Geology and Mineral Deposits of the Duluth Complex, Minnesota and why it will be mined someday

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A Looming Stewardship Question for Minnesotans:

When should we develop this immense copper-nickel-precious metal mineral resource?
Talk Outline

• Geology of the Duluth Complex
• Mineral Deposits of the Duluth Complex
• History of Exploration
• Why the Duluth Complex ore deposits will be mined …someday
THE MIDCONTINENT RIFT

An attempt at continental separation 1.1 billion years ago
Evolution of the Midcontinent Rift

A. Rift Magmatism
- Gabbro
- Basalt Flows

Crust
Mantle

B. Sediment Infilling
- Sandstone

1,109-1,086 Ma

Mantle Plume

1,090-900 Ma

C. Compression

1,000-900 Ma
Midcontinent Rift Exposure in the Lake Superior Region
Igneous Rocks of the Midcontinent Rift

- North Shore Volcanics
- Crust: ~40 Km
- Mantle
- Felsic Magma Cupola
- Subvolcanic Gabbroic Intrusions
- Subvolcanic Granitic Intrusions
- Midcrustal Gabbroic Intrusions
- Mafic Lava Eruptions
- Felsic Lava Eruptions
- Rhyolite
- Granite
- Basalt
- Gabbro
- Mantle Melting
- Subcrustal Mafic Magma Chamber
- Crustal Melting
Sequential Emplacement of Duluth Complex Intrusions
Creation of the Cu-Ni-PGE Sulfide Deposits of the Duluth Complex
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
**Twin Metals MN** – Nokomis, Maturi, Dunka Pit, Birch Lake, Spruce Rd
**Encampment** – South Filson Cr.
Why Will the Duluth Complex Ore Deposits be Mined Someday?

- New technological advances in processing sulfide minerals
- The US is the principal consumer of Copper, Nickel, Cobalt and Precious Metals, but relies on the rest of the world to supply these resources
- Cu, Ni, and PGE are critical metals in a modern, green world
- The deposit occur adjacent to an area of taconite mining with an estimated 50 year life span
- These deposits constitute the largest undeveloped Cu-Ni resource on Earth
Mineralogy of Magmatic Cu-Ni Sulfide Deposits

**Sulfide Minerals**
- Pyrrohotite – 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$_4$
An Inconvenient Reality

Most of the world’s metals comes from sulfide minerals

- Chalcopyrite: $\text{CuFeS}_2$
- Chalcocite: $\text{Cu}_2\text{S}$
- Bornite: $\text{Cu}_5\text{FeS}_4$
- Pentlandite: $(\text{Fe},\text{Ni})_9\text{S}_8$
- Cinnabar: $\text{HgS}$
- Sphalerite: $\text{ZnS}$
- Molybdenite: $\text{MoS}_2$
- Galena: $\text{PbS}$
- Cobaltite: $\text{CoAsS}$
Copper Country of Upper Michigan: 

*Native Cu*

Native Miners

pre-1000 yrs

European Miners

1844-1972
Separating Metal from Sulfur

THEN
Roasting/Smelting

NOW
Hydrometallurgy
The Challenge

Preventing Acid Mine Drainage

\[ 2\text{FeS}_2(\text{s}) + 7\text{O}_2(\text{g}) + 2\text{H}_2\text{O}(\text{l}) \rightarrow 2\text{Fe}^{2+}(\text{aq}) + 4\text{SO}_4^{2-}(\text{aq}) + 4\text{H}^+(\text{aq}) \]
United States – The #1 consumer of mineral resources, that produces little for itself

<table>
<thead>
<tr>
<th>Metal</th>
<th>% Mined by US</th>
<th>% Imported for US consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>7.7%</td>
<td>40%</td>
</tr>
<tr>
<td>(Chile (30%), US, Indonesia, Peru)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nickel</td>
<td>0%</td>
<td>54%</td>
</tr>
<tr>
<td>(Russia, Australia, Canada, Indonesia)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cobalt</td>
<td>0%</td>
<td>78%</td>
</tr>
<tr>
<td>(Congo (30%), Zambia, Australia, Canada)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Palladium</td>
<td>6.6%</td>
<td>78%</td>
</tr>
<tr>
<td>(Russia (44%), South Africa (38%))</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Statistics from US Geological Survey
Mineral Commodity Summaries, Jan. 2006
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

NW Mining Association, 2009

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

Cu in a Prius
80 lbs
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%

- **Sudbury**
- **Skaergaard**
- **Voisey's Bay**
- **Fenno-Scandian**
- **Noril'sk**
  - Pt 18%
  - Pd 67%
  - Rh 36%

- **Jinchuan**

- **Rincon del Tigre**

- **Bushveld**
  - Pt 74%
  - Pd 24%
  - Rh 60%

- **Great Dyke**

- **Munni Munni**

- **Munni**

Legend:
- ○ PGE-reefs in Ultramafic/Mafic Complexes
- ● PGE-reefs in Tholeiitic Intrusions
- ● PGE as by-product in Cu-Ni Sulfide Deposit

Note: 1997 production numbers
Bushveld Complex
South Africa
Supplying the 70% of the World’s Platinum
Palladium: "The Environmental Metal"
The Stillwater Mine (Montana)
Only Precious Metals Mine in the U.S.
(owned by Noril’sk Nickel)
Noril’sk, Russia
Cu-Ni-PGE Deposits
Supplies 60% of the World’s Palladium

Sulfide Smelter in Monchegorsk, Russia
In 1998, responsible for 50% of $SO_2$ in the northern hemisphere
Adjacent to the Taconite Mines of the Eastern Mesabi Range

Provides a ready-made infrastructure and labor force
New Plant Facilities
~ within existing plant footprint

Electro-winning Plant

Hydromet Plant

Oxygen Plant

Flotation Plant
World Class Ores of the Duluth Complex

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

- #1 or 2 in contained Copper
- #2 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

Nickel

Copper

PGE

Ore, million tonnes

PGE g/t
The Largest UNDEVELOPED Cu-Ni Deposit on Earth

Duluth deposits are perceived as low grade. Let’s compare them to the other great type of disseminated ore deposit; Porphyry Copper’s. These data include secondary enrichment zones in the porphyry’s.

Compared to porphyry copper deposits, the Duluth Complex ores are HIGHER GRADE with MORE METAL than nearly all porphyry systems.

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

From Peterson, 2010