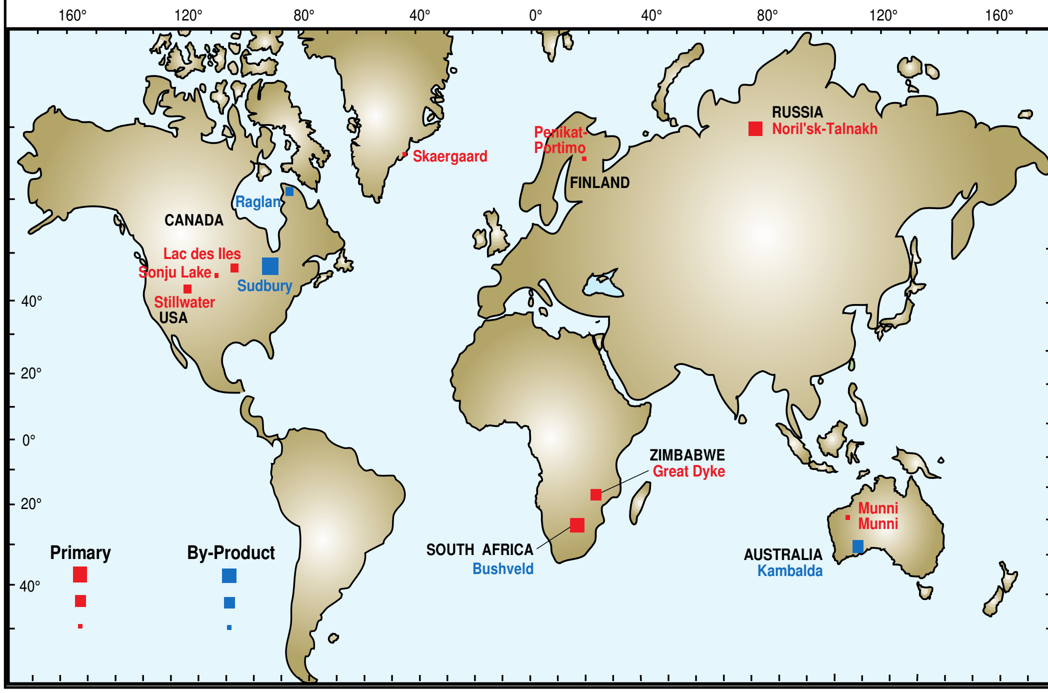
Geology, Genesis, and Exploration for Magmatic PGE-(Cu)-(Ni) Deposits

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

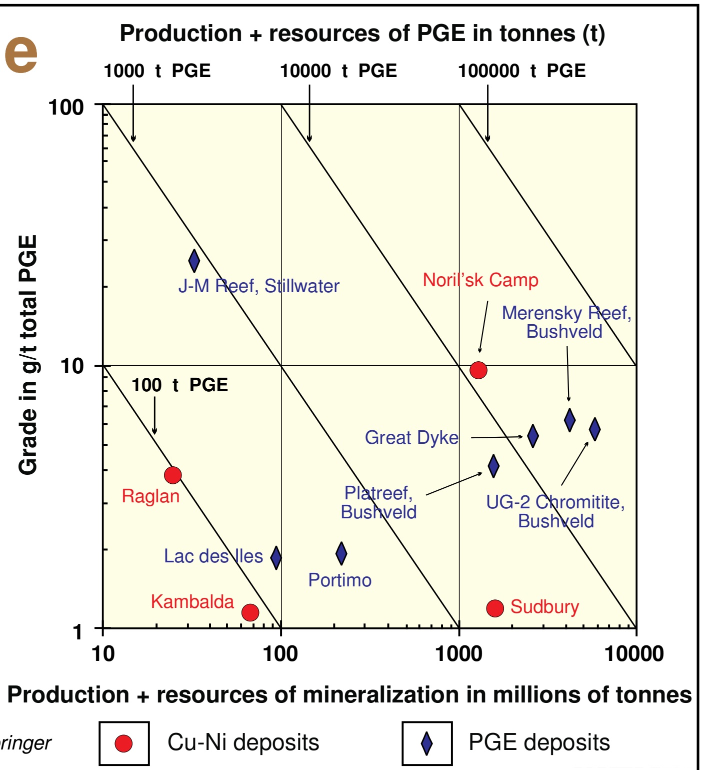


adapted from USGS

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

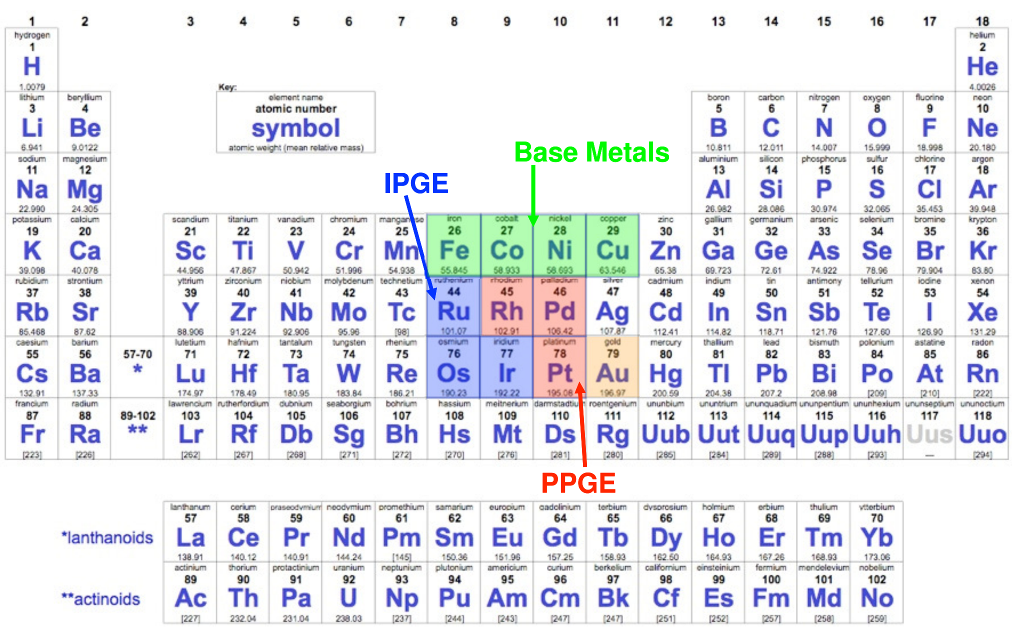


Naldrett 2004 *Springer*

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



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** (10^5-10^6x) **into sulfide melt relative to silicate melt, varying with T, composition, fO_2, and fS_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

Os	Ir	Ru	Rh	Pt	Pd	Au	Ni	Cu	Reference
Sulphide Liquid — Silicate Liquid									
>31 000	>50 000	>12 000	>140 000	>18 000	>92 000		810-1300		Sattari et al. (2002)
	130 000			9100	88 000	1200			Stone et al. (1990)
230	310 000	2500	27 000	>1 000 000	55 000	16 000			Bezmen et al. (1994)
	35 000				43 000				Peach et al. (1994)
	450 000				33 000				Peach et al. (1994)
				36 000	25 000				Helz and Rietz (1988)
10 000	51 000	35 000		13 000	25 000	1200			Crocket et al. (1997)
	14 000				23 000	15 000-18 000	575-836	1383	Peach et al (1990)
30 000	26 000	6400		10 000	17 000				Fleet et al. (1996)
700-5300	1500-4700	1200-4100		1100-6900	1200-6300	30-3000			Fleet et al. (1999)
48 000									Roy-Barman et al. (1998)
							315-424	913-1006	Francis (1990)
						110-1300	350-1070		Jana and Walker (1997)
Monosulphide Solid Solution — Sulphide Liquid Sulphur Saturated									
4.3	3.6	4.2	3.03	0.2	0.2	0.09	0.84	0.27	Fleet et al. (1993)
3.4-11		1.17-3.0	0.05-0.13	0.09-0.2		0.36-0.8	0.2-0.25		Barnes et al. (1997b)
Monosulphide Solid Solution — Sulphide Liquid Sulphur Undersaturated									
0.77 1	0.14	0.19	0.02		0.23				Fleet and Stone (1991)
	0.08-1.4		0.4-0.8	0.01-0.05	0.01-0.07		0.18-0.36	0.17-0.2	Barnes et al. (1997b)
Monosulphide Solid Solution — Sulphide Liquid Sulphur Oversaturated									
	5-17		3.9-11	0.14-0.24	0.13-0.24		0.7-1.2	0.22-0.27	Barnes et al. (1997b)
Spinel — Silicate Liquid									
		22-25	78-90		0.2				Capobianco and Drake (1990)
		300-1200	130-430		0.4-1.2				Capobianco et al. (1994)
							3.5-6.8		Sattari et al. (2002)
Alloy — Silicate Liquid									
10^6 -10^7	10^{12}			10^{15}	10^7	10^7			Borisov and Palme (1997)
						1005-3543	57-1607		Jana and Walker (1997)
	300 000					800 000	6000		Wolf and Anders (1980)
	100 000					>40 000	3100	80	Kloch et al. (1986)

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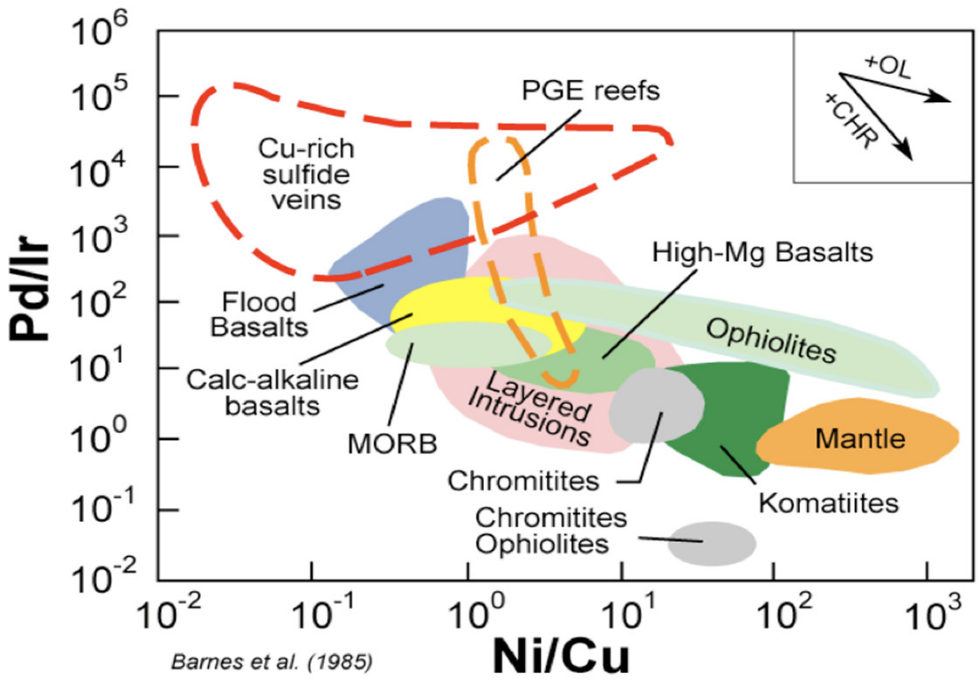
as compiled by S-J Barnes & Maier 2002 *CIM v54*



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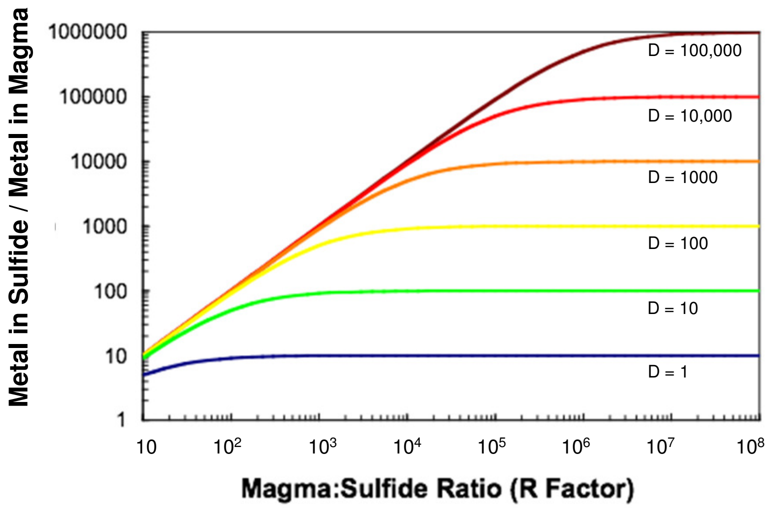
Effect of Magma:Sulfide Mass Ratio (R)



Elements with high Ds (PGE-Au ~ 10^6) **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**

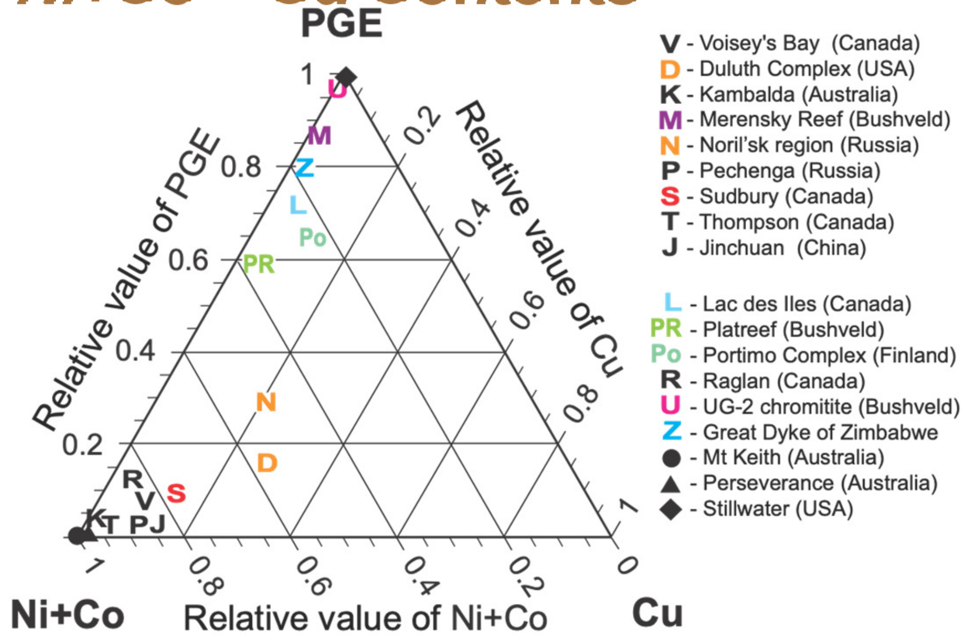
D = conc in sulfide melt/conc in silicate magma. **Elements achieve maximum abundances only if R > 10D, which means that when R < 10D, the abundances are strongly controlled by the R factor** (magma:sulfide ratio).

Major Producing Districts

District	Deposit/ Type	Age (Ma)	Size (Mt)	Pt:Pd	Pt+Pd (g/t)
Bushveld	**Merensky**	2054	26.15	2:1	6-8
	UG-2		32.72	1.5:1	5-8
	Platreef		6.58	1:1.3	5
Noril'sk-Talnkh		250	~400	1:3	12.2
Stillwater		2711	23.8	1:4	23
Lac des Iles		2740	159	1:9	1.7
Sudbury	**Contact**	1850	1655	1:1	0.7
	Offset				2.5
	Footwall				5-20

compiled by CEG Farrow from Dummett (2002), Lightfoot & Keays (2001), Farrow & Lightfoot (2002), NAP (2001 Results: 13 Mar 2002)

PGE – Ni+Co – Cu Contents



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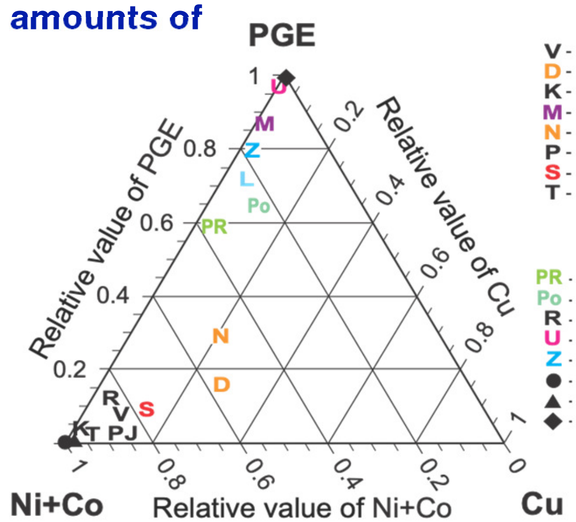
PGE, Ni-Co, and Cu Contents

- **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**



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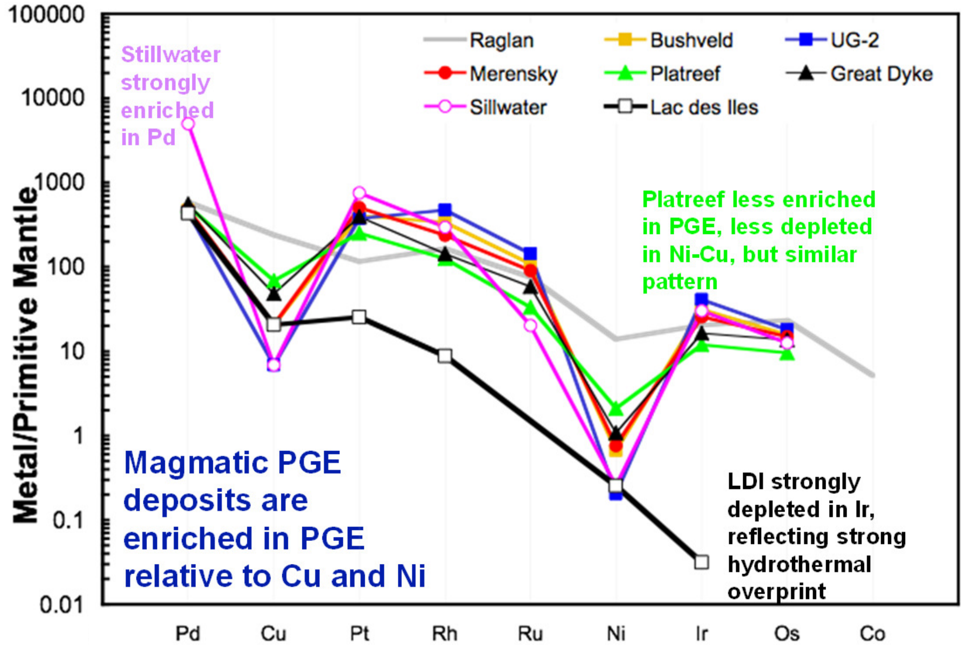
Geochemical Patterns



NB. data are *not* normalized to 100% sulfides

data from Naldrett 2004 *Springer*

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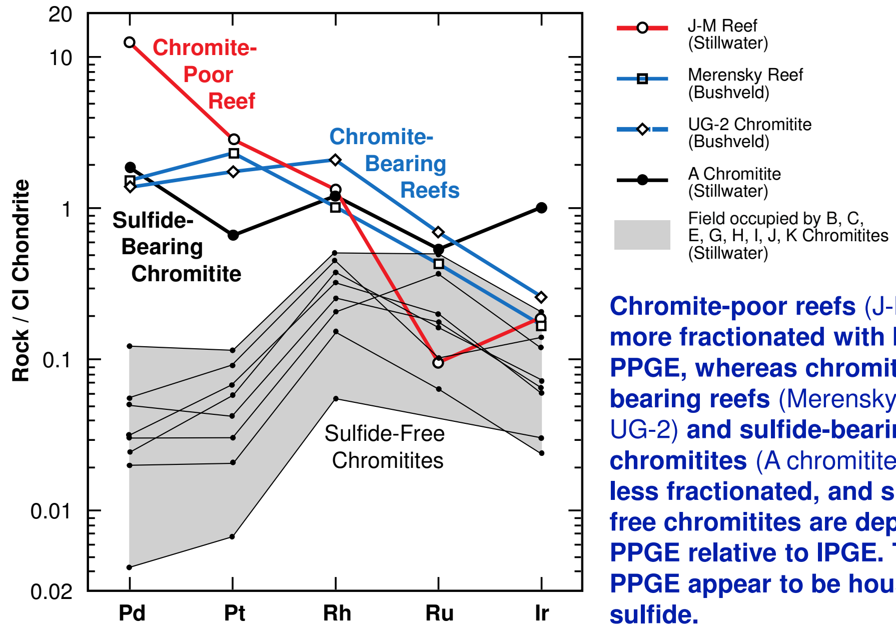
Geochemistry

- **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-exisiting 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)

PGE in Reefs and Chromitites



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.**

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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)

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scheme adapted from Lesher & Keays 2002 *CIM,* examples from Naldrett 2004 *Springer*

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

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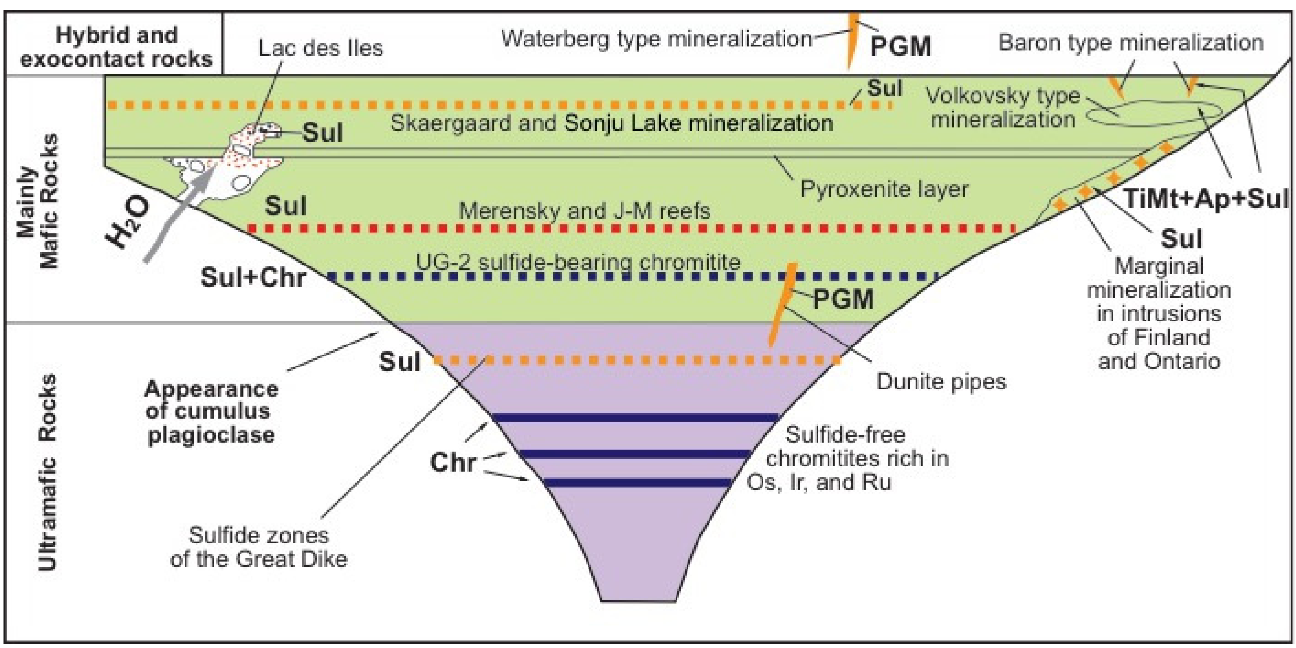
Stratigraphic Settings



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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**

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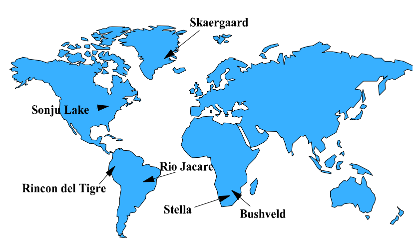
adapted from S-J Barnes 2008 *Quebec Exploration*

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**



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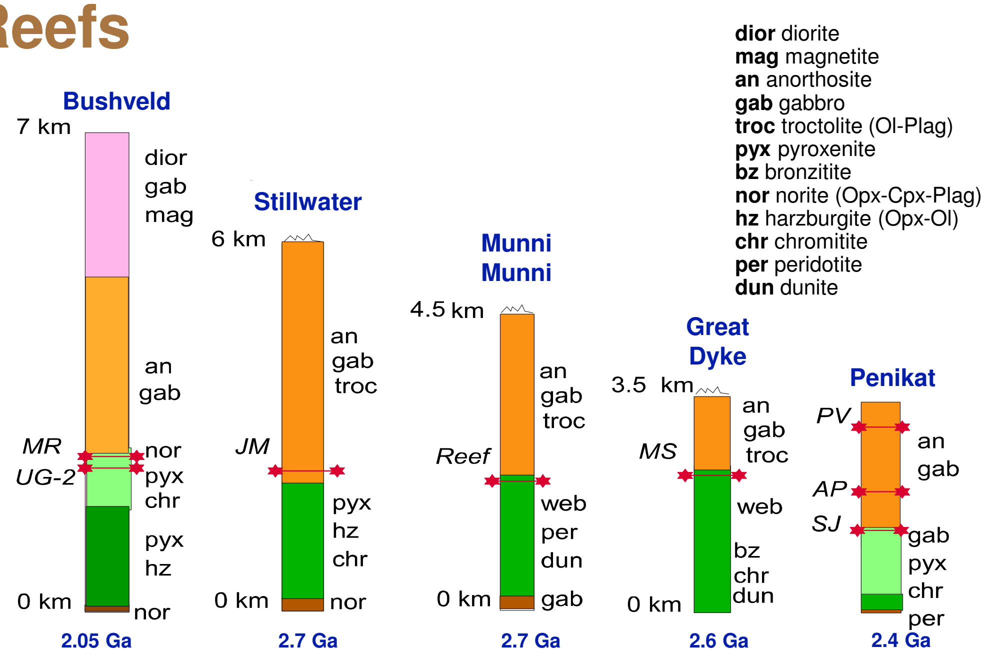
S-J Barnes 2008 *Quebec Exploration*

Stratigraphy of Layered Intrusions Containing PGE Reefs



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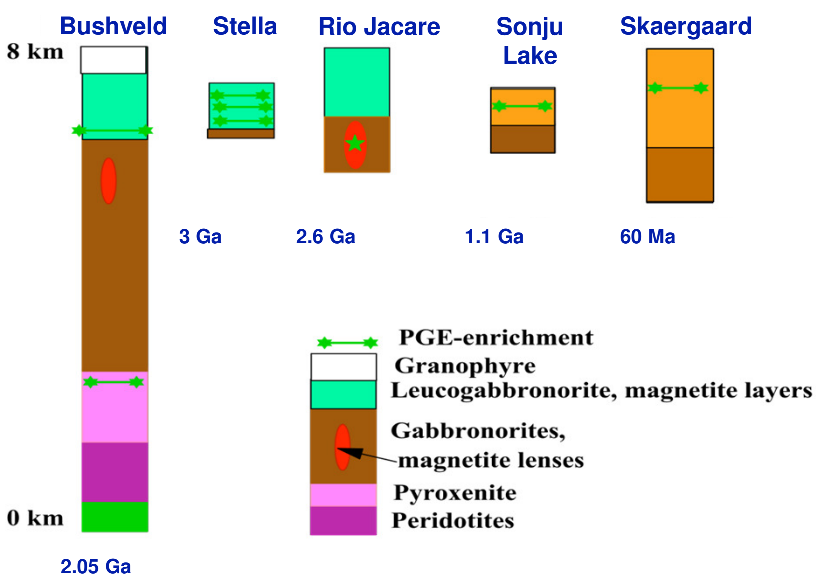
Stratigraphy of Layered Intrusions Containing PGE Reefs in Upper Parts



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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)

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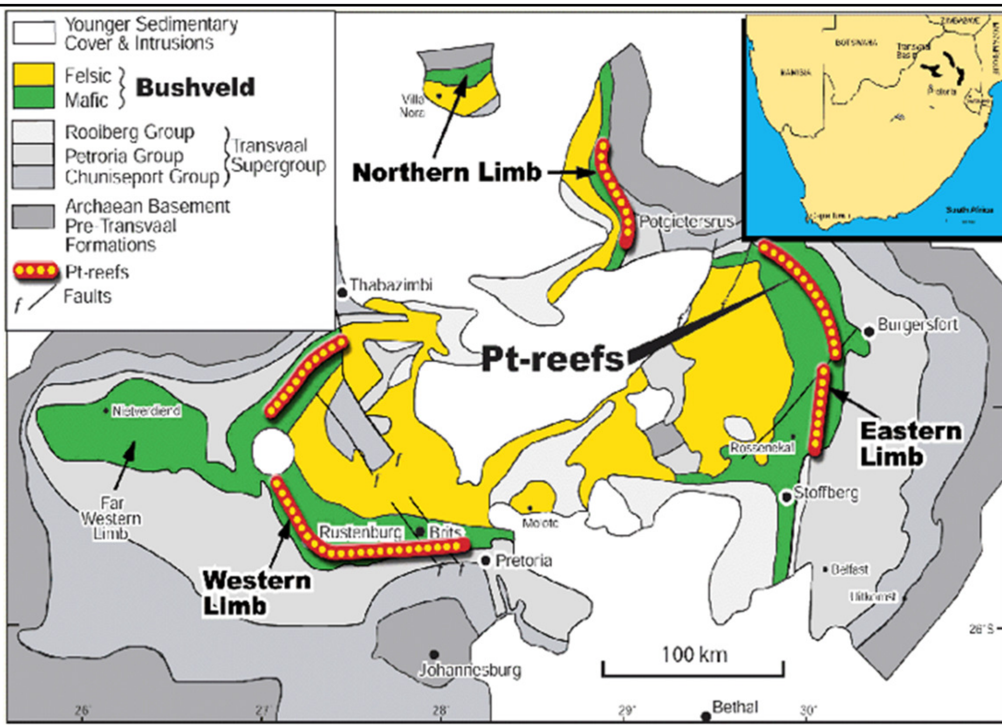

S-J Barnes & Maier 2002 *CIM v 54*, as modified after Cawthorn & Lee 1998 *SAIMM Guidebook*

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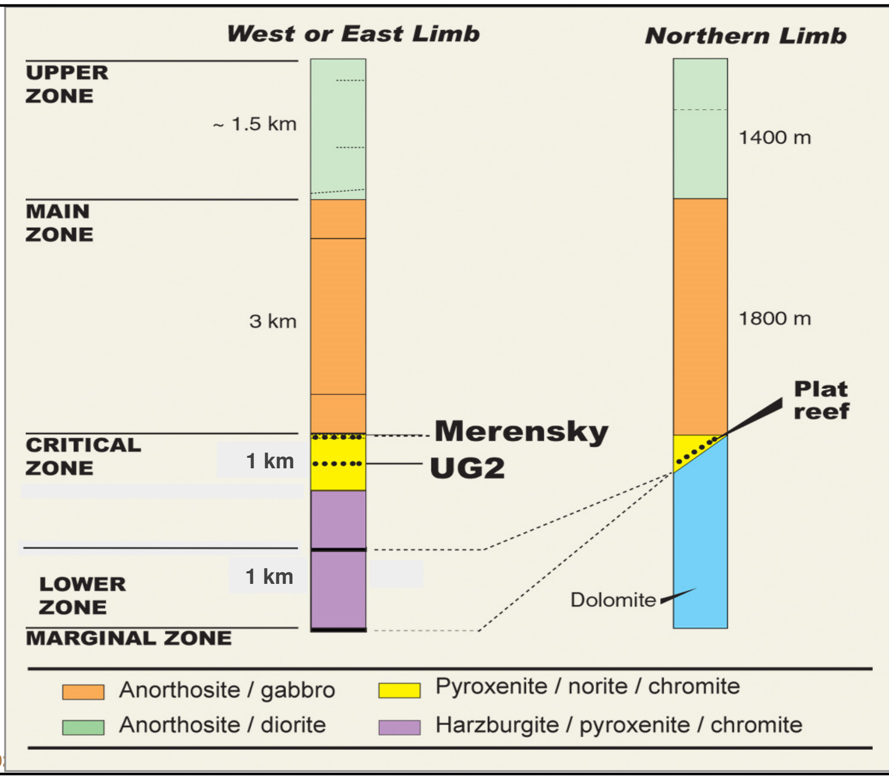
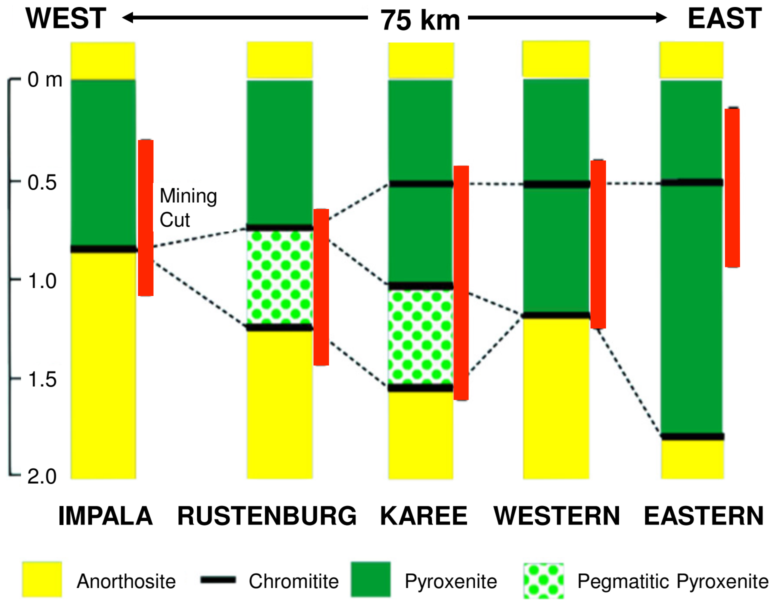


S-J Barnes & W Maier 2002 *CIM v54*

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



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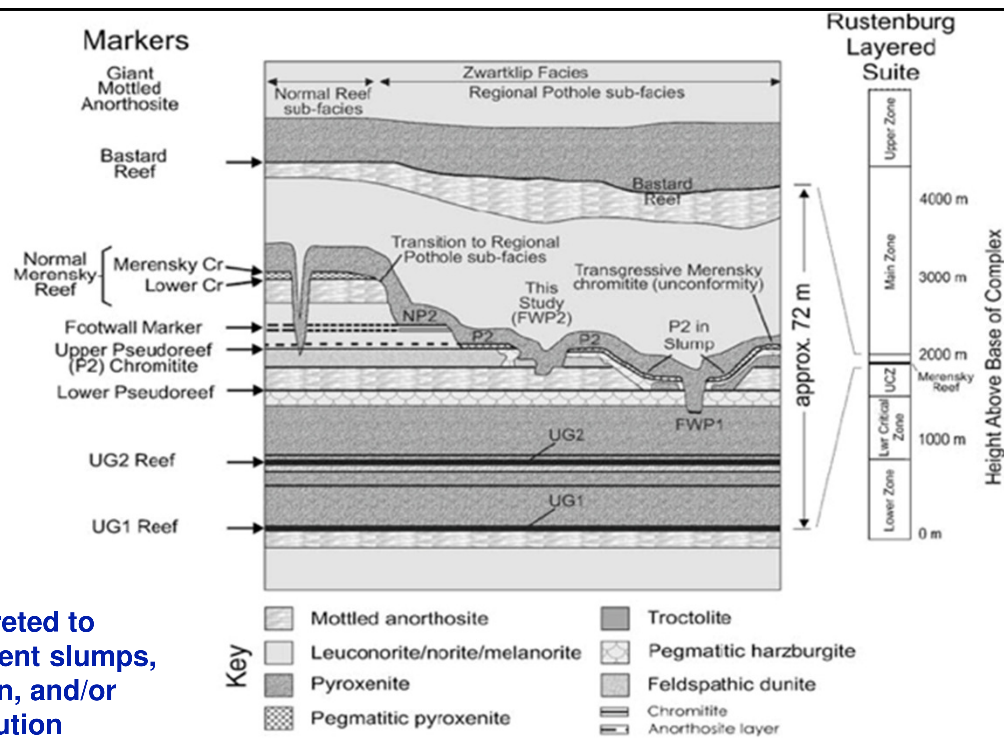
Cawthorn et al. 2004 *Econ Geol 100th Anniv*

Potholes



Interpreted to represent slumps, erosion, and/or dissolution

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Smith & Basson 2006 *Min Dep*

Merensky Reef

Hanging wall pyroxenite

Chr

Merensky Reef

Chr

Footwall anorthosite

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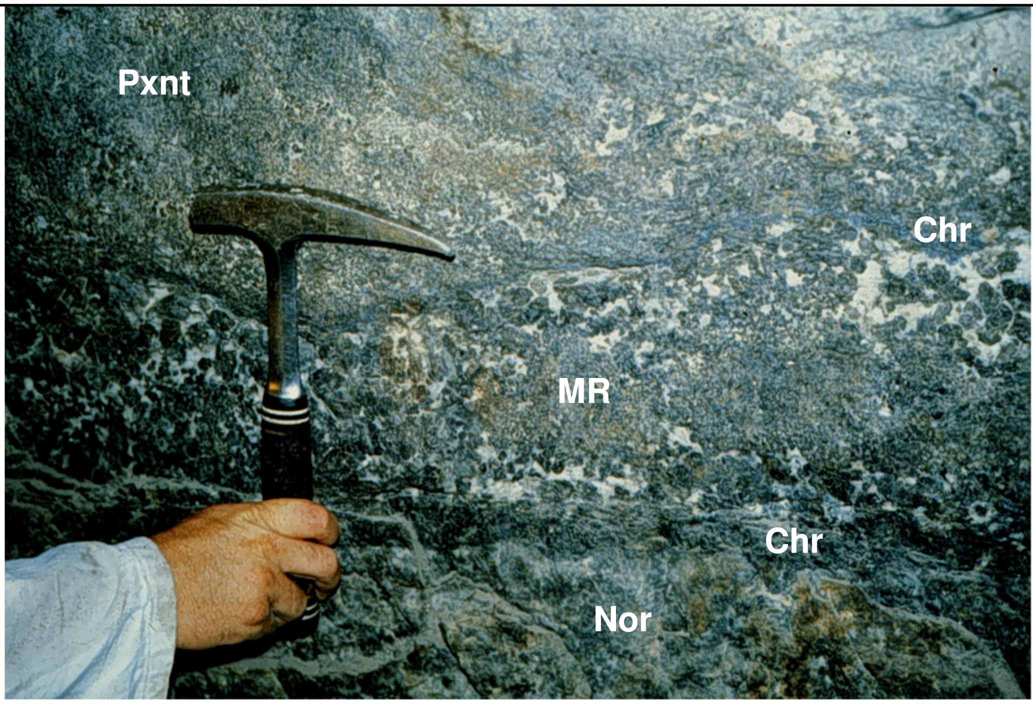
photo Ron Hieber, Angloplatinum



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

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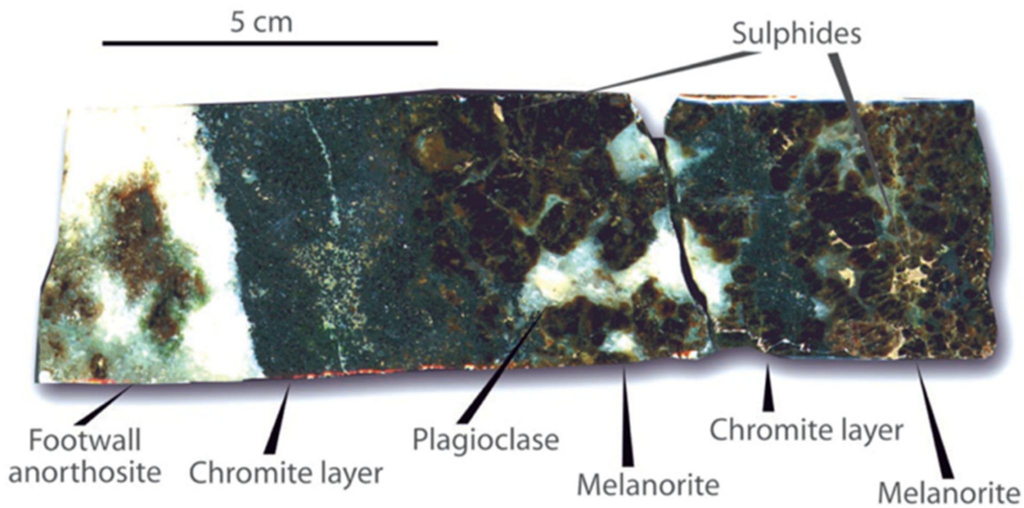
Merensky Reef



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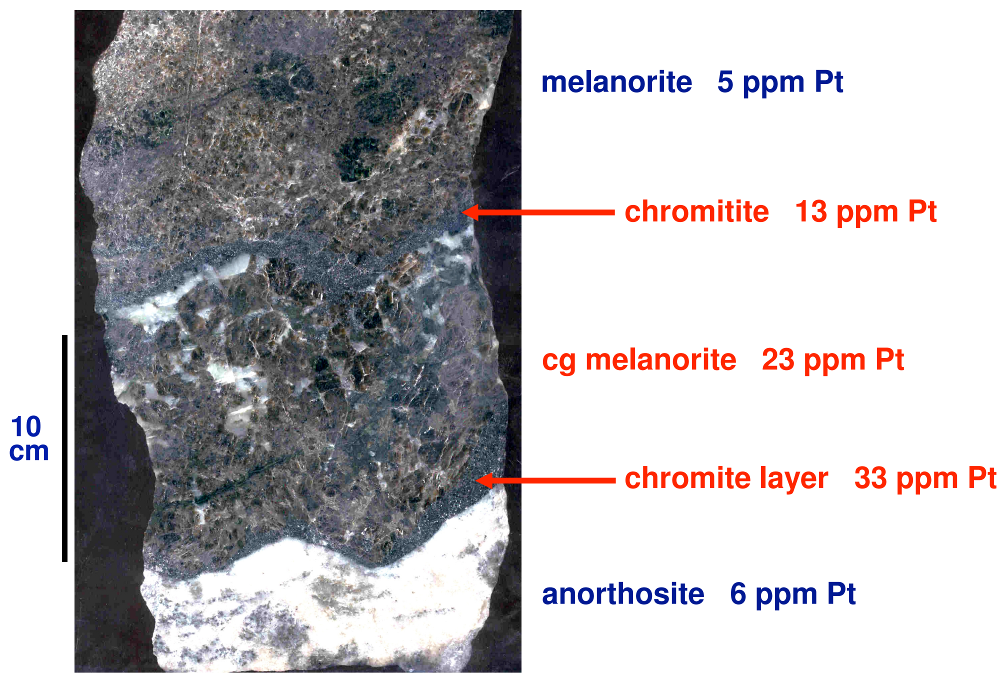
Normal Merensky Reef, Impala Mine

S-J Barnes & Maier 2002 *J Pet*



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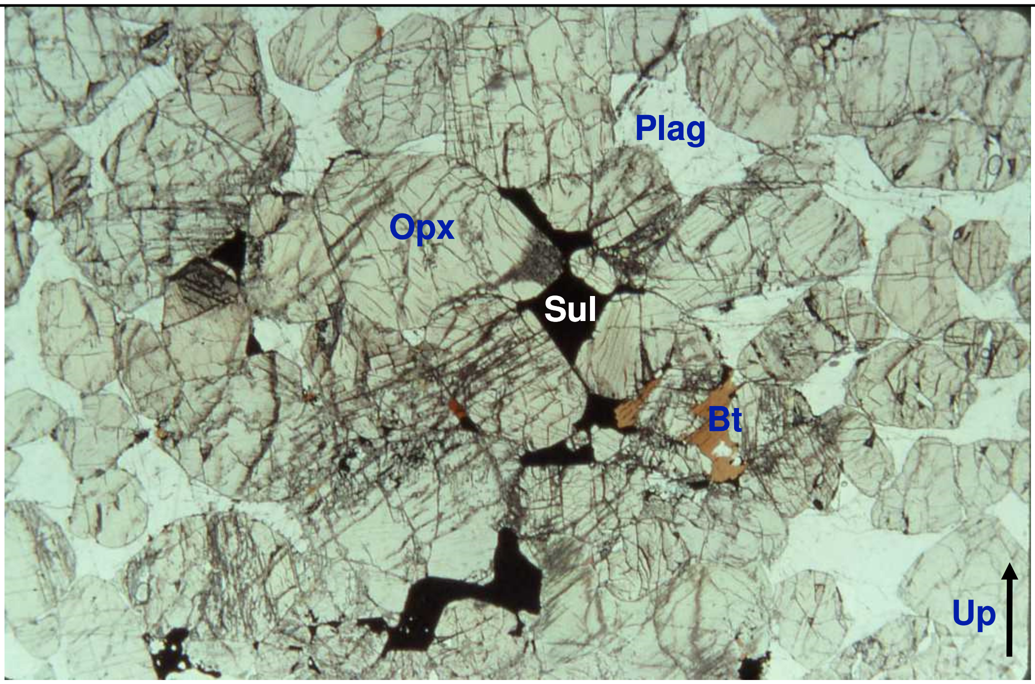
Normal Merensky Reef, Rustenburg Mine

Godel et al. 2007 *J Pet*



Photomicrograph of normal Merensky Reef, Rustenburg Mines (photo S-J Barnes)

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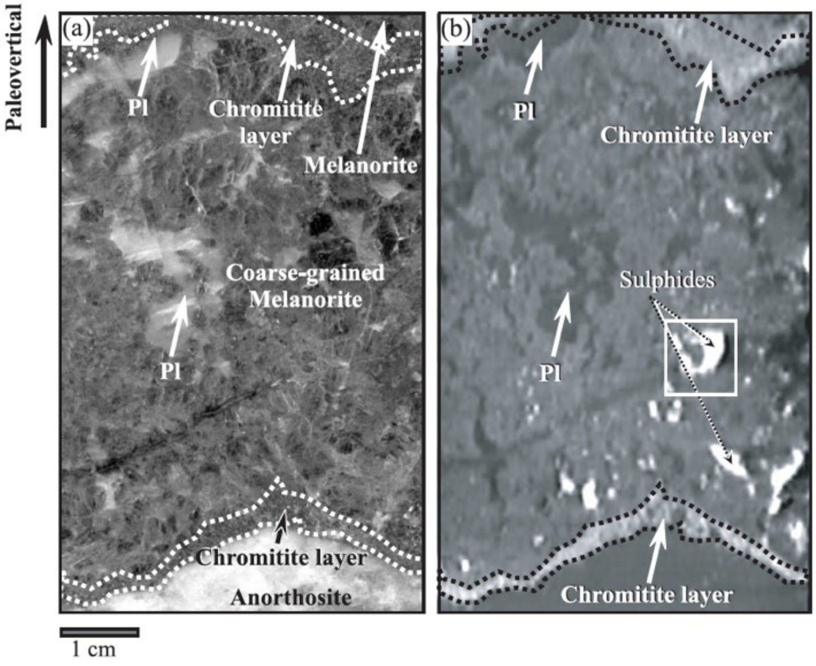

Photomicrograph (left) **and CT scan** (right) **of Merensky Reef, Rustenburg Mines** (Godel et al. 2007 *J Pet*)

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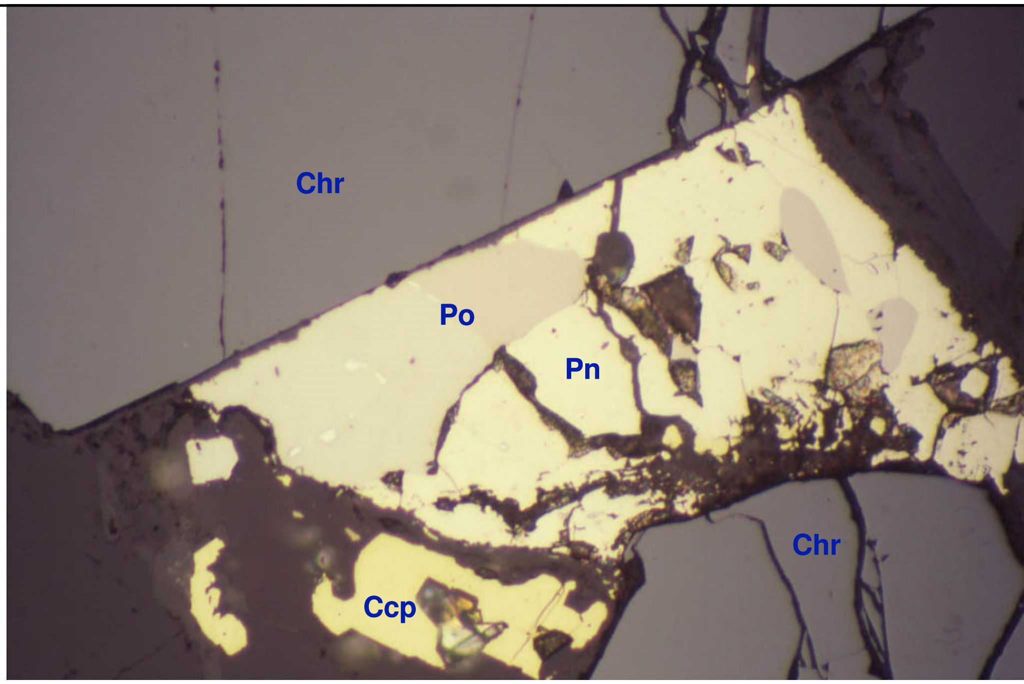
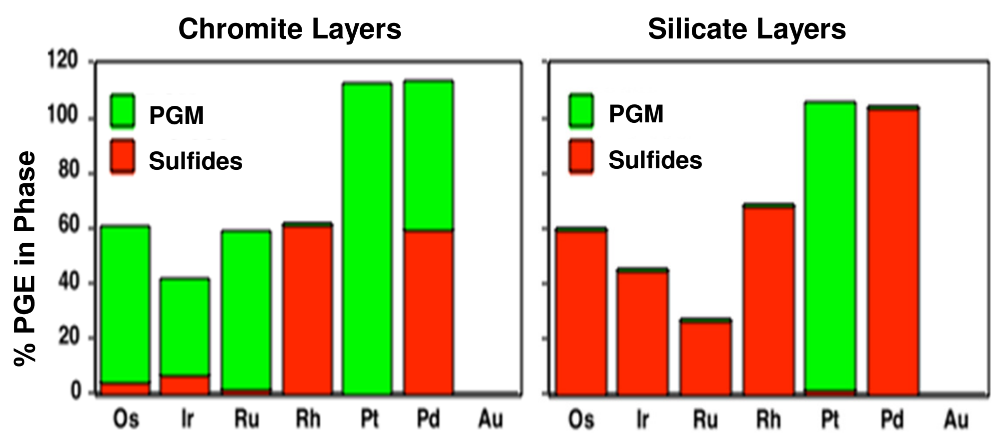


Photomicrograph of Fe-Ni-Cu sulfides between chromite grains in Merensky Reef (photo S-J Barnes)

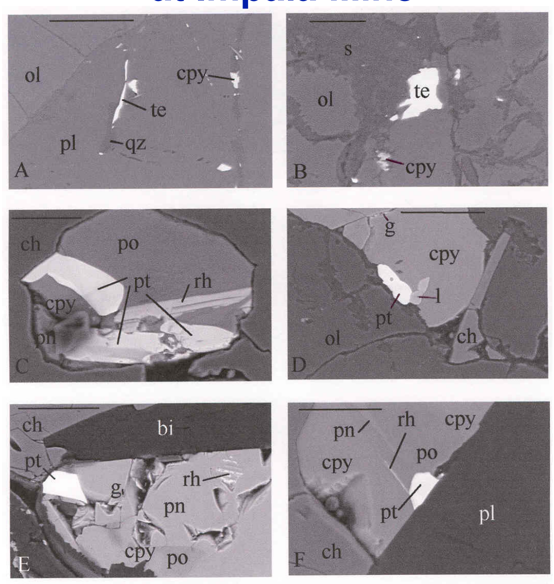
PGE Distributions
Merensky Reef at Rustenberg



Godel et al. 2007 *J Pet*

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

PGM in Merensky Reef at Impala Mine



te: Pt–Pd– Bi telluride, **ch**: chromite, **cpy**: chalcopyrite, **g**: galena, **l**: laurite, **ol**: olivine, **pt**: Pt sulfide, **pl**: plagioclase, **pn**: pentlandite, **po**: pyrrhotite, **rh**: Cu–Pt–Rh sulfide, **py**: pyrite, **qz**: quartz, **bi**: biotite, **s**: serpentine.

Prichard et al. 2004 *Can Min*

Textural Associations of PGM in Merensky Reef at Rustenburg Mine

	Silicate Rocks	Chromitites
Along Sulfide-Silicate Contacts	40%	31%
Included in Sulfides	46%	18%
Included in Silicates	14%	3%
Along Chromite-Silicate Contacts	nil	44%
Included in Chromite	nil	4%

from Godel et al. 2007 *J Pet*

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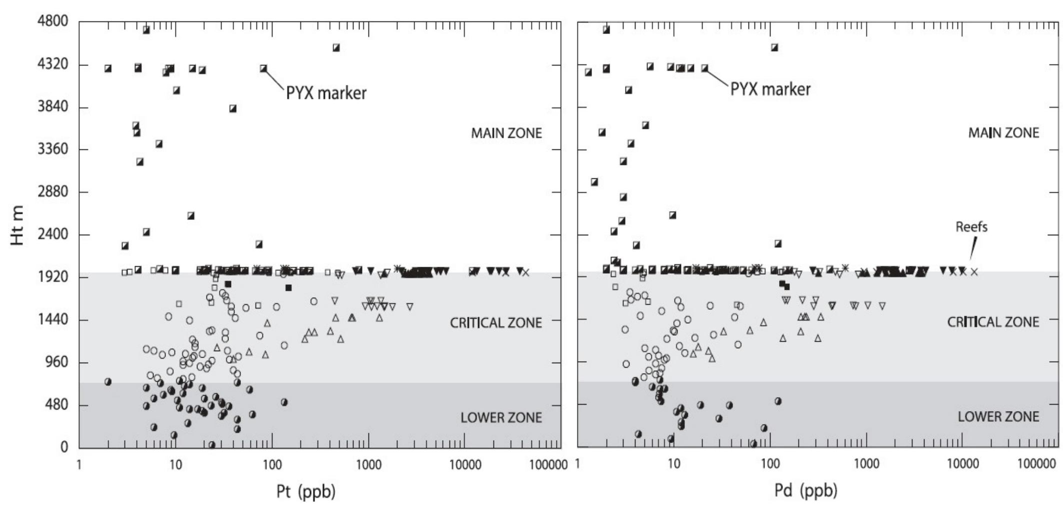
Pt and Pd vs. Stratigraphic Height



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, subeconomic 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**

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