Copper-Rich Magmatic Ni-Cu-PGE deposits

David R. Burrows
Copper-Rich Magmatic Ni-Cu-PGE deposits
Outline of Talk

• Introduction and characteristics
• Examine key examples of Cu-rich magmatic systems to highlight Cu-enrichment processes
  • **Sudbury**: FC processes-maximized as slow cooling
  • **Noril’sk**: High R factor and sulphide FC
  • **Voisey’s Bay**: High Cu, rel. low PGEs ores; limited FC
  • Mid Continental Rift in USA and Canada
    • **Duluth Complex**: Very Cu-rich mineralization
    • **Eagle deposit**: Small high grade deposit
• Summary of exploration criteria for Cu-rich magmatic mineralization
• Potential in Brazil for Cu-rich magmatic Cu-Ni-PGE deposits
Copper-Rich Magmatic Ni-Cu-PGE deposits
Magmatic Ni-Cu-PGE deposits
General Model

From Begg et al., 2010, Econ. Geol., 105, 1057-1070

Low-MgO (Mafic) style

1. Mantle plume impact and flow towards areas of thinner lithosphere
2. Decompression melting of plume at shallower levels (sulfur undersaturated magmas)
3. Transfer of melts into the (upper) crustal environment via active trans-lithospheric faults and an interconnected intrusion (sills) network
4. Variable interaction of melts with crust (sulfur saturation)
5. Nickel sulphide precipitation and accumulation

High-MgO (Ultramafic) style

(e.g. Norilsk, Voisey's Bay, West Musgrave)

(peri-cratonic)

(e.g. Raglan, Thompson, Kambalda, Agnew-Wiluna)

Diagram:
- Mantle plume impact and flow towards areas of thinner lithosphere
- Decompression melting of plume at shallower levels (sulfur undersaturated magmas)
- Transfer of melts into the (upper) crustal environment via active trans-lithospheric faults and an interconnected intrusion (sills) network
- Variable interaction of melts with crust (sulfur saturation)
- Nickel sulphide precipitation and accumulation

Diagram notes:
- Sub-Continental Lithospheric Mantle
- (paleo) craton margin
- marginal basin
- 1. Mantle plume impact
- 2. Decompression melting
- 3. Transfer of melts
- 4. Variable interaction
- Sub-Continental Lithospheric Mantle
Why are some magmatic deposits richer in copper than others?

1. Composition of source, and conditions during melting and degree of partial melting

2. Degree of fractional crystallization (FC) ± crustal contamination prior to sulphide segregation

3. The amount of silicate magma that reacts with the sulphide melt (R factor)

4. Degree of FC of sulphides after it has segregated from magma
Cu-rich magmatic Ni-Cu-PGE deposits
Distribution of Cu-rich variety
## Cu-rich magmatic Ni-Cu-PGE deposits

### Top magmatic deposit producers (2007-2008)

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Location</th>
<th>Operator(s)</th>
<th>Cu pa (tonnes)</th>
<th>Cu Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noril'sk</td>
<td>Taimyr Peninsula, Russia</td>
<td>Noril'sk Nickel</td>
<td>364,400</td>
<td>2.60%</td>
</tr>
<tr>
<td>Sudbury</td>
<td>Ontario, Canada</td>
<td>Vale Glencore</td>
<td>134,000</td>
<td>1.27%</td>
</tr>
<tr>
<td>Voisey's Bay</td>
<td>Labrador, Canada</td>
<td>Vale</td>
<td>55,400</td>
<td>1.53%</td>
</tr>
<tr>
<td>Jinchuan</td>
<td>Gansu Province, PRC</td>
<td>Jinchuan Non-Ferrous Metal Corp.</td>
<td>52,000</td>
<td>0.66%</td>
</tr>
<tr>
<td>Selibi-Phikwe</td>
<td>Botswana</td>
<td></td>
<td>24,289</td>
<td>0.55%</td>
</tr>
<tr>
<td>Caraiba</td>
<td>Curaca Valley, Bahia, Brazil</td>
<td></td>
<td>22,720</td>
<td>1.00%</td>
</tr>
<tr>
<td>Pechenga</td>
<td>Kola Peninsula, Russia</td>
<td>Noril'sk Nickel</td>
<td>18,000</td>
<td>0.35%</td>
</tr>
<tr>
<td>Phoenix</td>
<td>Botswana</td>
<td>Noril'sk Nickel</td>
<td>13,400</td>
<td>0.18%</td>
</tr>
<tr>
<td>Raglan</td>
<td>Nunavik, Canada</td>
<td>Glencore</td>
<td>7,134</td>
<td>0.68%</td>
</tr>
<tr>
<td>Aguablanca</td>
<td>Extremadura, Spain</td>
<td></td>
<td>5,484</td>
<td>0.40%</td>
</tr>
<tr>
<td>Santa Rita (Mirabela)</td>
<td>Bahia State, Brazil</td>
<td></td>
<td>3,239</td>
<td>0.13%</td>
</tr>
<tr>
<td>Nkomati</td>
<td>RSA</td>
<td></td>
<td>2,300</td>
<td>0.13%</td>
</tr>
<tr>
<td>Montcalm</td>
<td>Ontario, Canada</td>
<td>Glencore</td>
<td>1,179</td>
<td>0.61%</td>
</tr>
<tr>
<td>Karatungk (Kalatongke)</td>
<td>Xinjiang, China</td>
<td></td>
<td></td>
<td>1.30%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>703,545</strong></td>
<td><strong>0.81%</strong></td>
</tr>
</tbody>
</table>
Cu-rich magmatic Ni-Cu-PGE deposits

Significant Producers
Cu-rich magmatic Ni-Cu-PGE deposits

Value from different metals

Ni-Cu Rich
- Y1: Yilgarn Komatiite Type I (W Australia)
- Y2: Yilgarn Komatiite Type II (W Australia)
- Z: Zimbabwe High-Grade
- O1: Ontario Komatiite Type I
- T: Thompson High-Grade (Manitoba)
- R: Raglan (Nunavut)
- N: Noril’sk (Russia)
- D: Duluth (Minnesota)
- J: Jinchuan (China)
- S-P: Selibe-Phikwe (Botswana)
- Ta: Tati (Botswana)
- K: Kabanga (Tanzania)
- Mo: Monchegorsk (Russia)
- P: Pechenga (Russia)
- V: Voisey’s Bay (Labrador)
- Mt: Montcalm (Ontario)
- A: Aguablanca (Spain)
- S: Sudbury (Ontario)
- 153: McCreedy East 153 Zone (Sudbury)
- E: Eagle (Michigan)

PGE Rich
- B: Total Bushveld (South Africa)
- MR: MR - Merensky Reef (Bushveld)
- U: UG-2 (Bushveld)
- PR: Platreef (Bushveld)
- GD: Great Dyke (Zimbabwe)
- ST: Stillwater (Montana)
- Po: Portimo Complex (Finland)
- L: Lac des Iles (Ontario)
Sudbury Igneous Complex
Location of different Deposit Types

Av. Grade ~ 1%, 1% and 1g/t
Sudbury Footwall Copper deposits
Sulphide Fractional Crystallization

- Segregation of sulfide melt (1100°C) and Early crystallization of MSS
- Fractional crystallization of MSS → pyrrhotite rich cumulate (Ni)
  → Cu-rich residual (liquid) melt (Pd, Pt, Ag, Au, Bi etc. partition to late melt)
- Crystallization of ISS (→ cp ± pn)
- Late Cl-rich brines from the late-stage melt or from an exsolved magmatic fluid that remobilizes metals (Pt, Pd, Ag, Au, As, Bi, Te)
Sudbury Footwall Mineralization
Ore types in 153 ore body, Coleman mine
Sudbury Footwall Cooper mineralization
Chalcopyrite Vein, North zone, Norman property (KGHM)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Length Feet</th>
<th>Cu %</th>
<th>Ni %</th>
<th>TPM %</th>
<th>In Situ CDN$ / tonne</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>8.8</td>
<td>28.7</td>
<td>0.2</td>
<td>16.3</td>
<td>1,042.00</td>
</tr>
<tr>
<td>B</td>
<td>13.1</td>
<td>17.6</td>
<td>0.5</td>
<td>11.3</td>
<td>707.00</td>
</tr>
<tr>
<td>C</td>
<td>18.4</td>
<td>15.8</td>
<td>0.5</td>
<td>10.3</td>
<td>653.00</td>
</tr>
</tbody>
</table>
Sudbury Footwall Cooper mineralization
Irregular chalcopyrite-PGE veins in 153 Coleman ore body
Sudbury Basin
Vale Exploration Results from Victor / Capre area
Victor Footwall and Contact Ore bodies

North facing sketch section
Old Victor BH1294240
Mineralization from 268.4 to 288 m
2.74% Ni, 1.68% Cu, 0.89 g/t TPM over 19.6m (core length)
Estimated 10 % Cu, 2 % Ni over 30.4 m starting at 840 m
Victor Footwall Cu zone
BH MAC078F

Massive sulphide between 2533.9 - 2545.6m

1.9 % Ni, 9.1% Cu, 7.8 g/t TPM over 46.4m
Including 4.9% Ni, 24.3% Cu, 20.8 g/t TPM over 11.7m (core length)
Victor Footwall Cu zone
BH MAC078G

Mineralization between 2548.4 – 2631.7m
1.9 % Ni, 11.9 % Cu, 8 g/t TPM over 83.3m
Including 2.8% Ni, 26.1 % Cu, 15 g/t TPM over 13.1m (core length)
Noril’sk-Talnakh Area
Views towards Talnakh and Kharaelakh area
Kharaelakh and Talnakh Intrusions

West-facing Section through the Oktyabrsk Deposit

After Naldrett et al. (1992)
- Siberian Trap Basalt 250 Ma
- Permian sedimentary rocks
- Devonian sedimentary rocks (including evaporites/shales)
- Kharaelakh and Talnakh Intrusions and their apophyses
- Massive Sulphide
- Lower Talnakh Intrusion
- Faults

From Lightfoot & Zotov, 2006
Oktyabrsky deposit, 600L, Talnakh
Cubanite-mooihoekite-pentlandite basal ores

- Two different processes operating at Noril’sk
  1. Very high R factors (early sulphides enriched in PGEs, Cu and Ni)
  2. Late stage FC and fluid-assisted separation of Cu-PGEs (esp. Pd) into higher “Cuprous” zones

Tenors 25% Cu, 2.2% Ni, 60g/t Pd and 10g/t Pt
Cuprous replacement ores from Komsomolsky deposit
Vale’s Voisey’s Bay Deposit, Labrador
3D representation of VB conduit system (5km) looking SW

- Associated with troctolites (olivine gabbro) part of 1.34 Ga anorthositic Nain Plutonic Suite straddling a 1.8 Ga suture
- Sulphides moved up series of conduit dikes from a series of “staging chambers”- Cu enriched, PGE-depleted
Voisey’s Bay Deposit, Labrador
Glacially-polished massive sulphides prior to mining

32 Mt at 1.68 % Cu, 2.83 % Ni and 0.12 % Co (55ktpa Cu) - 250m
Voisey’s Bay Ovoid zone
Mineralogical and chemical zonation

- Ovoid broadly zones towards a upper central core with elevated Cu (with cubanite), Pt-Pd, Pb and Ag
- No major segregation of Cu-rich residual sulphide melts
Mid Continental Rift (MCR)- Keeweenawan
Location and Geological setting

Eagle- 1107 +/- 5Ma (Ding, 2008)
Duluth Complex, Minnesota
Geology Map

Maturi Deposit

South Kawishiwi Intrusion

Virginia Fm.
Sulfur source
Duluth Complex Mineralization

- Over 4.4 Billion tonnes of diss. Ni-Cu-PGE mineralization at ~0.6% Cu and 0.2% Ni

- 12 major deposits close to the basal contacts over 55 km in basal troctolites

- Nokomis, Maturi, Birch Lake, and Dunka Pit deposits in the South Kawishiwi intrusion

- Mesaba and NorthMet deposits in the Partridge River intrusion

Image from Jim Miller presentation at PCR 6th workshop, 2013
Mesaba Deposit (Teck)
Section L 3600 West looking ENE showing mineralization

% Cu, % Ni, ppb Pt-Pd-Au meters

200 meters

From Severson 3013: PCR 6\textsuperscript{th} workshop
Mesaba Deposit (Teck)
Typical coarse disseminated mineralization

- Immense Resource; processing issues; potential hydromet. options
- Teck, Antofagasta, Glencore all involved trying to optimize recovery
Eagle deposit, Michigan
Western section through deposit

Hosted in funnel-shaped peridotite
~ 450 m x 80-100m wide,
extending to at least 300m

1995: several drill holes at Eagle East
with disseminated Ni-Cu

2002: YD02-02 intersected 84 m at 6.3%
Ni & 4 % Cu, targeting

2003 36 holes, 17 hit SMS to MS

5 Mt at 3.68 % Ni, 3.06 % Cu and 0.1 %
Co Resource

From Rossell, PRC Cu-Ni workshop, Duluth, Oct. 2013; Ding et al., 2011
Eagle deposit, Michigan
Cu-rich net-textured sulphides

DDH 03EA-034, 220.7m: 0.41% Cu, 0.75 % Ni, 3.16% S

From Rossell, PRC Cu-Ni workshop, Duluth, Oct. 2013
Eagle deposit, Michigan
Cu-poor (lower) and Cu-rich massive sulphides

Grades ~ 3 % Cu, 6 % Ni, 0.1 g/t Pt+Pd

Grades ~ 4.5 % Ni, 10 % Cu & > 5-10 g/t Pt + Pd
Eagle deposit, Michigan
Chalcopyrite veinlets in footwall sediments in 03EA-030,

350.73M - 5.5% Cu, 0.4% Ni, 22.5 ppm Pt, 2.7 ppm Pd

From Rossell, PRC Cu-Ni workshop, Duluth, Oct. 2013
Why are some magmatic deposits richer in copper than others?

1. Partial Melting Processes: Oxidizing conditions, p.m of pyroxenitic sources (ferropicrites), possible component from "re-fertilized" SCML?

2. FC prior to sulphide segregation: More fractioned magmas (gabro): Cu increase with FC until sulphide saturation achieved

3. Silicate-sulphide melt interaction (R factor): Large volumes of magma interacting with small amounts of sulphides result in v. high Cu contents in sulphide

4. FC of MSS after sulphide segregation: critical in hot, slowing cooling systems (Norilsk, Sudbury) and to lesser extent important in Eagle and Voisey's Bay
Magmatic Ni-Cu-PGE deposits
Cu-rich varieties related to Low MgO (Mafic) intrusions

1. Mantle *plume* impact and flow towards areas of thinner lithosphere
2. Decompression melting of plume at shallower levels- LIP
3. Transfer of melts into the (upper) crustal environment via *trans-lithospheric faults at terrane boundaries* and an interconnected intrusion-sills networks
4. Variable interaction of melts with crust
5. Nickel sulphide segregation and accumulation

Norilsk, Voisey’s Bay, Nebo-Babel type targets

- **Small** intrusions (chonoliths) with ferropicritic and/or gabbroic compositions-often not magnetic
- Must be at right erosional level, or use *EM* to look beneath volcanic cover and/or look for metal depletion/contamination in coeval volcanics
- **Surficial geochemistry** effective but small footprint- pay attention to Cu + PGE anomalies (rather than Ni that reflects MUM intrusion)
Distribution of larger Ni-Cu-PGE deposits and camps
Paucity in Brazil

- Santa Rita only large Ni-Cu deposits currently known in Brazil

Mostly in mature, ± exposed ± less-weathered exploration terranes where EM works
Magmatic Ni-Cu-PGE deposits in Brasil
A few potential exploration areas

Ni deposits
Sulphide Deposits NDB
Laterite Deposits
Archean Nuclei
- Basic to ultrabasic
- Gneiss
- Meta-volcano-sedimentary greenstone belts
- Charnockites
- Orthogneiss
- Tholeiitic volcanics
Cover Rocks & Basins
- Plateau basalts
- Cover Rocks & Basins

Parnaiba
Limoeiro
Caraiba
Santa Rita
Boa Vista
Niquelândia
American do Brasil
Paraná
Paraná (and Parnaiba) Basins

- 120 Ma CAMP LIP related to formation of central Atlantic ocean
- Flood basalts cover ~ 1.4 million km² in southern Brasil; average thickness 500 m in series of sub-basins (high R factor, dynamic conduits)
- Flood basalts overlying sediments with potential sulphur sources (S-sat.)
- MgO-rich sills known (e.g. Lomba Grande), lots of available regional data
Thank you

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For a world with new values.