Geology, Genesis, and Exploration for Magmatic PGE-(Cu)-(Ni) Deposits

C.M. Lesher
Mineral Exploration Research Centre
Harquail School of Earth Sciences
Goodman School of Mines
Laurentian University
mlesher@laurentian.ca

Magmatic Ni-Cu-PGE Deposits

- **Sulfide-rich Ni-Cu-Co-(PGE) deposits**
  - Stratiform massive net-textured disseminated Ni-Cu-(PGE) mineralization: Sudbury, Noril’sk, Pechenga, Raglan, Thompson, Kambalda
  - Strata-bound disseminated to net-textured Ni-Cu-(PGE) mineralization: Jinchuan, Mt. Keith, Dumont, Damba-Silwane

- **Sulfide-poor PGE-(Cu)-(Ni) deposits**
  - Stratiform “reef style” low-sulfide PGE-(Cu)-(Ni) mineralization: Bushveld, Stillwater, Great Dyke
  - Strata-bound chromite-associated low-sulfide PGE-(Cu)-(Ni) mineralization: Uralian-Alaskan complexes
  - Discordant (modified magmatic or hydrothermal) low-sulfide PGE-(Cu)-(Ni) mineralization: Lac des Iles, Rathbun Lake (ON), New Rambler (WY), Wengeqi (CH)
Locations of PGE-(Cu)-(Ni) Deposits

PGE Grade vs Tonnage

Largest tonnages in Bushveld (Merensky Reef, UG-2, Platreef) and Great Dyke; Sudbury and Noril’sk have much larger tonnages than Stillwater, Portimo, or Lac des Iles

Highest grades at Stillwater and Noril’sk; Raglan ores have grades close to those of Bushveld and Great Dyke
Magmatic PGE-(Ni)-(Cu) Deposits

- **Sources**
  - S: normally the magma
  - PGE: normally the magma

- **Sinks**
  - Collection by sulfide melt
  - Collection by PGMs
  - Collection by chromite
  - Collection by PGE clusters
  - Collection by Cl-rich fluids

Platinum-Group Elements

- **Base Metals**
- **IPGE**
- **PPGE**

*lanthanoids*

*actinoids*
**Terminology**

- **PGE** = platinum-group *elements*
  - **PGM** = platinum-group *minerals*
- **PPGE** = Pt-group **PGE** = Pt + Pd + Rh
  - **IPGE** = Ir-group **PGE** = Ru + Ir + Os
- Au is not a PGE, but it also partitions strongly into sulfides, is commonly present in similar abundances as Pt-Pd, is commonly analyzed with Pt and Pd, and is sometimes (especially in low-grade deposits...) included in resource estimates as “TPM” (total precious metals)
- **Noble metals** (in terms of corrosion resistance) = PGE + Au
  - **Noble metals** (in terms of having filled d orbitals) = Au + Ag + Cu
- Precious metals = PGE + Au + Ag

**Metal Partitioning**

- **PGE** partition strongly \((10^5-10^6)x\) into sulfide melt relative to silicate melt, varying with T, composition, \(/O_2\), and \(/S_2\)
- Thus, small amounts of sulfides may contain very large amounts of PGE, provided that there is enough magma from which to extract PGE (i.e., high magma:sulfide ratio: R factor)
- **Cu** and **PPGE** partition preferentially into sulfide liquid relative to MSS \((D_{Cu}^{MSS/melt} < D_{PPGE}^{MSS/melt} < D_{Ni}^{MSS/melt} < D_{IPGE}^{MSS/melt})\), so sulfide fractionation may also produce enrichments in PPGE (e.g., Sudbury, Noril’sk)
- Pt and Pd are soluble in hydrothermal fluids (Wood 2002 *CIM v54*), but Ir appears to be almost insoluble (Keays 1982 *Econ Geol*; Lesher & Keays 1984 *IMM*; see also Farrow and Watkinson 1996 *EMJ*)
## Metal Partitioning

<table>
<thead>
<tr>
<th>Cus</th>
<th>Ir</th>
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<th>Rh</th>
<th>Pt</th>
<th>Pd</th>
<th>As</th>
<th>Ni</th>
<th>Cu</th>
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### Monosulphide Solid Solution — Sulphide Liquid Sulphur Saturated

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**Geology, genesis, and exploration for magmatic and magmatic-hydrothermal ore deposits**

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**Effect of Magma:Sulfide Mass Ratio (R)**

- **Elements with high Ds** (PGE-Au ~ $10^5$) achieve maximum abundance only at high R
- **Elements with intermediate Ds** (Cu 600-1000, Ni 100-500) achieve maximum abundance at intermediate R
- **Elements with low Ds** (Co ~30) achieve maximum abundance at low R

$D = \frac{\text{conc in sulfide melt}}{\text{conc in silicate magma}}$. Elements achieve maximum abundances only if $R > 10D$, which means that when $R < 10D$, the abundances are strongly controlled by the R factor (magma:sulfide ratio).

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**Major Producing Districts**

<table>
<thead>
<tr>
<th>District</th>
<th>Deposit/Type</th>
<th>Age (Ma)</th>
<th>Size (Mt)</th>
<th>Pt:Pd</th>
<th>Pt+Pd (g/t)</th>
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<tr>
<td>Bushveld</td>
<td>Merensky</td>
<td>2054</td>
<td>26.15</td>
<td>2:1</td>
<td>6-8</td>
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<tr>
<td></td>
<td>UG-2</td>
<td></td>
<td>32.72</td>
<td>1.5:1</td>
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<td></td>
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<td>250</td>
<td>~400</td>
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<td>Stillwater</td>
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<td>23.8</td>
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<td></td>
<td>Footwall</td>
<td></td>
<td></td>
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<td>5-20</td>
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</table>

Some Fe-Ni-Cu sulfide deposits contain significant amounts of PPGEs (e.g., Noril’sk, Duluth) and many contain recoverable amounts of PGEs.

Some PGE deposits contain significant amounts of Ni ± Cu (e.g., Plat Reef, Portimo, LDI).

Not a continuum, as the processes that form the two groups are, as we shall see, different in many ways.

However, the presence of Ni and Co with PGE in most deposits indicates that some of the processes are fundamentally similar in both groups.
Geochemical Patterns

Magmatic PGE deposits are strongly enriched in Pd relative to Cu and Ni

Platreef less enriched in PGE, less depleted in Ni-Cu, but similar pattern

LDI strongly depleted in Ir, reflecting strong hydrothermal overprint

NB. data are not normalized to 100% sulfides

Geochemistry

- Enrichment in PGE relative to Ni and Cu cannot be entirely explained by variations in magma:sulfide ratio (R factor)
- There are several possible explanations for the anomalously high PGE contents:
  - Enrichment of the magma in PGE (for example via partial melting of lower-T PGMs in pre-existing sulfides by a sulfide-undersaturated magma)
  - Incorporation of PGE alloys, which have 10x higher solid/melt partition coefficients than sulfides
  - Incorporation of PGE “clusters” (to be discussed below, but fundamentally similar to incorporation of PGE alloys)
Chromite-poor reefs (J-M) are more fractionated with higher PPGE, whereas chromite-bearing reefs (Merensky and UG-2) and sulfide-bearing chromitites (A chromitite) are less fractionated, and sulfide-free chromitites are depleted in PPGE relative to IPGE. Thus, PPGE appear to be housed in sulfide.

Classification

I) Basal contact mineralization: Portimo and Koillismaa (Finland), Platreef and Sheba’s Ridge (Bushveld), and East Bull Lake and River Valley (Ontario), Marathon (Coldwell), PGE-rich Ni-Cu deposits

II) Strata-bound internal mineralization
   A) Chromitite-Associated: Uralian-Alaskan podiform chromitites
   B) Sulfide-Associated: PGE-rich Ni-Cu deposits
   C) Magnetite-(Apatite)-Sulfide-Associated: Baron and Volokovsky (Urals)

III) Stratiform internal “reef” mineralization
   A) Chromitite-Associated: UG-1 and UG-2 (Bushveld), parts of Merensky Reef, parts of Sompujärvi Reef (Penikat), “A” chromitite (Stillwater), Panton Sill (WA)
   B) Sulfide-Associated:
      i) Early: J-M Reef (Stillwater), parts of Merensky Reef, Main and Lower Sulfide Zones (Great Dyke), Munni Munni (W Australia), RK and SK reefs (Portimo), parts of Sompujärvi Reef (Penikat)
      ii) Late: Platinova (Skaergaard), Sonju Lake (Duluth), Rincon del Tigre (Brazil), upper part of Bushveld
   C) Magnetite-(Apatite)-Associated: Bermuda (Coldwell)

IV) PGE-(Cu)-(Ni) deposits formed though magmatic-hydrothermal refining of Ni-Cu-(PGE) mineralization: Roby Zone (Lac des Iles), Sudbury footwall deposits, parts of Noril’sk, dunite pipes (Bushveld), Waterberg (Transvaal), New Rambler (Wy), Coronation Hill (NT-Aus), Rathbun Lake (ON), Wengeqi (CN)
Stratiform PGE: Overview

- **Age:** largest are mid-Archean to Proterozoic (after stabilization of continental crust)
- **Geologic Setting:** mostly in large (>3 km thick) layered mafic-ultramafic intrusions
  - Olivine abundant in lower parts of section (characteristic of high-Mg parental magmas)
  - Opx is dominant pyroxene in the lower parts (characteristic of crustally-contaminated basaltic magmas)
  - Most are associated with chromite layers (characteristic of komatiitic basaltic magmas)
- **Host rocks:** typically pegmatoidal gabbros/pyroxenites normally (but not always) after first appearances of chromite and plagioclase
- **Ore localization:** stratigraphic
- **Metal Fractionation:** Au-PPGE → IPGE → Cu-Ni-S
- **Composition of magma:** mantle-derived, anything more mafic than MORB, initially olivine-saturated (best) and sulfide undersaturated (critical)
- **Metal source:** normally the magma
- **S source:** probably not important, but mainly the magma
- **Ore-forming process:** magma mixing, contamination, and/or filter pressing with fluid-magma interaction

Modified from Naldrett 2004 Springer
PGE Reefs

- Originally from the Middle Low German and Middle Dutch “rif” or “ref” and the Old Norse “rif” for “rib”
- Applied by South African/Australian miners to narrow “bedded” gold seams, but subsequently applied to thin stratiform disseminated PGE mineralization
- Normally thin (10 cm - 2m) layers
- No particular rock type, but
  - Typically pyroxenitic or gabbroic
  - Generally coarse-grained or pegmatioidal
  - Generally contain minor sulfide (1-3%)
- Economic reefs grade >2 ppm Pd + Pt
- Often difficult to identify in the field

Stratigraphic Location

- Most major and many minor deposits occur in the lower parts of layered intrusions (e.g., Bushveld, Great Dyke, Stillwater, Munni Munni)
- But some minor (so far) deposits occur in the upper parts of layered intrusions (e.g., Skaergaard, Rio Jacare, Rincon del Tigre, Stella, Sonju Lake)
- “Reefs” are in the upper 1/3 of the intrusion
- Wide range of ages (3 Ga to 50 Ma)
- Dominant pyroxene is Cpx (not Opx)
- Main oxide is magnetite (not Chr)
- Parental magma is tholeiitic, but associated in some cases with flood basalts
Stratigraphy of Layered Intrusions Containing PGE Reefs

- **Bushveld**: 7 km, 2.05 Ga
  - dior, gab, mag

- **Stillwater**: 6 km, 2.7 Ga
  - an, gab, troc

- **Munni Munni**: 4.5 km, 2.7 Ga
  - an, gab, troc

- **Great Dyke**: 3.5 km, 2.6 Ga
  - an, gab, troc

- **Penikat**: 2.4 Ga
  - PV, AP, SJ, gab, pyx, chr, dun

**Geology, genesis, and exploration for magmatic and magmatic-hydrothermal ore deposits**

- **Diorite (dior)**
- **Magnetite (mag)**
- **Anorthosite (an)**
- **Gabbro (gab)**
- **Troctolite (Ol-Plag) (troc)**
- **Pyroxenite (pyx)**
- **Bronzitite (bz)**
- **Norite (Opx-Cpx-Plag) (nor)**
- **Harzburgite (Opx-Ol) (hz)**
- **Chromitite (chr)**
- **Peridotite (per)**
- **Dunite (dun)**

**Stratigraphy of Layered Intrusions Containing PGE Reefs in Upper Parts**

- **Bushveld**: 8 km, 2.05 Ga
  - 3 Ga, 2.6 Ga, 1.1 Ga, 60 Ma
  - PGE-enrichment
    - Granophyre
    - Leucogabbro-norite, magnetite layers
    - Gabbronorites, magnetite lenses
    - Pyroxenite
    - Peridotites

- **Stella**: 2.6 Ga

- **Rio Jacare**: 1.1 Ga

- **Sonju Lake**: 60 Ma

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S-J Barnes 2008 Quebec Exploration

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Critical Ingredients

- Stable continental crust to pond magma and support very large layered intrusion
- Large thermal anomaly (e.g., mantle plume) to provide large amounts of sulfide-undersaturated magma over a short time period
  NB. a magma enriched in PGE is probably necessary to generate an economically-robust deposit
- FC to bring magma close to sulfide saturation
- Mechanisms to induce magma mixing, contamination, and/or filter pressing and fluid-magma interaction
- Mechanism to achieve high R factor
- Mechanism to produce chromatographic fractionation of PGEs and base metals (to be discussed below)
Merensky Reef

- Located in the upper part of the Critical Zone
- Composed of coarse-grained to pegmatoidal pyroxenite
- Chromitites on upper (normally) and lower (almost always) contacts
- Underlain by anorthosite, overlain by pyroxenite
- PGE mineralization is *transgressive* to stratigraphy on both large and small scales
E-W Variation in Merensky Reef

- WEST
- 75 km
- EAST

- IMPALA
- RUSTENBURG
- KAREE
- WESTERN
- EASTERN

- Anorthosite
- Chromitite
- Pyroxenite
- Pegmatitic Pyroxenite

Potholes

- Interpreted to represent slumps, erosion, and/or dissolution

Key
- Mottled anorthosite
- Troctolite
- Leucorite/norite/melanorite
- Pyroxenite
- Pegmatitic pyroxenite
- Feldspathic dunite
- Chromitite
- Anorthosite layer

Smith & Basson 2006 Min Dep
Merensky Reef

Stope face exposing footwall norite, thin chromite seam, Merensky Reef, and hanging wall pyroxenite, Rustenburg Mine (photo AJ Naldrett)
Merensky Reef

Normal Merensky Reef, Impala Mine

S-J Barnes & Maier 2002 J Pet

Merensky Reef

Normal Merensky Reef, Rustenburg Mine

Godel et al. 2007 J Pet

Footwall
anorthosite
Chromite layer
Plagioclase
Melanorite
Chromite layer
Melanorite

5 cm

Sulphides

Chromitite  13 ppm Pt
Chromite layer  33 ppm Pt

10 cm

anorthosite  6 ppm Pt

melanorite  5 ppm Pt
cg melanorite  23 ppm Pt
chromite layer  33 ppm Pt
Photomicrograph of normal Merensky Reef, Rustenburg Mines (photo S-J Barnes)

Photomicrograph (left) and CT scan (right) of Merensky Reef, Rustenburg Mines (Godel et al. 2007 J Pet)
Photomicrograph of Fe-Ni-Cu sulfides between chromite grains in Merensky Reef (photo S-J Barnes)

PGE Distributions
Merensky Reef at Rustenberg

Different PGE are present in different phases (PGM or sulfides) in chromite layers and in silicate layers

Godel et al. 2007 J Pet
Pt and Pd vs. Stratigraphic Height

Variations in Pt and Pd concentrations with stratigraphic height on Western and Eastern Limbs projected onto the Union Section. Data sources listed in S-J Barnes & Maier (2002 CIM). ◁ = Lower Zone harzburgites and pyroxenites; ○ = Critical Zone harzburgites and pyroxenites; △ = chromitites of Lower Critical Zone; ▽ = chromitites of the Upper Critical Zone; □ = Critical Zone melanorites to leuconorites; ▲ = UG2; X = Pseudoreefs or Boulder Bed; ▼ = Merensky Reef; * = Bastard Reef; ▼ = Main Zone gabbronorites.

S-J Barnes & Maier 2002 CIM v54
Are There Other Ways?

- Most differentiated mafic-ultramafic intrusions contain thin, subeconimic concentrations of PGEs – are there circumstances (e.g., contamination, oxidation/reduction) under which larger amounts of PGE might be segregated?
- Most magmatic Fe-Ni-Cu sulfide deposits contain recoverable amounts of PGEs – are there any circumstances (e.g., oxidation/reduction) under which more PGE might partition into those sulfides or where they may fractionally crystallize more efficiently?
- Au-PPGE-Cu are more mobile than Ni-Co-IPGE – are there other environments in which hydrothermal systems have interacted with magmatic sulfides?

What Have We Overlooked?

- Most mafic-ultramafic magmas contain sufficient quantities of PGE to produce an ore deposit by several different mechanisms, as indicated by the wide range of deposit types and stratigraphic locations
- Are there other geologic settings/processes that have been overlooked?
- New deposits and new deposit types are often discovered by accident, but can be discovered by thinking laterally
Acknowledgements

- **Sarah-Jane Barnes** (Université Québec à Chicoutimi)
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- **Rebecca Sproule** (MERC/GeoDiscovery Group/NewGenCo/Tascan Geosciences)

Selected Review Papers and Books

Cabri LJ (Editor), 2002, The Geology, Geochemistry, Mineralogy, and Mineral Beneficiation of the Platinum-Group Elements, Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 54, 852 pp


Mungall JE (Editor), 2005, Exploration for Platinum Group Element Deposits, Mineralogical Association of Canada, Short Course Notes, v. 35, 512 pp


Chemical and Physical Properties Database:
http://www.platinummetalsreview.com/jmpgm/