations of Cu and Ni exceed residential soil guidelines.

Climate can play an important role in determining the behavior of mine waste associated with magmatic Ni-Cu sulfide deposits. Meldrum and others (2001) found that permafrost conditions, such as those found in Arctic Canada, can greatly reduce the oxidation rate of sulfide-rich mine wastes and the associated generation of acid drainage.

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