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Potential for New Nickel-Copper Sulfide Deposits in the Lake Superior Region

Scientists from the U.S. Geological Survey are evaluating the potential for undiscovered sulfide deposits containing varying amounts of nickel, copper, platinum-group metals, and cobalt in the Lake Superior region as part of an ongoing effort to assess the mineral potential of the United States. Similarities between rocks of the Midcontinent rift and rocks that host the Voisey Bay nickel-copper-cobalt deposit in Labrador, Canada, and the Noril'sk nickel-copper-platinum-group-metals deposits in Russia suggest a high potential for such sulfide deposits in rocks associated with the 1.1-billion-year-old Midcontinent rift in the Lake Superior region.

Introduction

The Lake Superior region has long been known for its iron and native copper deposits. Recently, scientists from the U.S. Geological Survey (USGS) have been working in cooperation with colleagues from State geological surveys and universities to evaluate the potential for other mineral resources in the region as part of the ongoing USGS effort to assess the mineral-resource potential of the Nation. Current emphasis is on evaluating the potential for sulfide deposits containing varying amounts of nickel (Ni), copper (Cu), platinum-group metals (PGM's), and cobalt (Co) because of the importance of these metals to the Nation and the recent availability of much new information on these kinds of mineral deposits. In particular, the discovery in 1993 of a large deposit of Ni-Cu-Co sulfides (~150 million tons) at Voisey Bay on the northeast coast of Labrador, Canada, has sparked considerable excitement in the minerals industry and new exploration efforts in search of similar deposits.

The Voisey Bay deposit shows geological similarities with the world-famous Ni-Cu-PGM sulfide deposits at Noril'sk, Siberia. The Noril'sk deposits have been the subject of a recent cooperative USGS and Russian study that has provided much greater understanding of the geological processes that led to the formation of these major ore deposits. Together, the Voisey Bay and Noril'sk deposits provide important guides for evaluating the potential for such deposits in other areas. USGS scientists are using these guides, along with other information, to evaluate the potential for similar sulfide deposits in the Lake Superior region.

Return to top of page

How are Ni-Cu Sulfide Deposits Formed?

The basic requirements for the formation of Ni-Cu sulfide deposits (known as magmatic sulfide deposits), as determined by recent studies at Noril'sk, Voisey Bay, and other deposits, are outlined in figure 1. Formation of these deposits begins with the melting of hot mantle rising as a plume from deep in the Earth (1). The melting produces basaltic magma that is relatively rich in metals but may be poor in sulfur, which then rises upward and intrudes into the crust (2), forming magma chambers. In these chambers, basaltic magma may interact with the crust and become contaminated. Sulfur from surrounding rocks may be incorporated into the magma. This contamination reduces the ability of the magma to keep sulfur in solution (3), and the magma may become sulfur saturated. When sulfur saturation occurs, droplets of sulfide liquid form; because the droplets are more dense than basaltic magma, they tend to settle into the lower part of the magma chamber (4). As the sulfide droplets segregate, they scavenge metals such as nickel, copper, platinum (Pt), and palladium (Pd) from the magma. If these sulfide droplets become sufficiently concentrated, a magmatic sulfide deposit is formed. The largest concentrations of sulfides appear to form in channels or conduits through which new magma flows into the magma chamber. Basaltic lavas (5) erupted from chambers undergoing sulfide segregation will be depleted in those elements enriched in the sulfide deposits. Recognition of such depleted basalts can therefore provide important evidence that sulfide separation has occurred at depth.

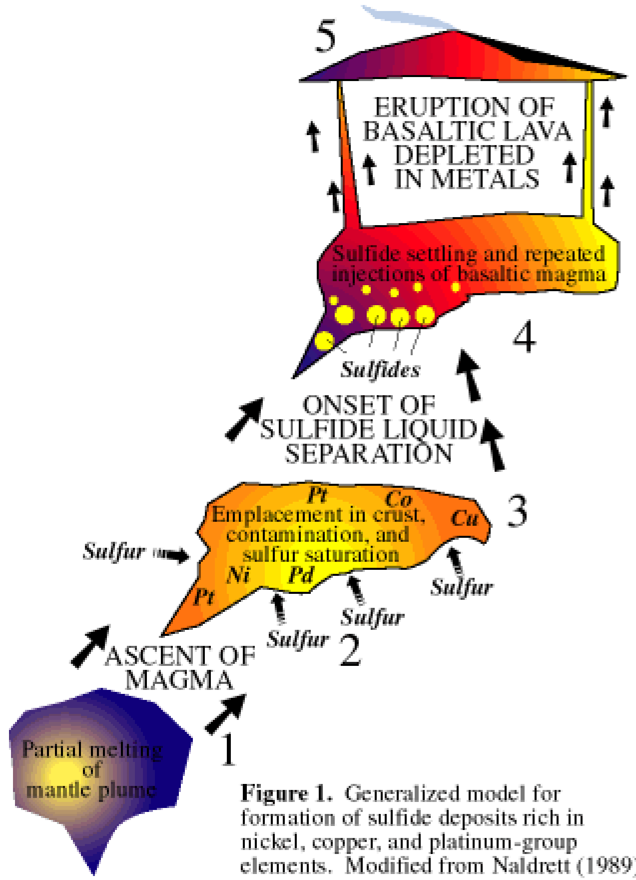
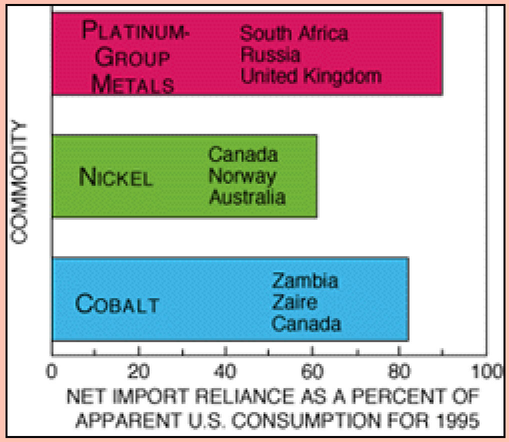


Figure 1. Generalized model for formation of sulfide deposits rich in nickel, copper, and platinum-group elements. Modified from Naldrett (1989).

Return to top of page

Why are Ni-Cu-PGM-Co Sulfide Deposits Important?

Nickel, platinum-group metals, and cobalt are increasingly important industrial commodities for which the United States has very limited or only subeconomic known resources. Currently, more than 65 percent of world nickel production is used in making stainless steel, demand for which has increased substantially in recent years. Nickel is also important for advanced nickel-based batteries under development for use in prototype electric vehicles. Platinum and palladium, two of the platinum-group metals, are of particular importance because they are used in catalytic converters to reduce air pollution from automobile exhaust. Cobalt has a wide variety of industrial uses. About 40 percent of domestic consumption is in the manufacture of superalloys, used mainly in aircraft gas-turbine engines. The United States currently is highly dependent on imports to meet its demand for these commodities (see figure at right). Copper, used mostly in building construction and electrical materials, is produced at about 40 mines in the United States and substantial reserves exist. However, increasing worldwide and domestic consumption of all these commodities and the depletion of known deposits require continued efforts to identify new sources.



Net import reliance (defined as refined imports - refined exports + adjustments for Government and industry stock changes) calculated as the percentage of apparent U.S. consumption. The countries listed for each commodity are the major suppliers to the United States.

Return to top of page

The Midcontinent Rift System

USGS scientists have been focusing their efforts to assess the potential for undiscovered Ni-Cu sulfide deposits in rocks related to the Midcontinent rift system. This rift system formed about 1.1 billion years ago when fracturing of the crust led to large outpourings of basaltic lava and emplacement of related intrusions. Although the rift extends for more than 2,500 kilometers northward from Kansas beneath Lake Superior and then southeast through Michigan, exposures of rocks related to the rift are found only in the Lake Superior region (fig. 2). Here the rift-related rocks consist of mostly basalt, associated gabbro intrusions, and minor rhyolite overlain by sandstone. Recent deep seismic-reflection surveys conducted jointly by the USGS and the Canadian Geological Survey show that rift-related rocks in the Lake Superior region are more than 30 kilometers thick.

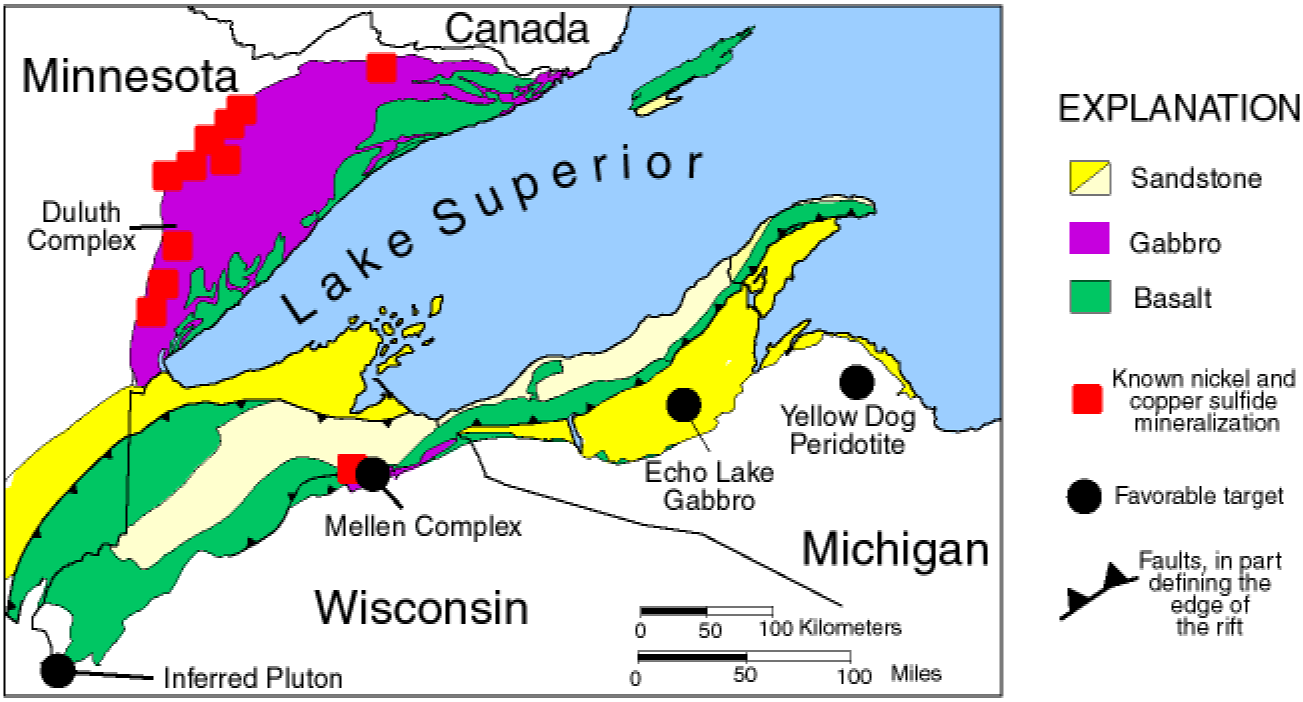


Figure 2. Generalized map of the western Lake Superior region showing the distribution of major rock types of the Midcontinent rift and locations of known Ni-Cu sulfide mineralization in Minnesota and Wisconsin. Also shown are the locations of favorable new targets for Ni-Cu-PGM exploration -- Mellen Complex, Echo Lake Gabbro, Yellow Dog Peridotite, and an inferred intrusion recognized from geophysical data in western Wisconsin.

Tilting and uplift of the central portion of the Midcontinent rift occurred along major faults late in the history of the rift. This uplift brought buried volcanic rocks and associated intrusions, some of which are sulfide-bearing, closer to the surface where they could be exposed by erosion.

Rift-related intrusive rocks, such as the Duluth Complex in Minnesota and the Mellen Complex in Wisconsin, are most commonly exposed along the margins of the rift (fig. 2). The presence of widespread disseminated Ni-Cu sulfide mineralization in basal units of the Duluth Complex and the Mellen Complex, along with several other similar mineral occurrences around Lake Superior, shows that processes necessary for the formation of sulfide deposits were active in some intrusions locally in the Midcontinent rift. However, to determine the potential for significant undiscovered mineralization in a poorly exposed igneous province the size of the Midcontinent rift system requires a variety of geologic information collected through multidisciplinary investigations at both regional and detailed scales.

Return to top of page

Comparisons Between the Midcontinent Rift and the Voisey Bay and Noril'sk Regions

Comparisons between the Midcontinent rift system and the Voisey Bay and Noril'sk settings point to several similarities that suggest that the Midcontinent rift is a likely setting for Ni-Cu mineralization. The continental rifting and associated voluminous igneous activity in all three regions formed in response to the rise of a hot plume of mantle material from deep in the Earth, fracturing the overlying continental crust (fig. 3). In the Midcontinent rift, melting of the plume produced more than 2 million cubic kilometers of mostly basalt lava flows and related intrusions.

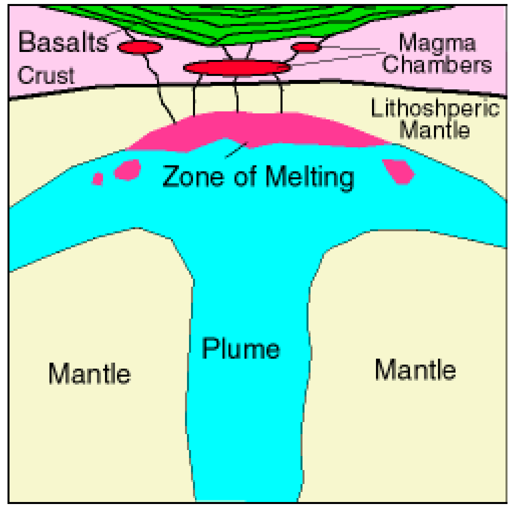


Figure 3. A localized hot plume rises through the mantle until it encounters the bottom of the lithosphere (crust + "cold" lithospheric mantle material that is welded to the base of the crust). The plume begins to melt due to decompression and may locally incorporate bits of lithospheric mantle into the magmas. These magmas follow fractures in the crust and may pond at various levels, creating magma chambers. Some magma is erupted from the chambers, forming a thick package of overlying basalts. Other magma solidifies in place, ultimately creating intrusions.

In all three regions, basalts derived from the mantle plume are enriched in trace elements, particularly in comparison to the most common basalts erupted on Earth, those formed at rifts in the oceans. Like basalts in the Noril'sk region, early basalts of the Midcontinent rift have compositions characterized by relatively high abundances of magnesium, chromium, nickel, and platinum, and relatively low abundances of sulfur. Such metal-rich but sulfur-poor basalt magmas can carry metals (such as Ni, Cu, and PGM's) to high levels in the crust because sulfur is not available to form a separate sulfide liquid that would scavenge metals from the magma while it is still deep below the surface. If these metal-rich basalts encounter a source of sulfur near the surface, and sulfur is incorporated into the basalt magma, they can be ripe for sulfide mineral formation.

Return to top of page

Where in the Midcontinent Rift is Ni-Cu Mineralization Most Likely to Occur?

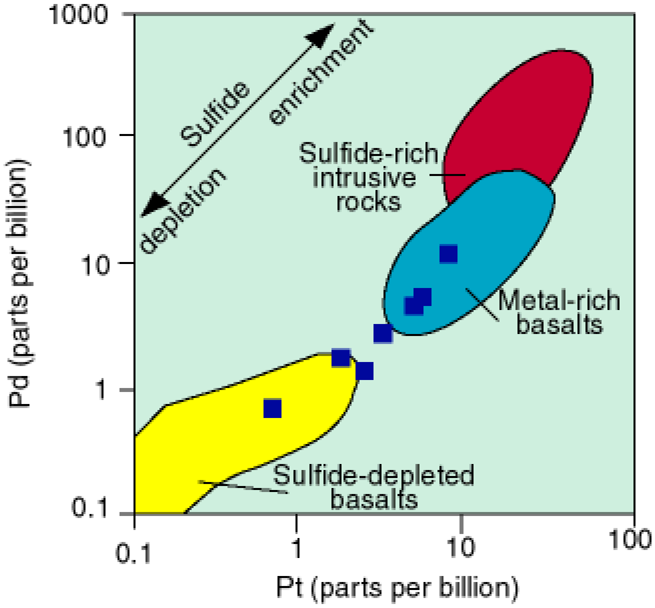


Figure 4. Variations in platinum (Pt) and palladium (Pd) abundances in basalts and related intrusive rocks from the Midcontinent rift, shown here, provide evidence that sulfide mineralization occurred at depth locally. Some rift basalts are relatively rich in Pt and Pd (blue field) and have compositions similar to those of metal-rich basalts from Noril'sk (squares). Intrusive rocks containing visible sulfide minerals have higher Pt and Pd contents (pink field) than the metal-rich basalts because those metals are preferentially concentrated into sulfide. In contrast, some rift basalts have very low abundances of Pt and Pd (yellow field) and are depleted because they experienced the removal of sulfides prior to eruption. Similarly depleted basalts at Noril'sk (squares with arrow attached; these samples have abundances below the detection limit for the analytical method used and are plotted using the detection limit values) are related to the formation of Ni-Cu-PGM sulfide deposits.

Although the Midcontinent rift appears to be a likely setting for Ni-Cu sulfide mineralization to form, the next question is where the mineralized areas may be located within the rift. This is a particularly important question because the individual intrusions that host sulfide ore deposits at Noril'sk and Voisey Bay are quite small, generally no more than few kilometers long, and the individual sulfide deposits are even smaller.

In the Voisey Bay and Noril'sk regions, sulfide deposits show a strong relationship to intrusions in which the original basaltic magmas were enriched in sulfur by contamination with crustal rocks. The enrichment of sulfur in these magmas resulted in sufficient sulfur to combine with metals and form a separate sulfide phase that was then concentrated by various processes in the magma chambers. Because of separation and segregation of the sulfide phase within the intrusions, erupting basaltic magma was anomalously low in those metals taken up by sulfides.

Data recently obtained by USGS scientists show that some Midcontinent rift basalts are depleted in just those elements that are enriched in sulfide deposits (fig. 4). In addition, isotopic analyses of sulfide minerals from mineralized rift rocks show that sulfur was derived from local crustal rocks and not from the mantle. Both of these features indicate that introduction of crustal sulfur resulted in the formation and removal of sulfides from the rift basalts before their eruption to the surface.

The concentration and enrichment of sulfides are enhanced by repeated injections of basalt into a magma chamber where it then can be stripped of its metals by interaction with sulfur introduced from the surrounding crustal rocks. Localized igneous centers characterized by multiple intrusions and a broad spectrum of volcanic compositions appear to focus the processes necessary for the formation of sulfide deposits. Thus, identification of localized igneous centers with anomalous metal depletion in associated basalts provides evidence that ore-forming processes operated at depth.

In order to expose the relatively deep sulfide deposits, uplift along faults is needed. At Noril'sk, uplift along faults and erosion have exposed several intrusions and their contained sulfide deposits. The Voisey Bay deposit has also been exposed through uplift and erosion. In the Midcontinent rift, compression late in its history resulted in uplift and tilting of the crust, exposing several intrusions along the margins of the rift. Some of these intrusions (for example, Duluth Complex, Mellen Complex, fig. 2) contain low-grade Ni-Cu sulfide mineralization, suggesting that uplift and erosion in the region have been sufficient to warrant exploration for additional sulfide mineralization.

Return to top of page

Potential for Undiscovered Sulfide Deposits in the Midcontinent Rift

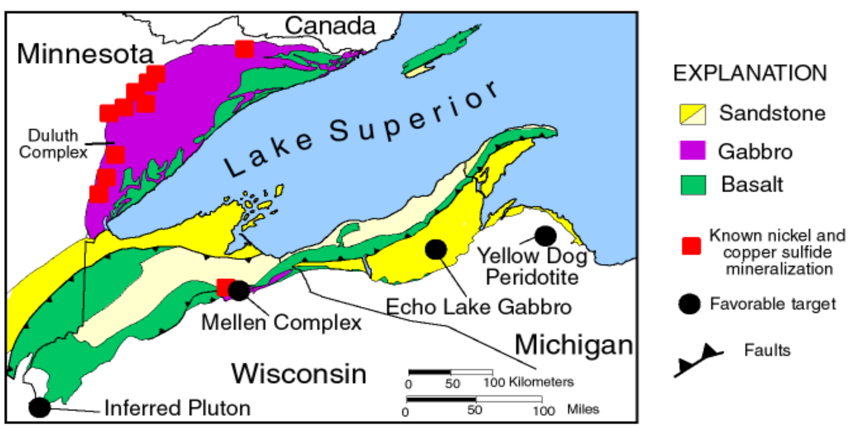


Figure 5. Generalized map of the western Lake Superior region. The locations of favorable new targets for Ni-Cu-PGM exploration are the Mellen Complex, the Echo Lake Gabbro, the Yellow Dog Peridotite, and an inferred intrusion recognized from geophysical data in western Wisconsin are indicated by black circles.

On the basis of data recently collected by USGS scientists and their collaborators and of comparisons with the Noril'sk and Voisey Bay regions, a high potential exists for undiscovered Ni-Cu (±PGM's ±Co) sulfide deposits to occur locally in Midcontinent rift rocks in the Lake Superior region. In particular, the Yellow Dog Peridotite and the Echo Lake Gabbro in Upper Michigan and the Mellen Complex and related feeder intrusions in northern Wisconsin are considered favorable targets (fig. 5). An inferred intrusion in western Wisconsin recently discovered by geophysical techniques may also have potential for sulfide mineralization (fig. 5). In addition, portions of the Mid- continent rift southwest of the Lake Superior region, particularly where the rift transects sulfur-rich rocks of certain older terranes, may also contain undiscovered sulfide deposits.

Return to top of page

Additional Reading

Lightfoot, P.C., and Naldrett, A.J., eds., 1995, Proceedings of the Sudbury- Noril'sk Symposium: Ontario Geological Survey Special Volume 5, 408 p.

Naldrett, A.J., 1989, Magmatic sulfide deposits: New York, Oxford University Press, 186 p.

Naldrett, A.J., Keats, H., Sparkes, K., and Morre, R., 1996, Geology of the Voisey Bay Ni-Cu-Co deposit, Labrador, Canada: Exploration and Mining Geology, v. 5, p. 169-179.

Nicholson, S.W., Cannon, W.F., and Schulz, K.J., 1992, Metallogeny of the Midcontinent rift system of North America: Precambrian Research, v. 58, p. 355-386.

Return to top of page

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Return to top of page

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Last updated 01/20/98 (lgw)