

MAGMATIC SULFIDE DEPOSITS **(MODELS 1, 2b, 5a, 5b, 6a, 6b, and 7a; Page, 1986a-g)**

by Michael P. Foose, Michael L. Zientek, and Douglas P. Klein

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Magmatic sulfide deposits are sulfide mineral concentrations in mafic and ultramafic rocks derived from immiscible sulfide liquids. A number of schemes exist for subdividing these deposits. Most are based on the tectonic setting and petrologic characteristics of the mafic and ultramafic rocks (Page and others, 1982; Naldrett, 1989), or on the spatial association of mineralized rock with enclosing ultramafic and mafic host rocks (stratabound, discordant, marginal, and other; Hulbert and others, 1988). Page (1986a-g) presented discussions of several different subtypes based, in part, on both these approaches (Models 1, 2b, 5a, 5b, 6a, 6b, and 7a). However, these deposits are similar enough that they can be treated as a group with regard to their geoenvironmental manifestations.

The similarity of these deposits result, in part, from similar genesis. Exsolution of immiscible sulfide liquids from mafic-to-ultramafic magmas is the fundamental process that forms magmatic sulfide deposits. Once formed, droplets of immiscible sulfide liquid settle through less dense silicate magma. The sulfide liquid acts as a "collector" for cobalt, copper, nickel, and platinum-group elements (PGE) because these elements are preferentially concentrated in sulfide liquids at levels 10 to 100,000 times those in silicate liquids. To a lesser degree, iron is also preferentially partitioned into the sulfide liquid and, because of its greater abundance, most immiscible sulfide liquid is iron-rich.

The combination of physically concentrating dense sulfide liquid and chemically concentrating elements in the sulfide liquid is responsible for forming most economically minable, magmatic-sulfide deposits. Magmatic sulfide ore is typically associated with: (1) abrupt variations in the cumulus-mineral succession, including major lithologic changes, reversals or changes in crystallization order, discontinuities in mineral fractionation patterns and cyclic units, (2) rocks near the lower contact of an intrusion that may contain country rock xenoliths and may be characterized by irregular variations in grain size, mineralogy, and texture, (3) rocks near the base of a flow, or (4) pegmatoids and rocks enriched in minerals that crystallize late from silicate magmas. However, for the purposes of developing a geoenvironmental model for this group of deposits, the principal variables are the composition of the host rocks, the abundance and types of sulfide minerals, and (to a much lesser extent) sulfide mineral composition. General characteristics for the deposit subtypes described by Page (1986a-g) are listed in table 1.

Examples

Magmatic sulfide minerals concentrated near the margins of intrusions:

- Stillwater nickel-copper (Model 1)-Mouat deposit, Stillwater Complex, Mont. (Zientek, 1993); Vaaralampi deposit, Suhanho-Konttjarvi intrusion, Finland (Alapieti and others, 1989)
- Duluth Cu-Ni-PGE (Model 5a)-Dunka Road deposit, Duluth Complex, Minn.; Great Lakes nickel deposit, Crystal Lake Gabbro, Ontario, Canada (Eckstrand and others, 1989)
- Synorogenic-synvolcanic Ni-Cu (Model 7a)-Brady Glacier deposit, La Perouse Intrusion, Alaska; Big Indian Pond, Moxie intrusion, Maine
- Noril'sk Cu-Ni-PGE (Model 5b)-Medvezhy Creek deposit, Noril'sk and Oktybr'sky deposit, Talnakh; Russia
- Impact-related intrusions-Sudbury Complex, Canada

Stratiform concentrations of disseminated magmatic sulfide minerals in layered intrusions:

- Merensky Reef PGE (Model 2b)-Merensky Reef, Bushveld Complex, Republic of South Africa (Naldrett and others, 1987); J-M Reef, Stillwater Complex, Mont. (Todd and others, 1982)

Magmatic sulfide mineral and PGE concentrations at or below impermeable layers:

- No model-Picket Pin deposit, Stillwater Complex, Mont. (Boudreau and McCallum, 1986)

Pegmatoidal lenses, pipes, and other discordant mineralization:

- No model-Vlakfontein nickel pipes, Bushveld Complex, Republic of South Africa (Vermaak, 1976); Janet 50 zone, Stillwater Complex, Mont. (Volborth and Housley, 1984)

Magmatic sulfide minerals concentrated in ultramafic volcanic rocks:

- Komatiitic Ni-Cu (Model 6a)-Kambalda deposits, Australia
- Dunitic Ni-Cu (Model 6b)-Mount Keith deposit, Australia

Magmatic sulfide minerals concentrated in ultramafic cumulates in ophiolite complexes:

- No model-Acoje, Philippines; Kraste, Albania

Table 1. General features of different magmatic sulfide deposit types. (Model numbers from Page, 1986a-g)

Deposit Type	Model no.	General description	Sulfide mineral abundance composition	Sulfide mineral	Size	Host rock
Still-water Ni-Cu	1	Disseminated to massive sulfide concentrations in mafic and ultramafic rocks at the base of large layered intrusions	Disseminated to massive	Fe>Ni>Cu	Small pods to large deposits that may exceed 100 million tons	Ultramafic and mafic
Meren-sky Reef	2b	Thin (1-5 m) disseminations of sparse (1-5 percent) sulfide minerals in mafic (gabbroic and troctolitic) rocks within the main body of large, layered intrusions	Disseminated	Fe-Ni-Cu PGE	Thin zones that may extend laterally for over 100 km. Individual mines within these zones often report reserves greater than 100 million tons	Mafic
Duluth Cu-Ni-PGE	5a	Disseminated to massive concentrations in mafic to ultramafic rocks in the basal parts of rift-related intrusions	Mostly disseminated, some massive	Fe>Cu>Ni	Small massive pods to disseminated bodies containing as much as several hundred million tons of ore	Mostly mafic, lesser ultramafic
Noril'sk Cu-Ni-PGE	5b	Disseminated sulfide in lower third, and massive sulfide near base of complex, subvolcanic, elongate intrusions less than 350 m thick	Extensive disseminated and massive ore	Fe>Cu>Ni>PGE	Disseminated deposits tens of meters thick over entire area of intrusion; Massive sulfide orebodies as much as 45 m thick and 2.5 km ² in area	Mafic, ultramafic, and meta-sedimentary
Komatiitic Ni-Cu	6a	Mostly massive, lesser disseminated, sulfide deposits at the base of Archean or Proterozoic ultramafic, komatiitic flows	Mostly massive, minor disseminated	Fe>Ni	Generally deposits less than 2 million tons; median size is 1.6 million tons	Ultramafic
Dunitic Ni Cu	6b	Disseminated sulfide deposits within Archean or Proterozoic komatiites	Disseminated	Fe>Ni	Large low grade deposits with median size about 30 million tons	Ultramafic
Syn-orogenic-syn-volcanic Ni-Cu	7a	Disseminated to massive sulfide deposits in the basal parts of mafic to ultramafic intrusions that were emplaced during orogenesis	Disseminated to massive	Fe>Cu>Ni	Generally fairly small, median size of about 2 million tons	Mostly mafic, lesser ultramafic

Spatially and (or) genetically related deposit types

Associated deposit types (Cox and Singer, 1986) include asbestos (Model 8d); soapstone; greenstone gold (Model 36a); Bushveld chromite (Model 2a); podiform chromite (Model 8a), Bushveld iron-titanium-vanadium (Model 3), platinum group element placer (Model 39a), nickel laterite (Model 38a).

Potential environmental considerations

- (1) Mining exposes sulfide minerals that have significant acid generating potential.
- (2) Metals associated with sulfide (particularly iron sulfide) ore may contaminate ground and surface water.
- (3) Some deposits are extremely large and development may involve ground disturbance throughout large areas.
- (4) Sulfur dioxide may be vented to the atmosphere during sulfide ore smelting; downwind acid and toxic metal

abundances may be enhanced.

(5) Significant amounts of sulfide-mineral-bearing tailings and slag are produced; these must be isolated from surface and ground water.

Many magmatic sulfide deposits are quite large or form groups that define large mining districts. Past mining of some of these deposits or districts has produced some well-known examples of severe environmental impact. The impact associated with mining in the Sudbury district (Canada) is probably the best documented; the severe environmental degradation associated with the Noril'sk district (Russia) is less well known. However, implementation of new pollution-control techniques and aggressive efforts at environmental remediation have substantially improved the environment around the Sudbury district. Recently permitted and currently ongoing mining of the palladium-platinum deposit in the Stillwater Complex, Mont., demonstrates that operations extracting ore from these deposits can meet the most rigorous modern environmental standards.

Exploration geophysics

Interconnected sulfide minerals produce electrically conductive zones that can be located with induced polarization, electromagnetic, and magneto-telluric surveys. Some of these deposits may be identified by magnetic surveys because they may contain abundant magnetite. Magnetite is also abundant in most mafic host rocks and may indicate regional targets or be a source of "noise" in mineral exploration. Large sulfide mineral masses may be located by seismic refraction. Sulfide-mineral concentrations and their mafic and ultramafic host rocks may be associated with mass excesses that can be identified by gravity surveys. Remote sensing may help identify areas in which ore is present. In particular, band ratioing can be used to identify gossans; more generally, images can be used to identify geologic settings that are favorable for the concentration of ore.

References

Naldrett (1979, 1981, 1989), Lightfoot and Naldrett (1994).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Deposit size ranges widely (table 1).

Host rocks

Host rocks are predominantly mafic to ultramafic igneous rocks. Occasionally significant ore is in footwall country rocks of diverse metasedimentary or meta-igneous origin and composition.

Surrounding geologic terrane

Deposits are in diverse geologic settings, including (1) deformed greenstone belts and calc-alkaline batholiths associated with convergent plate margins, (2) ophiolite complexes that formed at constructive plate margins, (3) intraplate magmatic provinces associated with flood-basalt type magmatism, and (4) passively rifted, continental margins.

Wall-rock alteration

Hydrothermal alteration related to ore-forming processes is generally not significant for magmatic sulfide deposits. Many deposits and host rocks have experienced varying amounts of alteration either as a result of deuteritic processes, metamorphism, or weathering. Primary silicate mineralogy consists of varying proportions of calcic plagioclase, orthopyroxene, clinopyroxene, and olivine. Brown amphibole and biotite may be minor accessory phases. Trace amounts of quartz, apatite, and potassium feldspar may be present. In most cases, alteration involves development of hydrous phases. Systematic alteration zoning may be developed adjacent to faults or fractures that focus fluid flow. Olivine is the phase most likely to be altered; alteration of plagioclase and pyroxene is somewhat less likely. Olivine is typically altered to serpentine minerals, magnetite, and minor calcite. Plagioclase is altered to epidote, clay minerals, sericite, and calcite. Pyroxenes are altered to actinolite/tremolite, serpentine, talc, and chlorite. Biotite is altered to chlorite.

Nature of ore

Sulfide minerals may be concentrated in structurally low areas at the base of intrusions or flows (fig. 1) or may be in zones where silicate magma interacted with xenoliths. Sulfide mineral concentrations in layered, cumulate

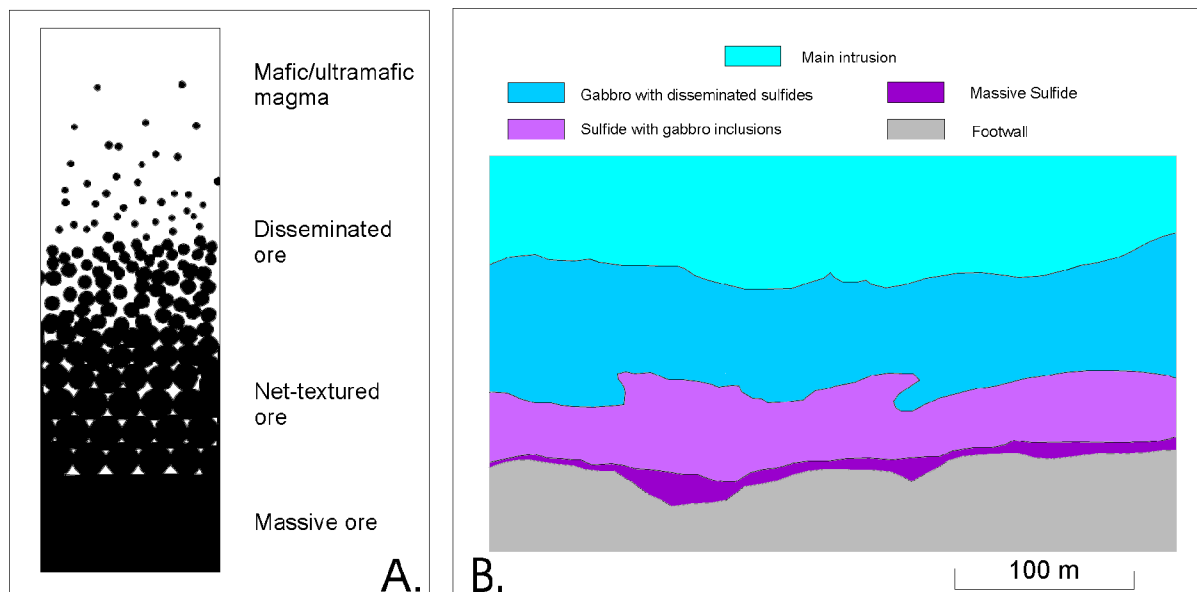


Figure 1. A, Schematic section of a magmatic sulfide deposit showing the vertical gradation downward from disseminated to massive ore. B, Generalized map showing massive sulfide mineral concentrations in footwall embayments of the Sudbury Complex (Canada).

sequences may be related to major lithologic features such as cyclic-unit boundaries, unconformities, chromite seams, pegmatoids, or stratigraphic intervals characterized by major changes or discontinuities in cumulus minerals.

Deformation and alteration can remobilize sulfide minerals into breccia ore and segregate sulfide minerals into fractures, cleavage planes, and veins. Remobilized sulfide-mineral assemblages may be copper-rich relative to sulfide mineral assemblages that are not remobilized. Sulfide-mineral assemblages that appear to have precipitated from fluids moving through fault zones or along joint surfaces are dominated by pyrite.

Deposit trace element geochemistry

Primary abundance variations of nickel, copper, and platinum group elements in magmatic-sulfide ore are controlled by the composition of the silicate magma and the mass ratio of silicate to sulfide liquid (Naldrett, 1989). In addition to sulfur, iron, nickel, copper, cobalt, and the platinum group elements (platinum, palladium, rhodium, ruthenium, iridium, and osmium), these sulfide minerals may contain minor Ag, As, Au, Bi, Hg, Pb, Sb, Se, Te, and Zn. Compositions of immiscible sulfide liquids are also affected by fractional crystallization of the host magma, which affects the concentrations of metals in the magma, and oxygen fugacity, which affects partition coefficients. Fractional crystallization of sulfide melt may result in sulfide mineral cumulates that are enriched in iron, cobalt, iridium, ruthenium, and rhodium and a residuum that is enriched in copper, palladium, platinum, gold, and other minor elements, including arsenic, bismuth, tellurium, and antimony (Naldrett, 1989; Zientek and others, 1990). Subsolidus equilibration of sulfide minerals with the enclosing silicate-rich or oxide-rich rock may modify bulk compositions of the sulfide-mineral assemblages Naldrett (1989); the greatest change occurs for small (tens of microns), scarce sulfide mineral inclusions in silicate or oxide minerals.

Three additional geologic factors control ore composition. First is the ratio of silicate host rock (mostly olivine, pyroxene, and plagioclase) to sulfide minerals. Silicate minerals are gangue that dilutes ore; as silicate abundance increases, ore grade decreases. Second is the composition of the magma from which the sulfide minerals separated. Ultramafic magmas produce sulfide ore with higher nickel-copper ratios than mafic magmas. Third is the relative abundance of the original immiscible sulfide liquid. Separation of relatively large amounts of immiscible sulfide liquid causes large amounts of iron to be extracted from the silicate magma, in addition to removal of less abundant nickel, copper, and platinum-group elements. Such ore is usually iron rich, but has low nickel, copper, and platinum-group element grades. Representative compositions of ore from several different deposits are shown in tables 2 and 3. Compositions in table 2 are recalculated to 100 percent sulfide minerals; silicate gangue causes measured ore grades to be significantly lower. Detailed mineralogic studies show that magmatic sulfide minerals (primarily pyrrhotite, pentlandite, and chalcopyrite) from the Noril'sk district, Russia, contain trace metals in the

Table 2. Representative major element compositions from some magmatic sulfide deposits normalized to 100 percent sulfides (after Naldrett, 1989). [Ni, Cu, and Co weight percent; Pt and Pd, ppb. ---, no data]

Deposit/ magma type	Ni	Cu	Co	Pt	Pd
Langmuir/ ultramafic	14.6	.67	.27	890	1,600
Katiniq/ ultramafic	10.5	3.7	.23	4,130	15,530
Merensky Reef/ mafic	10.9	4.65	---	279,000	120,000
Falconbridge/ mafic	5.35	1.52	.17	2,130	3,170
Noril'sk/ mafic	9.0	10.8	---	18,000	47,000
Minnimax/ mafic	3.91	17.2	.37	2,640	8,840

Table 3. Representative trace element compositions of magmatic ore. [Sulfur, weight percent; all others, ppm]

Deposit	S	Pd	Pt	Te	Bi	As	Sb	Hg	Sn
J-M Reef ¹	<0.01 1.64	0.38 182	0.33 51.6	0.03 17	<0.01 20	0.18 16.2	<0.05 1	<0.01 0.16	0.3 1.3
MSZ ²	0.36 2.8	0.088 3.1	0.26 6.1	0.35 4.8	0.62 5.8	0.42 2.2	<0.05 0.22	<0.01 0.38	0.30 0.60
Noril'sk- Talnakh Cu-poor ³	1.46 37	1.65 63	0.42 64	1 11	0.32 3.3	-- --	0.15 0.96	-- --	1.1 9.8
Noril'sk- Talnakh Cu-rich ³	31.9 34	140 583	41.8 --	22 210	5.5 42	-- --	0.285 4.85	-- --	15.7 84.5

¹ Median values of drill core from 3800 W stope of Stillwater Mine, J-M Reef (Zientek and others, 1990). Maximum values in second row.

² Median values of two intercepts through the Main Sulfide Zone, Great Dyke, Zimbabwe (Zientek and Wilson, unpub. data). Maximum values in second row.

³ Median values of all ore samples, Noril'sk Talnakh district (Zientek, unpub. data). Maximum values in second row.

approximate ranges of 60 to 650 ppm zinc, 130 to 390 ppm selenium, 11 to 210 ppm silver, 8 to 35 ppm cadmium, 15 to 35 ppm tin, 19 to 390 ppm tellurium, 150 to 690 ppm lead, and as much as 60 ppm gallium and 30 ppm indium (Czamanske and others, 1992).

Ore and gangue mineralogy and zonation

Sulfide-mineral ore assemblages, dominated by pyrrhotite, pentlandite, and chalcopyrite, result from solid-state recrystallization of high-temperature sulfide minerals. These three minerals are the principal acid generating phases in magmatic sulfide deposits and their proportions are determined by the initial bulk composition of the immiscible sulfide liquid. The sulfide mineral content of these ore deposits varies from less than ten to more than sixty percent.

Magnetite is commonly intergrown with the sulfide minerals. Minor phases include platinum-group-element minerals (sulfide, arsenide, telluride, antimonide, and alloy minerals), nickel- and cobalt-bearing arsenide minerals (for example gersdorffite), galena, sphalerite, and gold, silver, and lead telluride minerals.

Gangue mineralogy is the same as that of the host and consists primarily of plagioclase, orthopyroxene, clinopyroxene, and olivine. Minor, secondary phases include serpentine minerals, talc, magnetite, calcite, epidote, sericite, actinolite, chlorite, tremolite, and clay minerals.

Mineral characteristics

The mineralogy and textures of sulfide ore record a prolonged and complex process starting with solidification of the sulfide liquid, either as an iron-nickel-rich or an iron-copper-rich solid solution and continuing solid-state transformation and recrystallization; these textures can be substantially modified by alteration and weathering. Iron, nickel, and copper phases are commonly intimately intergrown.

When not modified by weathering or alteration, the textures of silicate and sulfide minerals record the distribution and abundance of the sulfide liquids and the interaction between solid silicate minerals and molten sulfide liquid. In rocks with less than 10 volume percent sulfide minerals (disseminated ore), sulfide minerals form fine (<1 mm)- to coarse-grained (>5 mm) droplet-shaped aggregates that are molded around and interstitial to the cumulus or earlier-formed silicate minerals or may be present as fine-grained, rounded aggregates enclosed in cumulus minerals. In rocks containing 10 to 60 volume percent sulfide minerals (matrix ore), aggregates of sulfide minerals are interstitial to earlier-formed silicate minerals but are interconnected. In rocks with more than 60 volume percent sulfide minerals (massive ore), sulfide minerals form the matrix of the rock.

The bulk sulfur content of sulfide-mineral aggregates is between 34 and 40 weight percent; the remaining 60 to 66 weight percent is mostly iron, plus copper and nickel. Consequently, the molecular-metal-sulfur ratio of magmatic sulfide minerals is relatively constant at about 1:1. In contrast, pyrite has a metal-sulfur ratio of 1:2. Therefore, magmatic sulfide ore has a much more restricted acid-generating capacity than ore that contains substantial pyrite.

Secondary mineralogy

Minerals that may form during alteration and weathering of sulfide minerals include violarite, bornite, mackinawite, cubanite, pyrite, marcasite, troilite, vaesite, smythite, polydymite, millerite, hematite, and magnetite. In supergene environments, chalcocite, malachite, native copper, cuprite, nickel-iron carbonate, nickel- and nickel-iron hydroxycarbonate, and nickel-silicate minerals may form. Gossans commonly form above sulfide-rich rocks.

Topography, physiography

Magmatic-sulfide deposits do not have diagnostic topographic or physiographic characteristics.

Hydrology

Many deposits form stratiform sheets and lenses, near the bottoms of intrusions or flows, that could localize ground water flow. However, no known consistent relation between magmatic sulfide ore and hydrologic controls are known.

Mining and milling methods

These deposits have been and are being mined both by underground and by open-pit methods. Underground mining is currently in progress at platinum-group-element deposits of the Stillwater, Mont., and Bushveld, South Africa, complexes and the komatiite-hosted nickel deposits in the Kambalda, Australia, district. Deposits being mined both by open pit and underground methods include those in the Sudbury Complex, Canada, the Manitoba, Canada, nickel belt, and the Noril'sk-Talnakh, Russia, district. Subsequent to mining, most ore is ground and concentrated by flotation, gravity, or magnetic methods to form either a bulk sulfide mineral concentrate or separate copper- and nickel-rich concentrates. Pyrrhotite-rich (iron-rich) concentrates at Noril'sk are being stored for later processing. Gravity concentrates may be sent directly to refineries, but most ore is smelted to separate iron-rich slag from nickel- and copper-rich matte. This matte is then refined by a variety of processes to extract nickel, copper, and platinum group elements. Pyrrhotite-rich concentrates may be treated by hydrometallurgical techniques.

Table 4. Composition of drainage water associated with Duluth and Stillwater Complex sulfide deposits (SCS Engineers, 1984; Feltis and Litke, 1987; Ritchie, 1988). Data in $\mu\text{g/l}$; --, no data.

	pH	Cu	Ni	Co	Zn
Duluth	6.4-7.7	1,800	40,000	2,400	2,400
Duluth	4.5-6.8	22,000	38,000	--	--
Duluth	6.4-7.1	900	9,000	900	200
Duluth	7.2	53	2,420	21	40
Stillwater	7.9	32	180	--	<3

ENVIRONMENTAL SIGNATURES

Drainage signatures

Studies show that the aqueous concentrations of nickel, copper, iron, and cobalt are largely controlled by their absorption on hydrous oxide minerals of iron and manganese (Richter and Theis, 1980). Estimates indicate that of the nickel transported by major rivers, 0.5 percent is in solution, 3.1 percent is adsorbed, 47 percent forms precipitated coatings, 14.9 percent is in organic matter, and 34.4 percent is crystalline material (Snodgrass, 1980; Nriagu, 1980). Only about 1 percent of copper in surface water is transported in a soluble form, while about 85 percent is moved as particulate crystalline phases, 6 percent is bound to metal hydroxide coatings on particles, 5 percent is associated with organic material, and 3 percent is adsorbed onto suspended particles (Nriagu, 1979).

Some of the limited data available for water draining unmined and mined deposits associated with mafic or ultramafic rocks are presented in table 4. The data include analyses of water that drains naturally exposed sulfide minerals at the base of the Stillwater, Mont., Complex and that from four different mining sites in the Duluth, Minn., Complex. The data from table 4 are plotted on a "Ficklin" diagram (fig. 2). Despite the fact that this water was analyzed for only a few of the metals typically reported on this plot, the analyses show quite high metal concentrations, especially for water that has a relatively neutral pH.

Additional information indicates that water discharged from some bulk-ore sample sites in the Duluth Complex contains nickel, copper, cobalt, and zinc abundances as much as 400 times baseline abundances (Eger and Lapakko, 1989); one study reports as much as 700 $\mu\text{g/l}$ copper and nickel in contaminated water, whereas adjacent ground water contained less than 25 $\mu\text{g/l}$ metal (Siegel and Ericson, 1980). Best- and worse-case water quality estimates were made for emissions from test pits and ore stockpiles as part of a regional environmental study. Estimates for the combined abundances of copper, nickel, cobalt, and zinc were between 107 and 6,610 $\mu\text{g/l}$ for

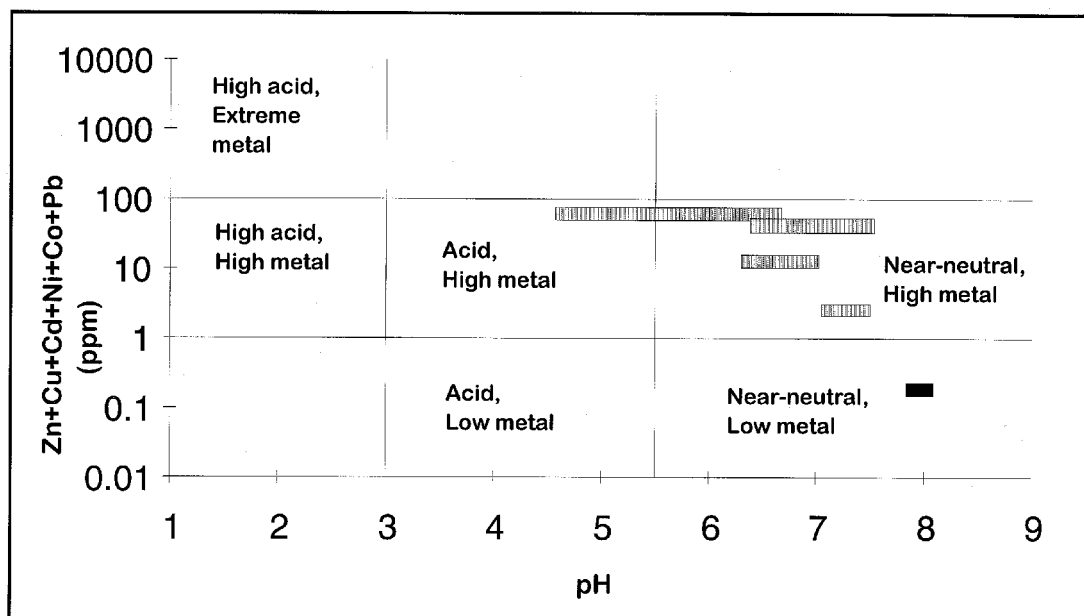


Figure 2. Plot of partial water analyses from the Duluth complex (striped) and Stillwater complex (solid).

discharges from tailings basins, 2,534 to 46,310 µg/l for emissions from ore stock piles, and 125 to 46,840 µg/l for mine water (Ritchie, 1988). "Mine water" used to simulate environmental effects related to the Duluth Complex in remediation studies has a pH of 4.5 and contains 2,000 µg/l sulfate and between 50 and 1,000 µg/l nickel (Hammack and Edenborn, 1992). Laboratory study of Duluth Complex ore (Lapakko and Antonson, 1994) has demonstrated a direct correlation between ore sulfur content and pH of associated drainage water. Drainage water associated with ore that contains 0.18 to 0.4 weight percent sulfur has a pH of 6.1, water associated with ore that contains 0.41 to 0.71 weight percent sulfur has a pH between 4.8 and 5.3, and water associated with ore that contains 1.12 to 1.64 weight percent sulfur has a pH between 4.3 and 4.9. Finally, a study of Sudbury ore from the Nickel Rim nickel-copper tailings impoundment demonstrates a well-developed vertical gradient within tailings water compositions. Water draining the uppermost part of the tailings has low pH (2.1 to 3.5), whereas that draining the basal part of the tailings, where acid-consuming minerals are more abundant, has a pH of about 6.5. The nickel abundance of tailings water is sensitive to pH; nickel abundances change from 250,000 µg/l to less than 10,000 µg/l as pH increases from 4.5 to greater than 5.8 (Blowes and Ptacek, 1994).

Metal mobility from solid mine wastes

Magmatic sulfide deposits may contain widely variable amounts of sulfide minerals. As a generalization, deposits may be separated into two groups. Platinum-group-element-rich deposits in large, layered intrusions tend to have low sulfide mineral abundances (1 to 5 weight percent) and low total-metal abundances. Consequently, they have a relatively restricted capacity to generate significant amounts of acidic and (or) metal-enriched drainage. Most of the other economically extractable magmatic-sulfide deposits contain substantial amounts of sulfide minerals (most greater than 15 weight percent, many exceeding 40 weight percent) and large metal abundances. They have significantly greater potential for generating acid and (or) metal-enriched drainage.

The limited data summarized in figure 2 are for deposits with high sulfide mineral concentrations. Mine water may contain high concentrations of metals, even when pH is near neutral. The relatively high pH of this water may reflect both the relatively restricted acid generating capacity of these sulfide minerals as compared to ore having lower metal-sulfur ratios and the acid buffering capability of mafic and ultramafic host rocks.

Kwong (1993) shows that acid generation capacity is directly proportional to both the metal-sulfur atomic ratio and to the proportion of ferrous iron in the sulfide phases. Pyrite, with its 1:2 metal-sulfur ratio, for example, has a much greater acid generating capacity than most magmatic sulfide ore, which has a metal-sulfur ratio of approximately 1. Non-iron-bearing phases with metal-sulfur ratios ≥ 1 do not generate acid. Further, calcic plagioclase and olivine present in the host rocks of most magmatic sulfide deposits are fast-weathering and fairly reactive minerals (Kwong, 1993). Consequently, both mafic and ultramafic igneous rocks have moderate acid buffering capacity. Although somewhat less reactive and slower weathering, serpentine also can be an effective buffer and field studies document that serpentine significantly increases mine water pH (Germain and others, 1994).

Soil, sediment signatures prior to mining

Soil above magmatic sulfide deposits typically has elevated metal contents, and soil geochemistry is commonly used as an exploration tool. Background and anomalous values depend on bedrock and ore compositions. The average (Levinson, 1980) copper content of soil is 20 ppm (range, 2 to 150 ppm), whereas its average nickel content is 30 ppm (range, 5 to 500 ppm); typical background and anomalous values for platinum-group elements are from 2-10 ppb and greater than 40 ppb (Smith, 1984).

Potential environmental concerns associated with mineral processing

Mining produces large amounts of waste. It is not unusual for 100 tons of rock to be extracted to obtain 1 ton of metal. Sulfide mineral-free waste may be used in road construction or similar uses. However, much waste contains sufficient sulfide minerals to generate acid and must be safely stored or isolated. Storage under water to reduce oxidation or as backfill in mining cavities is common. Surface storage requires collection of contaminated water for acid neutralization.

Tailings produced by the separation of ore from waste also contain significant amounts of sulfide minerals that can generate acid. Tailings are commonly used to backfill mined areas. Surface disposal of tailings often involves revegetation to stabilize and isolate sulfide minerals. However, these tails still have significant acid producing capability.

Smelter signatures

Magmatic sulfide ore concentrates are typically smelted and may produce SO₂- and metal-rich emissions. These,

in turn, may cause acid rain that significantly reduces the pH of local streams and lakes and distributes metals that contaminate adjacent soil and plants. As an example, the daily discharge in 1971 from one smelter in the Sudbury, Canada, district was 32.6 tons of iron, 6 tons of nickel, 5 tons of copper, 0.13 tons of cobalt, 0.5 tons of lead, and 0.4 tons of zinc (Hutchinson, 1979). Areas that have been heavily impacted by past emissions of sulfur-rich gases from smelters include Sudbury, Canada and Noril'sk, Russia.

Whereas old smelters released virtually 100 percent of the sulfur in ore as SO₂, new smelting technologies can trap all but about 10 percent of the sulfur (Crawford, 1995). Capture of sulfur emissions can result in rapid and dramatic changes in the environment. As an example, in 1980, 45 of the 104 lakes in the Sudbury district had a pH of less than 5.5. Implementation of new SO₂-emission controls resulted in rapid changes; by 1987, 84 lakes had pH values greater than 5.5.

Climate effects on environmental signatures

The effects of various climatic regimes on the geoenvironmental signature specific to magmatic sulfide deposits is not known. However, in most cases the intensity of environmental impact associated with sulfide-bearing mineral deposits is greater in wet climates than in dry climates. Acidity and total metal concentrations in mine drainage in arid environments are several orders of magnitude greater than in more temperate climates because of the concentrating effects of mine effluent evaporation and the resulting "storage" of metals and acidity in highly soluble metal-sulfate-salt minerals. However, minimal surface water flow in these areas inhibits generation of significant volumes of highly acidic, metal-enriched drainage. Concentrated release of these stored contaminants to local watersheds may be initiated by precipitation following a dry spell.

Geoenvironmental geophysics

Electrical geophysical techniques can be used to delineate low resistivity and polarizable minerals that may help identify the extent of sulfide deposits. In tailings and waste dumps, geophysical techniques can also be used to identify sulfide mineral concentrations and acidic water formed by sulfide mineral oxidation. Resistivity, shallow seismic refraction, and ground-penetrating radar can be used to map water-flow-controlling structures, determine thicknesses of tailing and waste dumps, and often can aid in identification of the water table. Active redox centers can be delimited by self-potential surveys, and possibly by shallow thermal probes, but their signals are susceptible to being masked by water flow and topography.

REFERENCES CITED

- Alapieti, T.T., Lahtinen, J.J., Huhma, Hannu, Hanninen, Esko, Piirainen, T.A., and Sivonen, S.J., 1989, Platinum-group element-bearing Cu-Ni sulfide mineralization in the marginal series of the early Proterozoic Suhanho-Konttjarvi layered intrusion, northern Finland, *in* Prendergast M.D., and Jones, M.J., eds., *Magmatic sulfides-the Zimbabwe volume*: London, The Institution of Mining and Metallurgy, p. 177-189.
- Blowes, D.W., and Ptacek, C.J., 1994, Acid-neutralization in inactive mine tailings, *in* Jambor, J.L. and Blowes, D.W., eds., *Short Course Handbook on Environmental Geochemistry of Sulfide Mine-wastes*, Mineralogical Association of Canada, v. 22, p. 271-292.
- Boudreau, A.E., and McCallum, I.S., 1986, Investigations of the Stillwater Complex: III. The Picket Pin Pt/Pd deposit: *Economic Geology*, v. 81, p. 1953-1975.
- Cox, D.P., and Singer, D.A., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.
- Czamanske, G.K., Kunilov, V.E., Zientek, M.L., Cabri, L.J., Likhachev, A.P., Calk, L.C., and Oscarson, R.L., 1992, A proton-microprobe study of magmatic sulfide ores from the Noril'sk-Talnakh district, Siberia: *The Canadian Mineralogist*, v. 30, p. 249-287.
- Crawford, G.A., 1995, Environmental improvements by the mining industry in the Sudbury Basin of Canada: *Journal of geochemical exploration*, v. 52, p. 267-284.
- Eckstrand, O.R., Cogulu, E.H., and Scoates, R.F.J., 1989, Magmatic Ni-Cu-PGE mineralization in the Crustal Lake layered intrusion, Ontario, and the Fox River sill, Manitoba, *in* Morey, G.B., ed., *Workshop on the applicability of gold and platinum-group-element models in Minnesota*: Minnesota Geological Survey Information Circular 30, p. 45-46.
- Eger, P., and Lapakko, K., 1989, Use of wetlands to remove nickel and copper from mine drainage, *in* *Constructed wetlands for wastewater treatment: Municipal industrial and agricultural*, Lewis Publishers, Chelsea, Mich., p. 780-787.

- Feltis, R.D. and Litke, D.W., 1987, Appraisal of water resources of the Boulder and Stillwater Basins, including the Stillwater Complex, south-central Montana: Montana Bureau of Mines and Geology Memoir 60, 121 p.
- Germain, D., Tasse, N., and Bergeron, M., 1994, Acid mine drainage in tailings of ultramafic metasedimentary rock deposits: Case of Canadian Malartic: Geological Association of Canada, Program with abstracts, vol. 19, p. A40.
- Hammack, R.W., and Edenborn, H.M., 1992, Removal of nickel from mine waters using bacterial sulfate reduction: Applied microbiology and biotechnology, v. 37, p. 674-678.
- Hulbert, L.J., Duke, J.M., Eckstrand, O.R., Lydon, J.W., Scoates, R.F.J., Cabri, L.J., and Irvine, T.N., 1988, Geological environments of the platinum group elements: Geological Survey of Canada Open-File Report 1440, 148 p.
- Hutchinson, T.C., 1979, Copper contamination of ecosystems caused by smelter activities, in Nriagu, J.O., ed., Copper in the Environment, John Wiley & Sons, Inc., New York, New York, p. 451-502.
- Kwong, Y.T.J., 1993, Prediction and prevention of acid rock drainage from a geological and mineralogical perspective: MEND Project 1.32.1.
- Lapakko, K.A., and Antonson, D.A., 1994, Oxidation of sulfide minerals present in Duluth Complex rock, in Alpers, C.A., and Blowes, D.W., eds., Environmental geochemistry of sulfide oxidation, American Chemical Society, Washington, D.C., p. 593-607.
- Levinson, A.A., 1980, Introduction to Exploration Geochemistry: Applied Publishing Ltd., Wilmette, IL, 924 p.
- Lightfoot, P.C., and Naldrett, A.J., 1994, Proceedings of the Sudbury-Noril'sk Symposium: Ontario Ministry of Northern Development and Mines Special Volume 5, 423 p.
- Naldrett, A.J., ed., 1979, Nickel-sulfide and platinum-group element deposits: The Canadian Mineralogist, v. 17, part 2, 514 p.
- _____, 1981, Nickel sulfide deposits: Classification, composition and genesis: Economic Geology 75th Anniversary volume, p. 628-685.
- _____, 1989, Magmatic Sulfide Deposits: Oxford University Press, 186 p.
- Naldrett, A.J., Cameron, G., von Gruenewaldt, G., and Sharpe, M.R., 1987, The formation of stratiform PGE deposits in layered intrusions, Chapter 10, in Parsons, Ian, ed., Origins of Igneous Layering: D. Reidel Publishing Company, p. 313-397.
- Nriagu, J.O., 1979, The global copper cycle, in Nriagu, J.O., ed., Copper in the Environment, John Wiley & Sons, Inc., New York, New York, p. 1-17.
- _____, 1980, Global cycle and properties of nickel, in Nriagu, J.O., ed., Nickel in the environment, John Wiley & Sons, Inc., New York, New York, p. 1-26.
- Page, N.J., 1986a, Descriptive model of Stillwater Ni-Cu, in Cox, D.P. and Singer, D.A., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 11-12.
- _____, 1986b, Descriptive model of Bushveld Cr, in Cox, D.P. and Singer, D.A., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 13.
- _____, 1986c, Descriptive model of Duluth Cu-Ni-PGE, in Cox, D.P. and Singer, D.A., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 16.
- _____, 1986d, Descriptive model of Noril'sk Cu-Ni-PGE, in Cox, D.P. and Singer, D.A., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 17.
- _____, 1986e, Descriptive model of komatiitic Ni-Cu, in Cox, D.P. and Singer, D.A., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 18-19.
- _____, 1986f, Descriptive model of dunitic Ni-Cu, in Cox, D.P. and Singer, D.A., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 24.
- _____, 1986g, Descriptive model of synorogenic-synvolcanic Ni-Cu, in Cox, D.P. and Singer, D.A., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 28.
- Page, N.J., Foose, M.P., and Lipin, B.R., 1982, Characteristics of metallic deposits associated with ultramafic and mafic rocks, in Erickson, R.L., ed., Characteristics of mineral deposit occurrences: U.S. Geological Survey Open-File Report 82-795, p. 1-12.
- Richter, R.O. and Theis, T.L., 1980, nickel speciation in soil/water system, in Nriagu, J.O., ed., Nickel in the Environment, John Wiley & Sons, Inc., New York, New York, p. 189-274.
- Ritchie, I.M., 1988, Environmental management of new mining operations in developed countries: The regional copper-nickel study, in Salomons, W., and Forstner, U., eds., Environmental management of solid waste dredged material and mine tailings: Springer-Verlag, Berlin, p. 182-323.

- SCS Engineers, 1984, Summary of damage cases from the disposal of mining wastes: Report prepared for the U.S. Environmental Protection Agency under contract 68-02-3179, 596 p.
- Siegel, E.I., and Ericson, D.W., 1980, Hydrology and water quality of the copper-nickel study region, northeastern Minnesota: U.S. Geological Survey Water Resources Investigations Open file report 80-739, 87p.
- Smith, B.H., 1984, Geochemical exploration for nickel sulphides in lateritic terrain in Western Australia, *in* Buchanan, D.L. and Jones, M.J., eds, Sulphide deposits in mafic and ultramafic rocks, Institute of Mining and Metallurgy, London, p. 35-42.
- Snodgrass, W.J., 1980, Distribution and behavior of nickel in the aquatic environment, *in* Nriagu, J.O., ed., Nickel in the environment, John Wiley & Sons, Inc., New York, New York, p. 203-274.
- Todd, S.G., Keith, D.W., LeRoy, L.W., Shissel, D.J., Mann, E.L., and Irvine, T.N., 1982, The J-M platinum-alladium Reef of the Stillwater Complex, Montana: I. Stratigraphy and petrology: *Economic Geology*, v. 77, p. 1454-1480.
- Vermaak, C.F., 1976, The nickel pipes of Vlakkfontein and vicinity, western Transvaal: *Economic Geology*, v. 71, p. 261-286.
- Volborth, A., and Housley, R. M., 1984, A preliminary description of complex graphite, sulphide, arsenide, and platinum group element mineralization in a pegmatoid pyroxenite of the Stillwater Complex, Montana, USA: *Tschermaks Mineralogische und Petrographische Mitteilungen*, v. 33, p. 213-230.
- Zientek, M.L., Fries, T.L., and Vian, R.W., 1990, As, Bi, Hg, S, Sb, Sn, and Te geochemistry of the J-M Reef, Stillwater Complex, Montana: Constraints on the origin of PGE-enriched sulfides in layered intrusions: *Journal of Geochemical Exploration*, v. 37, p. 51-73.
- Zientek, M.L., 1993, Mineral resource appraisal for locatable minerals: the Stillwater Complex, *in* Hammarstrom, J.M., Zientek, M.L., and Elliott, J.E., eds., Mineral resource assessment of the Absaroka-Beartooth study area, Custer and Gallatin National Forests, Montana: U.S. Geological Survey Open-File Report 93-207, p. F1-F83.