Metallogeny of Chromite, Ni, Cu and PGE deposits Hosted in Mafic and Ultramafic Complexes of North America

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Talk outline

• Overview
• Genesis of Ni and Cr deposits
• Ni resources in North America
  – Geological context of major Ni camps
• Cr resources in North America
  – Geological context of Cr deposits
Large degrees of melting in the mantle
Segregation of sulfide or chromite from primitive magmas
Probable need for assimilation
S for Ni deposits
Iron formation for Cr deposits?
Plume magmas

- Passive margin
- Continental crust
- Lithospheric mantle
- Convecting mantle
- Plume head
- Rift alkaline lavas
- Intracontinental rift

Vertical exaggeration 10x
Plume magmas

submarine plate margin lavas

rift picrites, komatiites

vertical exaggeration 10x
Mechanisms of sulfide deposition

- Separation of immiscible sulfide liquid droplets
- Collection of base and precious chalcophile elements by sulfide
- Rain of sulfide droplets into cumulates to produce disseminated, net, and massive sulfide at the base of the liquid zone
- Conduits allow for a large amount of magma to be processed allowing for mass balance problems to be circumvented
- Structural traps like depressions, widenings of conduits
Chromite precipitation

- Magma mixing
- Assimilation
- Melt-crystal-fluid reactions
- Complex variations on these
Assimilation of iron formation

Compositions of picrite and assimilants used in the MELTS modeling.

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<th>Fe$_2$O$_3$</th>
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<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na$_2$O</th>
<th>K$_2$O</th>
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Increases modal proportion of chromite in cumulates from < 1% to < 5%
Conduits as chemical reactors

- influx of fresh magma
- contamination, sulfide saturation
- excess chromite crystallization
- depleted magma exits system
- sulfide collects in deepest parts of system
- chromite forms layers
Mechanisms of chromitite deposition

- Mechanical sorting of chromite and silicate may be a viable mechanism for the formation of chromitites
- In turbulent systems such as conduits crystals may be held in suspension until flow slows
- Conduits allow for a large amount of magma to be processed allowing for mass balance problems to be circumvented
- Channels and layers in conduits
- Stratiform deposition from slurries or turbid suspensions in layered intrusions
Physical environments

- Raglan
- Expo Ungava, Thompson
- Blackbird, Black Thor, Fox River
- Eagle's Nest
- Eagle
- South Raglan
- Voisey's Bay
- Duluth
Ni-Cu-PGE Deposits in North America

- Mid-Continent Rift
- Nain Plutonic Suite
- Sudbury Impact Structure
- Circum-Superior
- Superior Province greenstone belts

Map showing locations of deposits such as Thompson Nickel, Raglan, Voisey's Bay, Eagle's Nest, Abitibi, Duluth Complex, and Eagle.
After Naldrett (2003)

Production+reserves of Ni in millions of tonnes (m.t.)

- Raglan 25 (2.72)
- Eagle’s Nest 515 (1.06)
- Thompson 150 (2.32)
- Jinchuan 1309 (1.77)
- Kambalda 67 (2.90)
- Sudbury 1648 (1.20)
- Perseverance 52 (1.90)
- Pechenga 339 (1.18)
- Platreef 1597 (0.41)
- Voisey’s Bay 137 (1.59)
- Mt. Keith 478 (0.60)
- Duluth 4000 (0.20)
- Great Dyke 2574 (0.21)
- Merensky Reef 4210 (0.15)

Production+reserves of ore in millions of tonnes

- Cu-Ni deposits
- PGE deposits

After Naldrett (2003)
Ni-Cu-PGE in the Superior Province

Ring of Fire complex

Lac Des Iles

Shebandowan

Montcalm, Shaw Dome etc
Eagle’s Nest

- Massive sulfide sheet tight up against NW margin
- Net-textured sulfide forms bulk of deposit, sitting on top (SE) of massive
- Slightly overturned
- Steeply plunging blade-shaped body
Ni-Cu-PGE Deposits in North America

- Mid-Continent Rift
- Nain Plutonic Suite
- Sudbury Impact Structure
- Circum-Superior
- Superior Province greenstone belts
Circum-Superior Raglan deposits
Thompson Ni Belt

Fig. 2. Simplified regional geology of the northern (A) and southern (B) half of the exposed Thompson nickel belt (after Macek, 2001), showing the distribution of the lithologic units, lakes, and nickel deposits mentioned in the text. Metamorphic isograds after Costain et al. (2007).
Raglan horizon

- Channelized lava flows
- Subvolcanic feeder sills
- Complex overlapping relations
- Thermal erosion of underlying units.

Lesher et al. 2007
Cape Smith Belt
Expo Intrusive Suite – feeders to Raglan
Thompson Ni Belt Stratigraphic Column

<table>
<thead>
<tr>
<th>FORMATION</th>
<th>MEMBER</th>
<th>LITHOLOGY</th>
<th>ULTRAMAFIC SILLS</th>
<th>ORE DEPOSITS</th>
<th>SEDIMENTARY SULFIDES</th>
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- Mafic to ultramafic metavolcanics
- Rare felsic metavolcanics or felsic epiclastic rocks
- Metaconglomerates, greywackes, and minor pelites
- Interlayered quartzites and schists (metaturbidites)
- Pelitic schists
- Silicate facies iron-formation (SIIF)
- Sulphide facies iron-formation (SUIF)
- Dolomitic marble
- Impure calcareous metasediments
- Semipelitic schists
- Basal metaquartzite
- Local basal conglomerate, mostly small quartz pebbles
- Angular unconformity with local relics of a regolith
- Archean basement gneisses

modified from Bleeker (1990)

Bu = Bucko, Bi = Birchtree, M = Manbridge, P = Pipe, S = Soab, T = Thompson

Fig. 3. Reconstructed Ospwagan Group lithostratigraphy for the Thompson nickel belt (modified after Bleeker, 1990a).
Ni-Cu-PGE Deposits in North America

- Mid-Continent Rift
- Nain Plutonic Suite
- Sudbury Impact Structure
- Circum-Superior
- Superior Province greenstone belts
Mead
268.7 km
Creighton Embayment

Footwall rocks

Sulfide liquid accumulation in embayment structure

Sudbury Igneous Complex
Ni > 0.7% MINERAL INTERCEPTS
Looking from Southwest Morrison, 1999
Ni-Cu-PGE Deposits in North America

- Mid-Continent Rift
- Nain Plutonic Suite
- Sudbury Impact Structure
- Circum-Superior Province greenstone belts
Voisey’s Bay

After Kerr and Ryan
2000
After Li and Naldrett (1999)
Ni-Cu-PGE Deposits in North America

- Mid-Continent Rift
- Nain Plutonic Suite
- Sudbury Impact Structure
- Circum-Superior
- Superior Province greenstone belts
Mid-Continent Rift

Duluth Complex

Nokomis
550 Million Tonnes Indicated
0.639% Cu, 0.200% Ni
0.660 ppm Pt + Pd + Au
274 Million Tonnes Inferred
0.632% Cu, 0.207% Ni
0.685 ppm Pt + Pd + Au

NorthMet
910 Million Tonnes
0.27% Cu, 0.08% Ni
400 ppm Pt + Pd + Au

Maturi
120 Million Tonnes
0.67% Cu, 0.25% Ni
380 ppb Pt + Pd + Au

Spruce Road
529 Million Tonnes
0.43% Cu, 0.15% Ni

Birch Lake
169 Million Tonnes
0.56% Cu, 0.17% Ni
932 ppb Pt + Pd + Au

Dunka Pit
Cu-Ni-PGE

Nickel Lake
Cu-Ni-PGE

South Filson Creek
Cu-Ni-PGE

Serpentine
257 Million Tons
0.42% Cu, 0.14% Ni

Mesaba
~1 Billion Tons
0.43% Cu, 0.09% Ni
plus Pt + Pd + Au

Wetlegs
38 Million Tons (surface)
0.57% Cu equivalent
16 Million Tons (underground)
0.94% Cu equivalent

Wyman Creek
Cu-Ni-PGE

Titanium Resources
~220 Million Tons
~ 10% TiO₂

Precambrian Geologic Map of Minnesota

Map Area
**DESCRIPTION OF UNITS**

**MESOPROTEROZOIC (1.1 Ga.)**

**Duluth Complex and related rocks**

**South Kawishiwi Intrusion**

- **Anorthositic troctolite to troctolite (ATA Series)**: Medium to coarse-grained, homogeneous, well-foliated and locally layered anorthositic troctolite, troctolite, and ophitic troctolitic rocks.

- **Augite-bearing troctolite (Main AGT)**: Heterogeneous, coarse-grained to subophitic to ophitic, poorly foliated augite troctolite characterized by scattered augite-rich pegmatitic clots and patches. Commonly capped by hanging wall inclusions (Hb & Al) indicating that this unit is associated with the BMZ and not the ATA Series.

- **Sulfide-bearing troctolitic rocks (BMZ)**: Heterogeneous, sulfide-bearing vari-textured troctolite, augite troctolite, anorthositic troctolite, and olivine gabbro with 0.5 - 5% disseminated chalcopyrite, cubanite, pentlandite, and pyrrhotite.

**Anorthositic Series**

- **Anorthosite inclusion (AN-G & Al)**: Undifferentiated Anorthositic Series inclusions. Includes well-foliated anorthositic gabbro, troctolite-anorthosite, poliklitic troctolitic anorthosite, gabbroic anorthosite, and rarely gabbro and troctolite. Inclusions range in size from a few centimeters to elongated bodies measured in kilometers.

- **Anorthositic gabbro to gabbro (Upper Gabbro)**: Mixed group of Anorthositic Series rocks that occur in the central portion of the map. Includes well-foliated anorthositic gabbro, gabbro, anorthosite, hornblende gabbro, and augite troctolite. As a package, this unit represents the "Upper Gabbro" unit of Severson (1994) in drill holes.

**North Shore Volcanic Group**

- **Basaltic hornfels (Upper Basalt)**: Fine-grained, granoblastic to polycrystalline basaltic hornfels; consists of variable amounts of plagioclase, augite, olivine, hypersthene, and inverted pigeonite. Commonly associated with Anorthosite xenoliths (unit Al).

**ARCHEAN (~2.68 Ga.)**

- **Giants Range Batholith**
  - **Porphyritic quartz monzonite (GRB)**: Pink, coarse-grained, hornblende-porphyritic quartz monzonite with large (1-2 cm) orthoclase phenocrysts. Strongly recrystallized and partially melted locally among the contacts with the South Kawishiwi Intrusion.
Mid-Continent Rift – Eagle Deposit

4.05 million tonnes with an average grade of 3.57% Ni, 2.91% Cu
Global Chromite Resources (Mt)

- South Africa (Bushveld)
- Zimbabwe (Great Dyke)
- Kazakhstan (Donskoye)
- Canada (ROF)
- India (Sukinda)
- Finland (Kemi)
- Turkey (various podiform)
- Philippines (podiform)
- Brazil (various stratiform)
Chromite occurrences in North America

- Muskox Intrusion
- Oregon Resources Corp
- Big Trout Lake
- Double Eagle complex
- Mouatt Mine
- Stillwater Complex
- Bird River Belt
Chromite in the Superior Province

Bird River greenstone belt

Big Trout Lake intrusion

Double Eagle complex
Double Eagle Complex – 2735 Ma
Blackbird Deposit

GROUND GRAVITY SURVEY:

- High Bouguer anomaly over peridotite
- Sharp local increase over chromitite
- Use of high pass filter successfully picks out chromitite beds
NOT 08 1G31

70 m chromitite intersection
Intercalated beds
Bird River belt

- 2745 Ma
- 3.6 Mt 21% Cr$_2$O$_3$
- 20 to 30% Cr$_2$O$_3$
- 40 to 44% Cr$_2$O$_3$ in chromite, Cr/Fe between 1 and 1.36 (Bateman, 1945)
Big Trout Lake

- 140 Mt 8.4% Cr$_2$O$_3$ (Platinex)
- 28.5% Cr$_2$O$_3$ over 3.3 m
Stillwater Complex 2705 Ma

Explanation

Rock Types
- unconsolidated deposits
- Phanerozoic sedimentary rocks
- Archean quartz monzonite
- older Archean rocks

Stillwater Complex
- Upper Banded series
- Middle Banded series
- Lower Banded series
- Ultramafic and Basal series
- JM Reef

Zeintek, 2005
Mouat Cr Mine (1940’s to 1962)

- Total Stillwater reserves 50 Mt ~ 22% Cr$_2$O$_3$ (Nevoro Inc)
- Only historic Cr production in North America
Conclusions

- Known giant deposits mostly mined out
- New deposits continue to be discovered
- Ring of Fire deposit group continues to grow
- > 200 Mt chromitite, 20 Mt Ni ore added to resources since 2008

- Are there any giant deposits left to discover?

Yes!