Exploration-Based Classification of Magmatic Ni-Cu-Co-(PGE) Systems

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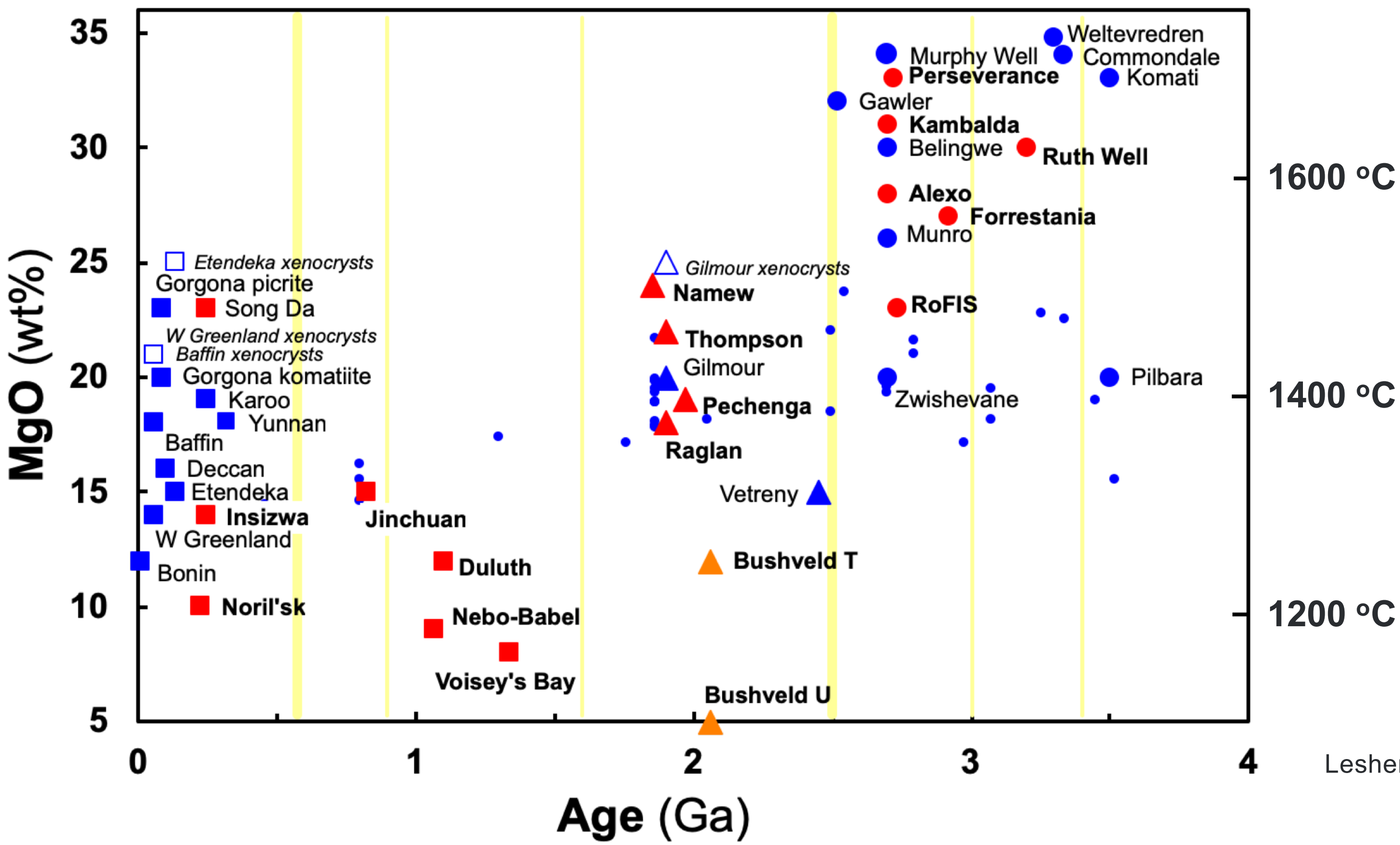
Ni-Cu-Co-(PGE) Deposits

- **Typically classified on the basis of age, tectonic setting, magma type, and mineralization type** (e.g., Naldrett 2004 *Elsevier*) **and/or cumulus mineralogy** (e.g., Nixon et al. 2015 *GSC*)
- **However, they formed:**
  - **throughout geological time** (Mesoarchean to Cenozoic)
  - **in a wide range of tectonic settings** (extensional to convergent)
  - **from a wide range of parental magmas** (high-Mg komatiitic to quartz dioritic)
  - **with variable cumulus mineralogy** (Ol ± Opx ± Cpx ± Plag ± Hb ± Phlog)
  - **with variable metal ratios** (Ni/Cu, Pd/Ir) **and mineralogy**
- **Thus, none of these attributes are particularly useful *exploration criteria***

Wide Range of Age and Magma Composition



Non-mineralized parental magmas in blue

Ni-Cu-Co-(PGE) parental magmas in red

PGE-(Cu)-(Ni)-(Co) parental magmas in orange

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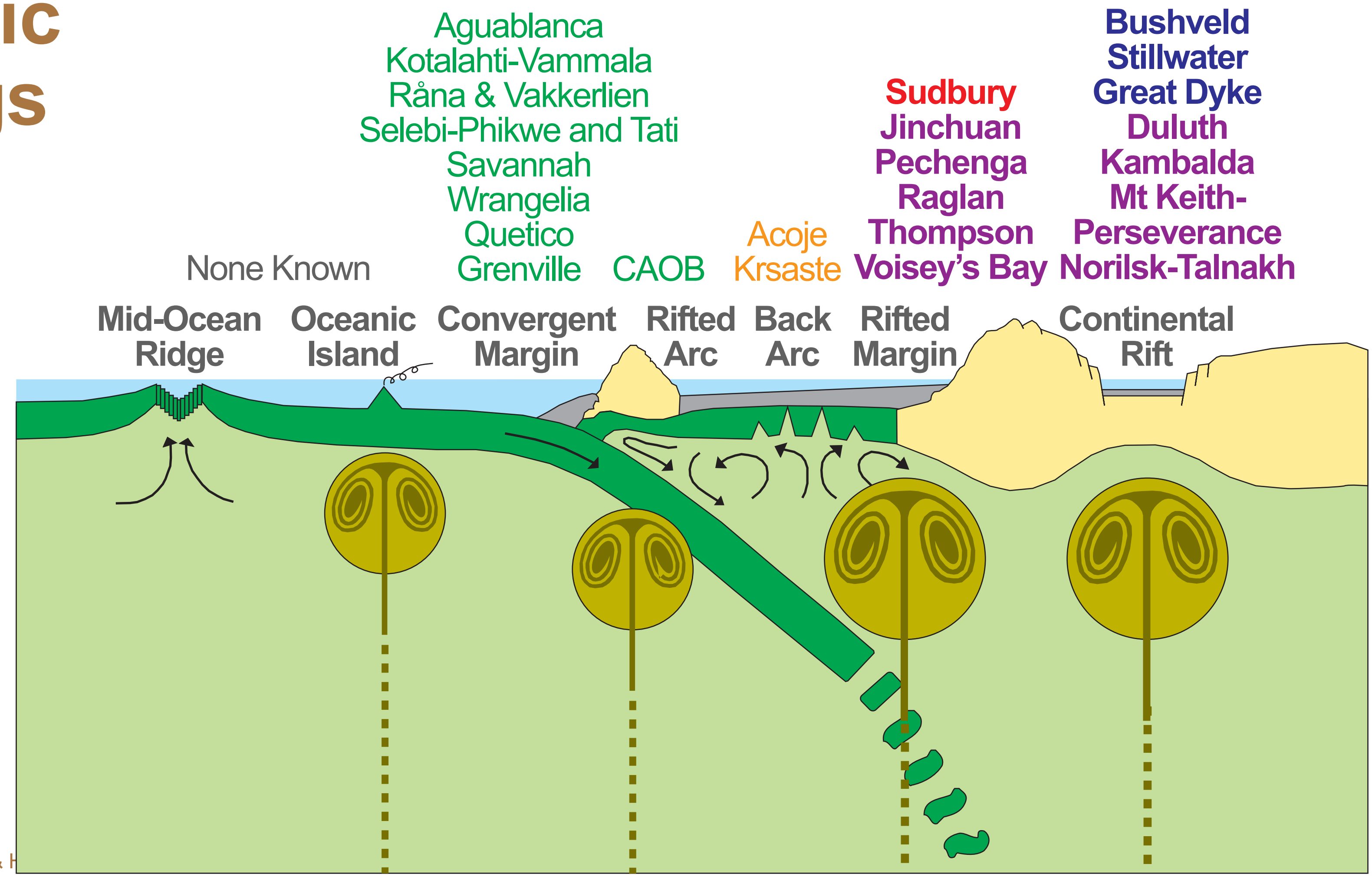
Tectonic Settings



Largest deposits in extensional settings

Group 1
Group 2
Group 3
Group 4
Group 5

Most Flavours of Magma

- **High-Mg Al-depleted komatiite**: Boa Vista BR, Forrestania WA, Ruth Well WA
- **High-Mg Al-undepleted komatiite**: Alexo ON, Dumont QC, **Kambalda WA**, Langmuir-Redstone ON, **Mt Keith-Perseverance WA**
- **Low-Mg Al-undepleted komatiite**: Eagle's Nest ON, Namew Lake SK, **Thompson MB**
- **Komatiitic basalt**: Kingash RU, **Raglan QC**
- **Ferropicrite**: **Jinchuan CH, Pechenga RU**
- **High-Al basalt**: **Voisey's Bay NL**
- **Flood basalt**: **Duluth MN**, **Norilsk RU**
- **Hydrous picrite/basalt**: Xiarihamu CH, Uralian-Alaskan Complexes
- **Alkali basalt/picrite**: Coldwell ON, Ivrea IT, Mordor AU
- **MORB**: none known
- **Quartz diorite**: **Sudbury ON**
- **Thus, composition of mantle source, degree of partial melting, and depth of melt separation** are *not* important factors in genesis or exploration

Wide Spectrum of Cumulus Mineralogy I

- **Ol±Chr**: Dumont QC, **Mt Keith WA**, **Thompson MB**
- **Ol-Cpx±Chr**: **Kambalda WA**, **Raglan QC**, Vammala FI
- **Ol-Opx±Sp**: Kotalahti FI, Nova-Bollinger WA
- **Ol-Plag**: **Voisey's Bay NL**
- **Ol-Opx-Cpx**: E&L BC, Ferguson Lake NU, Lynn Lake MB, Montcalm ON, Portneuf-Mauricie QC, Xiarihamu CH
- **Opx-Plag±Chr±Ol**: **Sudbury ON**

Also *not* an important factor in genesis or exploration, except that **lower-degree melts are inherently cooler, more viscous, and more fractionated**, leading to lower Ni/Cu and higher Pd/Ir

Wide Spectrum of Cumulus Mineralogy II

- **Ol-Cpx±Hb±Phlog**: Duke Is AK, Nizhni Tagil RU, Tulameen-Turnagain BC
- **Ol-Opx±Hb**: Americano do Brasil BR, Giant Mascot BC, Gordon Lake ON, Nickel King NWT
- **Ol-Opx-Cpx±Hb**: Aguablanca SP, E&L BC, Ferguson Lake NU, Lynn Lake MB, Montcalm ON, Portneuf-Mauricie QC, Xiarihamu CH
- **Phlog-Cpx-Ksp-Ap**: Coldwell ON, Mordor NT

Hydrous melts are inherently less volumetric and cooler, generally resulting in smaller, lower grade, lower tenor mineralization

Deposit Classification I

A more useful classification is based on the *form of the host units* (Lesher & Houle 2022 *QM+É*):

- **Group 1: impact melt sheets** (e.g., Sudbury ON)
- **Group 2: layered mafic-ultramafic intrusions** (e.g., Platreef SA, Duluth MN, Stillwater MT, Muskox NU)
- **Group 3: channelized mafic-ultramafic lavas/sills/dikes** (e.g., Dumont – Raglan-Expo QC, Thompson MB, Voisey's Bay NL; Kambalda-Mt Keith-Perseverance WA, Norilsk-Talnakh and Pechenga RU)
- **Group 4: mafic-ultramafic pipes/plugs/stocks** (e.g., Duke Is AK, Lynn Lake MB, Montcalm ON, Giant Mascot BC, Jingbulake CH)
- **Group 5: ophiolitic/orogenic peridotites**: (e.g., Zambales PH; Decar BC; Portneuf-Mauricie QC)

Deposit Classification II

- Ores and host rocks vary widely between and within groups in terms of **size**, **form**, **orientation**, **composition,** and **degree of zoning/differentiation/ layering/brecciation**, which are difficult to predict during the early stages of exploration, so initially more-or-less equally prospective
- **However, form affects how they are mapped/drilled** and to some degree which geological/geochemical/geophysical methods are used in exploration

Deposit Classification

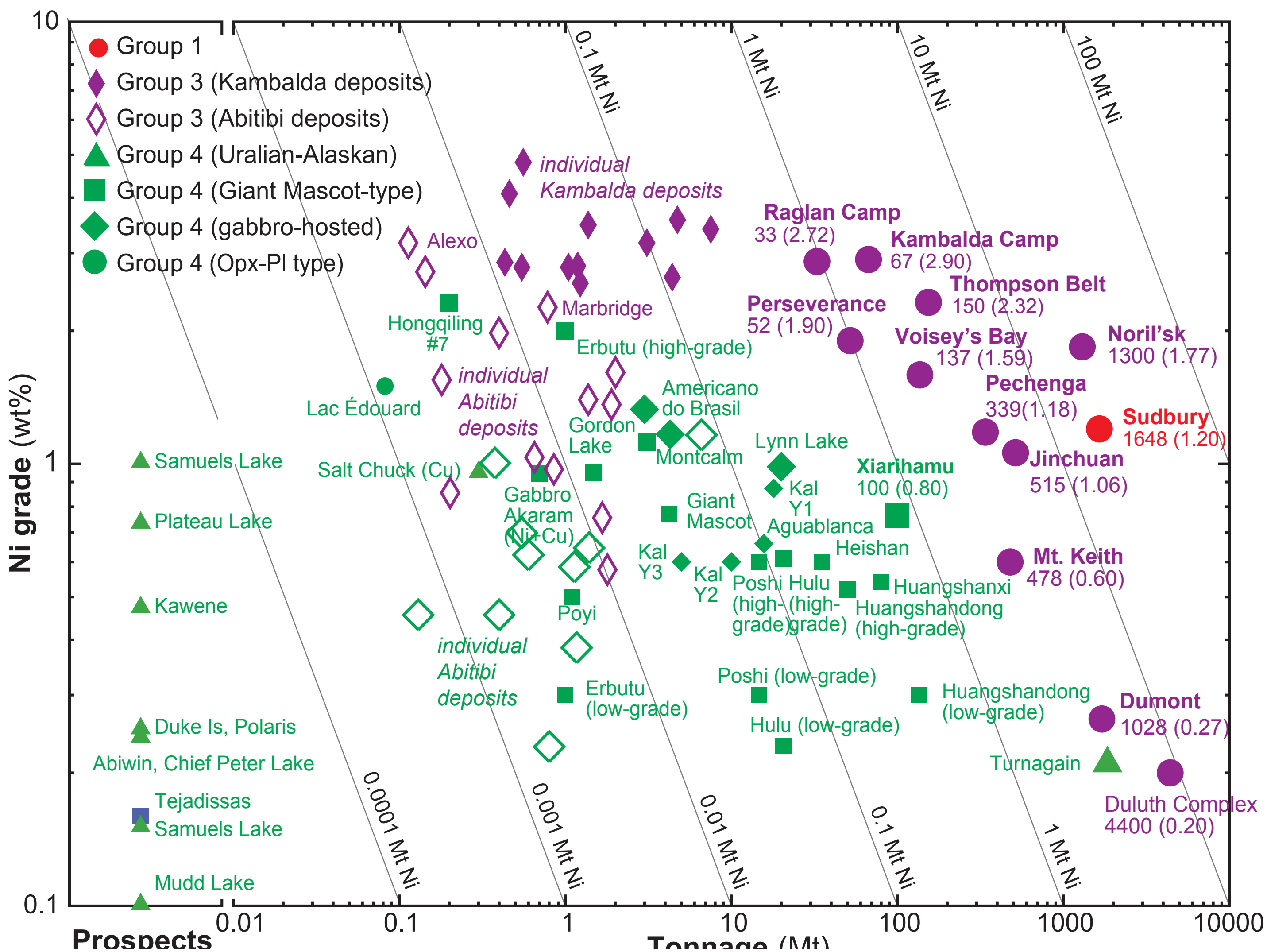
modified from Lesher & Houle 2022 *QM+É*

Group	Setting	Notes	Examples
Group 1 impact melt sheets	Impact	Very **dynamic**, but must be large and target must contain Fe-Ni-Cu-(PGE)	**Sudbury ON**
Group 2 layered intrusions	LIPs	Large and **variably dynamic**, but **low flux**, so low grades and tonnages	Platreef SA, Stillwater MT, Muskox NU
Group 3 lava/magma conduits	LIPs	Individually small-large, but **very high flux,** so high tenors, often form large camps	Duluth MN, **Jinchuan CH** **Kambalda-Mt Keith-Perseverance WA** **Raglan QC**, **Thompson MB** **Pechenga-Norilsk RU**
Group 4 pipes/plugs/stocks	Convergent Margin	Uralian-Alaskan (Ol-Cpx-Hb±Phlog) type complexes	Nizhni Tagil RU, Duke Island AK Tulameen-Turnagain BC, Quetico ON
		Giant Mascot (Ol-Opx-Hb) type complexes	Americano do Brasil BR, CAOB CH, Giant Mascot BC, Gordon Lake ON
		Gabbroic (Ol-Opx-Cpx-Hb) complexes	Aguablanca SP, Lynn Lake MB, Portneuf-Mauricie QC, Xiarihamu CH
		Alkalic (Phlog-Cpx-Ksp-Ap) complexes	Coldwell ON, Mordor AU
Group 5 ophiolitic/orogenic/ abyssal peridotites	Oceanic crust/mantle	Ophiolite complexes	cumulates: Zambales PH, Troodos CY mantle: Middle Arm Brook NL, Shetland UK, Thedford QC
		Orogenic peridotites	Lherz FR, Lanzo – Ivrea-Verbano IT, Rhonda SP

Pre-Mining Tonnage vs Grade

Group 1 and **Group 3** generally have higher grades and tonnages

Group 4 generally has lower tonnages and/or grades



after Naldrett 2004 *Springer*,
Nixon et al. 2015 *GSC*,

Group 1: Impact Melt Sheets

- **Morphology**: circular or near-circular
- **Shock metamorphism**: shattercones, pseudotachylite, PDFs, etc.
- **Intense localized deformation**: brecciation, fracturing, faulting
- **Gravity anomalies**: fractured and brecciated rocks will be less dense, but extend to only ~1/3D and may be compensated by uplift of denser underlying rocks (e.g., Pilkington & Grieve 1992; Grieve & Pilkington 1996)
- **Magnetic anomalies**: variable, depending on lithologies and thermal overprints (see e.g., Spray et al. 2004 *MPS*)
- **Composition**: anomalous Ir and/or entirely crustal geochemical and isotopic signature with no mantle component
- **S-bearing target rocks** (Huronian volcanics, EBLI suite, Nipissing suite)

Group 1: Exploration Targeting

- **Melt sheets form only in large** (>25 km dia) **impacts** *(e.g.,* French 2008 *LPI)*
- **Mineralization appears to form only where target rocks contain abundant S ± Ni ± Cu ± Co ± PGE** (e.g., Nipissing Diabase and East Bull Lake intrusive suites at Sudbury)
- Mineralization formed relatively early and is associated with the most magnesian and most contaminated rocks at the **base of the melt sheet** (e.g., inclusion-rich Sublayer norite) and the **cores of quartz-diorite "offset" dikes** (e.g., inclusion quartz diorite)

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Group 2: Layered Intrusions

- **Occur worldwide throughout geological time since the Mesoarchean** (Smith & Maier 2021 *ESR*) when cratons first stabilized
- **May occur associated with LIPs** (Ernst and colleagues):
  - Along circular fault systems that circumscribe plume centres
  - Along linear rifts that may converge on plume centres
  - Single/unclassified intrusions
- **Host a wide range of magmatic mineralization** (top to base):
  - **Stratiform Fe-Ti-V**
  - **Stratiform PGE-(Cu)-(Ni)**
  - **Stratiform Cr**
  - **Stratabound PGE-(Cu)-(Ni)**
  - **Stratabound Ni-Cu-(PGE)**

Group 2: Exploration Targeting

- **Mafic magmas normally contain sufficient Ni-Cu-Co-(PGE)**
- **Stratiform disseminated PGE-(Cu)-(Ni) mineralization represents the point at which fractional crystallization ± magma mixing induced sulfide saturation**
  - **Magmas can dissolve only small amounts of S** (1000-2000 ppm), so little sulfide is produced
- **Larger amounts of sulfide require incorporation of S from country rocks**
- **Two broad types:**
  - **Periodically-replenished magma chambers** (e.g., Bushveld, Stillwater): dynamic, but low-flux and very high R, so little sulfide
  - **Composite differentiated sills** (e.g., Duluth): locally dynamic, but low-flux

Group 3: Channelized Mafic-Ultramafic Lavas/Sills/Dikes

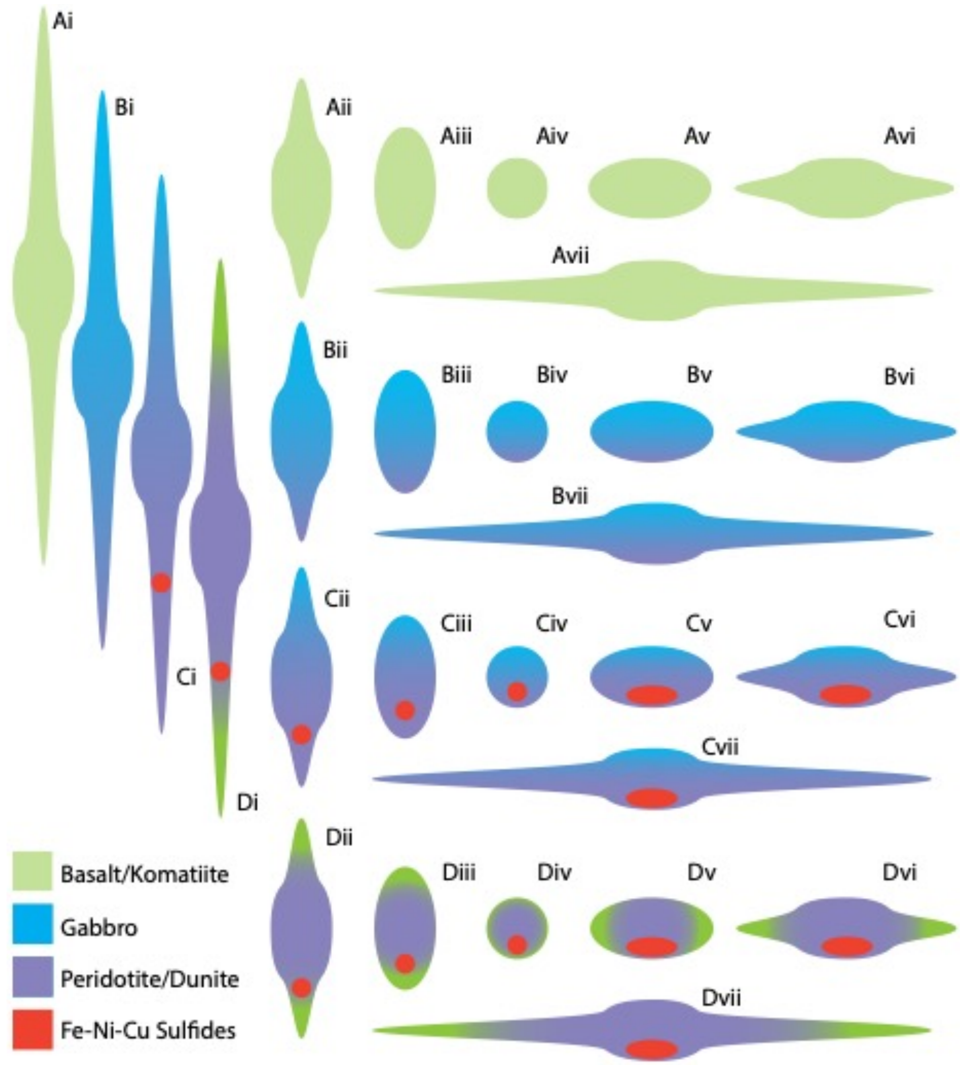
- **Vary widely in**
  - **size**
  - **form**
  - **original** (and current) **orientation**
  - **composition**
  - **degree of differentiation**
- **Difficult to predict during the early stages of exploration**, but more-or-less equally prospective at that stage

Group 3: Forms

Lava channels	**Perseverance WA** parts of Raglan QC
Channelized sheet flows	**Kambalda WA** parts of **Raglan QC**
Channelized sills	Grasset, Marbridge QC **Jinchuan CH** **Mt Keith WA** **Norilsk**, **Pechenga RU**
Chonoliths	Kalatongke CH Mirabella BR Nebo-Babel, Savannah WA
Channelized blade-shaped dikes	Eagle's Nest ON Expo-Méquillon QC Hongquiling, Huangshan CH

Group 3: Host Units

- **Most are *channelized* subhorizontal dikes, sills, or chonoliths**
- **High magma flux**
- **Moderately to strongly enriched in cumulus Ol**
  - Unenriched units are typically barren
- **Weakly to moderately differentiated, depending on the timing of “ponding”**



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Group 3: Exploration Targeting

- **Most mafic-ultramafic magmas contain sufficient Ni-Cu-Co-(PGE)**
- **More magnesian is better**: hotter so more likely to incorporate external S
- **More more dynamic is better**: hotter and higher magma:sulfide ratios produce higher metal tenors

Raglan camp **Expo-Méquillon camp**	**World-class district with considerable brownfields and greenfields exploration potential**
Labrador Trough	**Also part of Circum-Superior continental margin, but *thus far* less prospective**: less magnesian ± less dynamic ± less access to crustal S?
Superior **Grenville**	**Historically less prospective, but key may be to identify camps not individual deposits**

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Group 4: Pipes/Plugs/Stocks

- ***Generally* circular to elliptical, <10 km diameter, and subvertical**
- **Zoned or unzoned**
- **Layered** (e.g., Duke Island AK) **or unlayered** (Lac des Iles ON)
- **May contain magmatic breccias** (e.g., Aquablanca SP)
- **May be Cpx-rich** (e.g., Uralian-Alaskan) **or Opx-rich** (e.g., Giant Mascot BC)
- **Type of mineralization varies with subgroup**
  - **Cpx-Rich**: PGE alloys with chromite
  - **Opx-Rich**: Ni-Cu-(PGE)

Group 4: Exploration Targeting

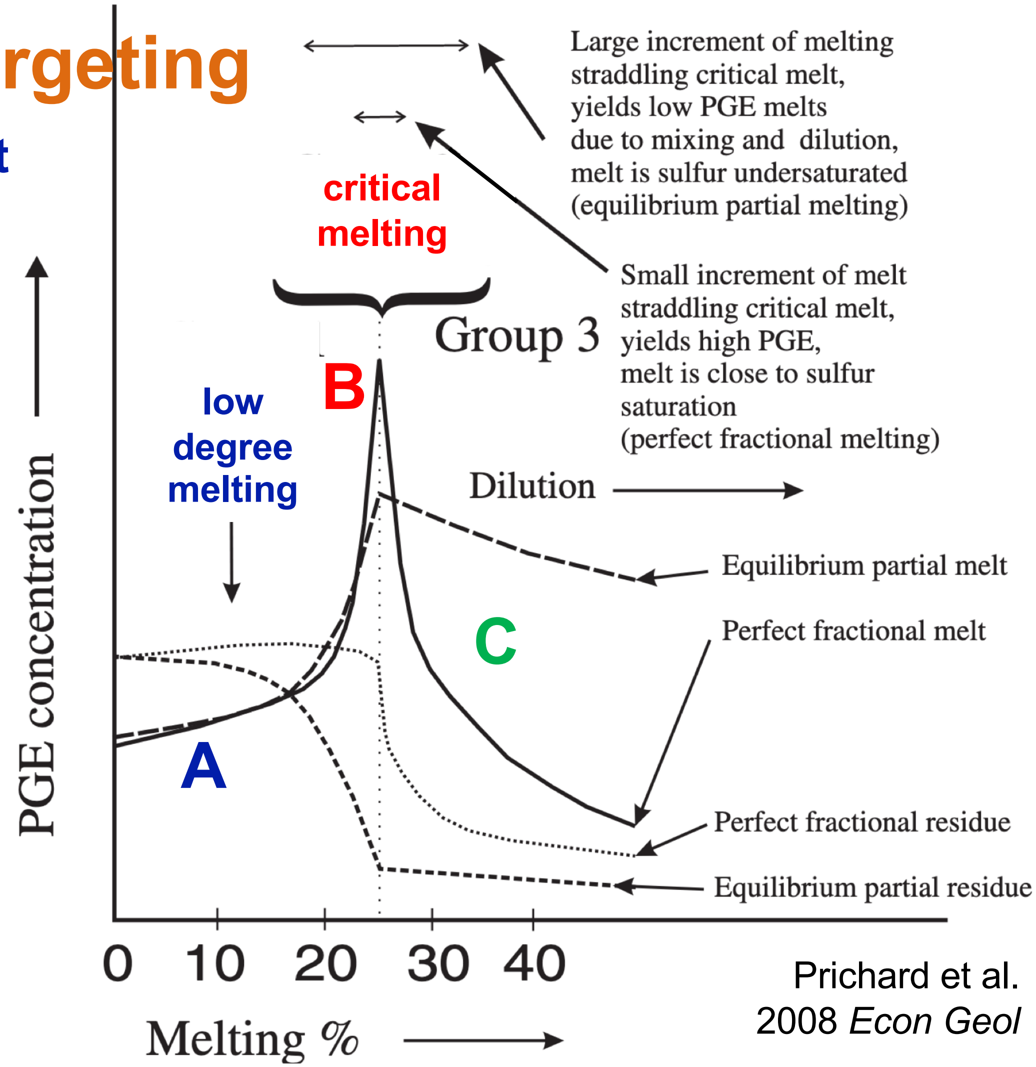
- **Less magnesian than Group 4**: cooler, so less likely to incorporate S-bearing country rocks
- **Less dynamic and lower flux than Group 4**: cooler and lower magma:sulfide ratios produce lower metal tenors
- **Degree of zoning and differentiation** does not appear to be critical

Group 5: Orogenic Peridotites

- **Basal parts of ophiolite complexes** (AKA alpine peridotites)
- **Cumulate dunites-peridotites** and/or **upper mantle residues**
- **Degree of partial melting of the mantle** controls localization and nature of mineralization (Prichard et al. 2008 *Econ Geol*): **can be predicted from relative proportion of basal dunite**
- **Some contain Pt-Pd alloys, some contain Ir-Os alloys, some contain both**

Group 5: Exploration Targeting

- **Low degree melting will not extract the PGE from the mantle** and will form PGE-poor pyroxenites and troctolites with little dunite
- **Critical melting will produce PGE-rich magma** that will crystallize chromitite enriched in all PGE
- **Moderate melting** will form PGE-enriched chromitites in thick dunites
- **High-degree melting will dilute Pt and Pd** and they will crystallize with the first base metal sulphides in the crustal gabbros, whereas Os, Ir and Ru are concentrated in the chromitite



Prichard et al. 2008 *Econ Geol*

Conclusions

- **Group 1 systems** (e.g., Sudbury) **are world class, but rare**: require large impacts *and* Fe ± Ni ± Cu ± PGE sulfide-bearing target rocks)
- **Group 2 systems** (e.g., Muskox, Stillwater) have low fluxes and most have small Ni-Cu-Co resources
- **Group 3 systems** (e.g., **Kambalda-Mt Keith-Perseverance, Noriksk-Talnakh, Nova-Bollinger, Pechenga, Raglan-Expo, Thompson**) have highest fluxes and are most prospective
- **Group 4 systems** (e.g., Portneuf-Mauricie) have low fluxes and are less prospective
- **Low-grade Group 5 systems** (e.g., Decar) also have low fluxes and are less prospective

Thus, Group 3 deposits are presently the most attractive exploration targets, but as needs for Ni-Cu-Co-(PGE) increase, other types will become more prospective