Future of Base and Precious Metal Mining in Minnesota

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A Looming Stewardship Question for Minnesotans:

When should we develop this immense copper-nickel-precious metal mineral resource?
THE MIDCONTINENT RIFT

An attempt at continental rifting 1.1 billion years ago
Tectonic and Magmatic Evolution of the Midcontinent Rift

A. Rift Magmatism

1,109-1,086 Ma

Gabbro

Basalt Flows

1,090-900 Ma

Crust

Mantle

Mantle Plume

B. Sediment Infilling

1,000-900 Ma

Sandstone

C. Compression

1,000-900 Ma
Midcontinent Rift
Exposure in the
Lake Superior
Region
Partridge River Intrusion
South Kawishiwi Intrusion
Partridge River Intrusion

MESOPROTEROZOIC
BEAVER BAY COMPLEX AND MISCELLANEOUS INTRUSIONS
- Mafic Intrusions
- Felsic Intrusions

DULUTH COMPLEX
- Layered Series (MLI)
- Anorthositic Series
- Early Gabbro Series
- Felsic Series
- Cu-Ni(-PGE) deposits

PALEOPROTEROZOIC
- Virginia/Rove Fm
- Biwabik/Gunflint Fe-Fm

ARCHEAN
- Supracrustal Rocks
- Granitoid Rocks

NORTH SHORE VOLCANIC GROUP
- Basaltic to rhyolitic flows

Kilometers
Duluth
Lake Superior
90°
92°
91°
48°
47°
Ely
Grand Marais
Sequential Emplacement of Duluth Complex Intrusions
Sulfur Contamination creating the Cu-Ni-PGE Sulfide Deposits of the Duluth Complex

Dunka Pit (East Wall)
History of Cu-Ni-PGE Exploration in the Duluth Complex

1948 – Cu-sulfide mineralization discovered by F.W. Childers
1951 – Childers and Whiteside drill first exploration drill hole at Spruce Road
1954 – INCO begins drilling program at Maturi deposit
1958 – Bear Creek (Kennecott) begins drilling program at Babbitt deposit
1966 – Minnesota opens state lands for minerals lease sale
1967 – INCO sinks shaft at Maturi deposit
1969 – Total of 198,000’ of drill core acquired
1974-78 – State conducts Cu-Ni Regional Study
1974-82 – State suspends lease sale
1976 – AMAX sinks shaft at Babbitt deposit
1981 – AMAX abandons Babbitt deposit
1985 – High PGE values discovered at Birch Lake deposit
1988 – Lehmann and Assoc. begin drilling of the Birch Lake deposit
1997-2000 – Polymet, Teck Cominco, Franconia, Wallbridge (Duluth Metals) begin active exploration drilling
2007 – Total of 322,000’ of drill core acquired
Current Exploration Activity

**Polymet** – Northmet

**Teck American** – Mesaba

**Duluth Metals** – Nokomis, Maturi, Dunka Pit, Birch Lake, Spruce Rd

**Encampment** – South Filson Cr.
Mineralogy of Magmatic Cu-Ni Sulfide Deposits

**Sulfide Minerals**
- Pyrrhotite – FeS$_{1-x}$
- Chalcopyrite - CuFeS$_2$
- Pentlandite - (Fe,Ni)$_9$S$_8$
- Bornite - Cu$_5$FeS$_4$
- Chalcocite - Cu$_2$S
- Cobaltite – CoAsS
- Pt Group Minerals – Pt, Pd, Au, Bi, Te, As, ...

**Silicate/Oxide Minerals**
- Olivine - (Mg,Fe)$_2$SiO$_4$
- Plagioclase – (Ca,Na)(Al,Si)$_4$O$_8$
- Augite – Ca(Mg,Fe)Si$_2$O$_6$
- Titano-magnetite – (Fe,Ti)$_3$O$_4$
The Challenge

Preventing Acid Mine Drainage

$$2\text{FeS}_2(s) + 7\text{O}_2(g) + 2\text{H}_2\text{O}(l) \rightarrow 2\text{Fe}^{2+}(aq) + 4\text{SO}_4^{2-}(aq) + 4\text{H}^+(aq)$$
Another Inconvenient Truth

Most of the world’s metals comes from sulfide minerals

- Chalcopyrite: CuFeS$_2$
- Bornite: Cu$_5$FeS$_4$
- Chalcocite: Cu$_2$S
- Sphalerite: ZnS
- Cinnabar: HgS
- Galena: PbS
- Pentlandite: (Fe,Ni)$_9$S$_8$
- Cobaltite: CoAsS
- Molybdenite: MoS$_2$
Upper Michigan: America’s First Mineral Rush 1844-1972 of Native Cu
Separating Metal from Sulfur

**THEN**
Roasting/Smelting

Sudbury, Ont.

Monchegorsk, Russia

**NOW**
Hydrometallurgy

![Diagram of Hydrometallurgy Process](image)
United States – The #1 consumer of mineral resources, that produces little for itself

**Minerals Imported by the United States**

In spite of its size and mineral wealth, the United States is not able to produce all of the minerals it needs to be self-sufficient. To maintain our lifestyle and provide all of the consumer products and infrastructure we use every day, various amounts of the following minerals must be imported from foreign countries.


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**Metal** | **% Mined by US** | **% Imported for US consumption**
--- | --- | ---
Copper | 6.9% | 30%
(Chile (41%), Canada (33%))
Nickel | 0% | 43%
(Canada (44%), Russia, Australia, Norway)
Cobalt | 0% | 81%
(Norway, Russia, China, Canada)
Palladium | 5.9% | 58%
(Russia (44%), South Africa (37%))

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**2010 U.S. NET IMPORT RELIANCE FOR SELECTED NONFUEL MINERAL MATERIALS**

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Percent</th>
<th>Major Import Sources (2008-09)</th>
</tr>
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<tbody>
<tr>
<td>ARSENIC</td>
<td>100%</td>
<td>China, Belgium</td>
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<tr>
<td>ASBESTOS</td>
<td>100%</td>
<td>Canada</td>
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<tr>
<td>BARITE</td>
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<td>China, Mexico</td>
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<td>CERAMIC</td>
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<td>FLUORITE</td>
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<td>GRAPHITE (natural)</td>
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<td>INDIUM</td>
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<td>China, Mexico, Germany</td>
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<tr>
<td>MAGNESIUM</td>
<td>100%</td>
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<tr>
<td>MICA, sheet (natural)</td>
<td>100%</td>
<td>China, Mexico, Germany</td>
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<tr>
<td>MICA, thick (natural)</td>
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<tr>
<td>OXIDES/CERAMIC</td>
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<td>RARE EARTH</td>
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<td>NITROGEN (fixed), AMMONIA</td>
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<tr>
<td>COPPER</td>
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<tr>
<td>NICKEL</td>
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*In descending order of import share.*
COPPER
An Important Metal in a Green Economy

A Single 3MW Wind Turbine Needs:

- 335 tons of steel
- 4.7 tons of copper
- 1,200 tons of concrete (cement and aggregates)
- 3 tons of aluminum
- 2 tons of rare earth elements
- Aluminum
- Zinc
- Molybdenum

Cu in a Standard Car with Combustion Engine
43-55 lbs

Cu in a Prius
80 lbs

NW Mining Association, 2009
PGE – Platinum Group Elements

Pt – Platinum, Pd – Palladium, Os – Osmium, Ru – Ruthenium, Rh – Rhodium, Ir - Iridium

Major PGE Deposits and Targets

- **Stillwater**
  - Pt <5%
  - Pd 90%
  - Rh <5%

- **Voisey's Bay**

- **Duluth**

- **Sudbury**

- **Fenno-Scandian**

- **Skaergaard**

- **Noril'sk**
  - Pt 18%
  - Pd 67%
  - Rh 36%

- **Jinchuan**

- **Great Dyke**
  - Pt 74%
  - Pd 24%
  - Rh 60%

- **Bushveld**

- **Munni Munni**

- **Rincon del Tigre**

**Key Points**:
- **PGE-reefs in Ultramafic/Mafic Complexes**
- **PGE-reefs in Tholeiitic Intrusions**
- **PGE as by-product in Cu-Ni Sulfide Deposit**

1997 production numbers
Bushveld Complex
South Africa
Supplying the 70% of the World’s Platinum
Palladium: “The Environmental Metal”

Pd Uses

![Palladium World Production](image)

- Russia: 44%
- South Africa: 37%
- Other Countries: 19%
- Canada: 5%
- Zimbabwe: 3%
- Colombia: N/A

2003 Total: 5260

- Other
- Jewelry
- Electronics
- Dental
- Chemical
- Autocatalyst

Supplied by recovery
Stillwater Mine (Montana)
Only Precious Metals Mine in the U.S.
(owned by Noril’sk Nickel)
Sulfide Smelter in Monchegorsk, Russia
In 1998, responsible for 50% of $SO_2$ in the northern hemisphere

Noril’sk, Russia
Cu-Ni-PGE Deposits
Supplies 44% of the World’s Palladium
World Class Ores of the Duluth Complex

Compared to other **Magmatic Sulfide Deposits**, the Duluth Complex is:

- #1 or 2 in contained Copper
- #4 in contained PGE
- #3 in contained Nickel

Only the Bushveld, Great Dyke (PGE deposits) and Noril’sk contain more PGE

Data from Eckstrand & Hulbert, 2007

From Peterson, 2010
World Scale of the Nokomis Deposit

Data from Eckstrand & Hulbert, 2007
The addition of indicated & inferred is not 43-101 compliant
The Largest UNDEVELOPED Cu-Ni Deposit on Earth

Duluth deposits are perceived as low grade. But compared to the source of most of the world’s copper - Porphyry Copper Deposits...

...the Duluth Complex ores are **HIGHER GRADE** with **MORE CONTAINED METAL** than nearly all porphyry systems.

The largest copper ore deposits in the USA are on this diagram, and the Duluth Complex ores are much larger than all of them.

From Peterson, 2010
CONCLUSION: The base and precious metal deposits of the Duluth Complex are a World Class Resource that will be mined ... SOMEDAY

Stewardship question - If not now, when?