Geology, Genesis, and Exploration for Magmatic Ni-Cu-PGE Systems

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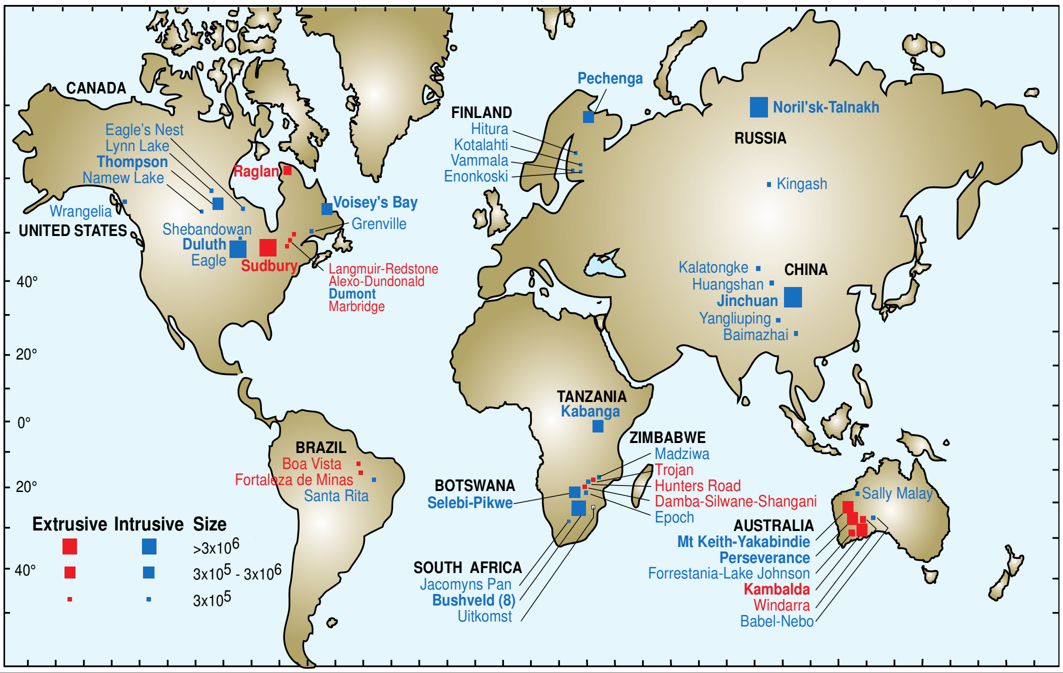
Magmatic Ni-Cu-PGE Deposits

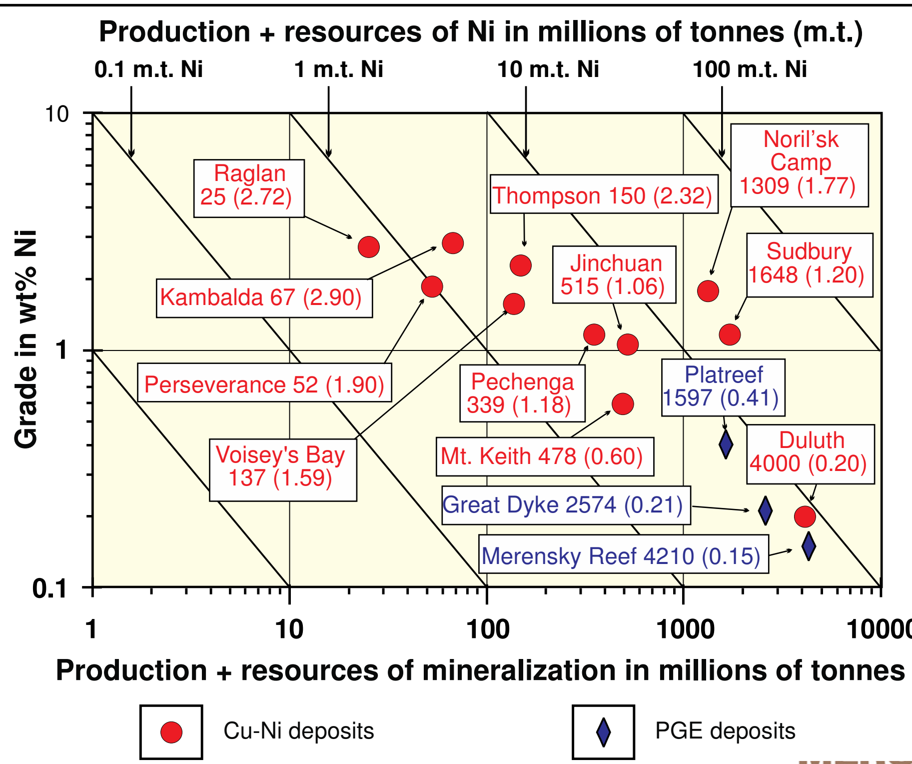
- **Sulfide-rich Ni-Cu-Co-(PGE) deposits**
  - **Stratiform massive\net-textured\disseminated Ni-Cu-(PGE) mineralization:** Alexo ON, Kambalda WA, Norilsk RU, Pechenga RU, Raglan QC, Sudbury ON, Thompson MB
  - **Strata-bound disseminated to net-textured Ni-Cu-(PGE) mineralization:** Dumont ON, Damba-Silwane ZI, Jinchuan CH, Mt Keith WA
- **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 Ni-Cu-PGE Deposits



adapted from USGS

Ni Grade vs Tonnage for Ni-Cu-PGE and PGE Deposits

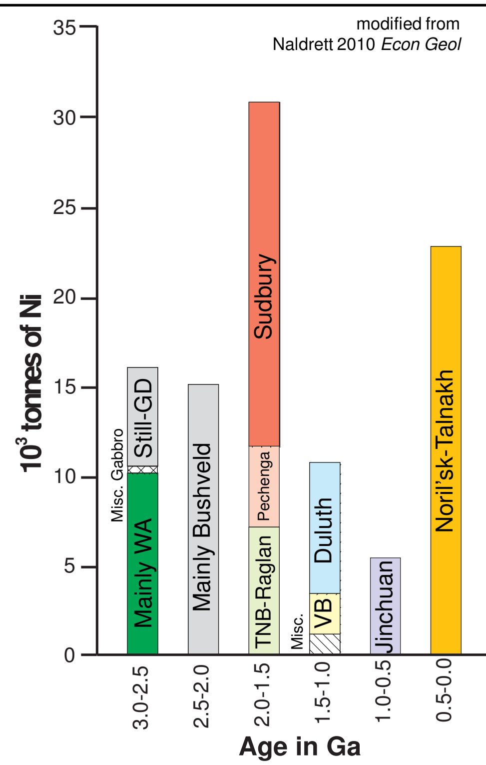


Ni-Cu-PGE Overview

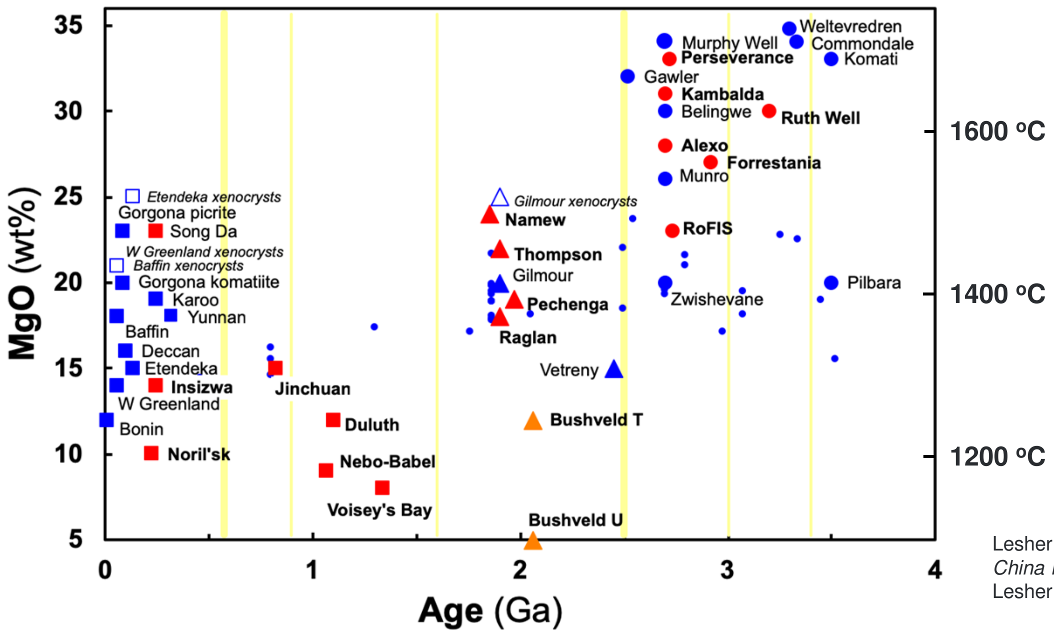
- **Age**: any
- **Tectonic setting**: mainly intracratonic rifts, rifted continental margins, rifted arcs
- **Host rocks**: dunites, peridotites, norites, gabbros
- **Composition of magma**: mantle-derived, anything more mafic than MORB
- **Metal source**: normally the magma
- **S source**: primarily the country rocks
- **Ore-forming processes**: partial melting of mantle, incorporation of country rocks, generation of sulfide xenomelts, upgrading of metal tenors, gravitational and/or fluid dynamic segregation
- **Ore localization**: footwall embayments, dilational 'jogs' in dikes
- **Metal fractionation**: varies with cooling rate
- **Mineralogy**: pyrrhotite $Fe_{1-x}S$, pentlandite $(Fe,Ni)_9S_8$, chalcopyrite $CuFeS_2$, and magnetite Fe_3O_4 with PGMs (alloys/sulfides/sulfarsenides/arsenides/bismuthides/antimonides/tellurides)

Age

- **Major deposits formed throughout geological time**
- **Archean deposits are much more numerous**
- **Individual Proterozoic-Phanerozoic deposits tend to be larger than individual Archean deposits**



Age Not Important



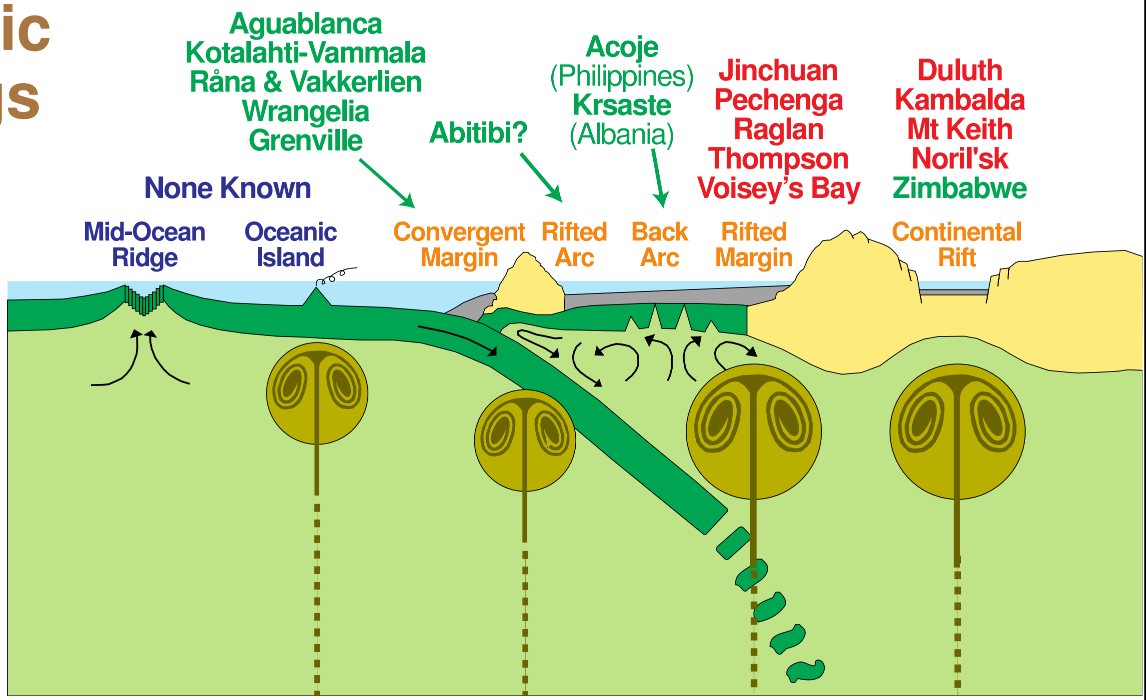
Lesher & Barnes 2009 *China Publ House*; Lesher 2019 *CJES*

But There Are Some Secular Variations

	Archean	Proterozoic	Phanerozoic
Host Rock	dunite-gabbro	dunite-gabbro	peridotite-gabbro
Host Magma	up to 32% MgO	up to 22% MgO	up to 14% MgO
Ni/Cu and Ir/Pd	higher	intermediate	lower
Inclusions	uncommon	more common	abundant
Volcanic Setting	*commonly* extrusive	*predominantly* subvolcanic	*exclusively* intrusive
Tectonic Setting	continental rifts rifted “arcs”	continental rifts rifted margins	continental rifts rifted margins rifted arcs transtensional

Tectonic Settings

Largest deposits are in rift-related settings



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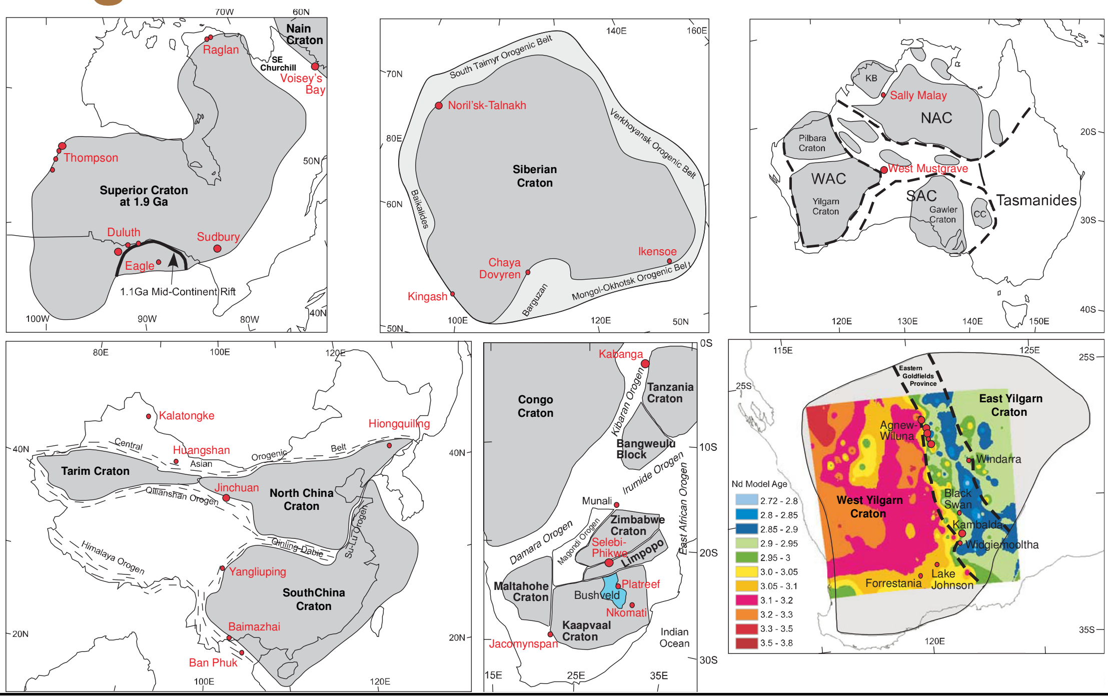
Craton Margins

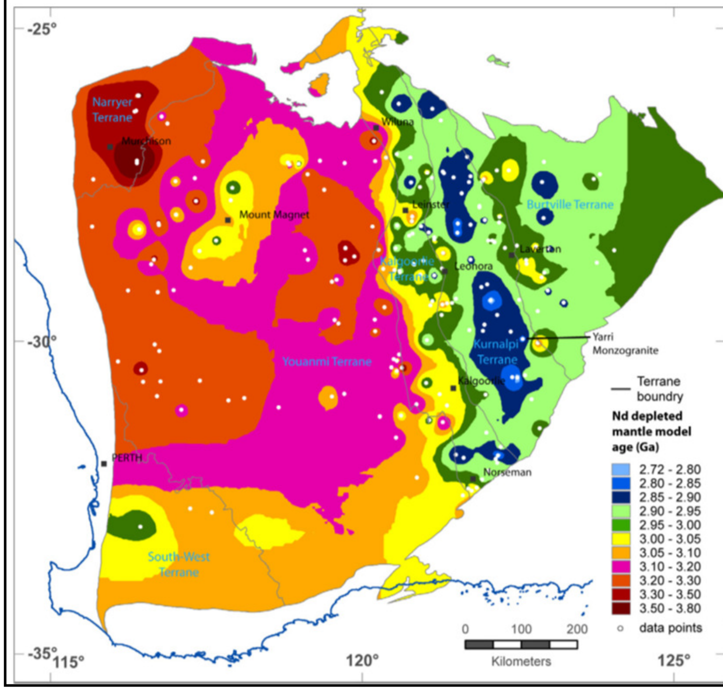
Many (but not all) **occur on or near craton margins**

First noted by Inco and Newmont in the 1960s



Begg et al. 2010 *Econ Geol*

Tectonic Setting

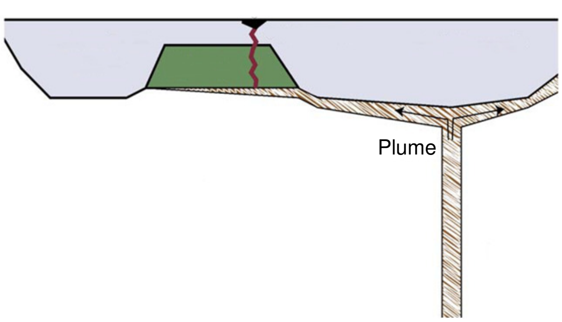


Ni-Cu-(PGE) deposits in the highly-mineralized Kalgoorlie Terrane (e.g., Kambalda-Perseverance-Mt Keith) **formed along the suture between two Paleocratons**

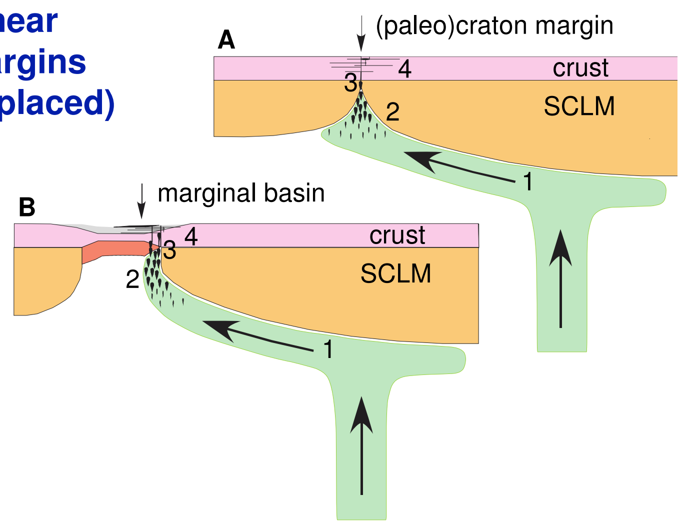
Map of Yilgarn Bock showing Nd isotope model ages of grantitic plutons (Champion & Cassidy 2007 *Geosci Aust*) **and location of highly-mineralized Kalgoorlie Terrane**

Significance of Craton Margins

Plumes are likely to have flowed laterally beneath and been 'steered' toward craton boundaries (Sleep 1997 JGR; 2006 *Earth Sci Rev*), **but lava and sills can flow hundreds of km from their volcanic centres, so not all will necessarily be near crustal-scale faults or along craton margins (and of course may be tectonically displaced)**



Sleep 2006 *Earth Sci Rev*

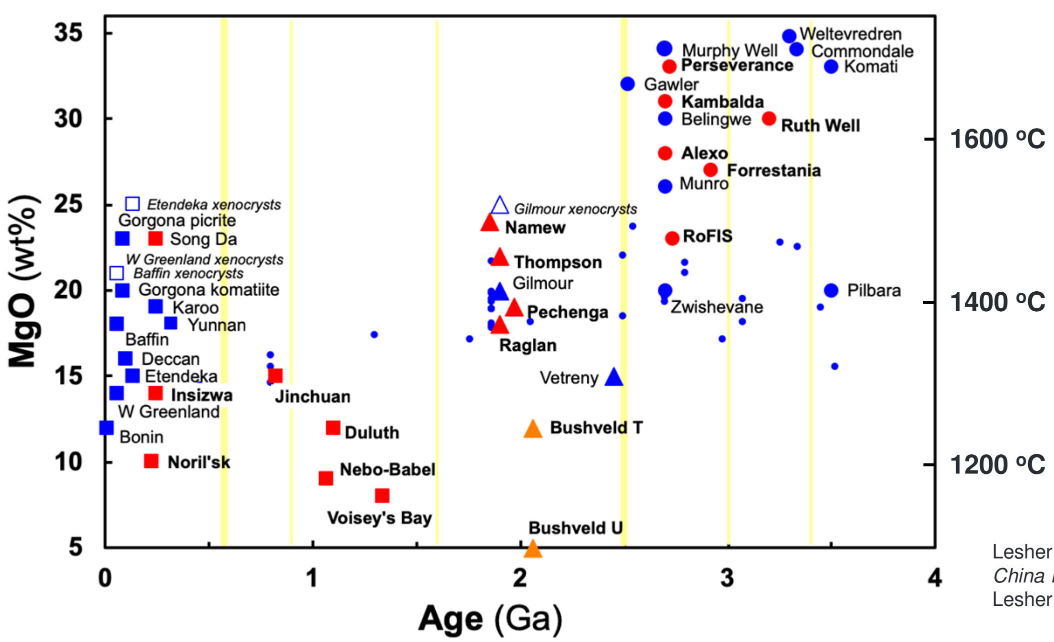


Begg et al. 2010 *Econ Geol*

Magma Type

- **Any plume-derived olivine-saturated magma**
  - **High-Mg Al-depleted komatiite**: Boa Vista, Forrestania, Ruth Well
  - **High-Mg Al-undepleted komatiite**: Alexo-Dundonald-Dumont, Kambalda-Widgiemooltha, Langmuir-Redstone-Texmont-Sothman-Bannockburn, Mt Keith-Perseverance, Windarra
  - **Low-Mg Al-undepleted komatiite**: Eagle's Nest, Namew Lake, Thompson
  - **Komatiitic basalt**: Kingash, Raglan
  - **Ferropicrite**: Pechenga, Jinchuan?
  - **Flood basalt**: Duluth, Norilsk, Voisey's Bay
  - **MORB, alkali basalt/picrite, meimechite**: none known (yet)
- **Thus, the composition of the mantle source, the degree of partial melting, and the depth of melt separation are not important in terms of whether a deposit will form**

Mg Content / Temperature Not Important



Lesher & Barnes 2009 *China Publ House*; Lesher 2019 *CJES*

Host Units

- **All ore deposits of this type are hosted by dynamic magmatic systems:**
  - **Lava channels**
  - **Magma conduits**
- **Non-dynamic systems derived from the same magmas in the same areas are barren**
  - **Sheet flows:** Walter Williams Fm WA, sheet flow facies of Cross Lake Fm QC
  - **Sheet sills:** Romeo I II sills QC, Boston Creek sill ON, barren Thompson sills MB
  - **Lava lobes**: Barberton SA, Belingwe ZI, Pyke Hill ON
  - **Volcaniclastic rocks:** Satasvaara FI

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Extrusive Host Units

- **Volcanic vents:** Epoch ZI, Kotselvaara RU
- **Lava channels and invasive lava channels:** Mt Keith – Perseverance WA; Zone 2-3 – Katinniq – Zones 6-8 QC; Trojan – Damba – Silwane – Hunters Road – Shangani ZI
- **Channelized sheet flows:** Alexo-Dundonald – Langmuir-Redstone – Texmont ON; Marbridge QC; Kambalda WA; Cross Lake – Zones 5-7 QC
- **Lava channel breakouts**: Bannockburn ON

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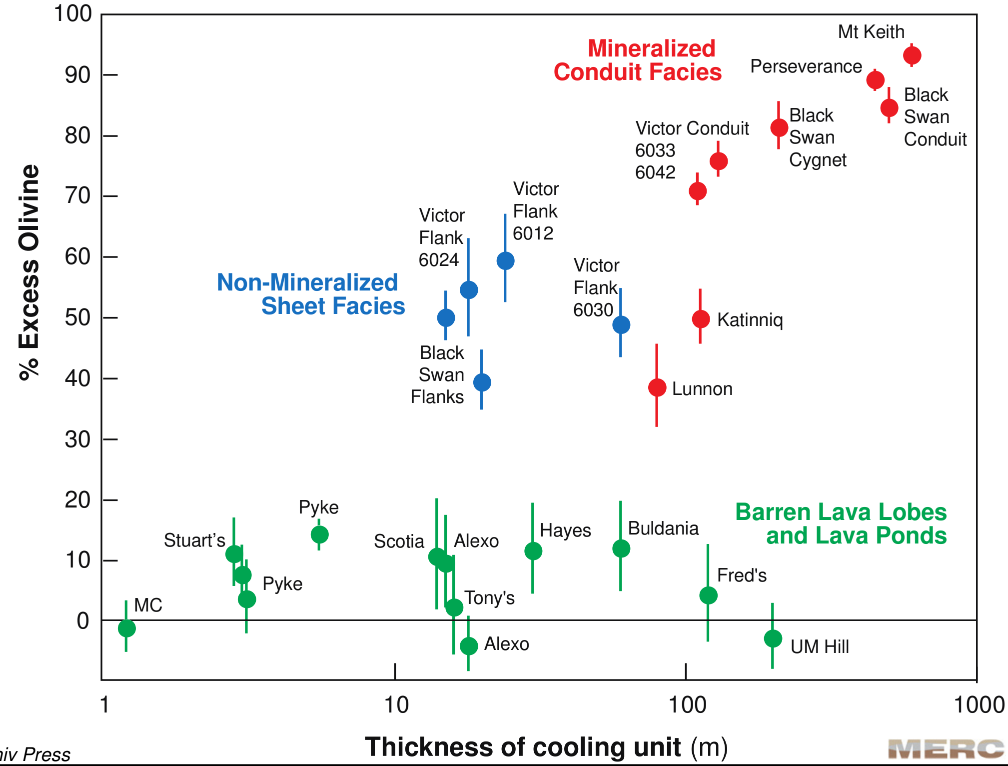
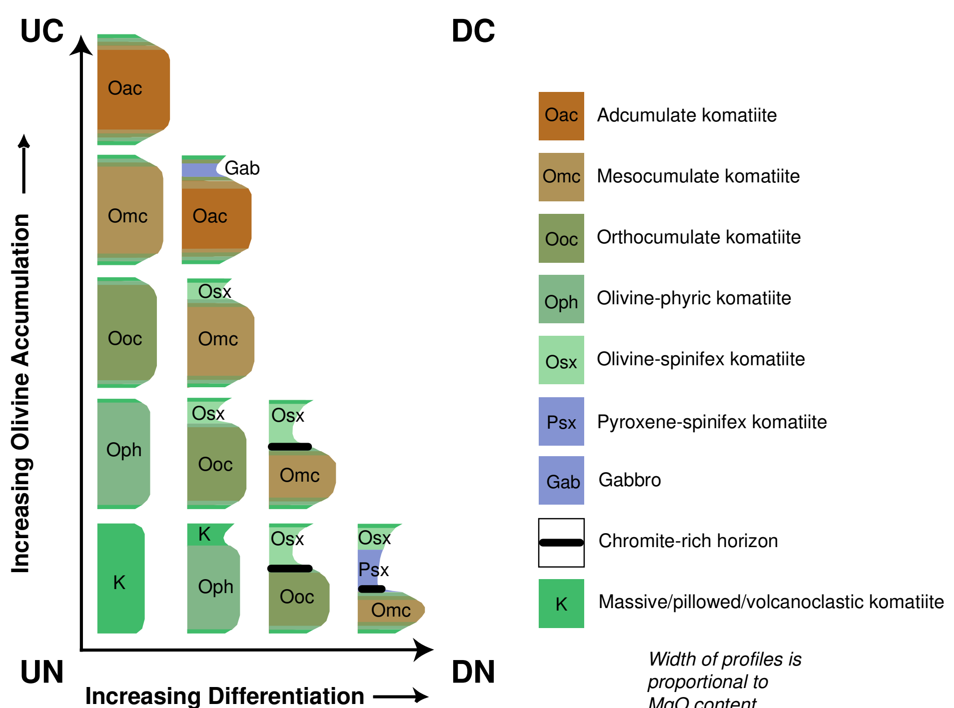
Host Units

Mineralized units are enriched in olivine relative to unmineralized units



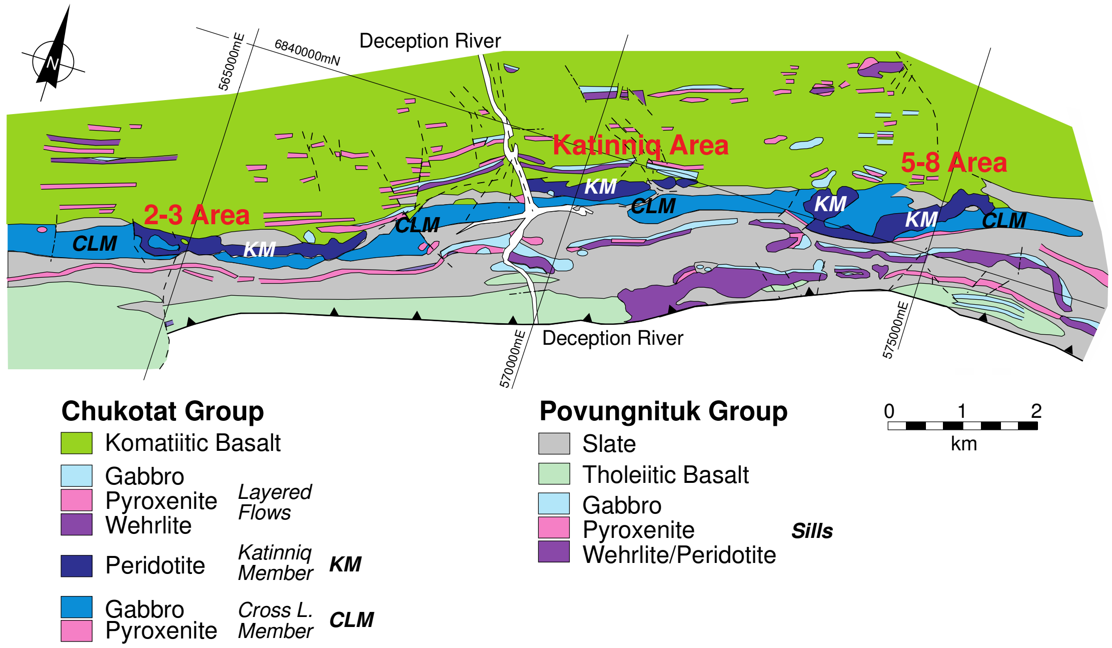
Lesher & Barnes 2009 *Publ House China*
after Arndt-Lesher-Barnes 2009 *Camb Univ Press*

Extrusive Host Units



Lesher et al. 1984 *IMM*

Lava Channels



Lesher 2007 *GAC-MDD Spec Pap*

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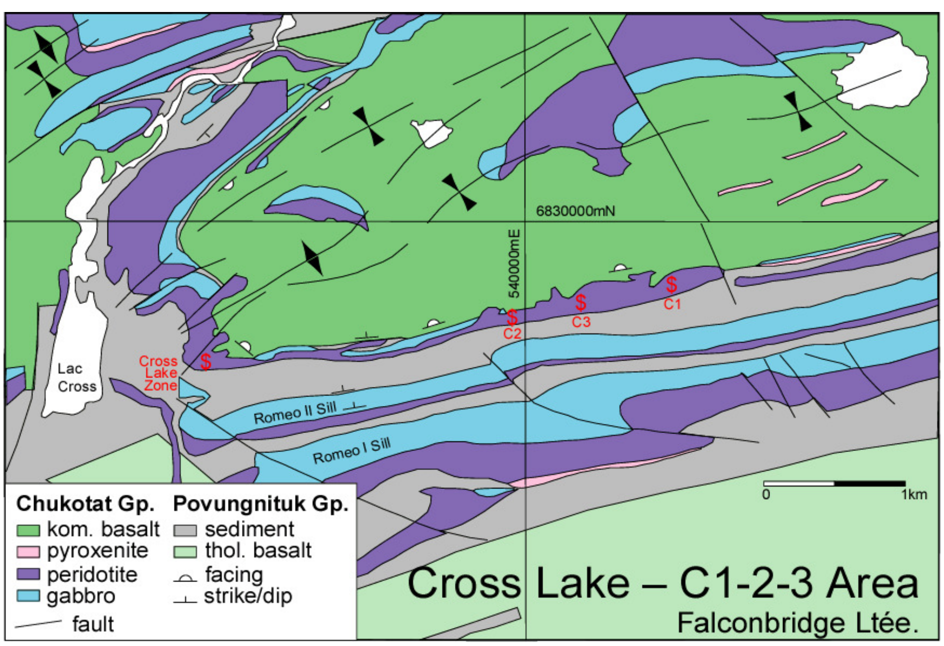
Channelized Sheet Flows and Sheet Sills



Lesher 2007 *GAC-MDD Spec Pap*

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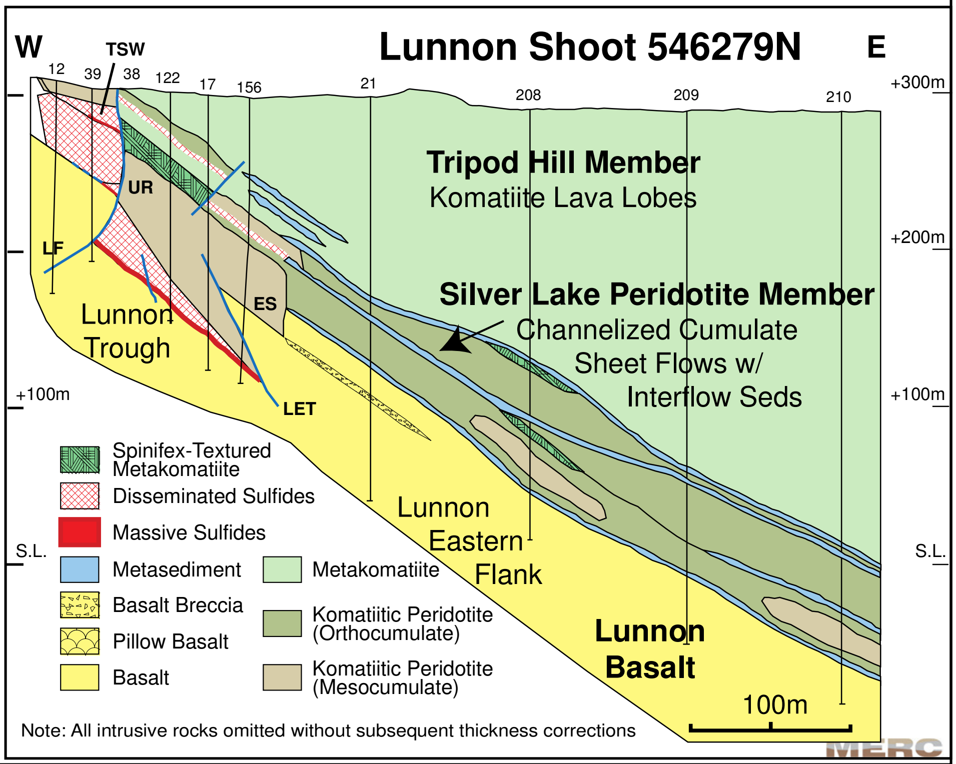
Lunnon Shoot, Kambalda

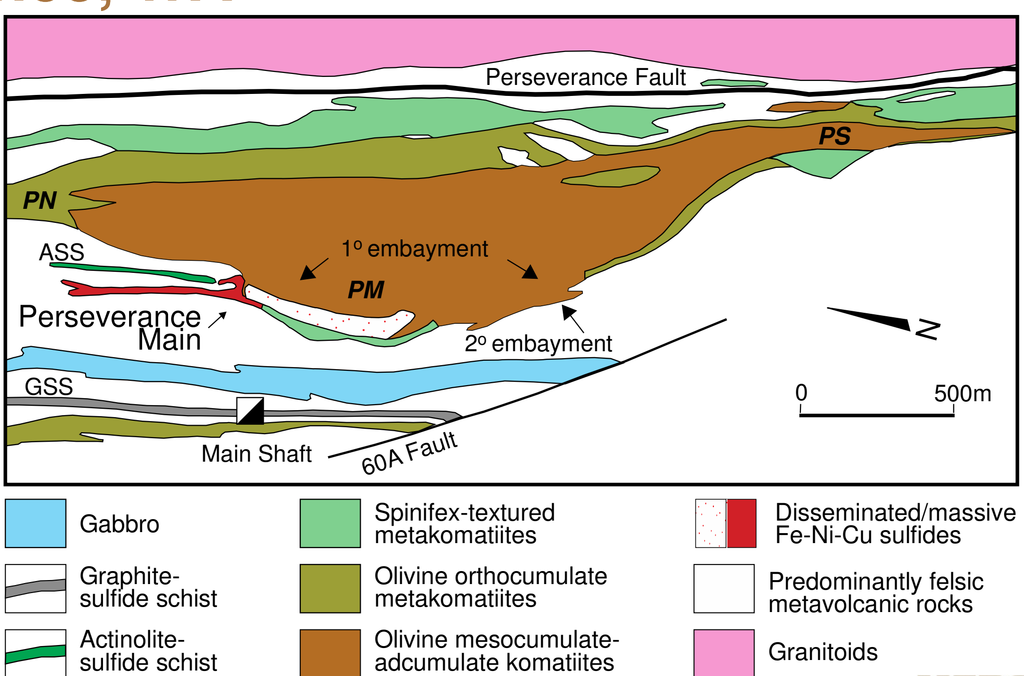
Channelized sheet flow



Lesher 1989 *Rev Econ Geol 4*

Perseverance, WA

Lava channel



modified from Barnes et al. 1988 *J Pet*

Intrusive Host Units

- **Channelized sills**: Dumont ON; Jinchuan CH; Norilsk-Talnakh – Pechenga RU; Mt Keith WA; Thompson MB; Wellgreen YK
- **Blade-shaped dikes**: Eagle MI; Eagle's Nest ON; Expo-Méquillon QC; Hongqiling #1 – Kalatongke – Huangshan – Huangshandong – Limahe – Qingquanshan CH; Savannah (Sally Mallay) WA
- **Tubes/chonoliths**: Current Lake ON, Nebo-Babel WA, Uitkomst SA, Limoeiro BR, Tamarack MI; Santa Rita (Mirabella) BR
- **Subhorizontal parts of feeder systems**: Voisey's Bay Ovoid

- **Only a few are subvertical dikes**: Reid Brook-Eastern Deeps NL; Copper Cliff-Foy-Whistle-Worthington ON
- **Only a few are subvertical Alaskan-Uralian-type intrusions**: Duke Island AK, Jingbulake CH; Turnagain – Tulameen BC

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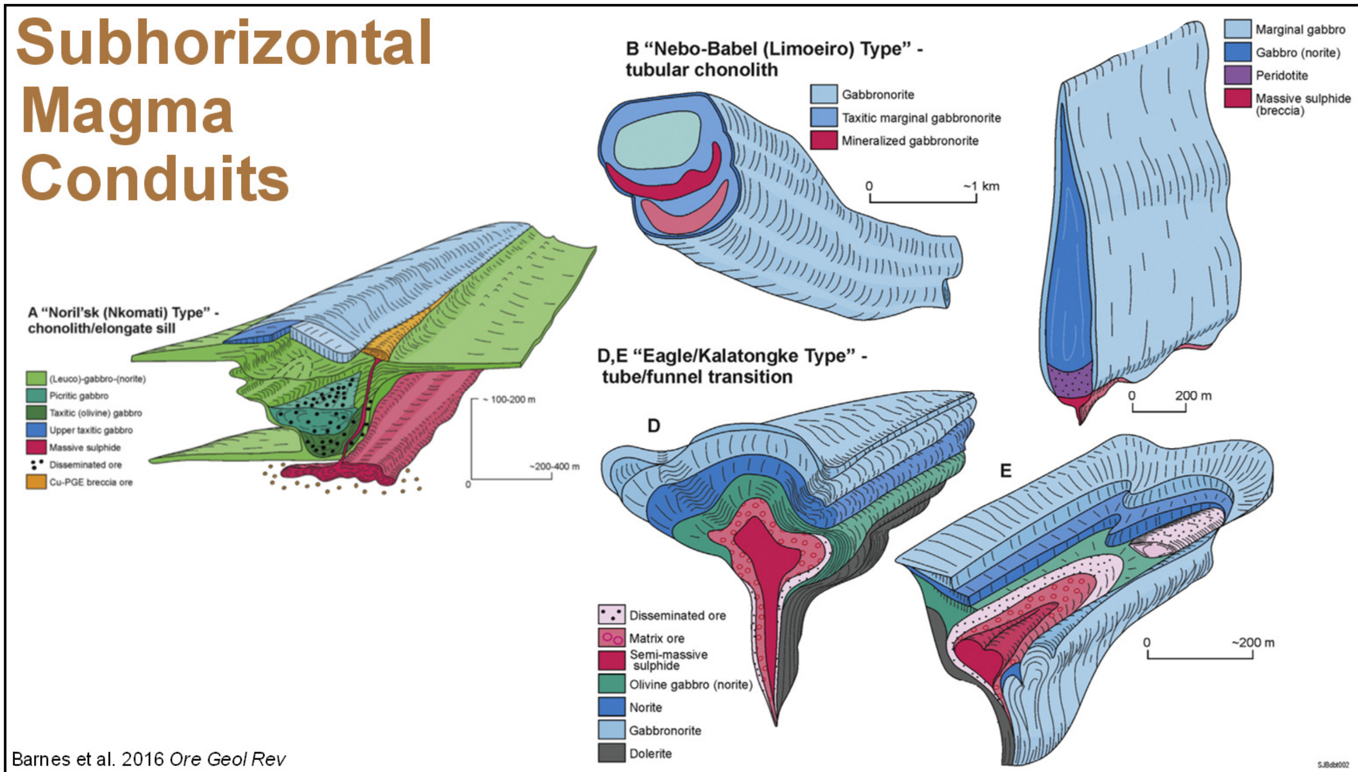
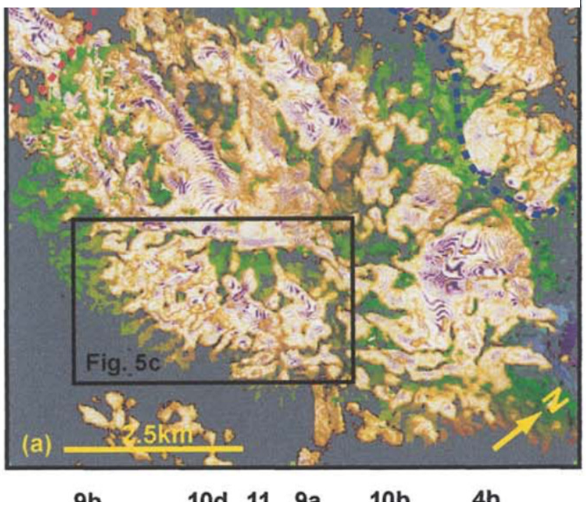
Subhorizontal Magma Conduits



Barnes et al. 2016 *Ore Geol Rev*

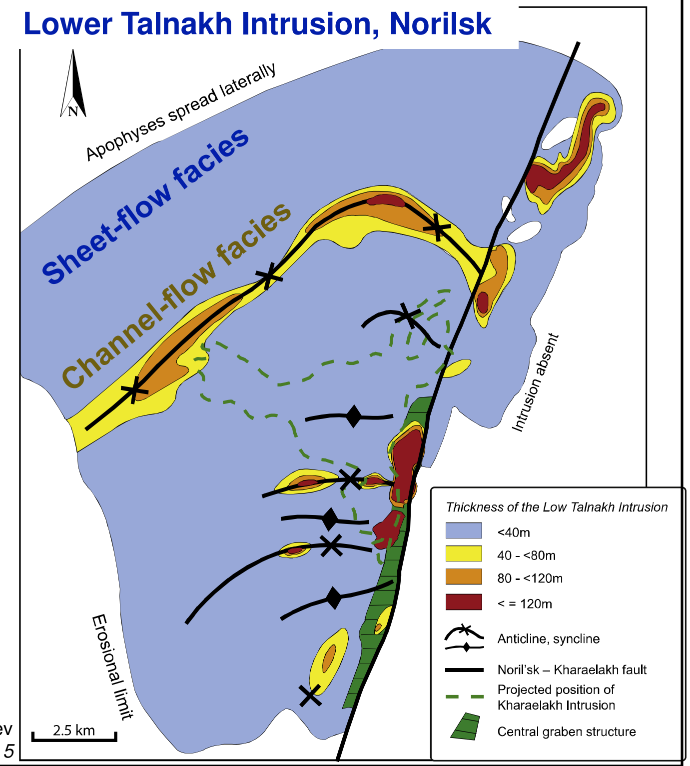
Channelized Sheet Sills

North Rockall Trough, North Sea



Thomson & Hutton 2004 *J Volc*

Lower Talnakh Intrusion, Norilsk



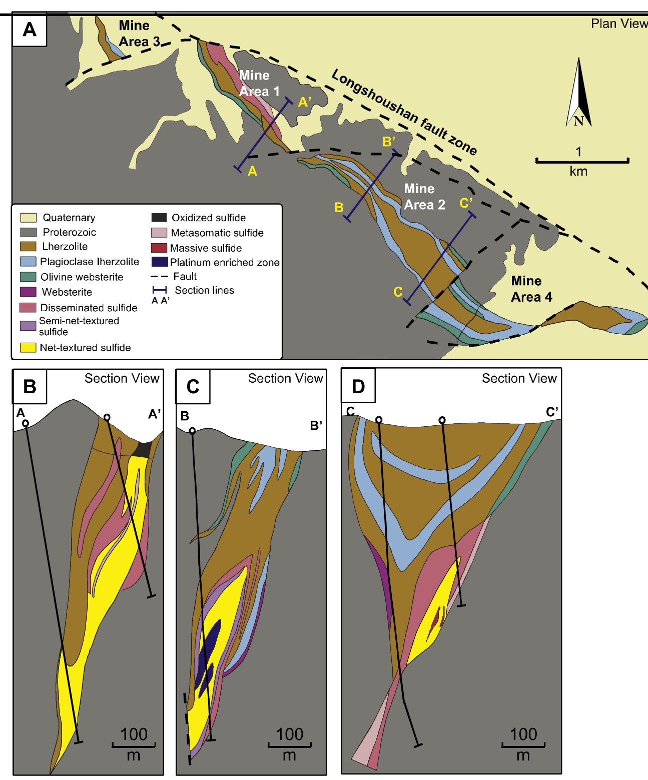
modified after Lightfoot & Evans-Lamswood 2015 Ore Geol Rev
and Zenko & Czamanske 1994 *OGS Spec Publ 5*

Jinchuan

Cross section looks like a funnel and some authors (e.g., Tang 193 GSC; Lightfoot and Evans-Lamswood 2015 Ore Geol Rev) **have interpreted it as a subvertical funnel, but the intrusion terminates to the NW and is more differentiated toward the SE**

Other authors (e.g., Lehmann et al. 2007 *Econ Geol*; Song et al. 2009 *Min Dep*; Tonnelier 2010 *PhD thesis*) **have argued that the intrusion is a sill rotated during deformation, which would make it a channelized sill, not a funnel**

If not a sill, then more likely a blade-shaped dike than a feeder funnel



Lightfoot & Evans-Lamswood 2015 *Ore Geol Rev*
after Tang 1992 *Min Dep China*; 1993 *GSC Spec Pap 40*

Eagle's Nest (ON)

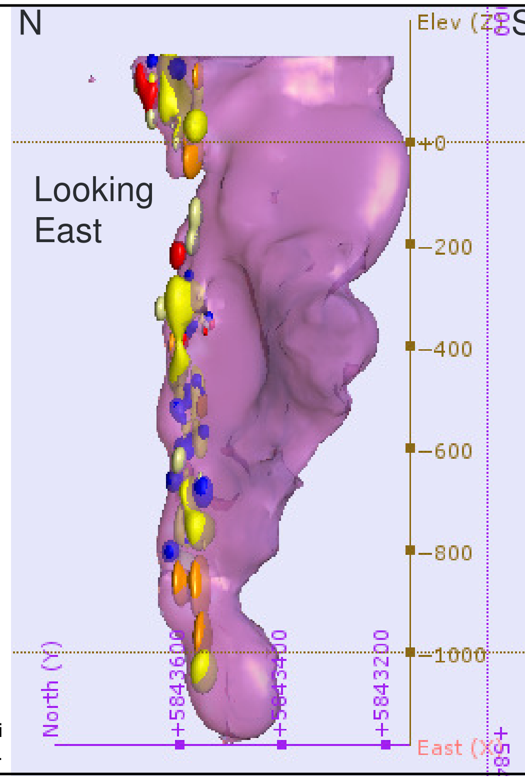
Structurally rotated (originally horizontal) **blade-shaped dike**

Massive sulfides in embayments along northern (formerly basal) **contact**

Overlain by more continuous net-textured and disseminated sulfides and barren peridotite

"Disrupted-net" sulfides have been invaded by a late pyroxenitic phase

Peridotite
Disseminated
Disrupted-net
Leopard-net
Semi-massive
Massive



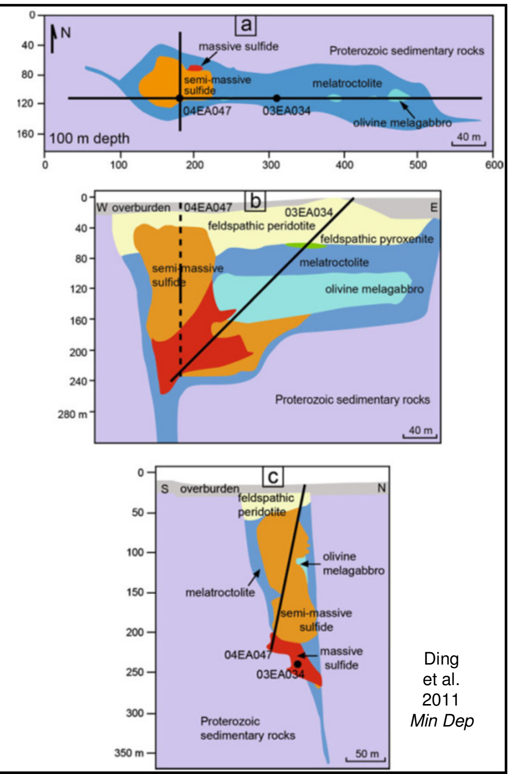
Zuccarrelli MSc in prep.

Eagle (MI)

Cross section looks like a funnel and has been interpreted to be a subvertical funnel (e.g., Ding et al. 2011 *Min Dep*; Lightfoot and Evans-Lamswood 2015 *Ore Geol Rev)*, **but the intrusion is asymmetrically differentiated**

How could molten sulfides be kept suspended over the feeder while it crystallized?

More likely a subhorizintal blade-shaped dike (Lesher in press *CJES*)

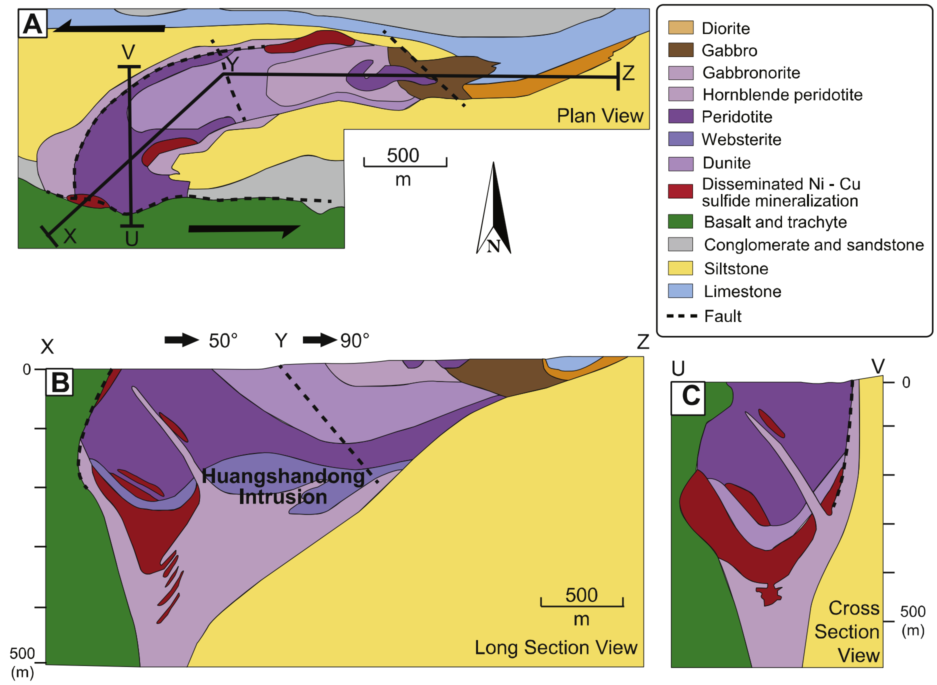


Ding et al. 2011 *Min Dep*

Huangshan

Cross section looks like a funnel and has been interpreted to be a subvertical funnel (Lightfoot and Evans-Lamswood 2015 *Ore Geol Rev)*, **but the intrusion is asymmetrically differentiated toward the NNE and is part of a series of intrusions with similar geometries**

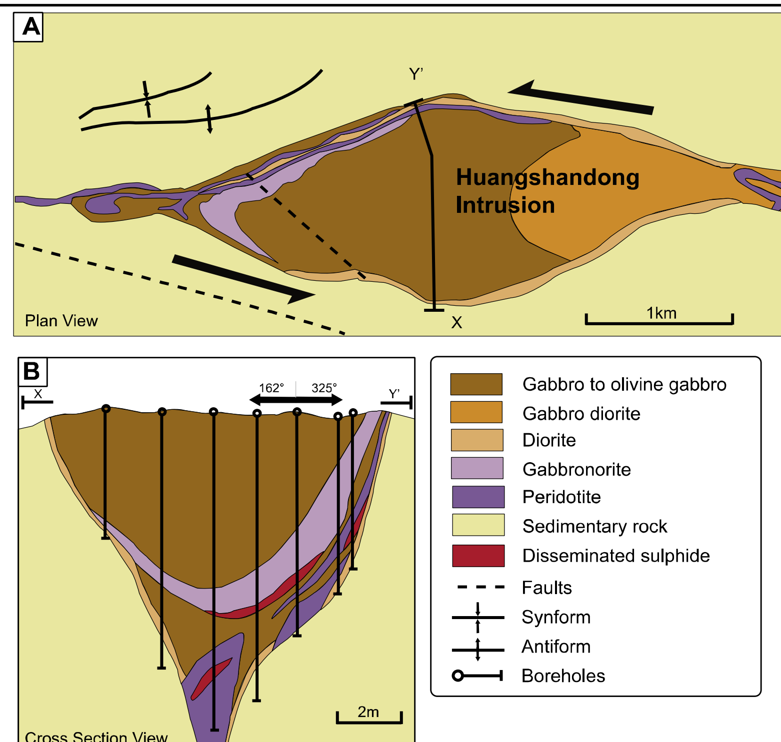
More likely a blade-shaped dike (Lesher in press *CJES*)



Lightfoot & Evans-Lamswood 2015 Ore Geol Rev after Wang et al. 1987 *Miner Rocks*

Huangshandong

Cross section looks like a funnel and has been interpreted to be a subvertical funnel (Lightfoot and Evans-Lamswood 2015 *Ore Geol Rev)*, **but the intrusion terminates toward the west, is asymmetrically differentiated toward the east, and is part of a series of intrusions with similar geometries**



Lightfoot & Evans-Lamswood 2015 Ore Geol Rev after Wang et al. 1987; Gao & Zhou 2011 *Lithos*)

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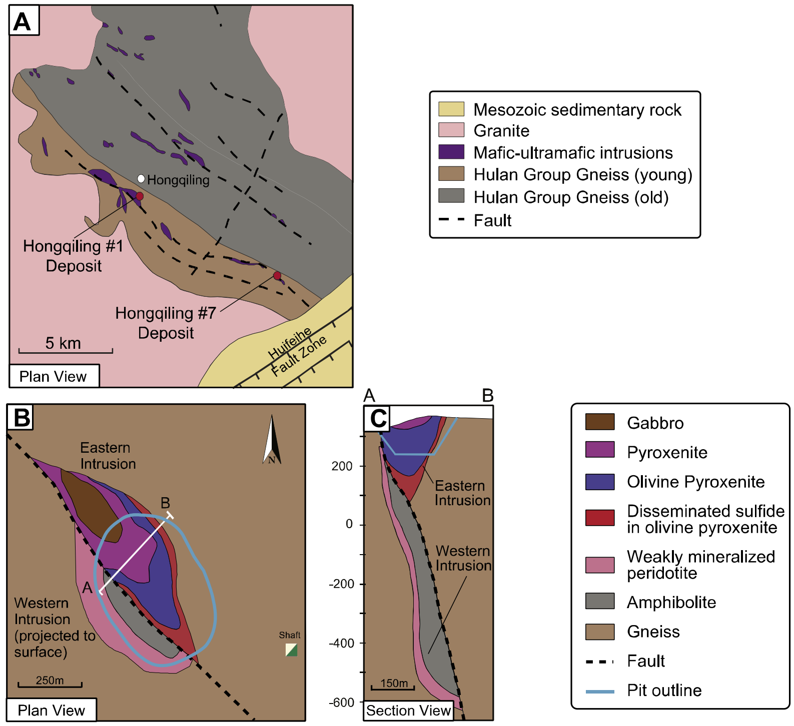
Hongquiling

Cross section looks like a funnel and has been interpreted to be a subvertical funnel (Lightfoot and Evans-Lamswood 2015 *Ore Geol Rev*), **but the intrusion is asymmetrically differentiated toward the NW and terminates to the SE**

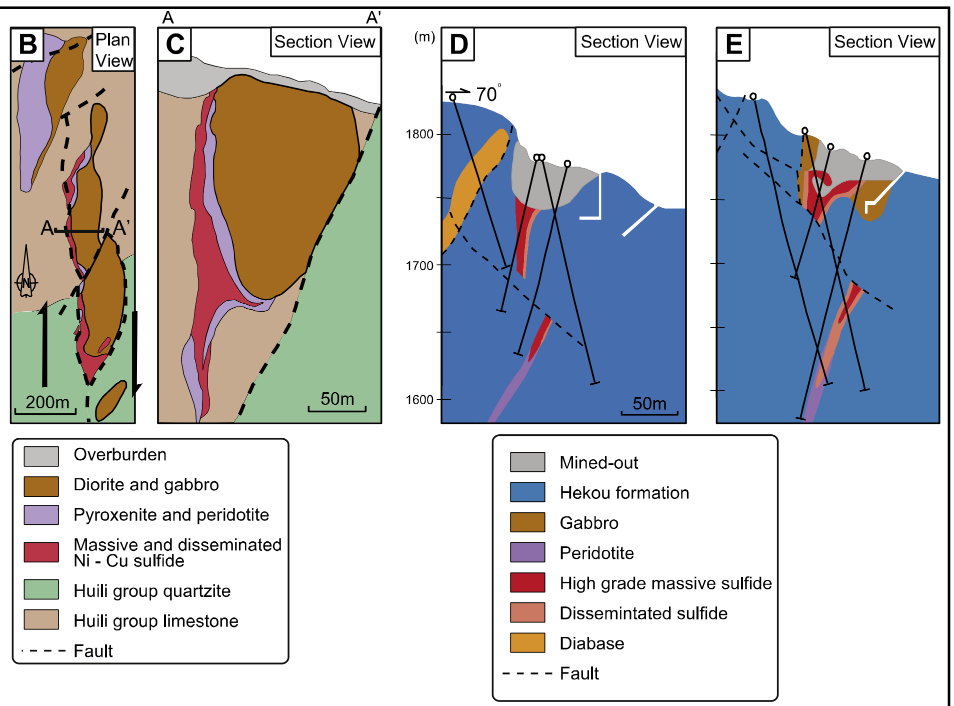


Lightfoot & Evans-Lamswood 2015 *Ore Geol Rev* after Wei et al. *Econ Geol* and Tang 1992 *Min Dep China*

Emeishan

Limae (B-C)
Qingkuangshan (D-E)

Same again: cross sections look like funnels and have been interpreted to be subvertical funnels (Lightfoot and Evans-Lamswood 2015 *Ore Geol Rev*), **but the intrusions are asymmetrically differentiated and appear to terminate at depth**

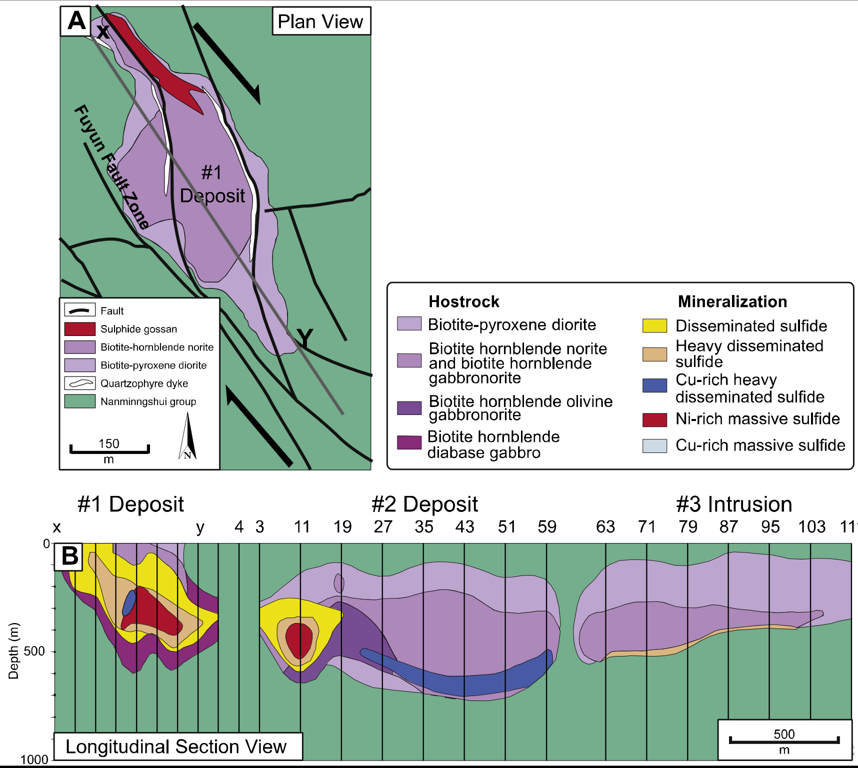


Lightfoot & Evans-Lamswood 2015 *Ore Geol Rev* after Wei et al. and Tang 1992 *GSC*

Kalatongke #1

Cross section looks like a funnel, but the intrusion is subhorizontal, terminates to the NNW and is differentiated toward the SSE

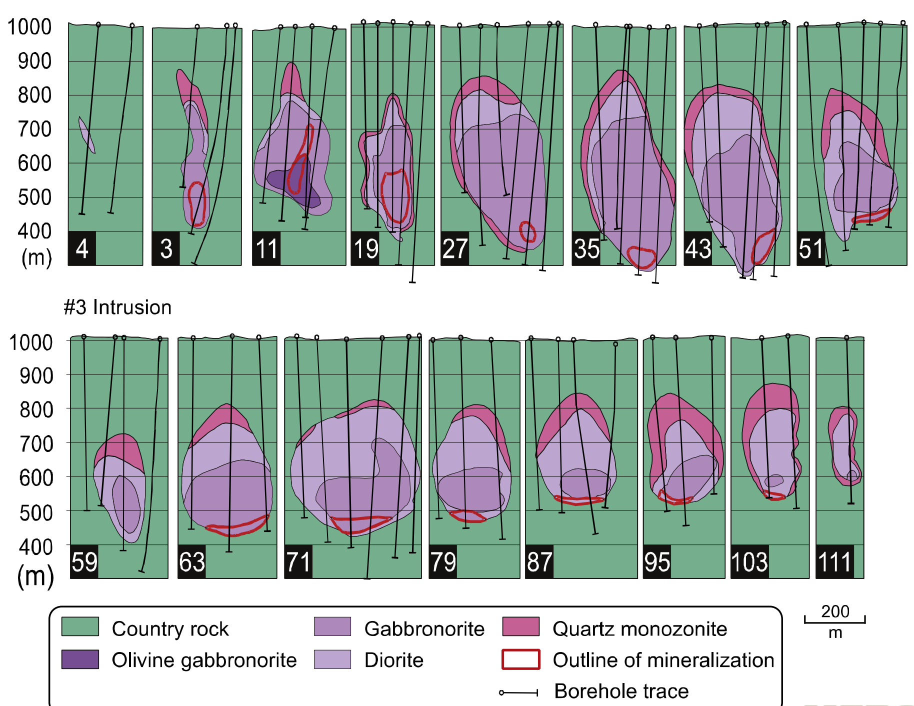
Extends to the SSE discontinuously? in the subsurface



Lightfoot & Evans-Lamswood 2015 *Ore Geol Rev*
after Tang 1992 *Min Dep China*, 1993 *GSC Spec Pap 40*

Kalatongke #2

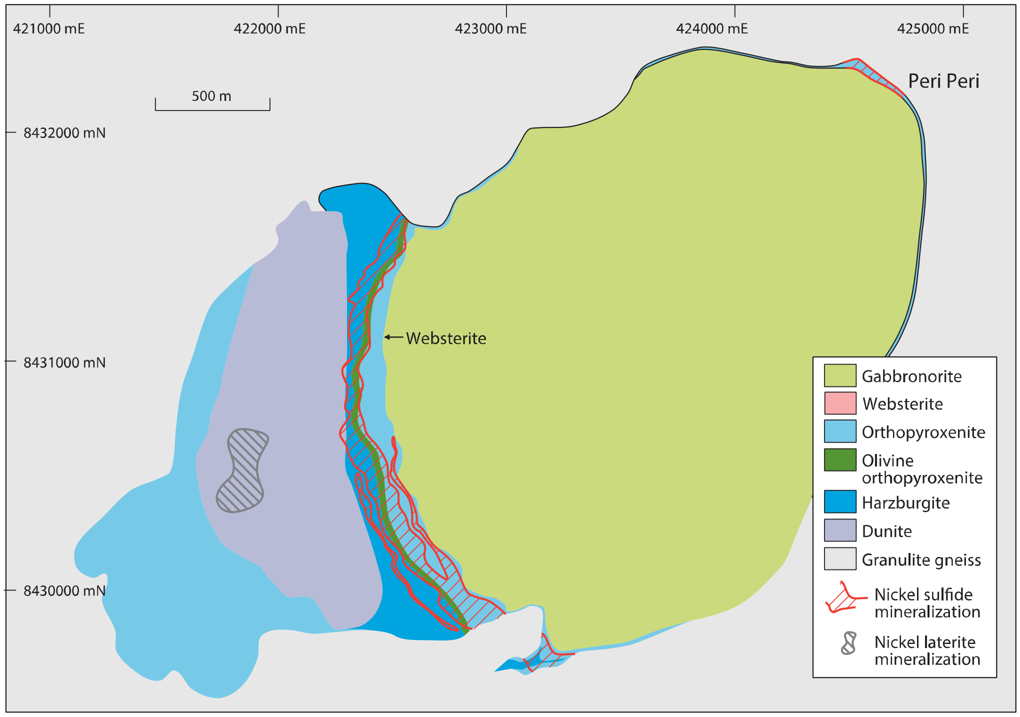
Clearly a chonolith in cross section



Lightfoot & Evans-Lamswood 2015 *Ore Geol Rev*
after Tang 1992 *Min Dep China*, 1993 *GSC Spec Pap 40*

Santa Rita (Mirabella)

Tilted chonolith



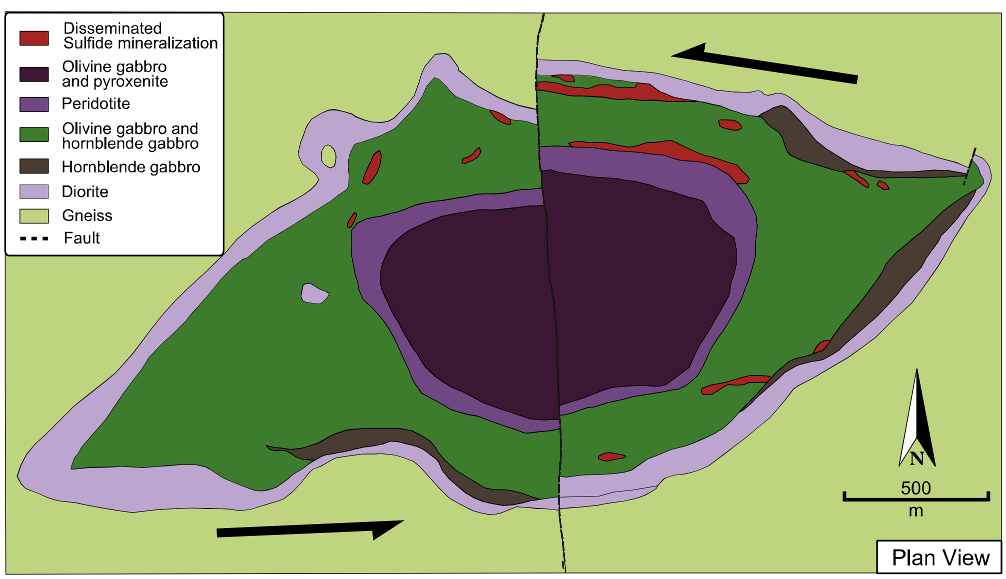
Barnes et al. 2011 *Econ Geol*

Jingbulake

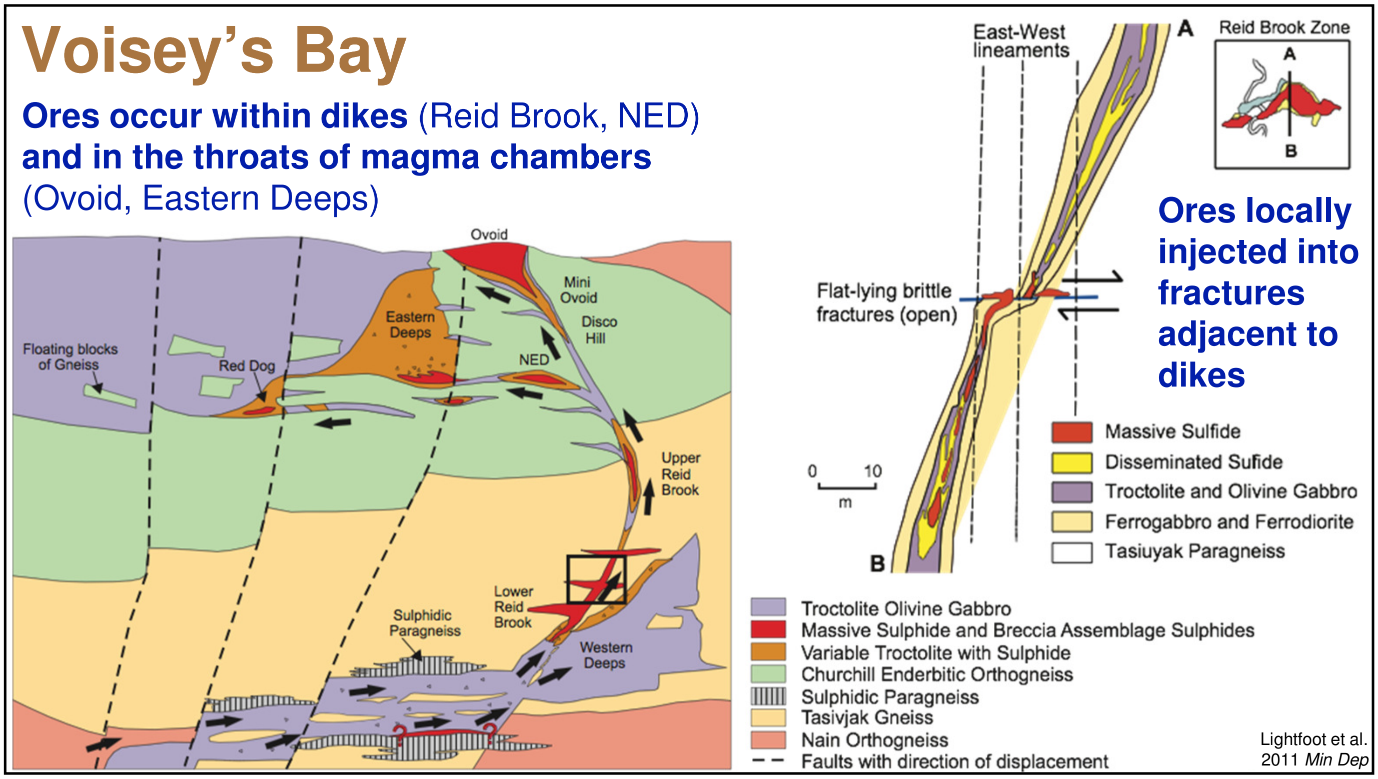
Symmetrically zoned

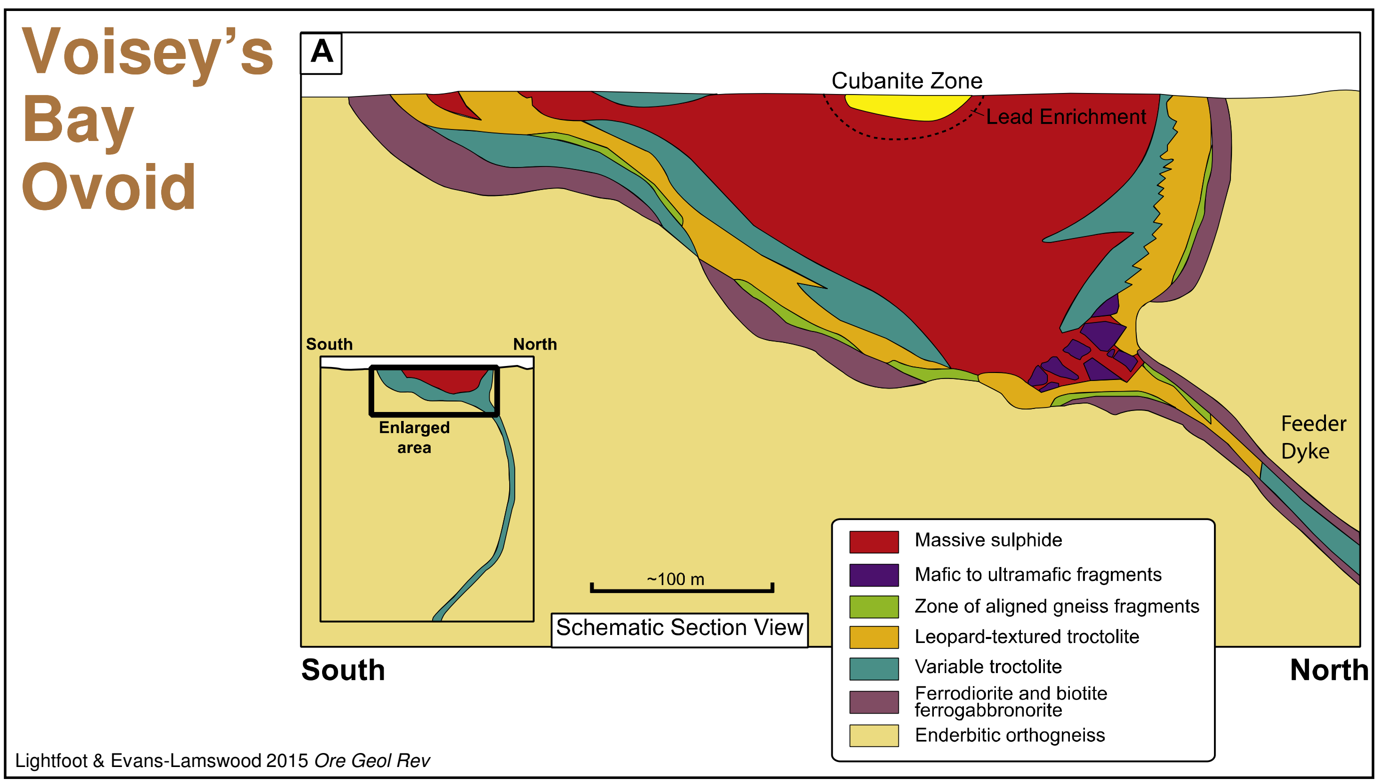
Mineralization in gabbro, not peridotite

More like an Alaskan-Uralian intrusion



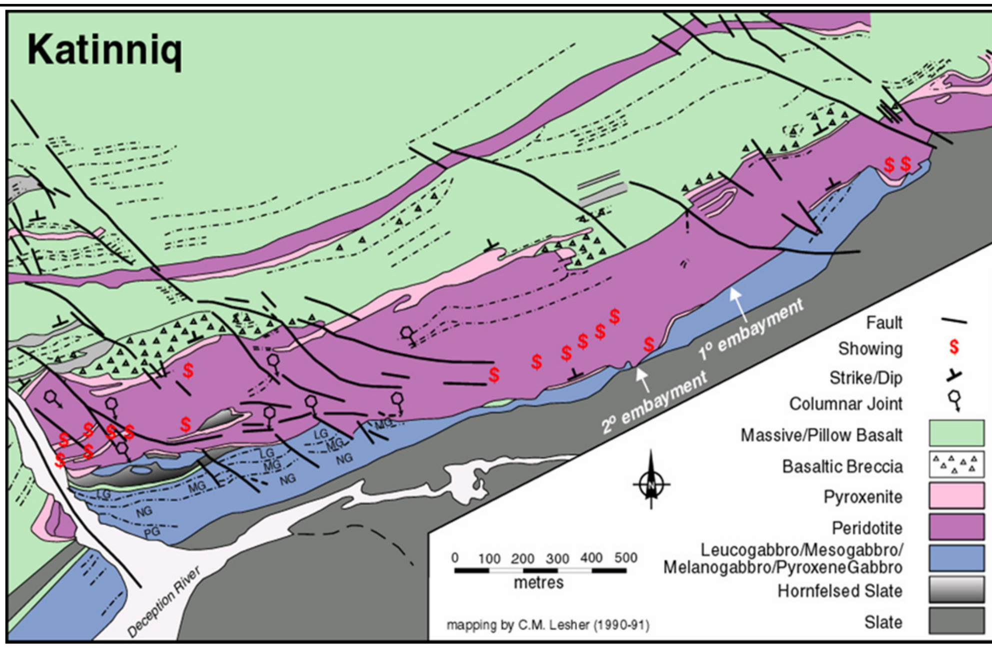
Lightfoot & Evans-Lamswood 2015 Ore Geol Rev after Yang et al. 2012 *Chem Geol*


Voisey's Bay
Ores occur within dikes (Reid Brook, NED) and in the throats of magma chambers (Ovoid, Eastern Deeps)
Ovoid
Mini Ovoid
Eastern Deeps
Disco Hill
Floating blocks of Gneiss
Red Dog
NED
Upper Reid Brook
Lower Reid Brook
Sulphidic Paragneiss
Western Deeps
East-West lineaments
A
Reid Brook Zone
A
B
Ores locally injected into fractures adjacent to dikes
Flat-lying brittle fractures (open)
0
10
m
B
Massive Sulfide
Disseminated Sufide
Troctolite and Olivine Gabbro
Ferrogabbro and Ferrodiorite
Tasiuyak Paragneiss
Troctolite Olivine Gabbro
Massive Sulphide and Breccia Assemblage Sulphides
Variable Troctolite with Sulphide
Churchill Enderbitic Orthogneiss
Sulphidic Paragneiss
Tasivjak Gneiss
Nain Orthogneiss
Faults with direction of displacement
Lightfoot et al. 2011 Min Dep

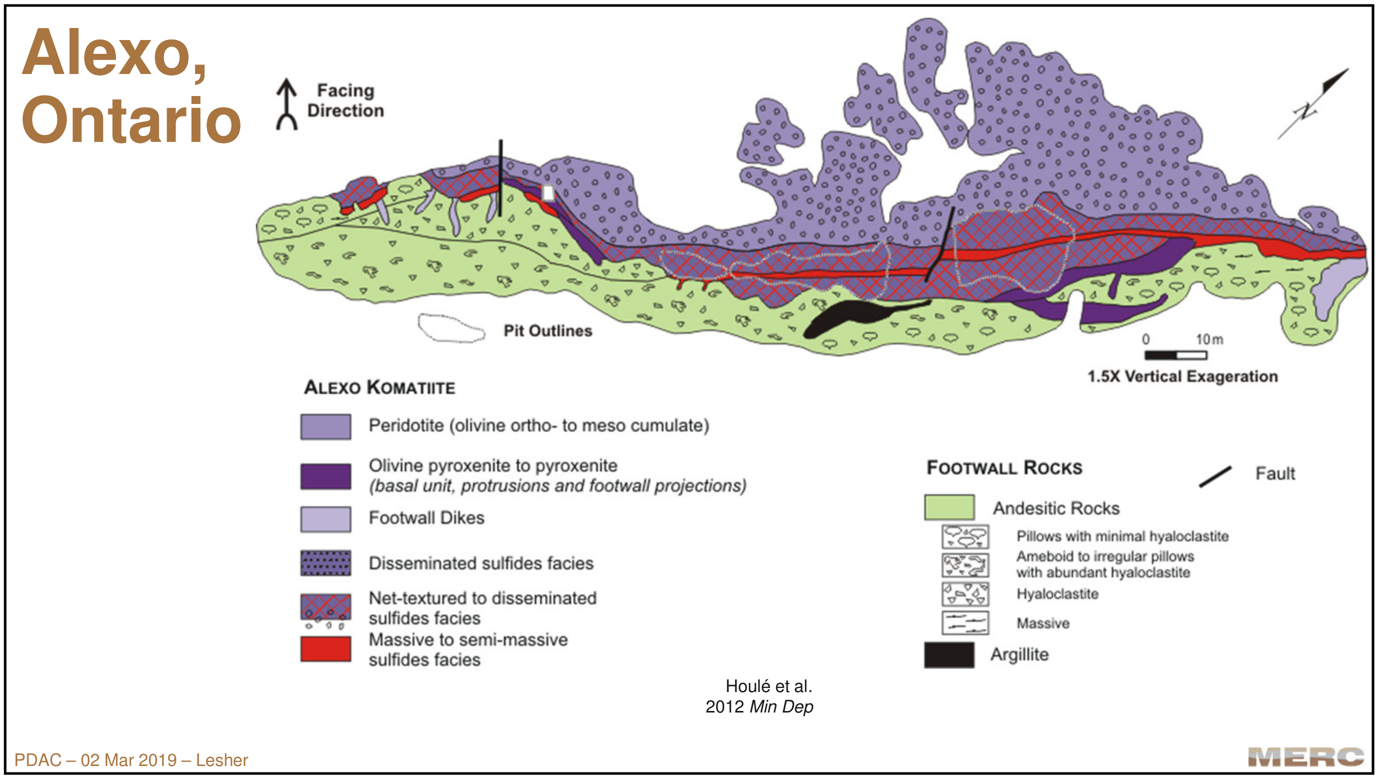

Voisey's Bay Ovoid
A
Cubanite Zone
Lead Enrichment
South
North
Enlarged area
Feeder Dyke
~100 m
Schematic Section View
South
North
Massive sulphide
Mafic to ultramafic fragments
Zone of aligned gneiss fragments
Leopard-textured troctolite
Variable troctolite
Ferrodiorite and biotite ferrogabbronorite
Enderbitic orthogneiss
Lightfoot & Evans-Lamswood 2015 Ore Geol Rev

Ore Localization

- **Most ores are localized in footwall embayments**
- **Some are volcanic topographic features modified by thermomechanical erosion:** e.g., Kambalda WA
- **Many appear to have been generated by thermomechanical erosion:** e.g., Alexo ON, Duluth MN; Norilsk and Pechenga RU, Perseverance WA; Raglan QC; Sudbury ON
- **Some are too deformed to tell:** e.g., Harmony WA; Redstone ON; Thompson MB



Geologic map of the Katinniq Ultramafic Complex (Lesher 2007 *GSC-MDD*)**. Lower contact transgresses hornfelsed slates and footwall gabbro; upper contact is capped by flow-top breccia, conformable with overlying basalts, and is not contact metamorphosed.**


Alexo, Ontario
Facing Direction
Pit Outlines
0 10 m
1.5X Vertical Exageration
ALEXO KOMATIITE
Peridotite (olivine ortho- to meso cumulate)
Olivine pyroxenite to pyroxenite
(basal unit, protrusions and footwall projections)
Footwall Dikes
Disseminated sulfides facies
Net-textured to disseminated sulfides facies
Massive to semi-massive sulfides facies
FOOTWALL ROCKS
Fault
Andesitic Rocks
Pillows with minimal hyaloclastite
Ameboid to irregular pillows with abundant hyaloclastite
Hyaloclastite
Massive
Argillite
Houlé et al. 2012 Min Dep
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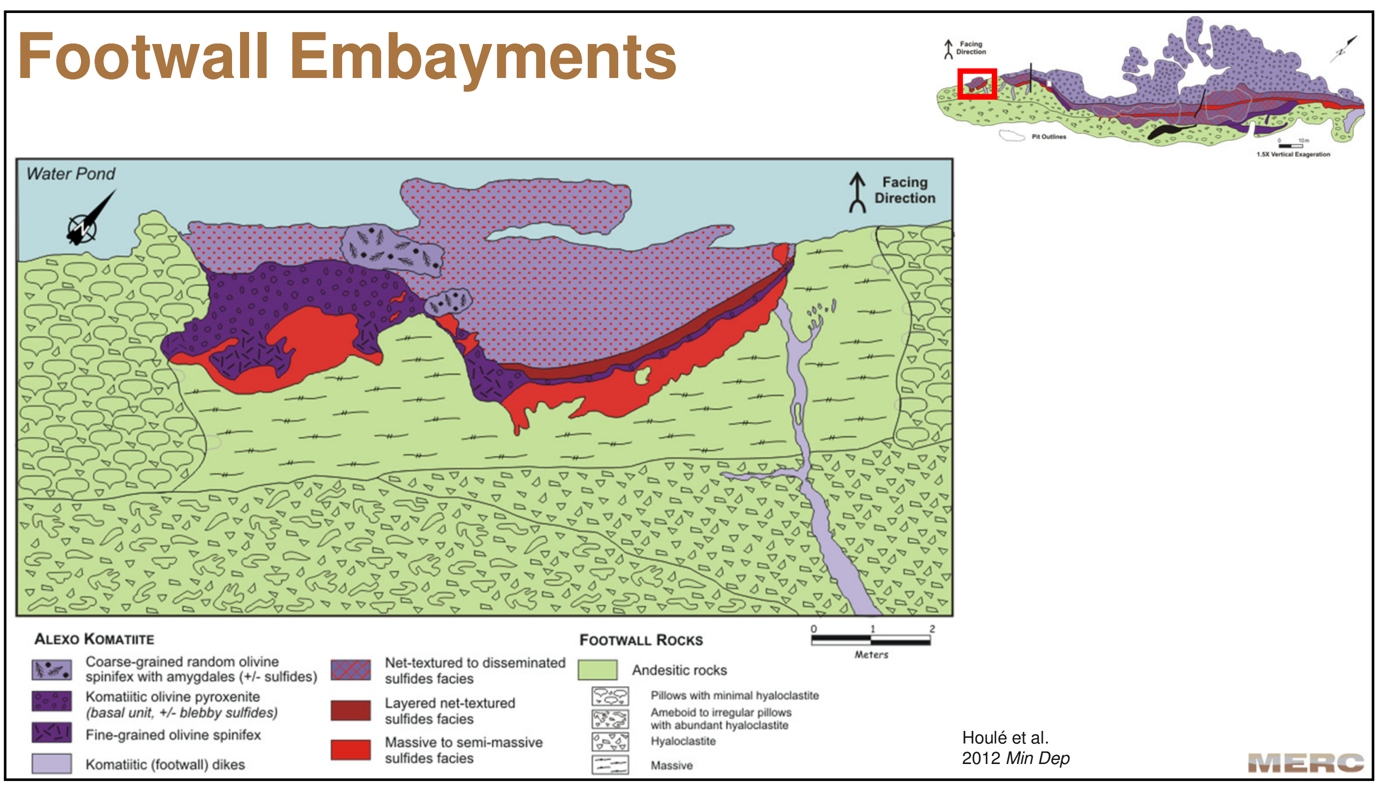
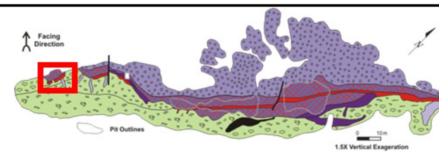
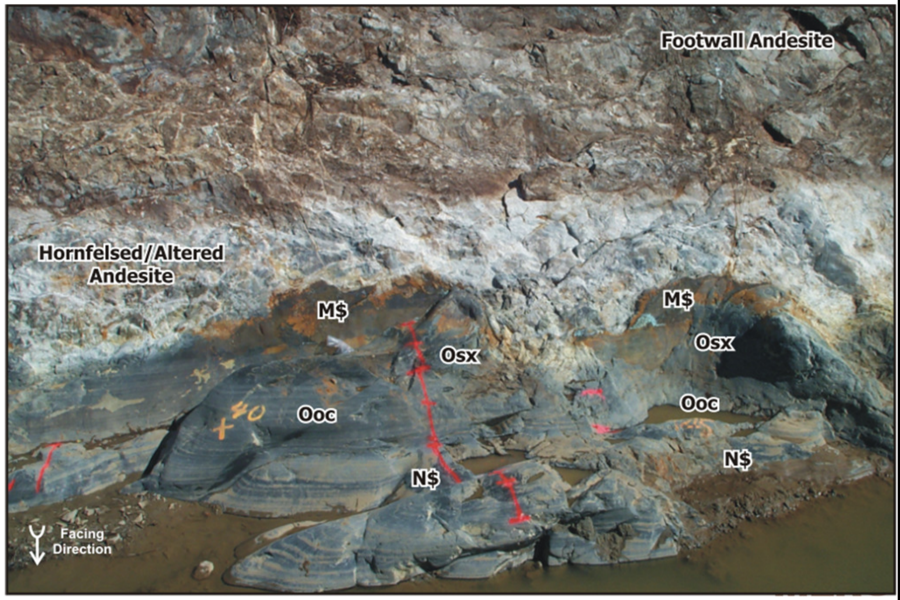

Footwall Embayments
Water Pond
Facing Direction
ALEXO KOMATIITE
Coarse-grained random olivine spinifex with amygdales (+/- sulfides)
Komatiitic olivine pyroxenite (basal unit, +/- blebby sulfides)
Fine-grained olivine spinifex
Komatiitic (footwall) dikes
Net-textured to disseminated sulfides facies
Layered net-textured sulfides facies
Massive to semi-massive sulfides facies
FOOTWALL ROCKS
Andesitic rocks
Pillows with minimal hyaloclastite
Ameboid to irregular pillows with abundant hyaloclastite
Hyaloclastite
Massive
0 1 2
Meters
Houlé et al. 2012 Min Dep
MERC

Footwall Embayments

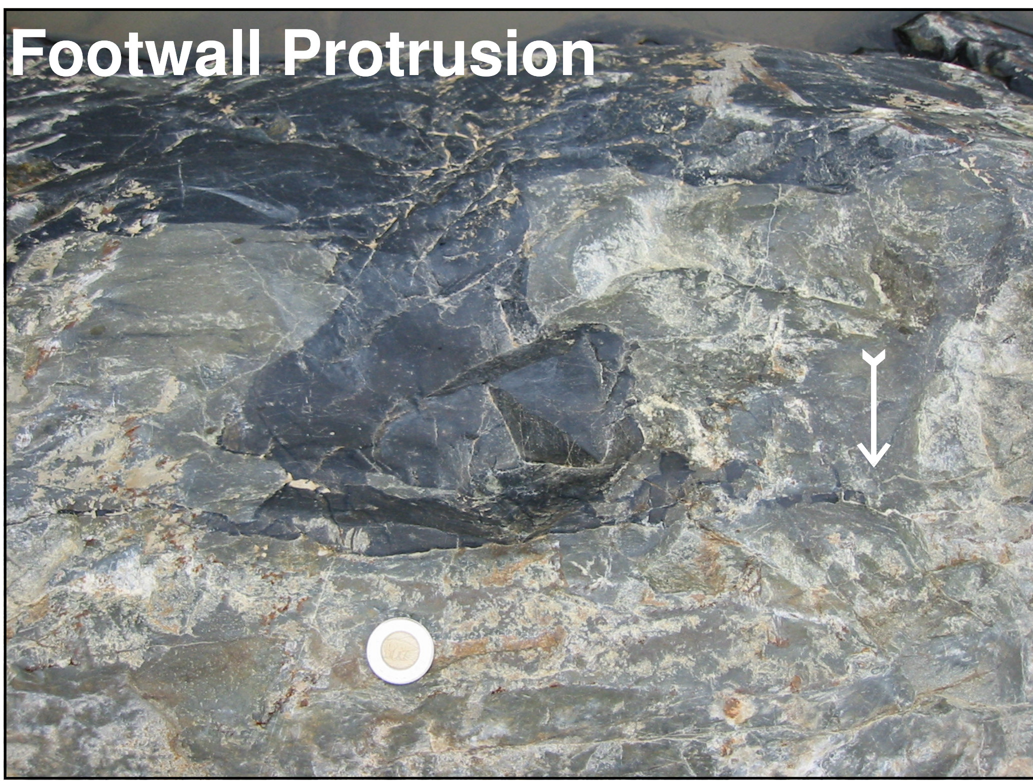


- Second-order embayments along footwall contact west of Alexo mine shaft
- Similar geometry was produced in an analog model (Huppert and Sparks, 1985 *J Pet*)



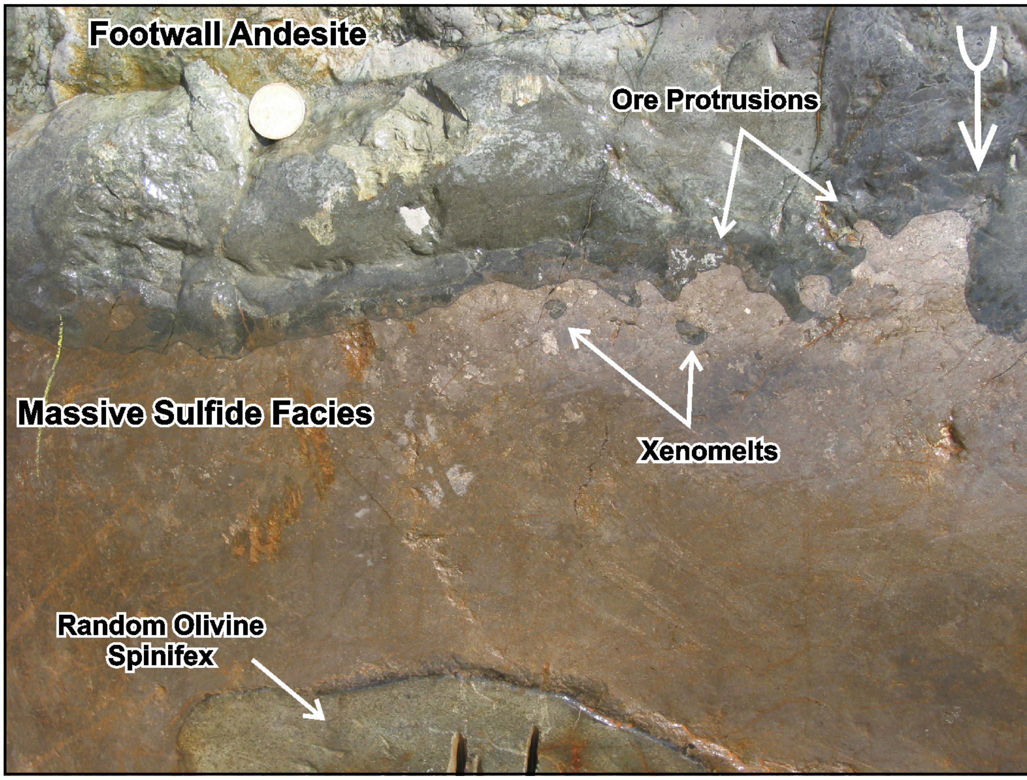
Houlé et al. 2012 *Min Dep*

Footwall Protrusion



- Denser komatiitic magma intruded downwards into andesitic footwall, forming reentrant bulb with flanking sills
- Greyer colour represents partial incorporation of andesitic material by komatiite melt

Houlé et al. 2012 *Min Dep*

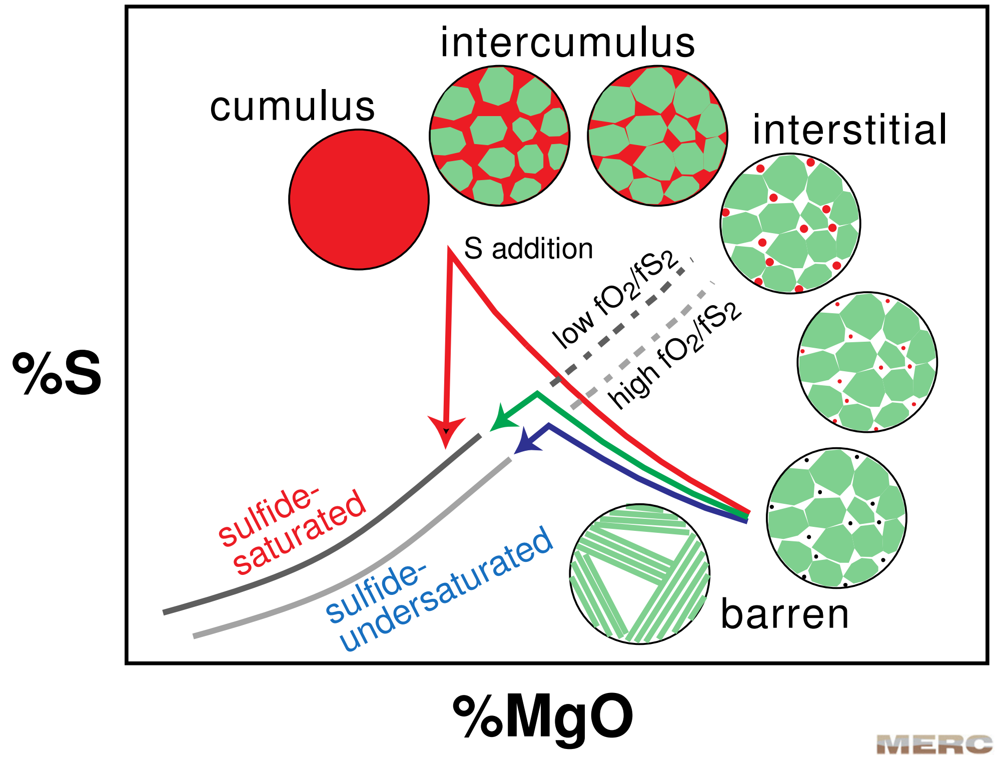


Houlé et al. 2012 *Min Dep*

Sulfide Textures

- **Komatiitic magmas are strongly undersaturated in sulfide and will crystallize Ol ± Pyx prior to reaching sulfide saturation and will produce only very sparse** (if any) **disseminated sulfides**
- **Magmas that evolve from sulfide-undersaturated to sulfide-saturated during Ol accumulation will produce very fine disseminated intersititial sulfides**
- **Magmas that crystallize/segregate Ol and sulfide in cotectic proportions** (~60:1: Duke 1986) **will produce fine disseminated intercumulus sulfides**
- **Magmas that continuously incorporate sulfides from country rocks will form larger amounts of sulfides and will produce net- or matrix-textured intercumulus sulfides**
- **Magmas that achieve sulfide saturation early and melt enough sulfides from wall rocks will produce massive cumulus sulfides**

Sulfide Textures



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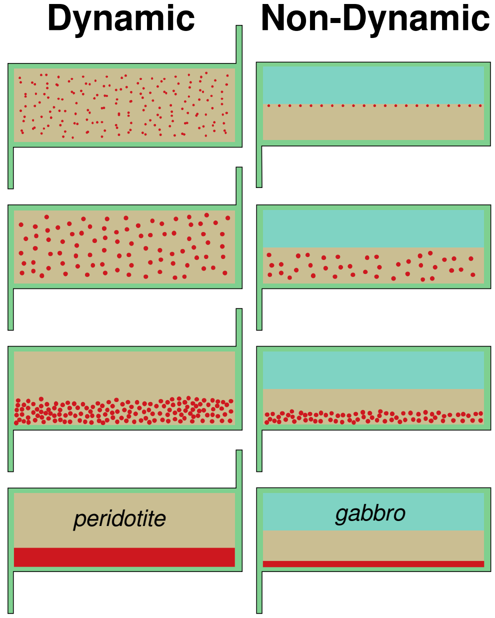
Timing vs. Dynamics

Sulfide Saturation	Examples	Dynamic	Non-Dynamic	Examples
Late/ Continuous	Dumont Mt Keith			Bushveld Stillwater
↑	Black Swan Jinchuan			Norilsk I
	Eagle's Nest Raglan			Pechenga
Early	Alexo Kambalda			Norilsk II Talnakh



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Mineralization Types

- **Type I stratiform basal massive-disseminated mineralization and associated vein systems:** e.g., Alexo ON, Kambalda WA, Norilsk RU, Sudbury contact-footwall veins systems ON, Thompson MB
- **Type II stratabound internal disseminated to net-textured mineralization:** e.g., Duluth MN, Dumont QC, Jinchuan CH, Mt Keith WA, Sudbury Sublayer and Offset ores ON
- **Type III stratiform internal 'reef'-type mineralization:** e.g., Bushveld SA, Stillwater MT
- **Type IV magmatic-hydrothermal mobilized mineralization associated with Type I mineralization:** e.g., parts of Thompson NB, Kambalda WA, Langmuir ON
- **Type V tectonically-modified and/or mobilized mineralization derived from Type I mineralization:** e.g., Thompson MB, parts of most other deposits

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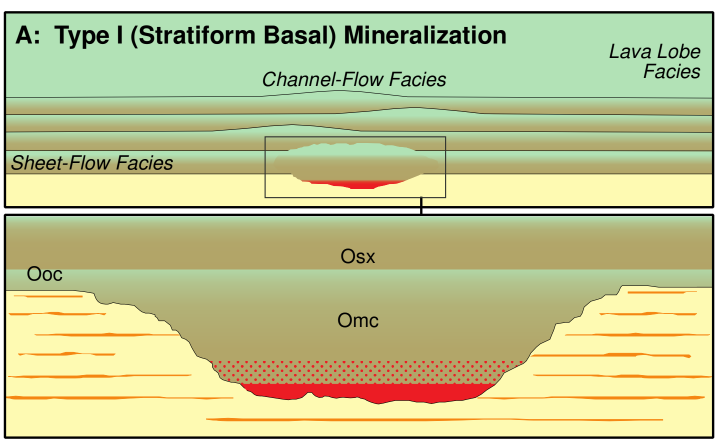
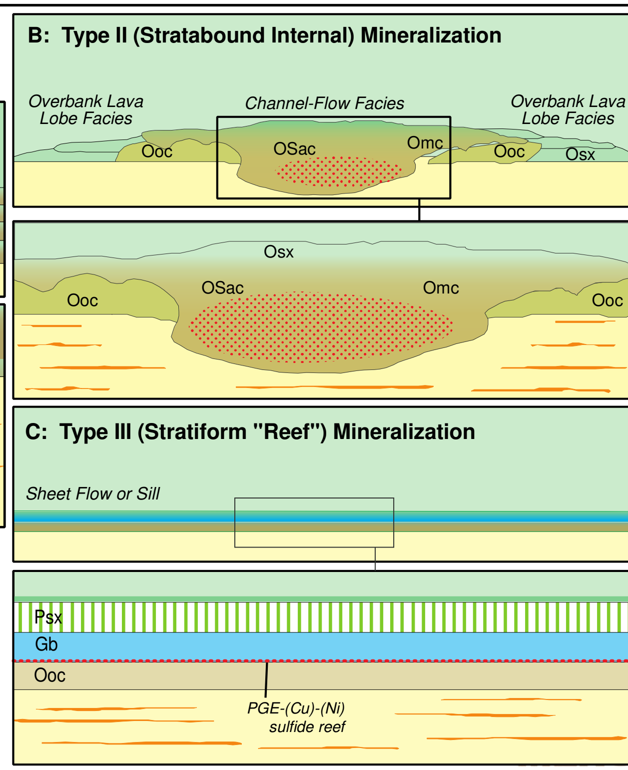
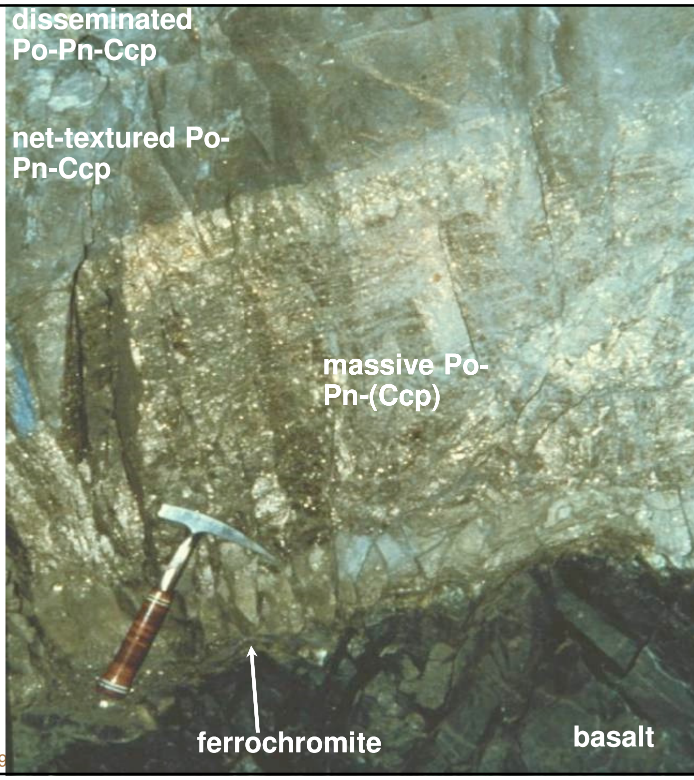
adapted from Lesher Keays 2002 *CIM v54*

Mineralization Types





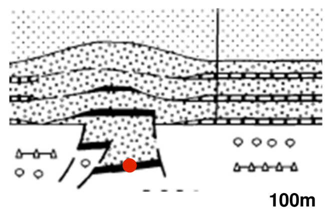
Lesher & Keays 2002 *CIM v54*; Lesher & Barnes 2009 *Publ House China*



Type I

Basal massive\net-textured/dissem-inated ore profile, Juan Main 1204 shoot, Kambalda, Western Australia

The *banding* in the massive ore is metamorphic



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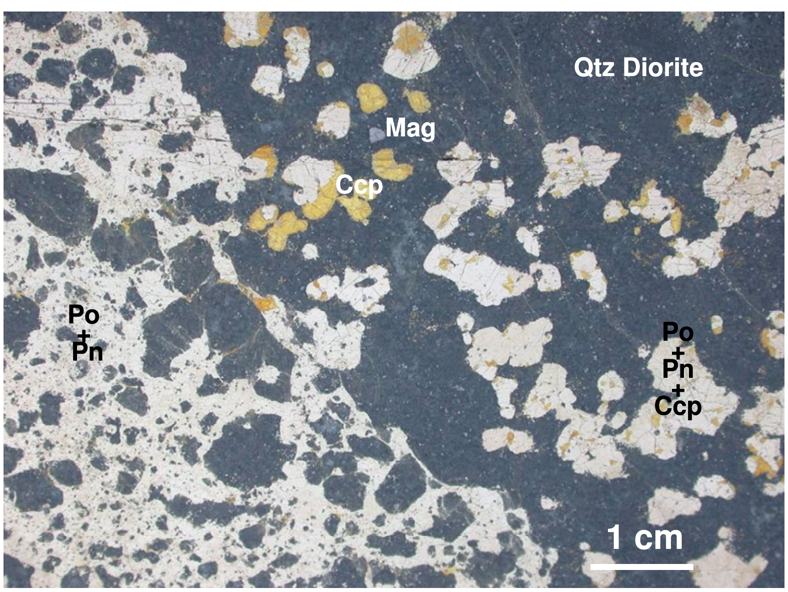
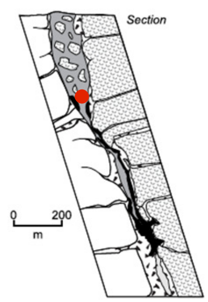
Type I





Inclusion-bearing massive MSS cumulate (left)**, local Cu-rich liquids** (centre)**, and relatively unfractionated blebby disseminated ore** (right)**, Frood Mine, Sudbury** (photo by Paul Golightly)

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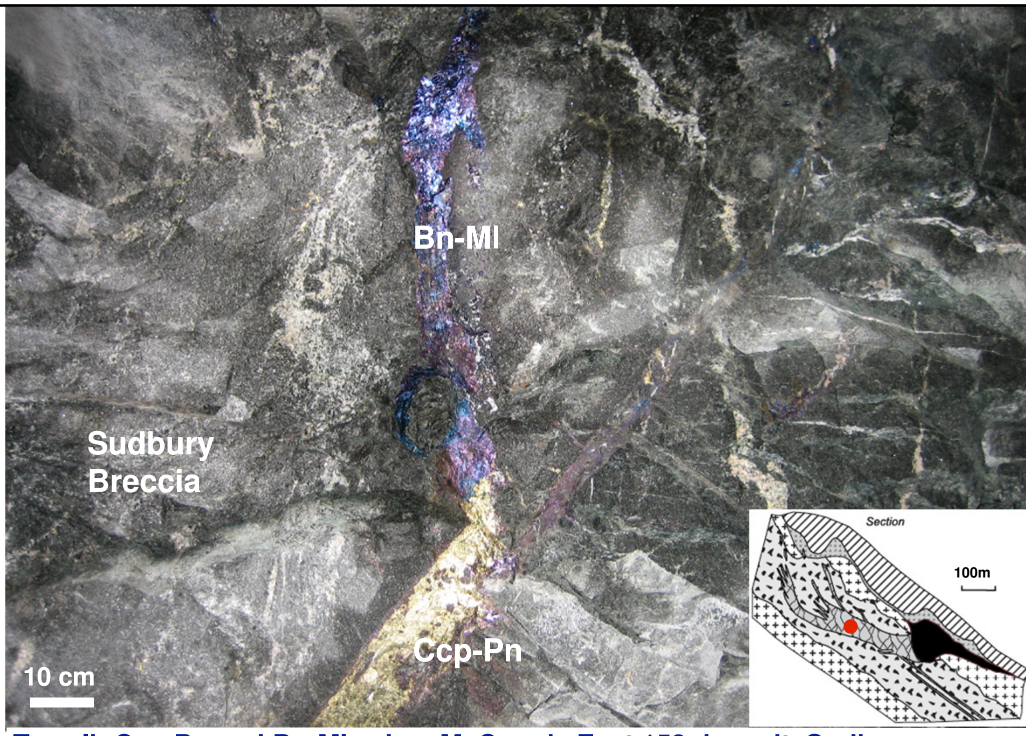
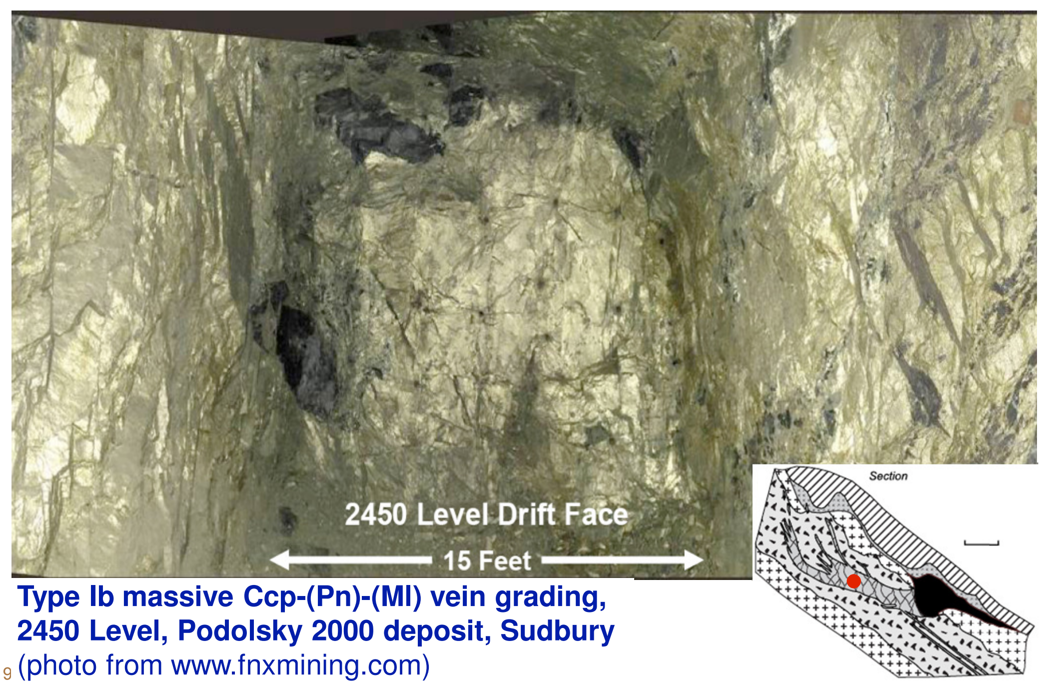
Type Ib



Type Ib Ccp-Pn and Bn-Ml veins, McCreedy East 153 deposit, Sudbury

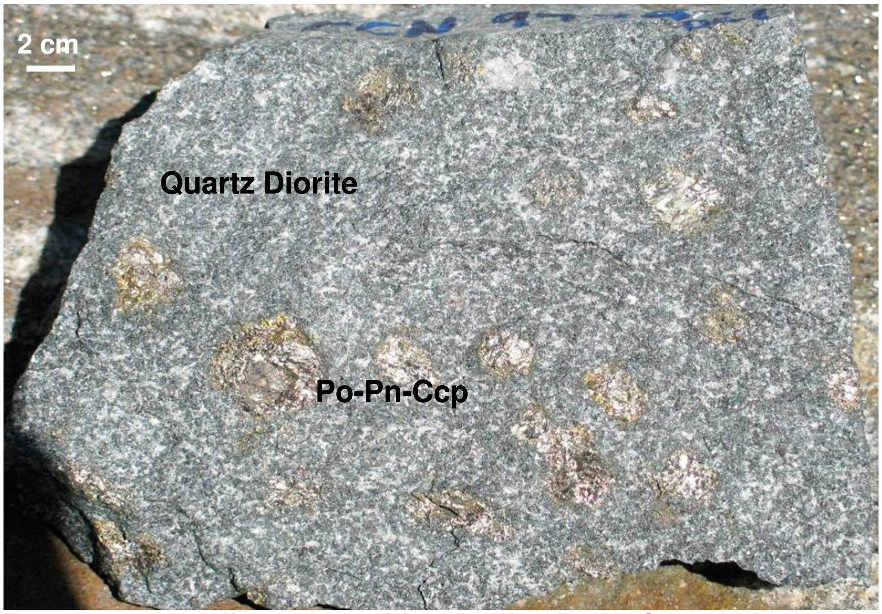
Type 1b

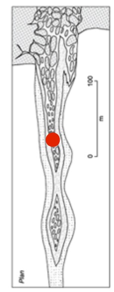
20-25% Cu, 1-2% Ni, 0.25-0.75 opt Pt+Pd+Au



Type Ib massive Ccp-(Pn)-(Ml) vein grading, 2450 Level, Podolsky 2000 deposit, Sudbury
(photo from www.fnxmining.com)

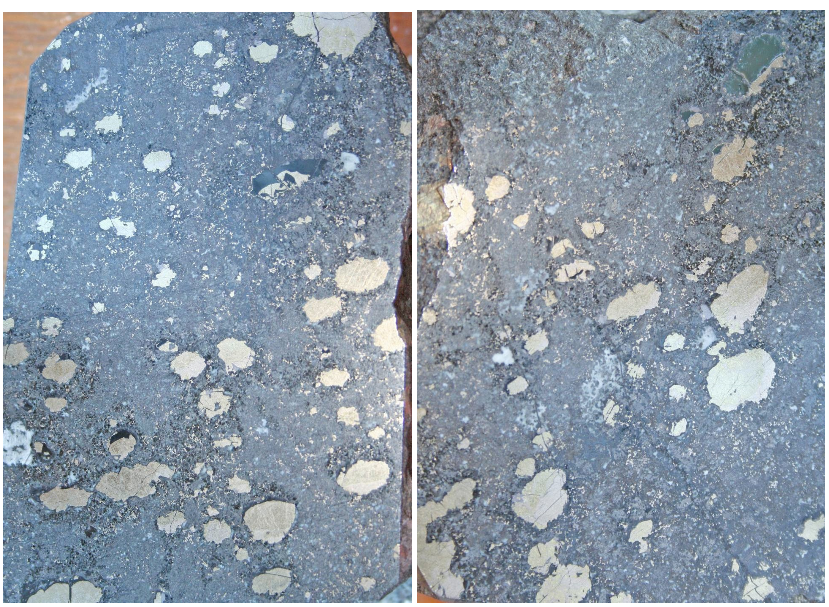
Type IIa





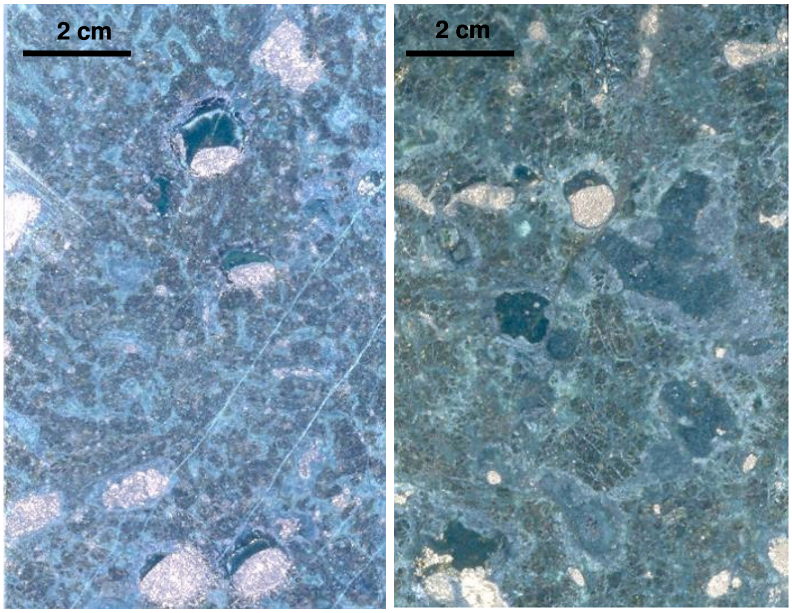
Type IIa coarse disseminated immiscible Fe-Ni-Cu sulfide droplets in quartz diorite, Copper Cliff North Mine, Sudbury

Type IIa



Segregation vesicles and sulfide globules in varitextured “taxitic” gabbro, Bear’s Brook Open Pit, Norilsk I Mine

Type IIa



Coarse (ave. ~2 cm) **Fe-Ni-Cu-(PGE) sulfide-filled segregation vesicles, Black Swan, Western Australia** (Dowling et al. 2004 *Min Dep*)

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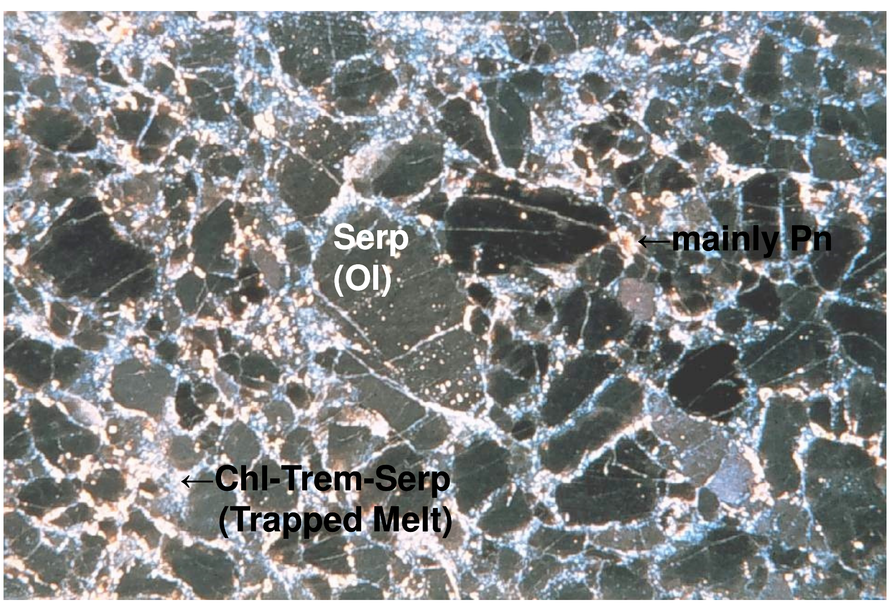
Type IIb



Fine disseminated Fe-Ni-Cu-(PGE) sulfides in serpentinized mesocumulate peridotite, Mt. Keith, Western Australia

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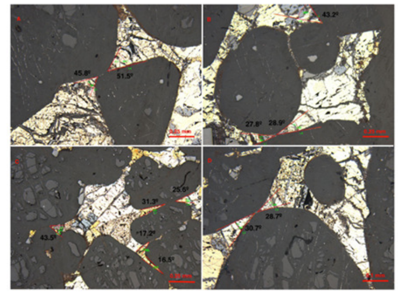
Type IIc



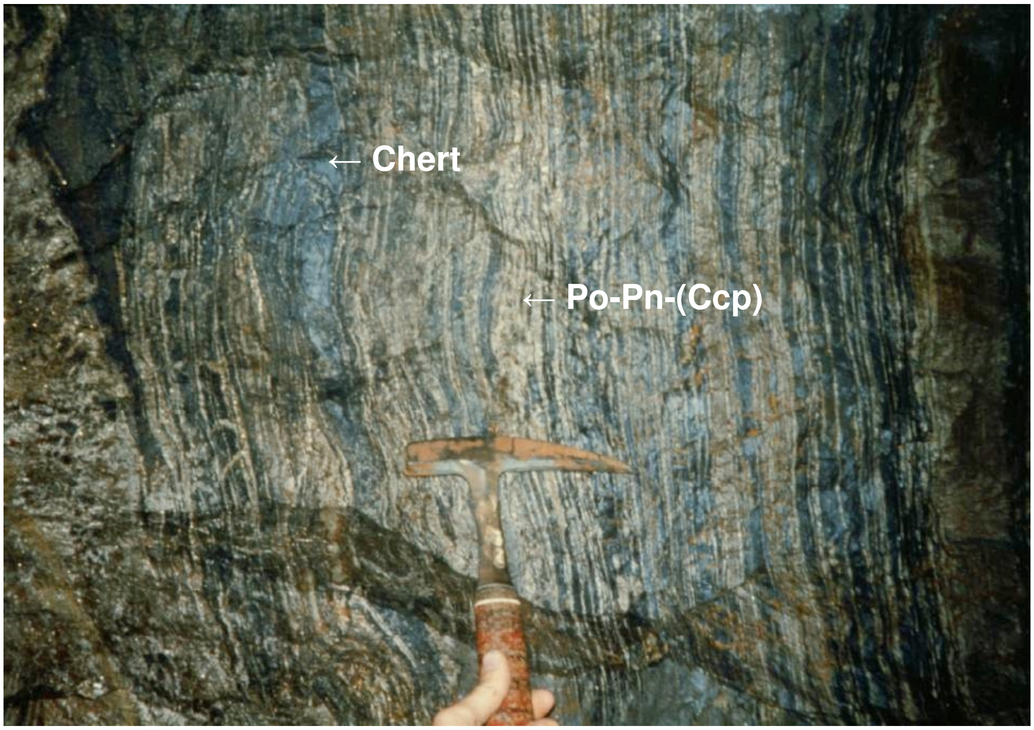
Small dihedral angles (as low as 14°) **indicate that sulfide wetted olivine and implies high fO_2** (Tonnelier 2010 PhD thesis)

PDAC – 02 Mar 2019 **Net-textured Po-Pn-(Ccp) ore, Jinchuan, China**

Type III

PDAC – 02 Mar 2019 – Lesher **Coarse stratiform disseminated sulfides, Murray Mine discovery site, Sudbury**

Type IV



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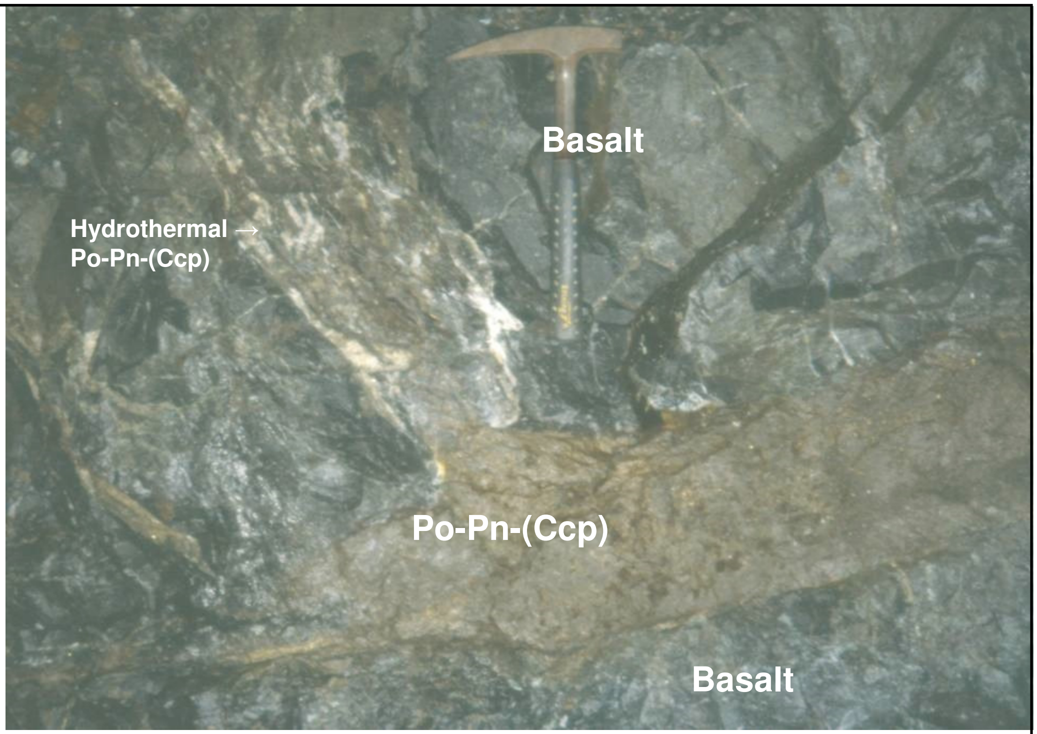
Ni-rich sulfidic metasediment, 204 stope, Jan shoot, Kambalda

Type IV



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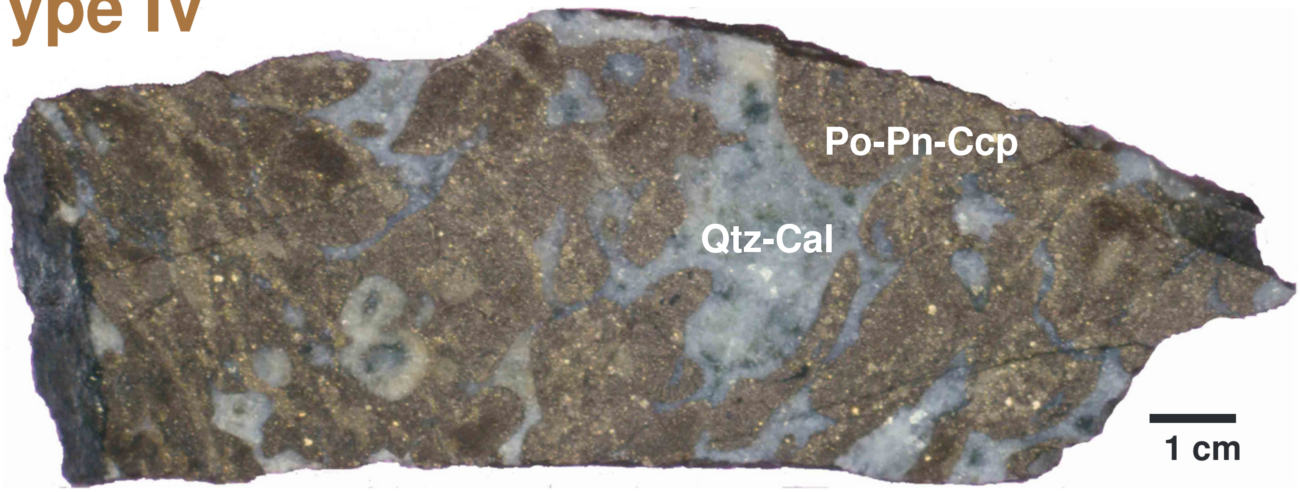
Hydrothermal Fe-Ni-Cu sulfides, Juan East 412/1 stope, Kambalda

Type IV



Hydrothermal Fe-Ni-Cu sulfides (Po-Pn-Ccp) **from sulfide-calcite vein in footwall basalts ~1m below contact ore zone, Juan B 1218 NNW shoot, Kambalda**

Similar in mineralogy to contact ores, except for anomalously low Cr and Ir contents (Lesher and Keays 1984 *IMM*)**.**

Type V

Massive sulfides containing folded fragments of Pipe Formation sulfide facies IF, Thompson T1 mine, 870 level ~2900N

Type V

Burnham 2000

Type V breccia ore containing garnet porphyroblasts rimmed by biotite, Birchtree Mine (Thompson Nickel Belt)

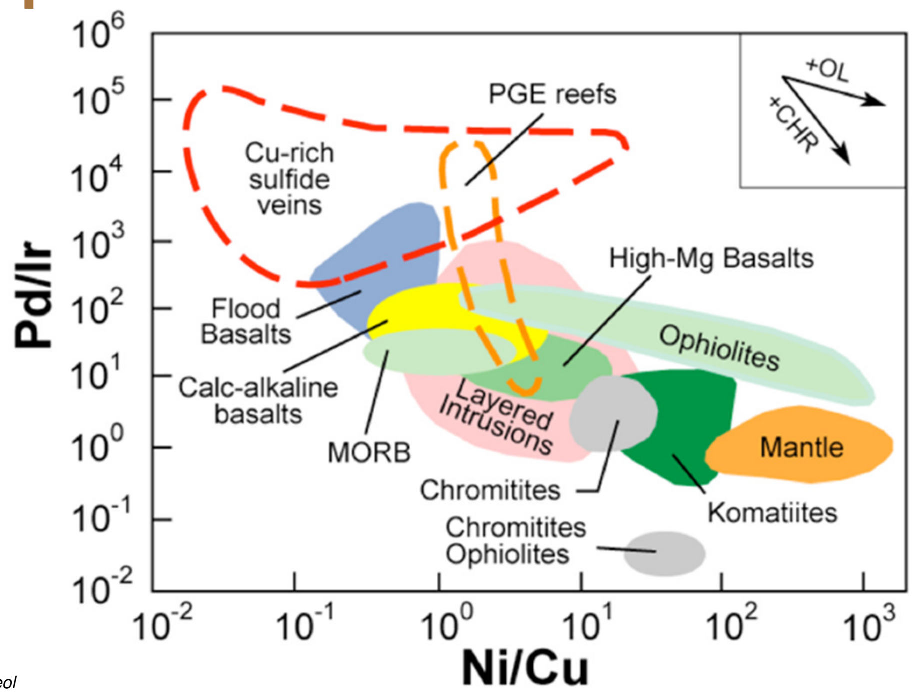
Liwanag 2000

Type V breccia ore containing pegmatite-derived feldspar and quartz inclusions, Thompson Mine

Controls on Ore Composition

- **Composition of magma**
  - **Source composition**
  - **fO_2 and degree of partial melting**
  - **Residue composition**
  - **FC and AFC processes**
- **Sulfide/silicate partition coefficients** (which vary as a function of T, fO_2, and fS_2)
- **Metal content of S source**
- **Silicate:sulfide mass ratio** (R factor)
- **MSS fractionation**
- **Alteration** (e.g., upgrading of Ni in disseminated ores during serpentinization)

Ore Compositions



from Barnes et al. 1985 *Chem Geol*

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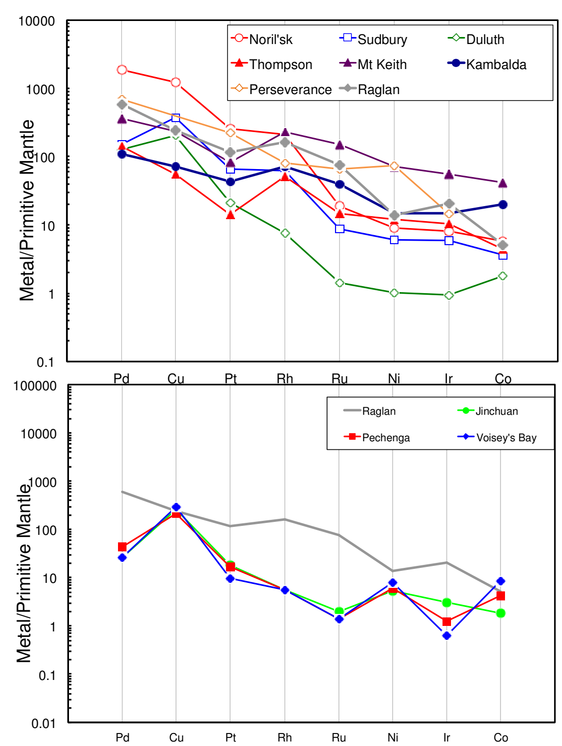
Average Ore Compositions

Most deposits exhibit relatively smooth patterns of decreasing abundance with decreasing compatibility, consistent with derivation from depleted (normal) **asthenospheric mantle**

Jinchuan, Pechenga, and Voisey's Bay are depleted in PGE relative to Ni-Cu-Co

1) Segregation of sulfides in "staging chambers"?

2) Magmas enriched in Ni-Cu-Co relative to PGE?



data from Naldrett 2004 *Springer*

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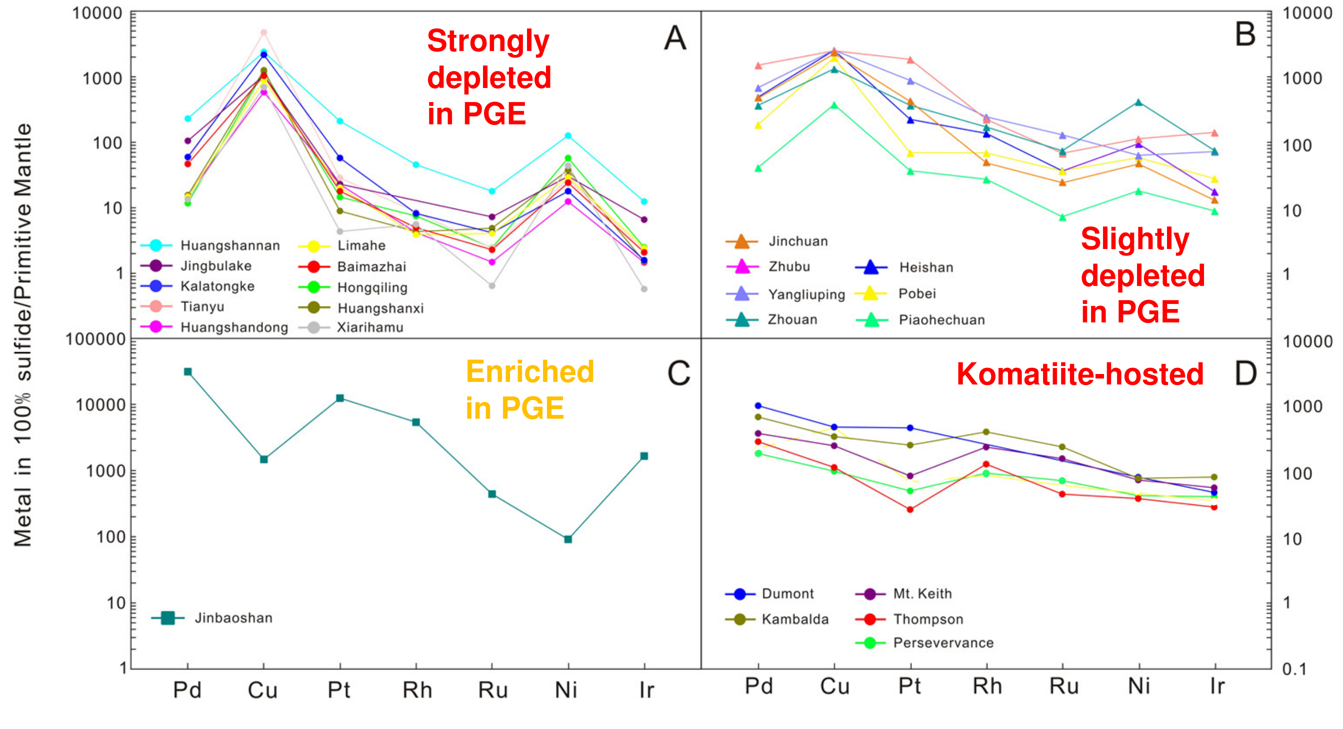

Lu et al. in revision *Ore Geol Rev*

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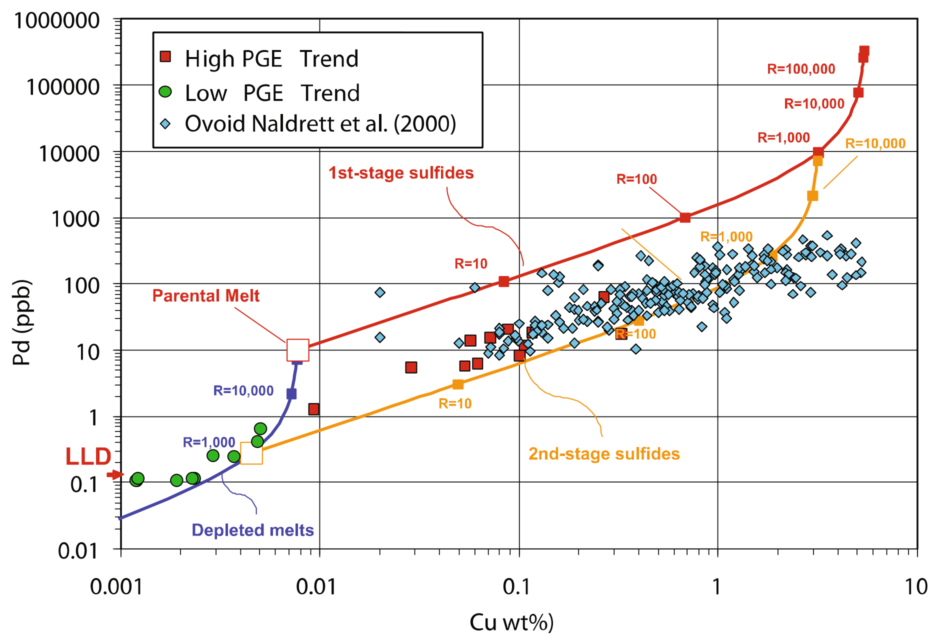
Voisey's Bay

Low Pd contents and Pd-Ni trend of ores have been attributed to two stages of metal depletion (Lightfoot et al. 2012 *Min Dep*)

However, the data do not fit the model very well and a better fit would require R factors up to 10^5, which are unlikely given the massive nature of the sulfides



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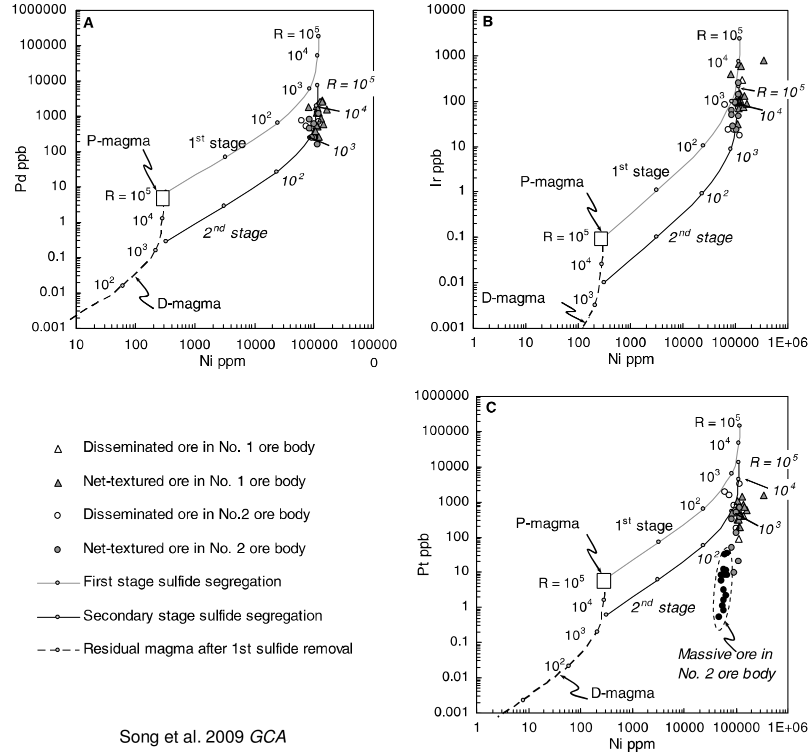
Lightfoot et al. 2012 *Min Dep*

Jinchuan

Low Pd-Pt-Ir contents of the ores have been attributed to two stages of metal depletion (Song et al. 2012 *GCA*).

The data fit the model better, but require very high R factors (up to 10^6 for Ir)**, which are also unlikely in a system containing so much sulfide**



Song et al. 2009 *GCA*

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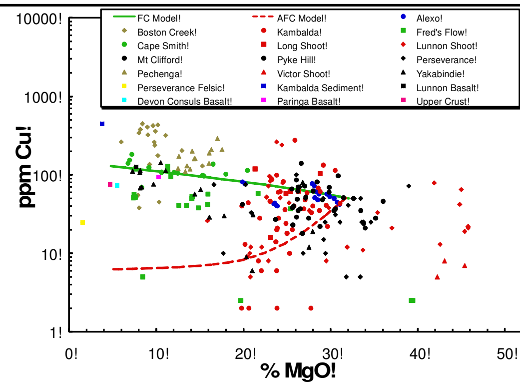
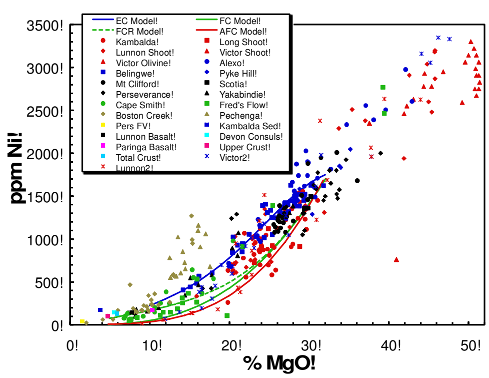
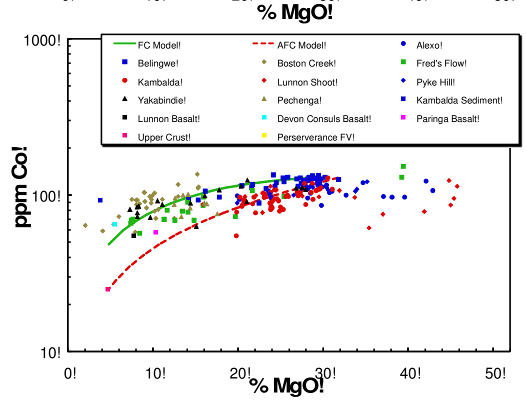
Source Enrichment

Ferropicritic magmas (e.g., Boston Creek and Pechenga in these figures) **are enriched in Ni-Cu-Co relative to komatiitic and tholeiitic magmas**







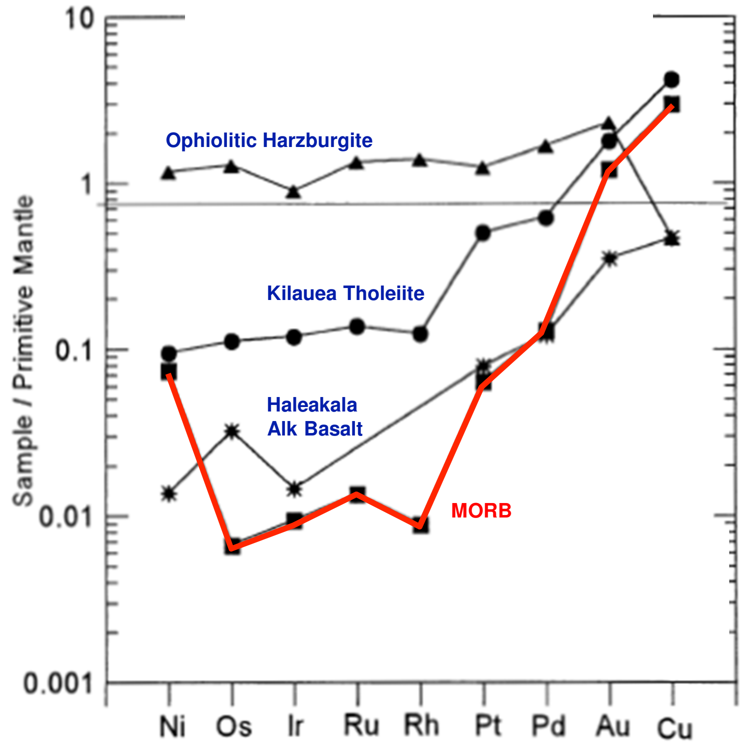
Lesher & Stone 1996 *GAC SC12*

MORB/Ecolgite Signature

MORB is depleted in PGE relative to Ni and Cu

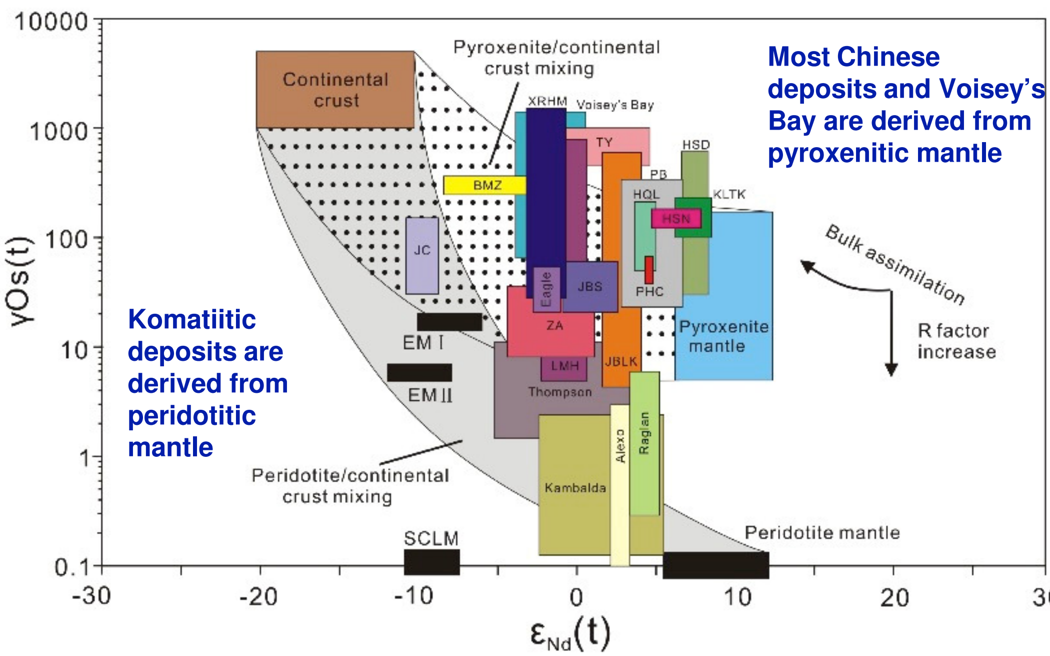
Mixture of asthenospheric mantle with an eclogitic component nicely explains high Ni-Co and low PGE contents of ferropicrites

Plotted in order of decreasing compatibility in this diagram



Crocket 2002 *CIM Spec Vol 54*

γOs vs εNd

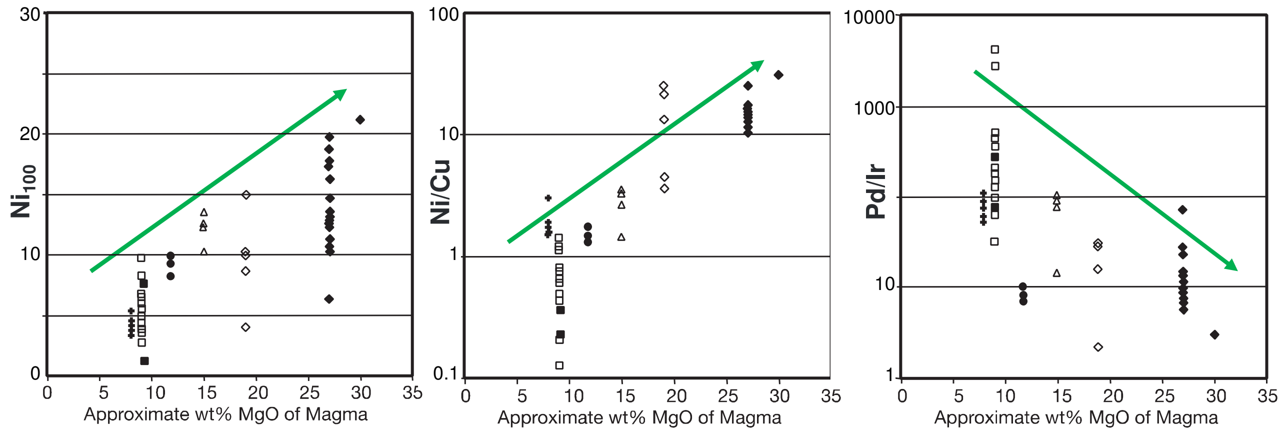


Most Chinese deposits and Voisey's Bay are derived from pyroxenitic mantle

Komatiitic deposits are derived from peridotitic mantle

Lu et al. *in revision* Ore Geol Rev

Ore Tenor vs. Mg in Magma



Naldrett 2010 *Econ Geol*

MERC

Metal Contents of Magmas

	Ni (ppm)	**Cu** (ppm)	**Pd** (ppb)	**Pt** (ppb)	**Ir** (ppb)	**Au** (ppb)
High-Mg Komatiite	1700	50	7.5	-	1.1	-
Low-Mg Komatiite	1246	64	10.5	10.5	1.7	2.9
Komatiitic Basalt	318	101	15.8	11.8	0.49	4.7
Ocean Island Basalt	370	119	4.6	4.3	0.28	2.7
Continental Flood Basalt	85	152	8.8	6.2	0.08	2.5
Island Arc Basalt	92	61	3	1.8	0.25	0.79
Ferropicrite	1100	240	4	4	0.2	2
MORB	144	88	0.46	0.41	0.03	1.2
Crustal Impact Melt	61	59	3.85	4.01	0.21	-

Metal contents of magmas vary widely, but even a crustal impact melt can form a major deposit (e.g., Sudbury)

low PGE-Au (Island Arc Basalt)

high Ni-Cu, low PGE (Ferropicrite)

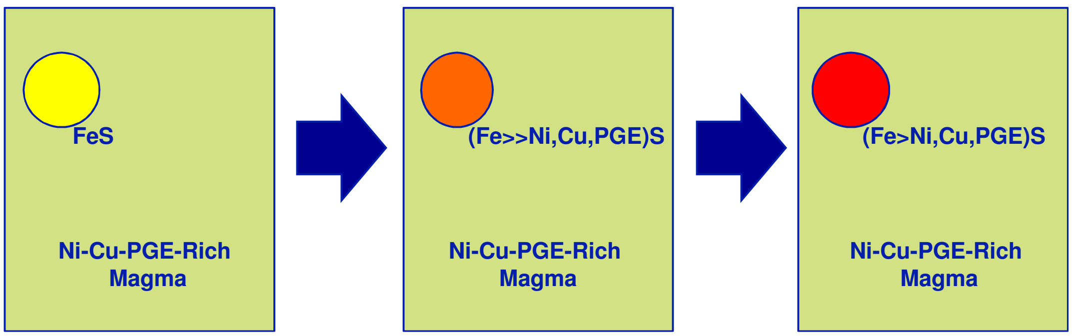
v low PGE (MORB)

low Ni-Cu (Crustal Impact Melt)

Sources: High-Mg Komatiite: Lesher & Campbell 1993 *Econ Geol*; Crustal Impact Melt: Keays & Lightfoot 2004 *Min Dep*, Ferropicrite: Barnes et al. 2001 *Can Min;* Others: Crocket 2002 *CIM v54*

Upgrading of Sulfide Xenomelt

Conversion of barren FeS xenomelt into (Fe,Ni,Cu,PGE)S by reaction with Ni-Cu-PGE-rich magma:



Magma: Sulfide Mass Ratio (R)

High R

High PGE sulfide melt

High PGE silicate melt

Metals with very high Ds partition strongly into sulfide melt, but a **low abundance of sulfide** does *not* deplete silicate magma significantly, resulting in **high** metal abundances in final silicate magma and sulfide

Low R

Low PGE sulfide melt

Low PGE silicate melt

Metals with very high Ds partition strongly into sulfide melt, but a **high abundance of sulfide** depletes the silicate magma significantly, resulting in **low** metal abundances in final silicate magma and sulfide

Final metal content of sulfide (Y^f) **and final amount of metal in the magma** (X^f) **depend on the initial metal content of the sulfide** (Y^o), **the initial amount of metal in the magma** (X^o), **the sulfide/silicate partition coefficient** ($D^{Sul/Sil}$), **and the silicate/sulfide mass ratio** (R):

Metal Mass Balance

sulfide/oxide derived *internally*
(Campbell & Naldrett 1979 *Econ Geol*)

$$Y_i^f = \frac{X_i^o D_i^{Sul/Sil}(R+1)}{R+D_i^{Sul/Sil}} \quad [1]$$

sulfide/oxide derived *externally* and $Y_i^o = 0$
(Naldrett 1981 *Econ Geol*)

$$Y_i^f = \frac{X_i^o D_i^{Sul/Sil} R}{R+D_i^{Sul/Sil}} \quad [2]$$

sulfide/oxide derived *externally* and $Y_i^o > 0$
(Lesher & Burnham 1999 *GAC*, 2001 *Can Min*)

$$Y_i^f = \frac{(X_i^o R + Y_i^o) D_i^{Sul/Sil}}{R+D_i^{Sul/Sil}} \quad [3]$$

dynamic upgrading
(Brügmann et al. 1993 GCA)

$$Y_i^f = X_i^o\left\{D-\left[(D-1) * e^{-(1/D*N)}\right]\right\} \quad [4]$$

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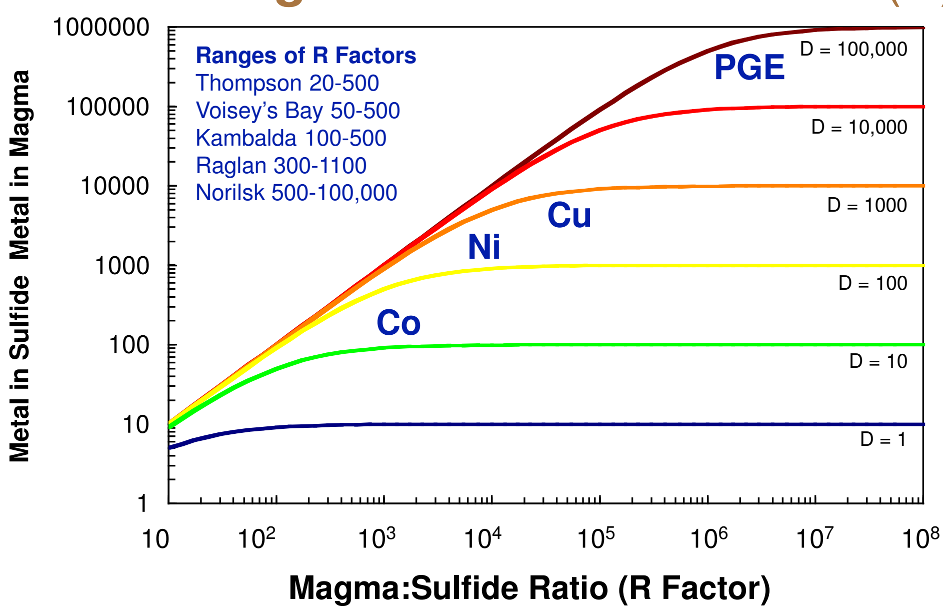
Effect of Magma:Sulfide Mass Ratio (R)



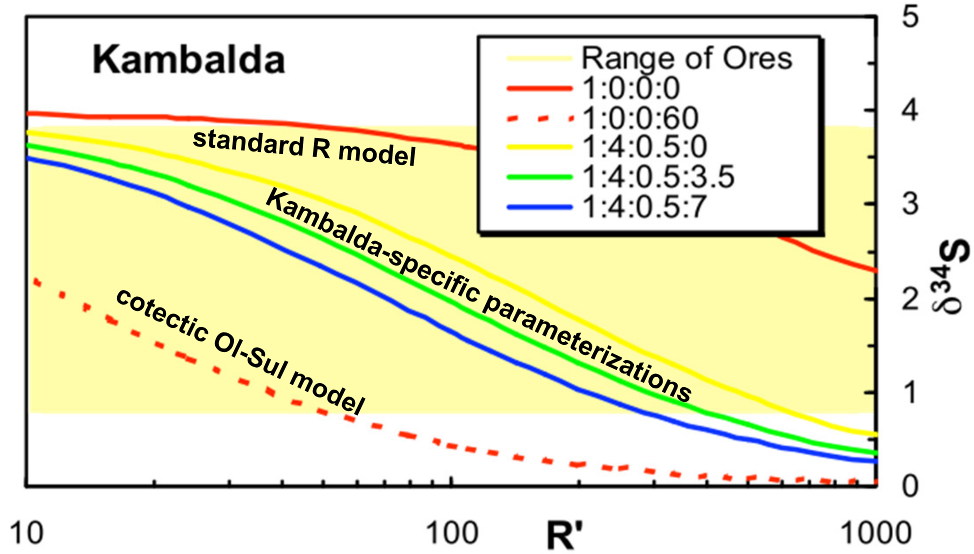
Elements with high Ds (PGE and Au) **achieve maximum abundance only at high R**

Elements with intermediate Ds (Cu and Ni) **achieve maximum abundance at intermediate R**

Elements with low Ds (Co) **achieve maximum abundance at low R**

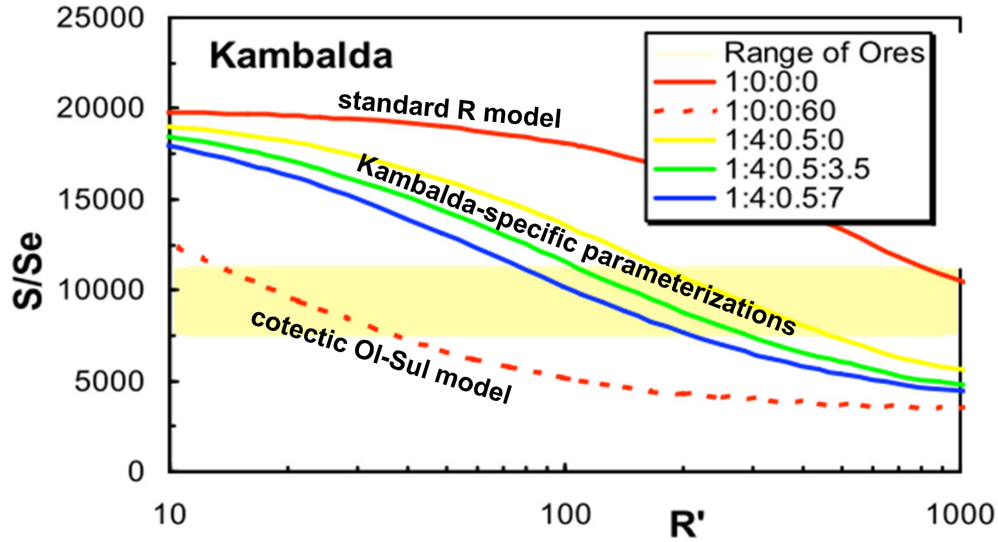
Elements achieve maximum abundances only if R 10D, which means that when R 10D, the abundances are strongly controlled by the R factor (magma:sulfide ratio).

S Isotope Mixing



Modeled S isotopic variations in Kambalda ores for different proportions of sulfide xenomelt : silicate xenomelt : residue : olivine as a function of mass fraction of silicate magma (from Lesher & Burnham 2001 *Can Min*)**. S isotopic data from Donnelly et al.** (1978 DSIR) **and Seccombe et al.** (1981 Econ Geol).

S/Se Mixing



Modeled S/Se variations in Kambalda ores for different proportions of sulfide xenomelt : silicate xenomelt : residue : olivine as a function of mass fraction of silicate magma (from Lesher & Burnham 2001 *Can Min*)**. S/Se isotopic data from Groves et al.** (1979 *Can Min*)**.**

Mechanisms to Achieve High R

- **Transport small immiscible droplets** (with high surface/volume ratios) **in the magma**
- **Transport segregated magma and sulfide, but maintain a turbulent interface** (Lesher & Cambell 1993 *Econ Geol*)
- **Flow magma through a "filter bed" of sulfides that are wetting inclusions and/or olivine** (Lesher 2017 *Ore Geol Rev*)
- **Redissolve some of the sulfide** (Lesher & Campbell 1993 *Econ Geol*; Lesher & Burnham 2001 *Can Min*; Kerr & Leitch 2005 *Econ Geol*)

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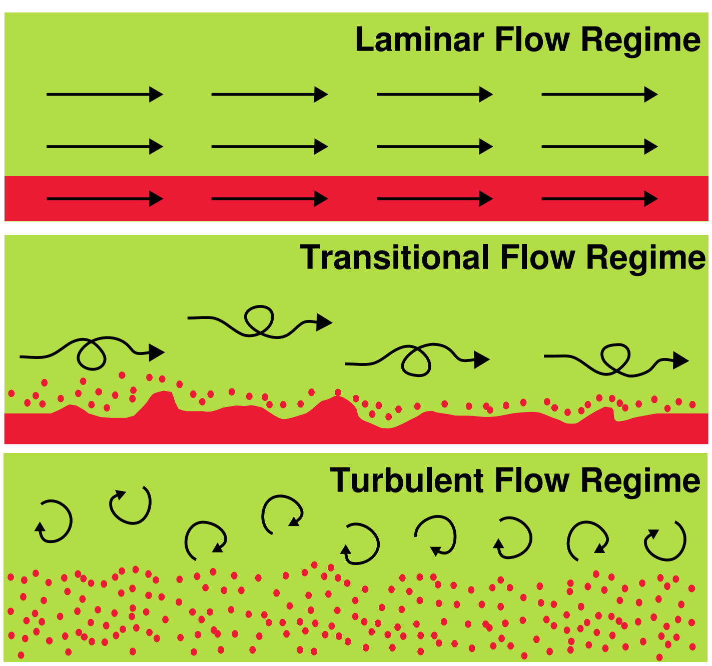
Fluid Dynamics



Planar interface, low surface area, low R factor

Scalloped contact with some entrained sulfides, intermediate surface area, intermediate R factor

Entrained sulfides, high surface area, high R factor

Lesher in press *CJES*

Decoupling with Variable R

Extra Low R *Crustal S, Se, Pb, Sr, Nd, & Os* *Very strong depletion PGE>Cu>Ni>>Co* Very high tonnage, very low tenor, Co>>Ni>Cu>PGE	**High R** *Crustal S & Se, mantle-like Pb, Sr, Nd, & Os* *Minor PGE depletion* Low tonnage, high tenor, Co=Ni=Cu>PGE
Very Low R *Crustal S, Se, Pb, Sr, & Nd, mantle-like Os* *Strong depletion PGE>Cu>>Ni>Co* High tonnage, low tenor, Co>Ni>>Cu>PGE	**Very High R** *Mantle-like S, Se, Pb, Sr, Nd, & Os* *Negligible chalcophile element depletion* Very low tonnage, very high tenor, Co=Ni=Cu=PGE
Low R *Crustal S, Se, & Pb, mantle-like Sr, Nd, & Os* *Moderate depletion PGE>>Cu>Ni>Co* Moderate tonnage, moderate tenor, Co>Ni>Cu>>PGE	**Extremely High R** *Mantle-like S, Se, Pb, Sr, Nd, & Os* *No metal depletion in magma* *No tonnage*

Lesher et al. 2001 *Can Min*

Fractional Crystallization

- **MSS concentrates Co-Os-Ir-Ru-Rh, leaving residual sulfide melt enriched in Cu-Pd-Pt-Au-Ag-Pb-As-Sb-Bi-Te-Se**
- **Extrusive ores** (e.g., Alexo, Kambalda, Raglan) **cool too quickly to fractionate much**
- **Intrusive ores with low Cu-PPGE contents** (e.g., Thompson) **do not fractionate much**
- **Disseminated mineralization even if high Cu** (e.g., Duluth, offset ores at Sudbury) **does not fractionate except on a small scale**
- **Intrusive net-textured ores** (e.g., Jinchuan) **may fractionate significantly**
- **Cu-rich massive ores** (e.g., Norilsk, Sudbury) **that cooled slowly fractionate Fe-Co-IPGE-rich MSS from Cu-PPGE-Au-As-Sb-Bi-Ag-Pb-rich sulfide melt**

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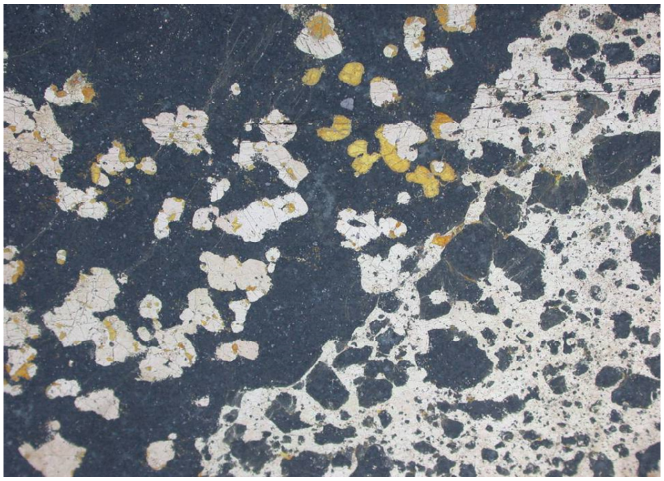
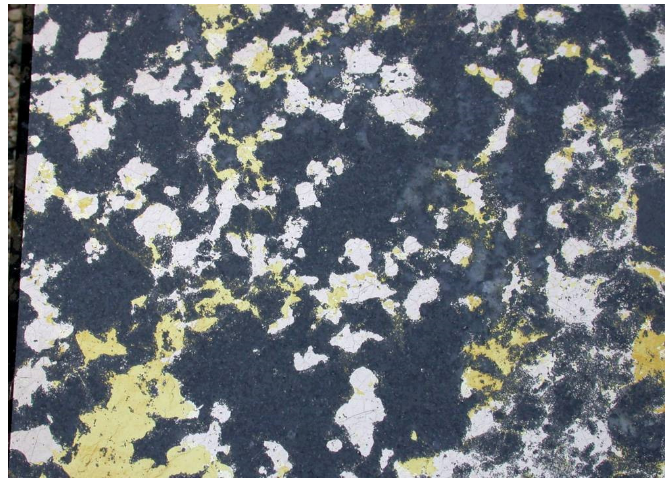
Frood (Sudbury)





Contact between blebby disseminated Po-Pn-Ccp and inclusion semi-massive ore

Disseminated ore showing segregation of Ccp (residual sulfide melt) **from Po-Pn** (MSS)

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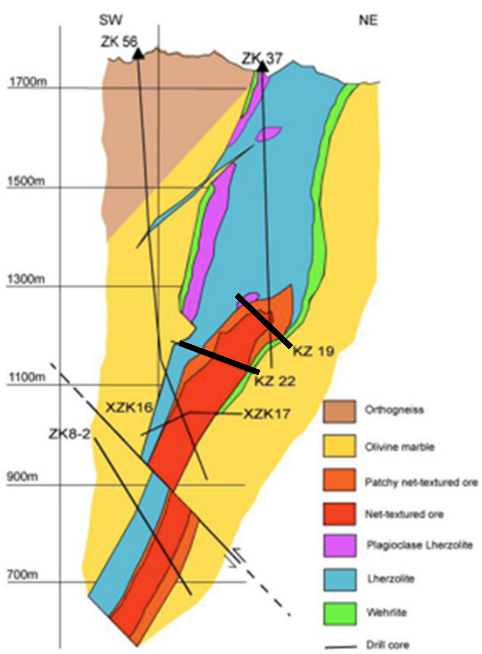
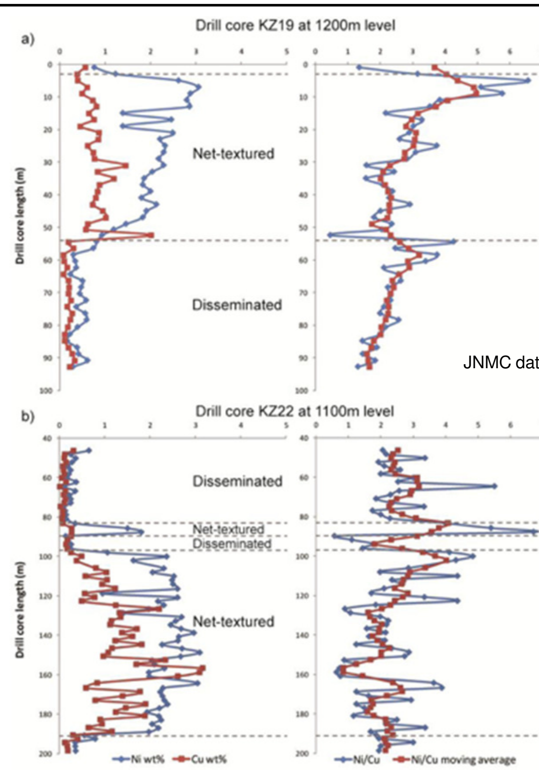
Jinchuan Ni/Cu





Tonnelier 2010 PhD Thesis

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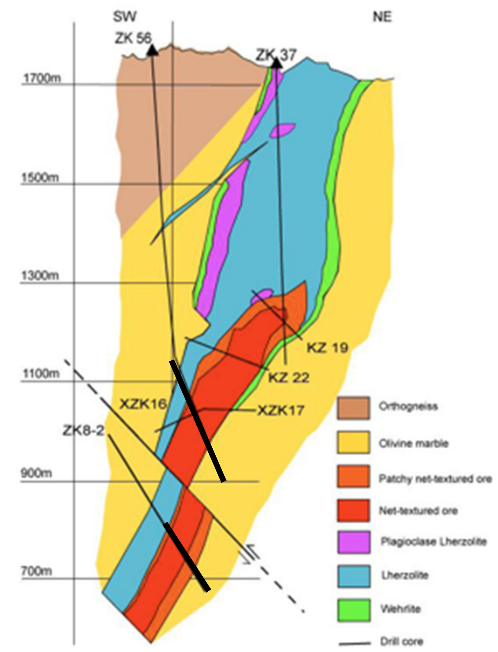
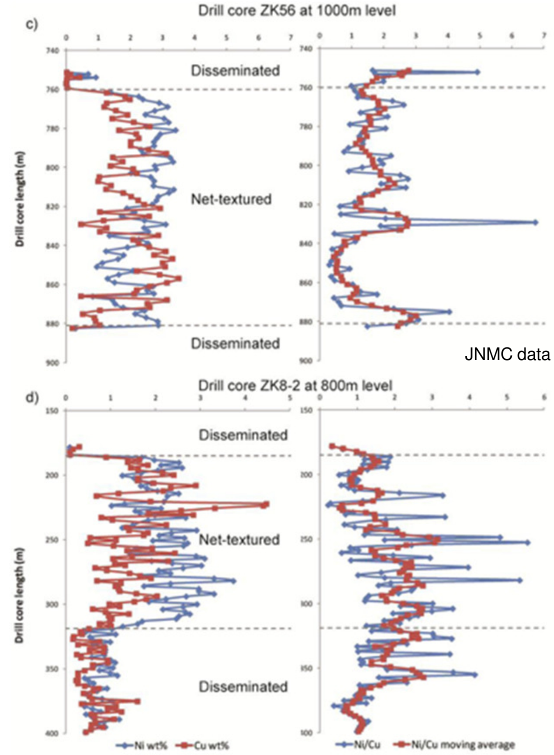
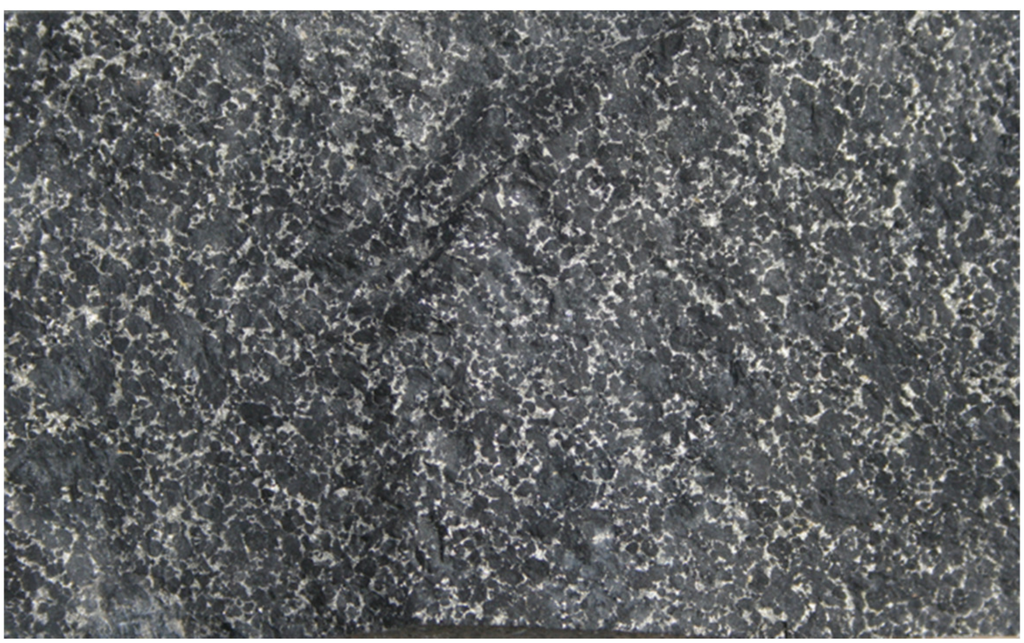
Jinchuan Ni/Cu



Tonnelier 2010 PhD Thesis

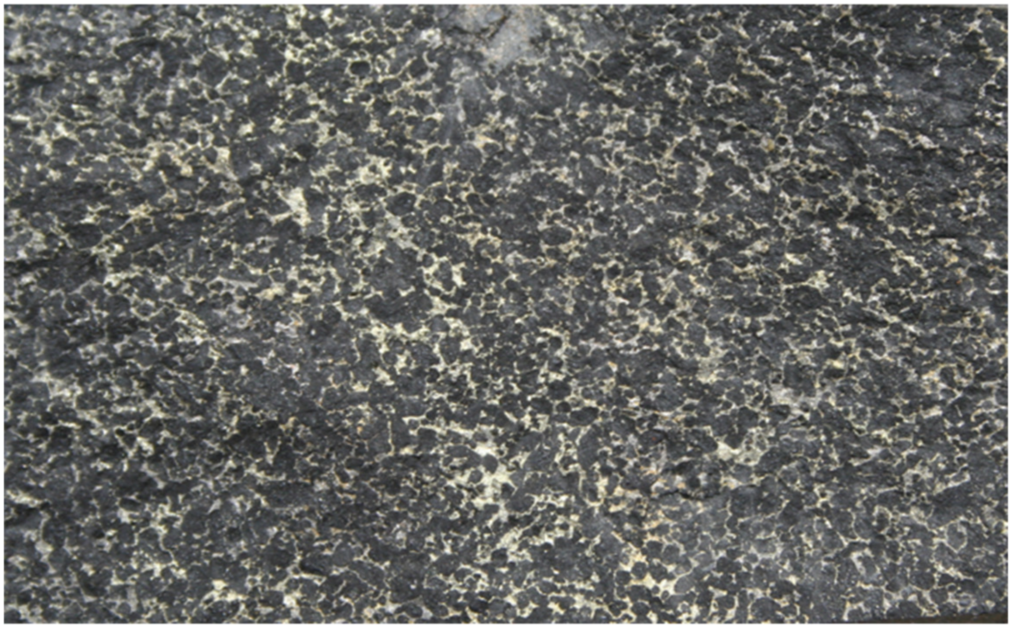


Cu-Poor Net-Textured Ore



Net-textured Po-Pn-(Ccp) ore, DDH Z8-2/248.0m, Jinchuan (5.4 cm NX core)

Cu-Rich Net-Textured Ore



Net-textured Ccp-(Po)-(Pn) ore, DDH ZK8-2/296.9m, Jinchuan (5.4 cm NX core)

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Ore Genesis

- **Almost all authorities agree on the need for crustal S** (e.g., Lesher et al. 1984 *IMM*; Ripley 1986 *Springer*; Arndt et al. and S-J Barnes & Lightfoot 2005 *Econ Geol 100th Anniv Vol*; Keays & Lightfoot 2010 *Min Dep*; Naldrett 2010 *Econ Geol*; Ripley & Li *2013 Min Dep*; SJ Barnes et al. 2016 *Ore Geol Rev*)
- **However, contrary to the wording in many of those papers** (e.g., S-J Barnes and Lightfoot 2005 Econ Geol 100th Anniv Vol; Keays & Lightfoot 2010 *Min Dep*; Naldrett 2010 *Econ Geol*; SJ Barnes et al. 2016 *Ore Geol Rev*) **high-grade magmatic Ni-Cu-(PGE) deposits do not form by "contamination" or "assimilation" of S from country rocks**
    - **Felsification does not produce enough sulfide and unless superheated, contamination is almost always accompanied by significant amounts of crystallization** (lowering Ni-Co contents and inhibiting segregation of sulfides)
    - **Significant amounts of sulfide cannot be dissolved** (the solubility of S is too low) **and reprecipitated** (once dissolved, S can be only incrementally extracted)

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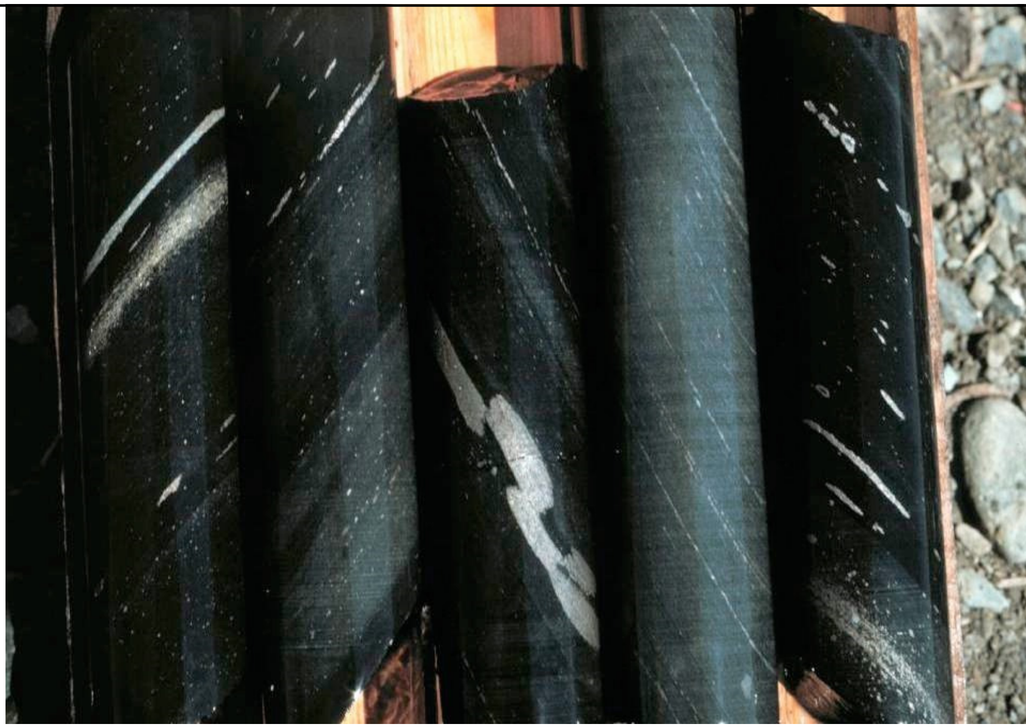
Model

- **Most high-grade magmatic Ni-Cu-(PGE) deposits form by thermomechanical erosion of country rocks** (Lesher et al. 1984 *IMM;* Lesher & Groves 1986 *Springer*) **producing** (Lesher and Campbell 1993 *Econ Geol*; Lesher 2017 *Ore Geol Rev*)**:**
  - **immiscible sulfide xenomelts**
  - **variably miscible silicate xenomelts and xenovolatiles**
  - **xenoliths and/or xenocrysts**
  - **residues/skarns**
- **Sulfide xenomelts are then upgraded via reaction with metal-bearing silicate magma** (Campbell & Naldrett 1979 Econ Geol)**, which also affects S-Os** (and also Fe-Ni-Cu-Pt-Pb) **isotopic ratios and S/Se ratios** (Lesher & Stone 1996 *GAC Short Course*; Lesher & Burnham 2001 *Can Min*)

S Sources

- **Most major magmatic sulfide deposits are associated with S-bearing country rocks**
  - **Sulfidic cherts:** Kambalda
  - **Sulfide-facies iron-formations:** Abitibi, Forrestania, Thompson, Windarra, Zimbabwe
  - **Sulfidic pelites:** Duluth, Pechenga, Raglan, Voisey's Bay
  - **"VMS" horizons:** Namew Lake, Alexo
  - **Evaporites:** Norilsk-Talnakh
- **Where the S source is not present locally, it can be constrained by S/Se and S isotopic compositions of the ores** (Os isotopes are often not sensitive enough, but trace metals are sometimes useful)



PDAC – 02 Mar 2019 – Le **Graphitic, sulfidic semi-pelite, DDH 718-5, C2 area, Raglan** MERC

PDAC – 02 Mar 2019 – Lesher **Sulfide facies iron formation, Pipe II pit, Thompson** MERC

Incorporation of anhydrite xenoliths, Norilsk

S Isotopes

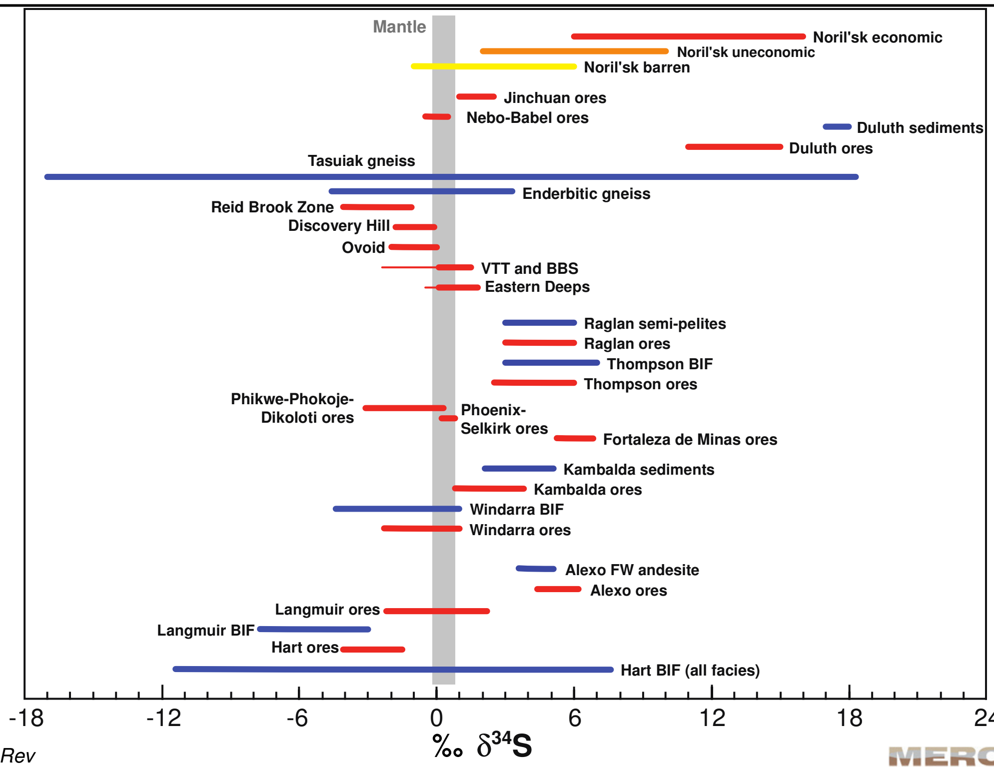
- **S isotopes indicate a crustal source in all high-grade Ni-Cu-PGE deposits** (e.g., Lesher & Groves 1986 *Springer;* Ripley 1986 *Springer*; Lesher & Keays 2002 *CIM*, Keays & Lightfoot 2010 *Min Dep*; Ripley & Li 2013 *Econ Geol*)
- **Potential exceptions include:**
  - **Jinchuan: $\delta^{34}S$ only slightly greater than 0‰,** but crustal source permitted by mass balance calculations
  - **Babel-Nebo: very constant $\delta^{34}S$ ~ 0‰,** but nearby S source has been recently identified (Karykowski et al. 2015 *Econ Geol*)
- **Note that near-zero $\delta^{34}S$ values do not require a mantle source, they only indicate that the source was not fractionated** (crustal rocks range from highly positive to highly negative, depending on the conditions of formation)

S Isotopes

Most are different from mantle S (0.1 ± 0.5 ‰ $\delta^{34}S$)

Variable within a district

Some indicate mixing between mantle S and crustal S (more on this later)



data sources in Lesher 2017 *Ore Geol Rev*

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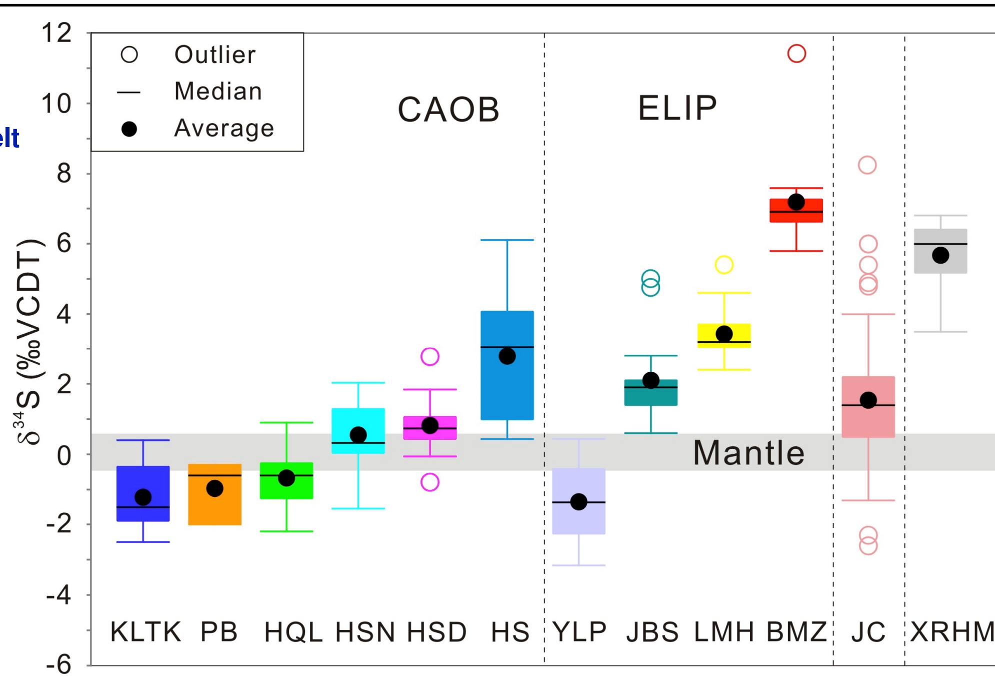
S Isotopes

Central Asian Orogenic Belt
- **KLTK** Kalatongke
- **PB** Pobei
- **HQL** Hongqiling
- **HSN** Huangshannan
- **HSD** Huangshandong
- **HS** Heishan

Emeishan LIP
- **YLP** Yangliuping
- **JBS** Jinbaoshan
- **LMH** Limahe
- **BMZ** Baimazhai

Rodina Breakup
- **JC** Jinchuan
- **XR** Xiarihamu



Lu et al. in revision *Ore Geol Rev*

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Geological Evidence for Local Thermomechanical Erosion

- **Cross-cutting relationships**: Alexo, Duluth, Kambalda, Perseverance, Raglan, Norilsk-Talnakh, Silver Swan, Sothman, Sudbury, Windarra
- **Silicate xenomelts**: Alexo, Kambalda, Silver Swan
- **Sulfide xenomelts**: all deposits!
- **Xenoliths of Country Rocks (and no Lower-Middle Crustal Rocks)**: Digger Rocks, Duluth, Forrestania, Silver Swan, Sudbury, Voisey's Bay
- **Residues/skarns**: Digger Rocks, Duluth, Forrestania, Kambalda, Norilsk-Talnakh, Thompson, Voisey's Bay
- **Varitextured (taxitic) gabbros**: Duluth, Norilsk

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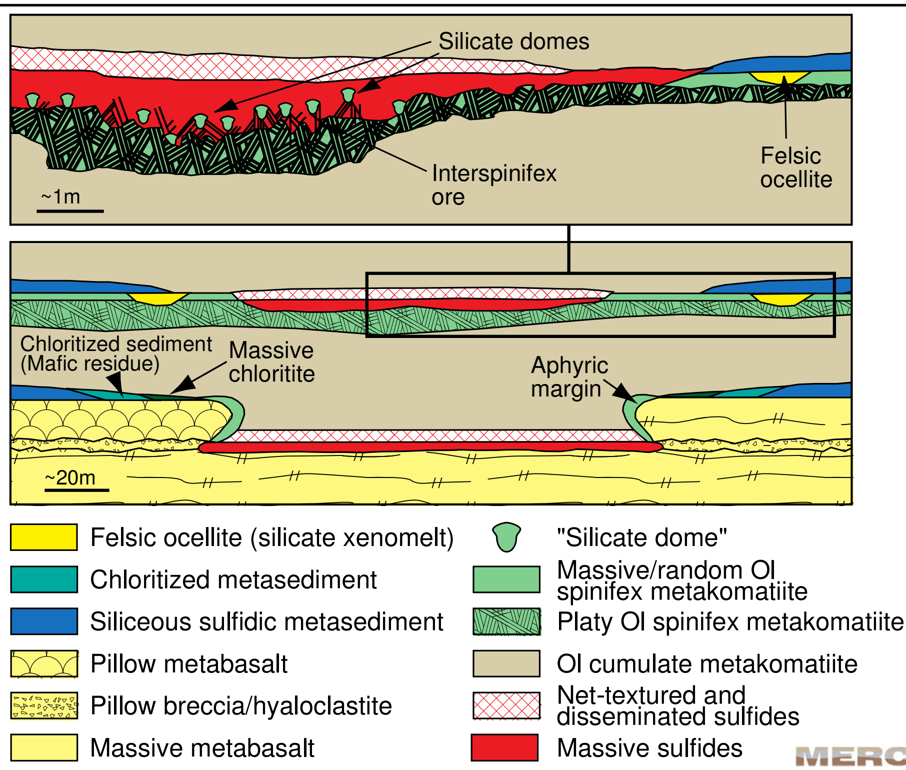
Schematic cross-section of a typical Kambalda ore shoot prior to deformation summarizing some of the field evidence for thermo-mechanical erosion of interflow sediments:

1) **Sediments grade from chloritized residues to absent in ore environment**
2) **Ores are locally transgressive to underlying lithologies** (komatiite or basalt)
3) **Silicate xenomelts** (felsic ocellite)



Lesher 2017 *Ore Geol Rev as adapted from Lesher et al. 1984 IMM; Groves et al., 1986 Nature; Frost and Groves 1989 IMM*

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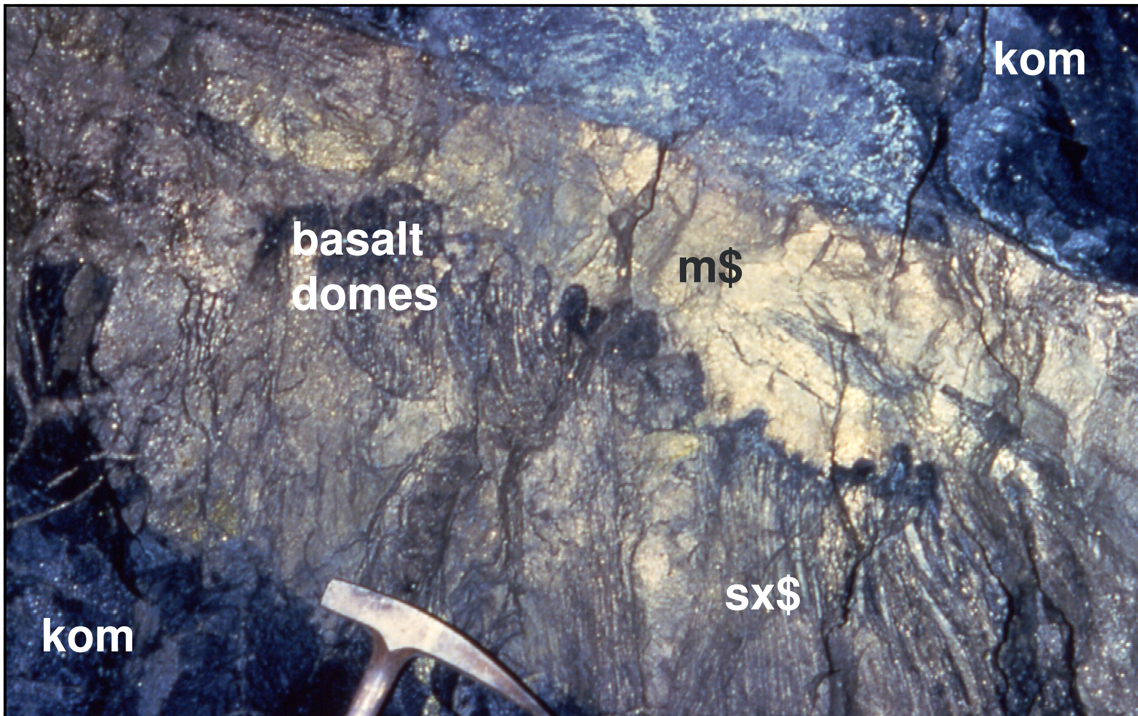
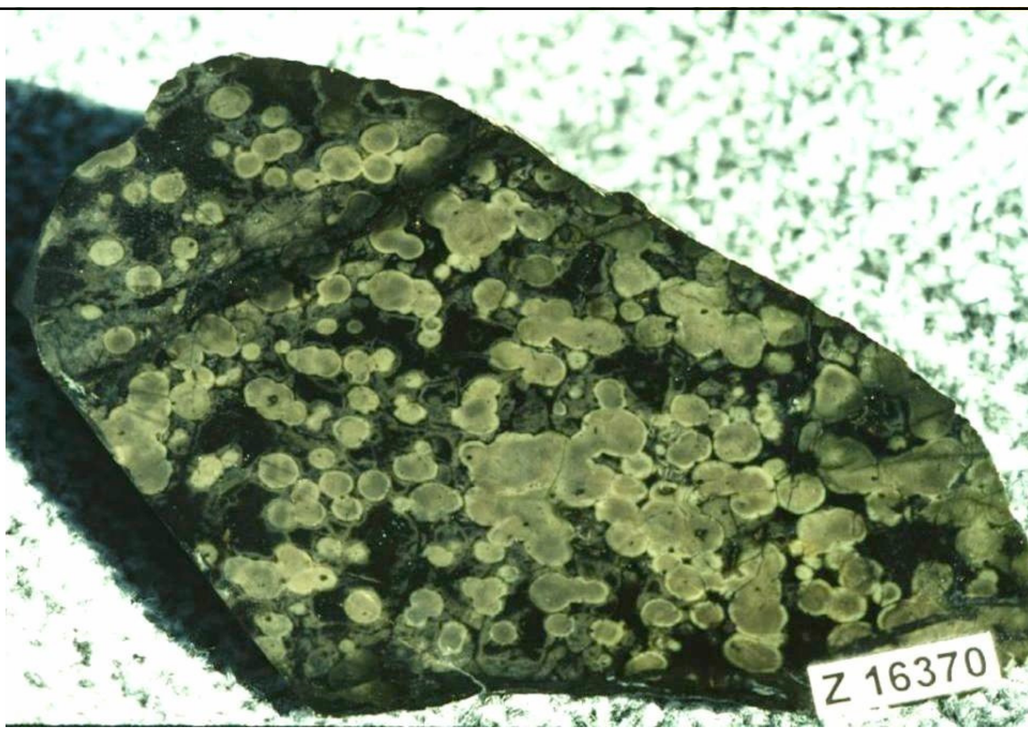
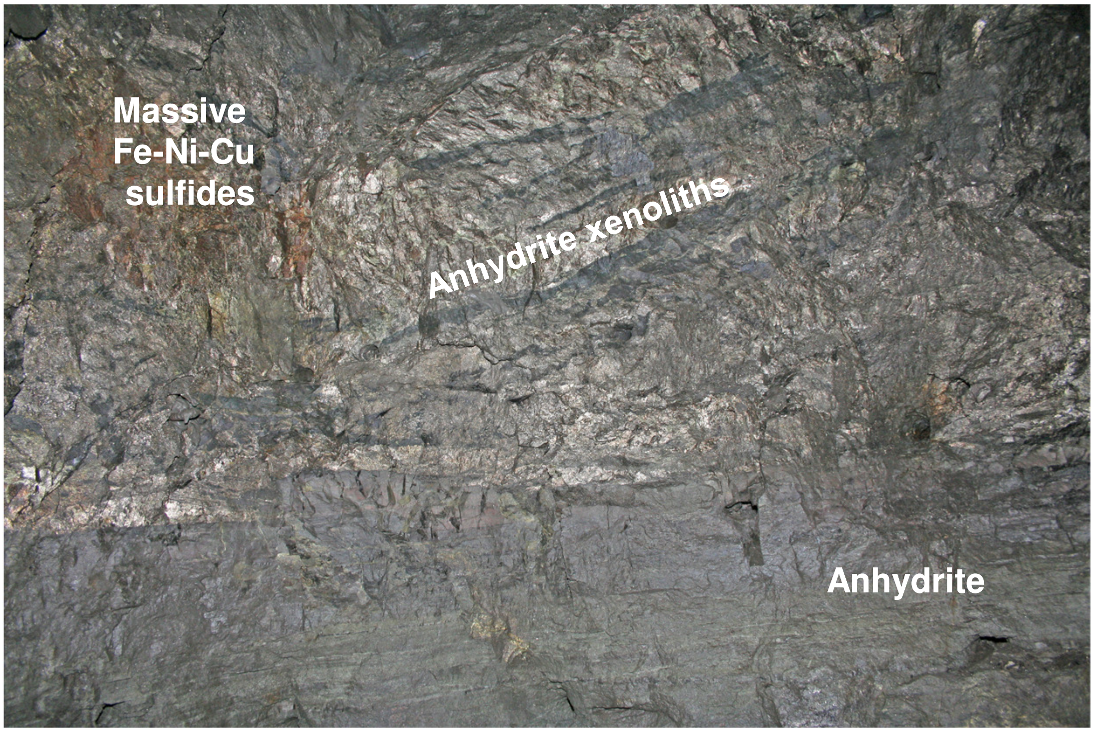


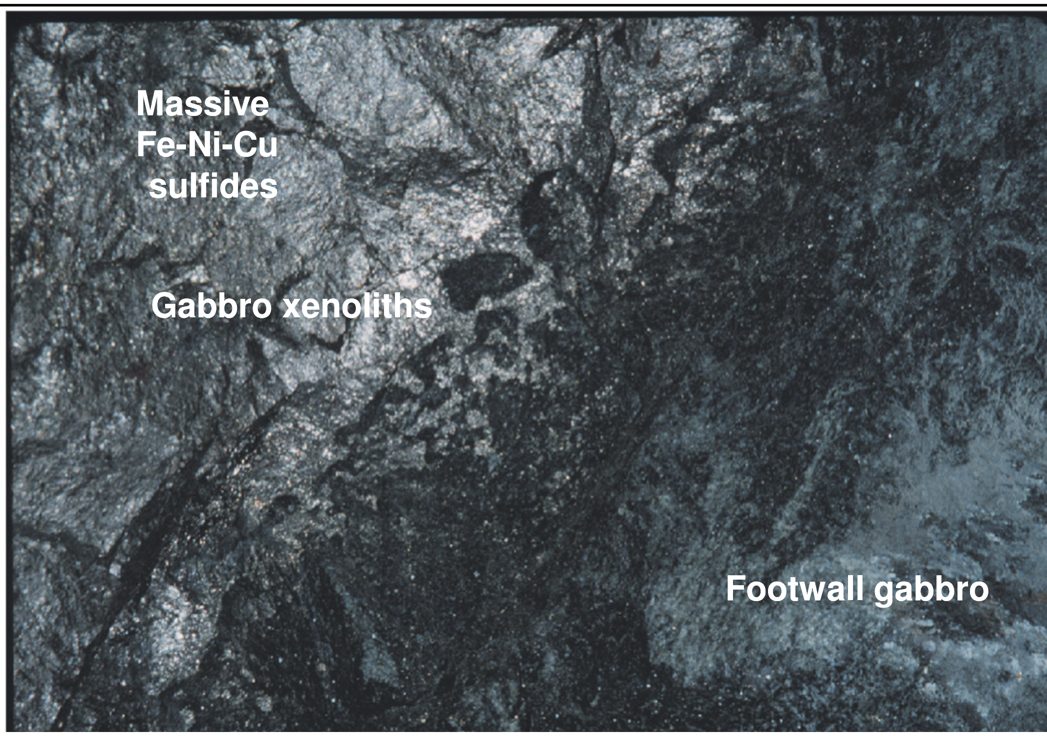
Erosional sulfide/komatiite contact, 682 Stope, Lunnon Shoot, Kambalda



Felsic ocellite (silicate xenomelt) **#Z16370, Kambalda, WA**



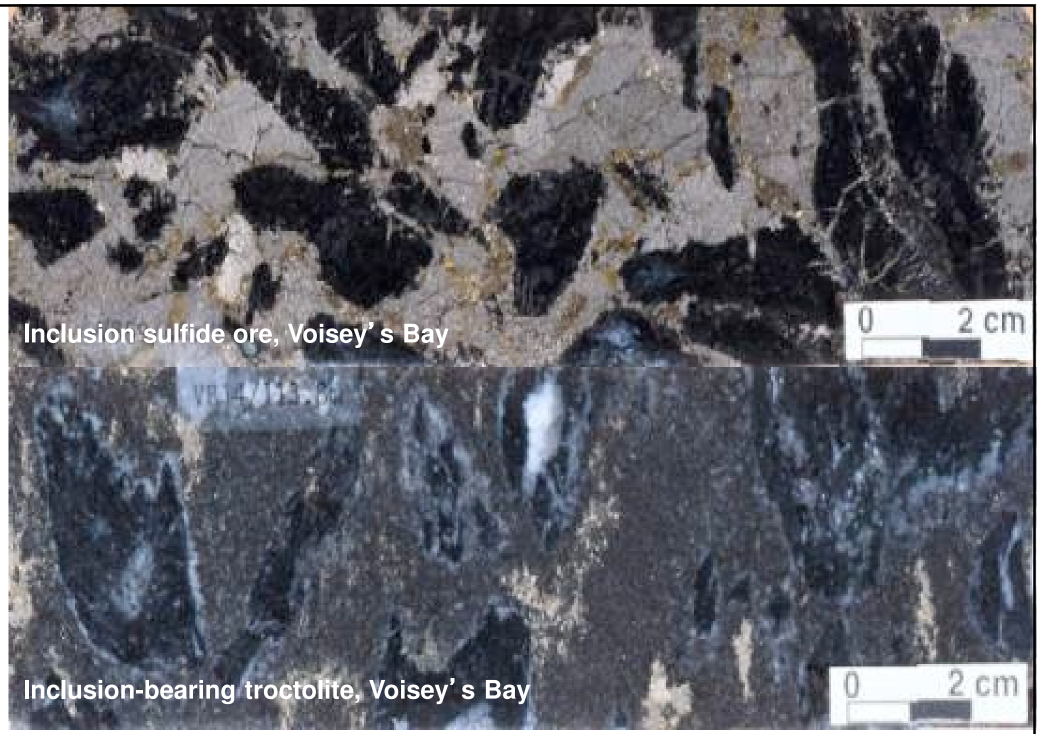
Anyhdrite xenoliths in massive sulfides, Norilsk



Gabbro xenoliths in massive sulfides, Katinniq C-1400-4 stope (Lesher 2007 *GAC-MDD Spec Publ 5*)

Voisey's Bay

Inclusions of local Tasiuyak gneiss



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photos by C. Li

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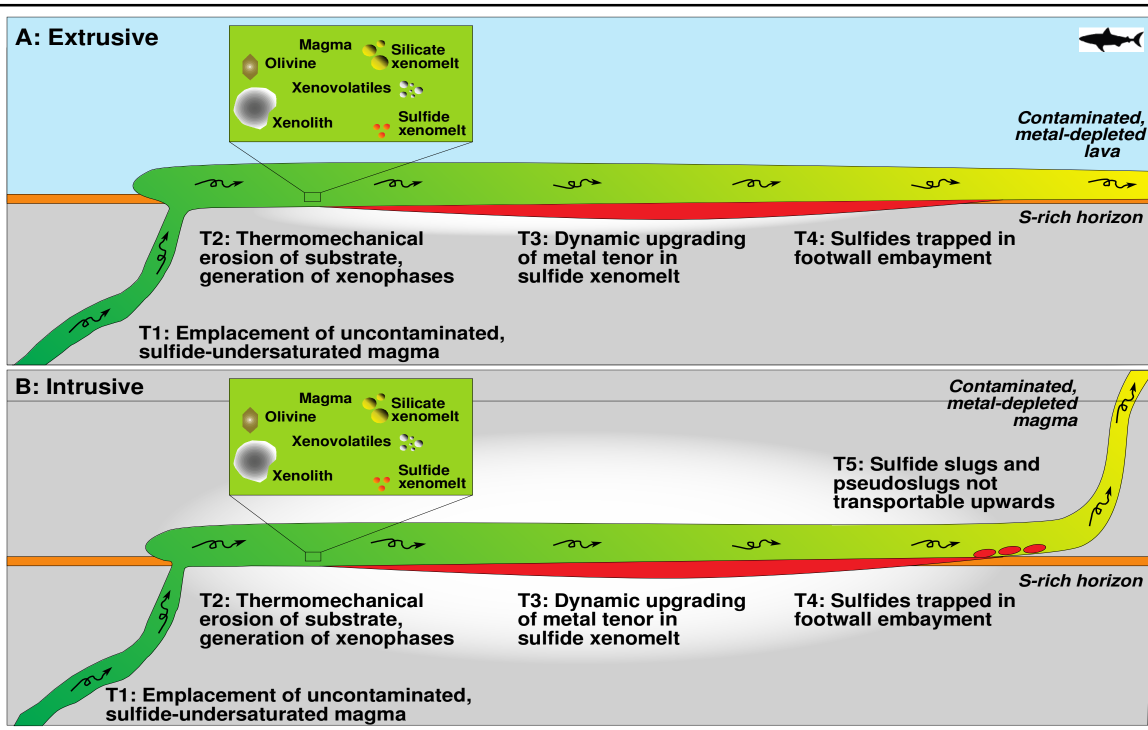

Lesher in press *CJES Special Issue on LIPs* (as modified from Lesher & Keays 2002 *CIM Spec Vol 54)*

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Local vs. Transported Sulfide

All volcanic and many subvolcanic deposits appear to have incorporated external S at the same stratigraphic level of emplacement, e.g.

- **Alexo**: Naldrett 1966 *CIM*; Lesher & Groves 1986 *Springer*
- **Duluth**: Mainwaring & Naldrett 1977 *Econ Geol*; Ripley 1981 *Econ Geol*
- **Kambalda**: Lesher et al. 1984; Lesher and Groves 1986 *Springer*
- **Langmuir**: Green and Naldrett 1981 *Econ Geol*
- **Norilsk**: Grinenko 1985 *Int Geol Rev*; Naldrett et al. 1992 *Econ Geol*; Arndt et al. 2003 *Econ Geol*
- **Pechenga**: S-J Barnes et al. 2001 *Can Min*
- **Raglan**: Lesher (Ed.) 1999 *MERC Field Guide*, Lesher 2007 *GAC-MDD Spec Vol*
- **Thompson**: Eckstrand 1989 *GAC-MAC*; Bleeker 1990 *PhD thesis*; Layton-Matthews et al. 2007 *GSC-MDD Spec Vol*
- **Voisey's Bay**: Ripley et al. 1999 *Lithos*; Ripley & Li 2002 *Econ Geol*

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Local vs. Transported Sulfide

Some intrusive mineralization has been proposed to have formed in "staging chambers" with physical transport of sulfides to higher levels:

- **Jinchuan**: Tang 1993 *GAC SP40*
- **Kotalahti**: Papunen & Vorma 1986 *GSF Bull 333*, Papunen 2003 *SGA*
- **Voisey's Bay**: Li & Naldrett 1999 *Lithos*; Lightfoot et al. 2012 *Min Dep;* Saumur & Cruden 2017 *Ore Geol Rev*
- **Aquablanca**: Tornos et al. 2001, 2006 *Min Dep*
- **Eagle** (Michigan): Ding et al. 2011 *Min Dep*
- **Norilsk**: Naldrett et al. 1992, 1996 *Econ Geol*; Arndt et al. 2001, 2003 *Econ Geol*
- **Review Papers**: Naldrett 2010 *Econ Geol*; Lightfoot & Evans-Lamswood 2015 *Ore Geol Rev*; Barnes et al. 2016 *Ore Geol Rev*

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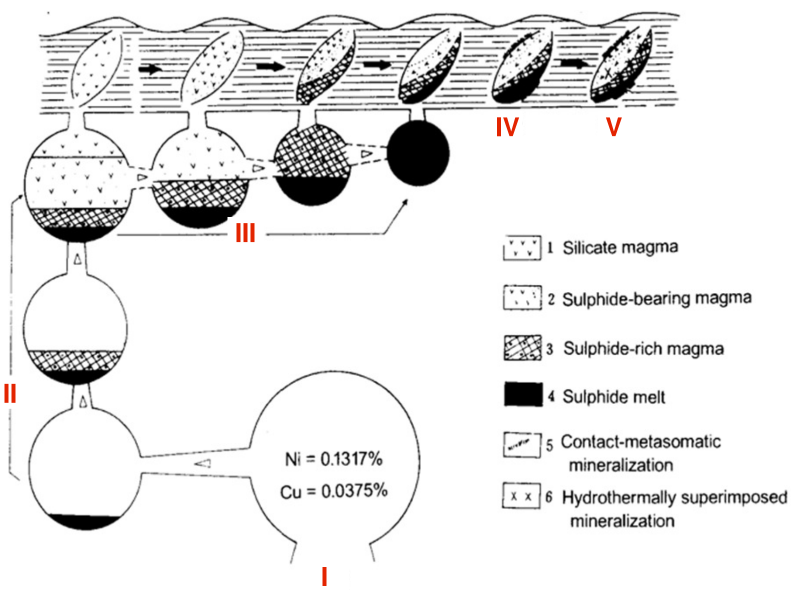
Jinchuan



Stage I: generation of Ni-Cu-bearing basaltic magma in a lower crustal magma chamber

Stage II: segregation of sulfide and olivine, forming a zoned magma chamber composed of silicate-olivine-sulfide magma overlying olivine-sulfide magma overlying massive sulfide magma

Stage III: progressive emptying of each of those components and migration to an upper chamber

Stages IV and **V:** contact metasomatic and hydrothermal modification of the mineralization

Tang 1993 *GAC Special Paper 40*

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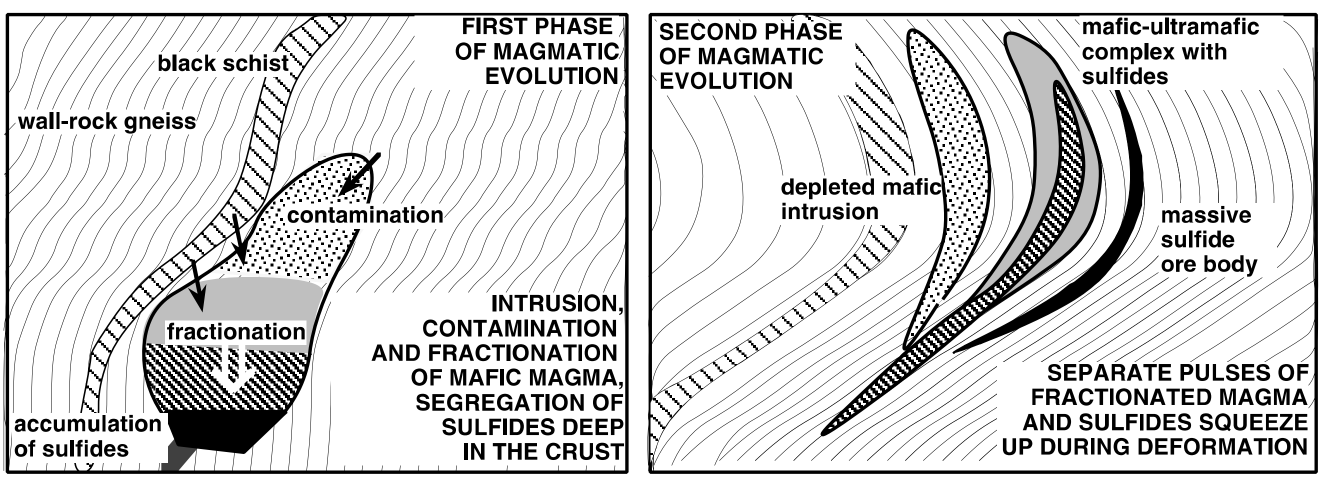
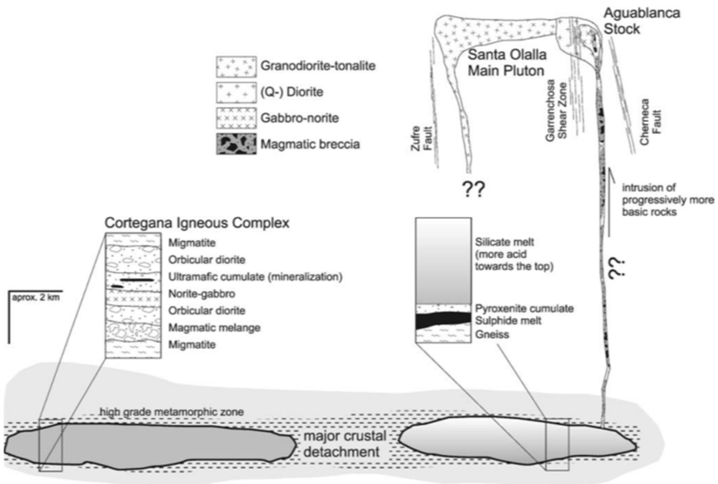
Kotalahti

Papunen et al. 2003 *SGA*

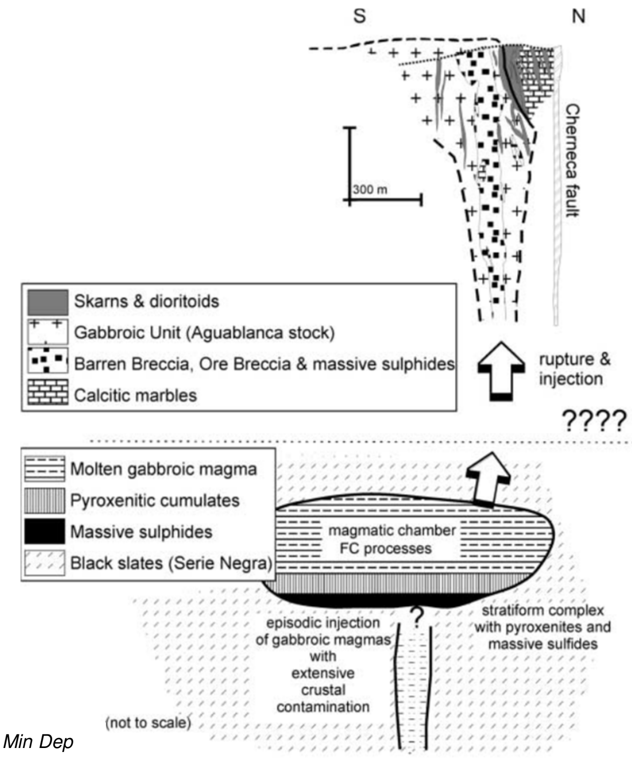


Model for evolution of synorogenic Ni-Cu deposit with massive offset orebody proposing 1) intrusion, contamination, and fractionation of mafic melt deep in the crust, followed by 2) subsequent deformation, which squeezes sequentially magmas and cumulate crystals to low-strain areas. However, tectonic forces are too slow to pump sulfides upward?

Aguablanca

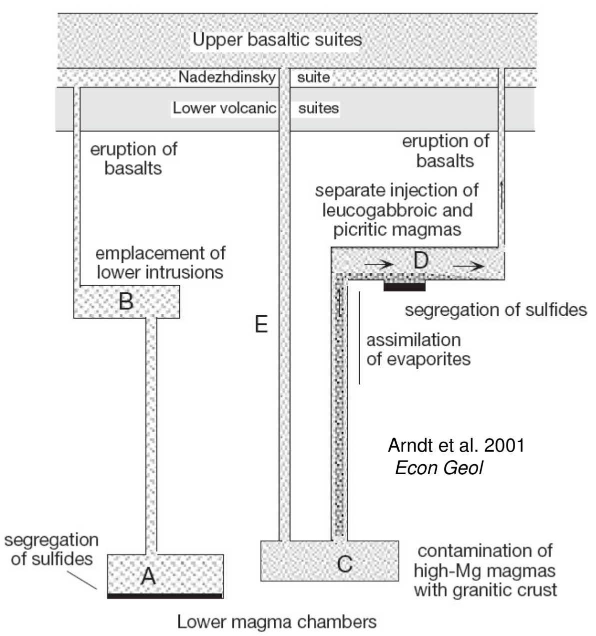


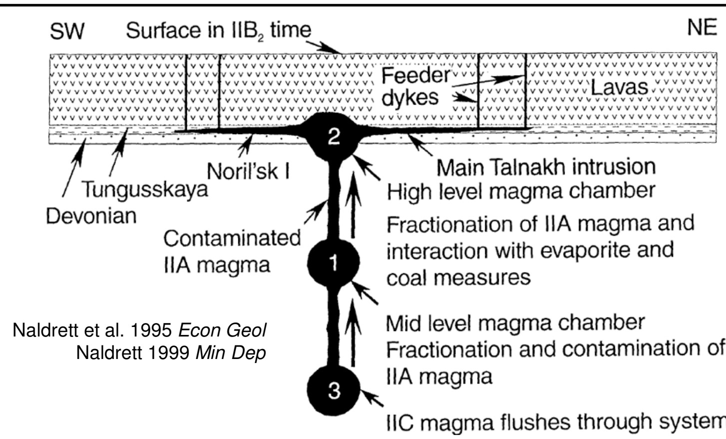
Tornos et al. 2006 *Min Dep*



Tornos et al. 2001 *Min Dep*

Norilsk





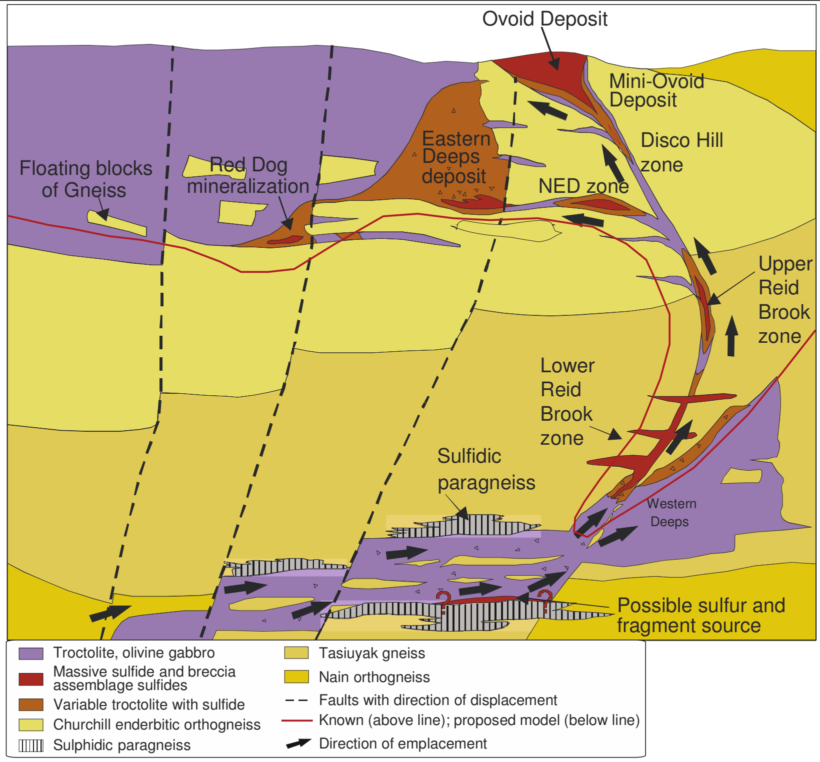
Naldrett et al. 1995 *Econ Geol*
Naldrett 1999 *Min Dep*

Multi-stage/multi-depth models for generation of mineralized intrusions, non-mineralized intrusions, and associated flood basalts at Norilsk

Models of this type are favoured to explain trace lithophile and chalcophile element geochemical and Sr, Nd, and Os isotopic variations, but have been challenged on the basis of field relationships (NN geologists), **modal mineralogy** (Latypov 2007 *IMM*)**, and S isotopes** (Ripley et al. 2003 *GCA*)

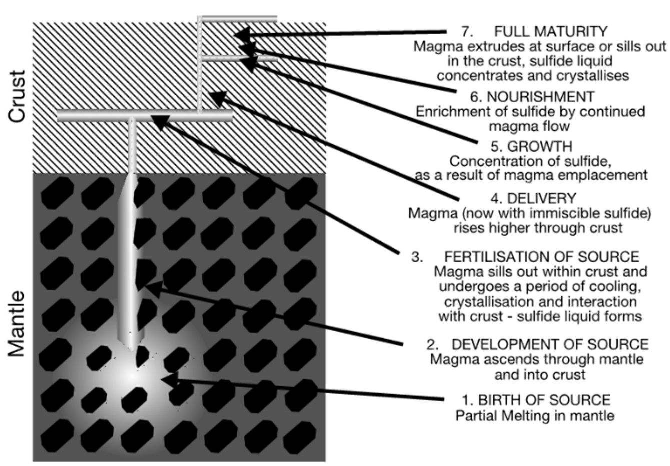
Voisey's Bay

Derivation of sulfides and xenoliths from depth with upward transport (arrows)

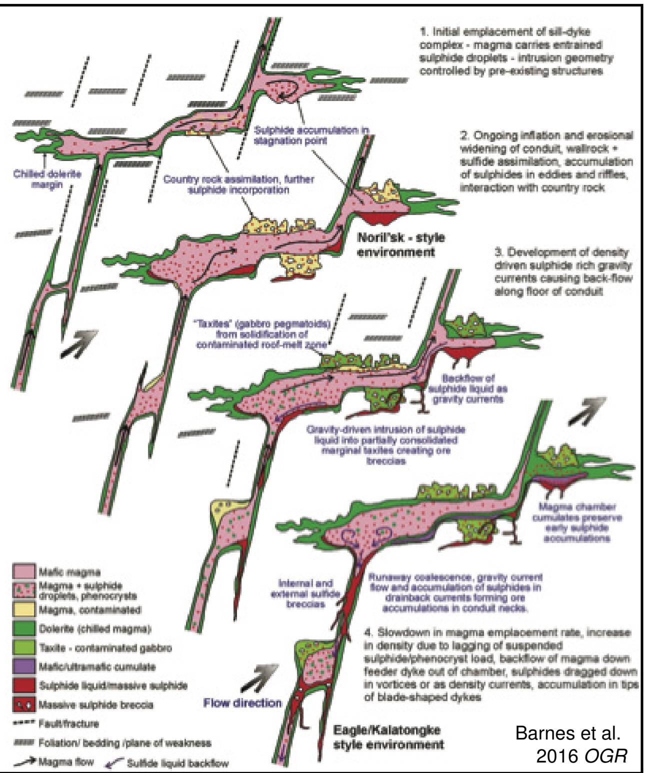


Lightfoot et al. 2012 Min Dep;
Lightfoot & Evans-Lamswood 2015 *Ore Geol Rev*

Other Upward Transport Models



Naldrett 2011 *Rev Econ Geol*



Barnes et al.
2016 *OGR*

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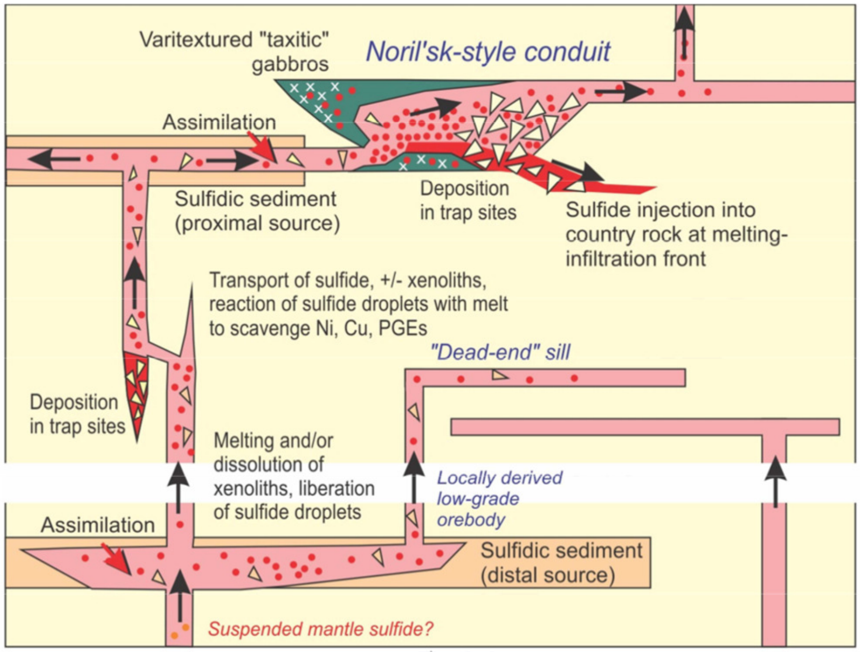
Other Upward Transport Models



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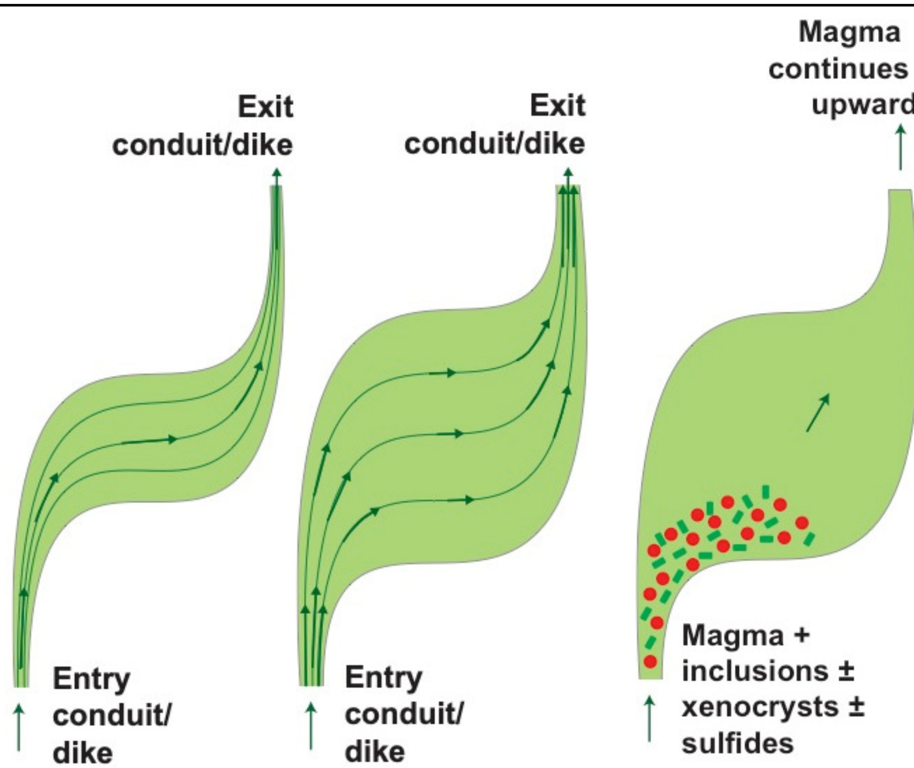
Barnes & Robertson 2019 *GeoSci Frontiers*

Upward Transport

In all of these cases, but especially in subvertical conduits/ chambers, the ore-localizing features are interpreted to have operated as fluid dynamic traps that collected upward-transported sulfides



Lesher 2017 *Ore Geol Rev*

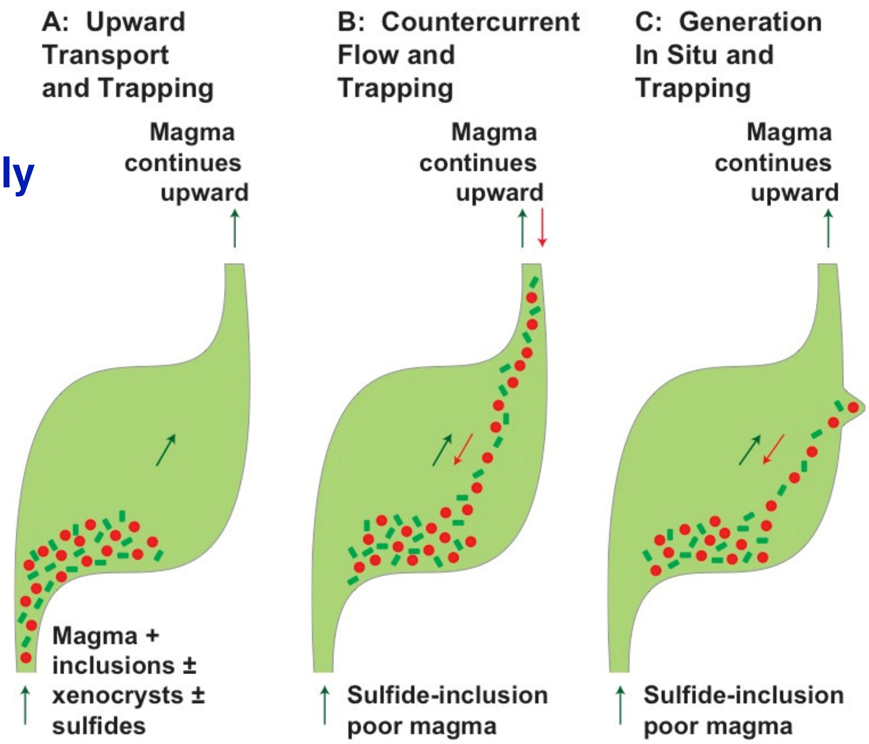
Sulfide Trap

However, traps work equally and are generally indistinguishable for:

A) dense phases coming up

B) dense phases coming down

C) dense phases generated in and retained in the trap

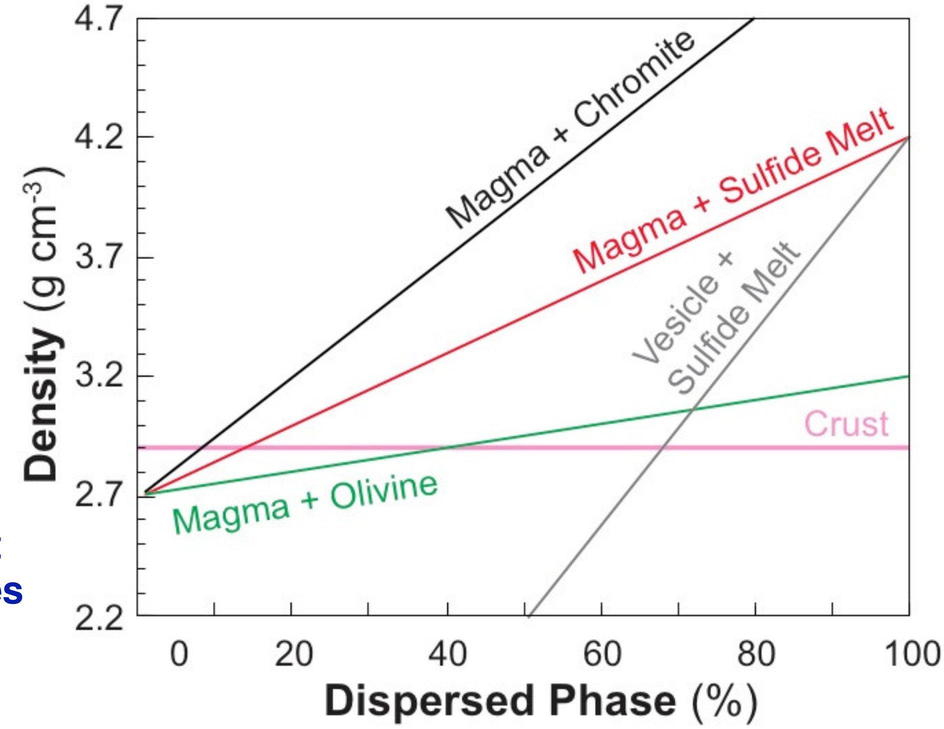


Lesher 2017 *Ore Geol Rev*

Sulfide Transport Mechanisms

- **In solution:** limited by low solubility, negative P dependence on S solubility, and difficulty in segregating quantitatively
- **Dispersed mist flow:** limited by negative P dependence on solubility
- **Dispersed droplet flow:** limited by bulk density
- **Droplets carried by gas bubbles**: reduces bulk density but few droplets appear to have floated
- **Droplets carried by crystals or xenoliths:** surface energy of nucleation is halved, also limited by bulk density
- **Slug flow:** limited by very high density
- **Seismic pumping:** the only way to transport *massive* sulfide melts, but too coincidental

Transport of Dispersed Phases



Magmas can transport
~70% sulfide + vesicles
~40% olivine
~13% sulfide
~4% chromite

Lesher 2017 *Ore Geol Rev*

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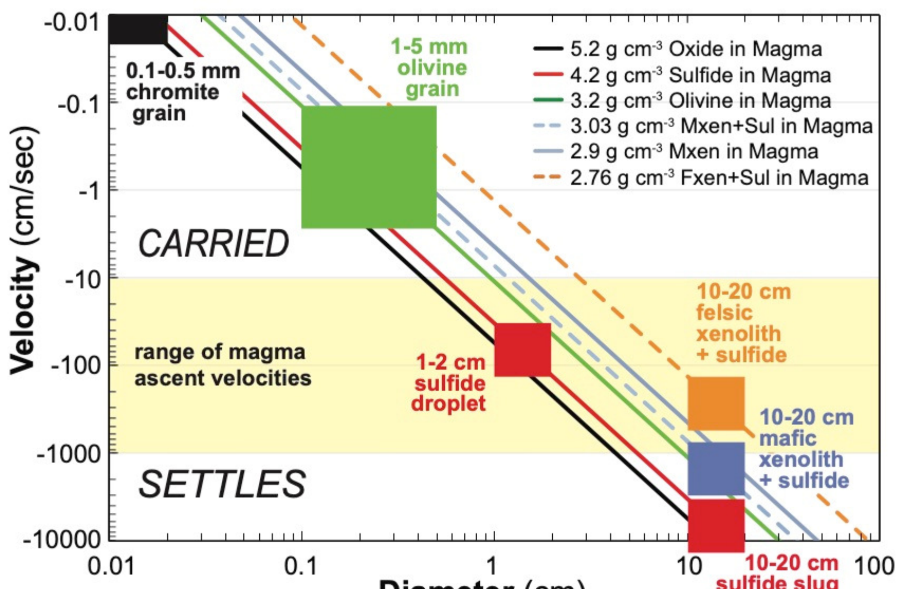
Settling Rates of Sulfide-Olivine-Xenoliths

Typical magma ascent velocities are 0.1-1 m sec^{-1} (Huppert and Sparks 1985 *J Pet*)

0.5 cm sulfide melt droplets can be carried at the lower rate and 6 cm droplets at the higher rate

Adding felsic xenoliths reduces settling, but only if smaller than 2-20 cm (felsic) **or 1-10 cm** (mafic)

Sulfide slugs settle very quickly



Lesher 2017 *Ore Geol Rev*; Lesher in press *CJES*

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Upward Transport: Problems

Despite the apparent ability to transport small (1-2 cm) **dispersed** (<13%) **sulfide droplets, there are several empirical observations that militate against this process:**

1) **S isotope evidence for local/nearby S sources**
2) **Physical evidence for local/nearby S sources**
3) **Field/geochemical/isotopic evidence for local/nearby contamination**
4) **Absence of sulfides or PGE enrichment in lavas overlying mineralized intrusions**

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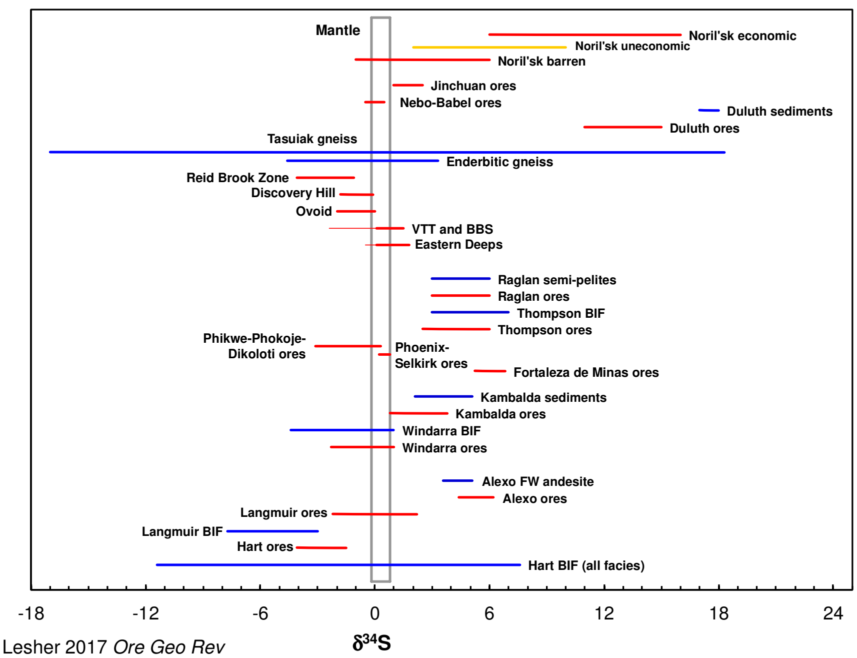
Upward Transport: Problem 1



Lesher 2017 *Ore Geo Rev*

S isotopic data indicate local/nearby crustal rather than deeper crustal sources of S in all major deposits

Upward Transport: Problems 2-3

Xenoliths and contaminants are local/nearby, not deeper crustal rocks

	Yilgarn	Abitibi	McFaulds Lake	Pechenga	Cape Smith Belt	Thompson
Lavas	mineralized	mineralized	not exposed	barren	mineralized	barren
Sills/dikes	mineralized	mineralized	mineralized	mineralized	mineralized	mineralized
Xenoliths	rare local	rare local	underlying BIF	???	rare local	rare local
Contamination	upper crust ± local rocks	upper crust ± local rocks	upper crust ± local rocks	upper crust ± local rocks	upper crust ± local rocks	upper crust ± local rocks
S source	local sulfidic cherts, argillites, felsic volc	local SUIF and argillite	local SUIF and an undiscovered source	underlying semi-pelite	underlying semi-pelite	adjacent SUIF

Lesher in press *CJES Spec Issue on LIPs*

Upward Transport: Problems 2-3

Xenoliths and contaminants are local/nearby, not deeper crustal rocks

	Norilsk-Talnakh	Duluth	Eagle-Tamarack	Voisey's Bay	Emeishan	Jinchuan
Lavas	barren	barren	barren	not exposed	barren	not exposed
Sills/dikes	mineralized	mineralized	mineralized	mineralized	mineralized	mineralized
Xenoliths	local	local	cognate	local	???	rare local
Contamination	upper and lower crust	adjacent pelites and OXIF	adjacent pelites	adjacent gneisses	upper crust	local marble and upper crust
S source	local evap and argillite	local pelite	adjacent pelites	local gneisses	not clear	not clear

Lesher in press *CJES Spec Issue on LIPs*

Upward Transport: Problem 4

In Archean and Proterozoic systems, the sulfides clearly formed at that stratigraphic level and were not transported from depth

	Yilgarn	Abitibi	McFaulds Lake	Pechenga	Cape Smith Belt	Thompson
Lavas	mineralized	mineralized	not exposed	barren	mineralized	barren
Sills/dikes	mineralized	mineralized	mineralized	mineralized	mineralized	mineralized
Xenoliths	rare local	rare local	underlying BIF	???	rare local	rare local
Contamination	upper crust ± local rocks	upper crust ± local rocks	upper crust ± local rocks	upper crust ± local rocks	upper crust ± local rocks	upper crust ± local rocks
S source	local sulfidic cherts, argillites, felsic volc	local SUIF and argillite	local SUIF and an undiscovered source	underlying semi-pelite	underlying semi-pelite	adjacent SUIF

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Upward Transport: Problem 4

In younger subvolcanic/plutonic systems, where exposed, overlying lavas are barren and are not enriched in PGE (as expected if they contained sulfides but degassed)

	Norilsk-Talnakh	Duluth	Eagle-Tamarack	Voisey's Bay	Emeishan	Jinchuan
Lavas	barren	barren	barren	not exposed	barren	not exposed
Sills/dikes	mineralized	mineralized	mineralized	mineralized	mineralized	mineralized
Xenoliths	local	local	cognate	local	???	rare local
Contamination	upper and lower crust	adjacent pelites and OXIF	adjacent pelites	adjacent gneisses	upper crust	local marble and upper crust
S source	local evap and argillite	local pelite	adjacent pelites	local gneisses	not clear	not clear

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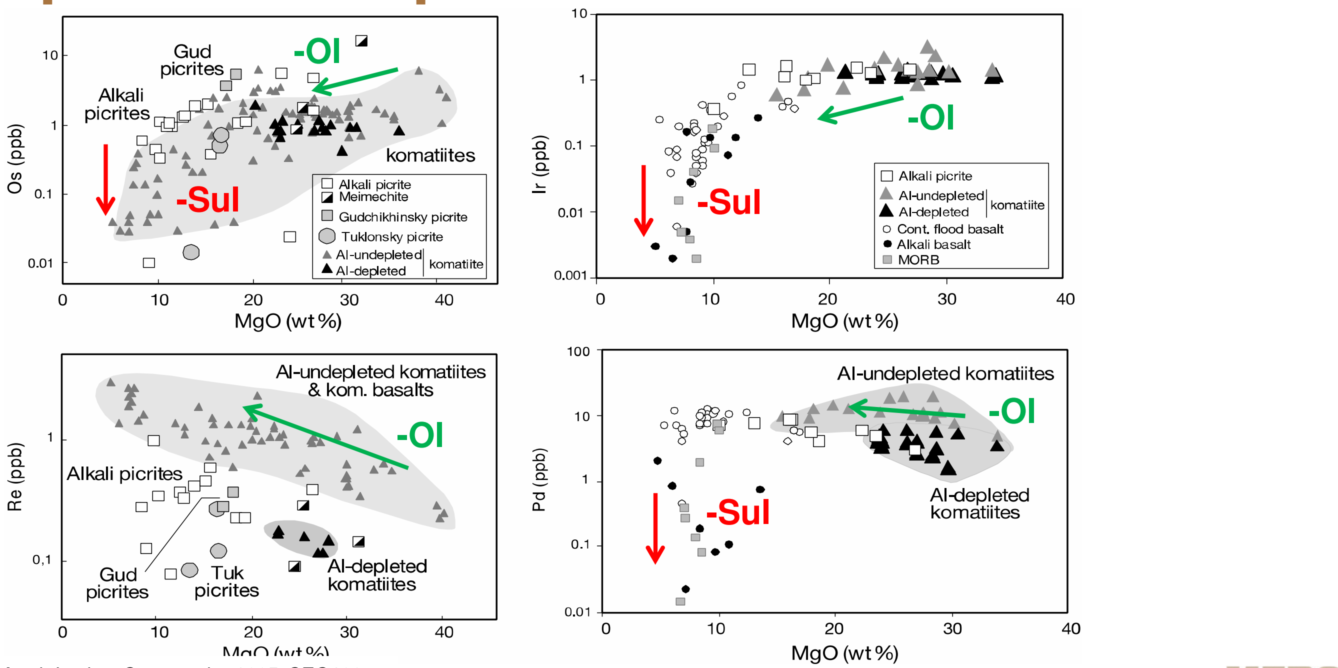
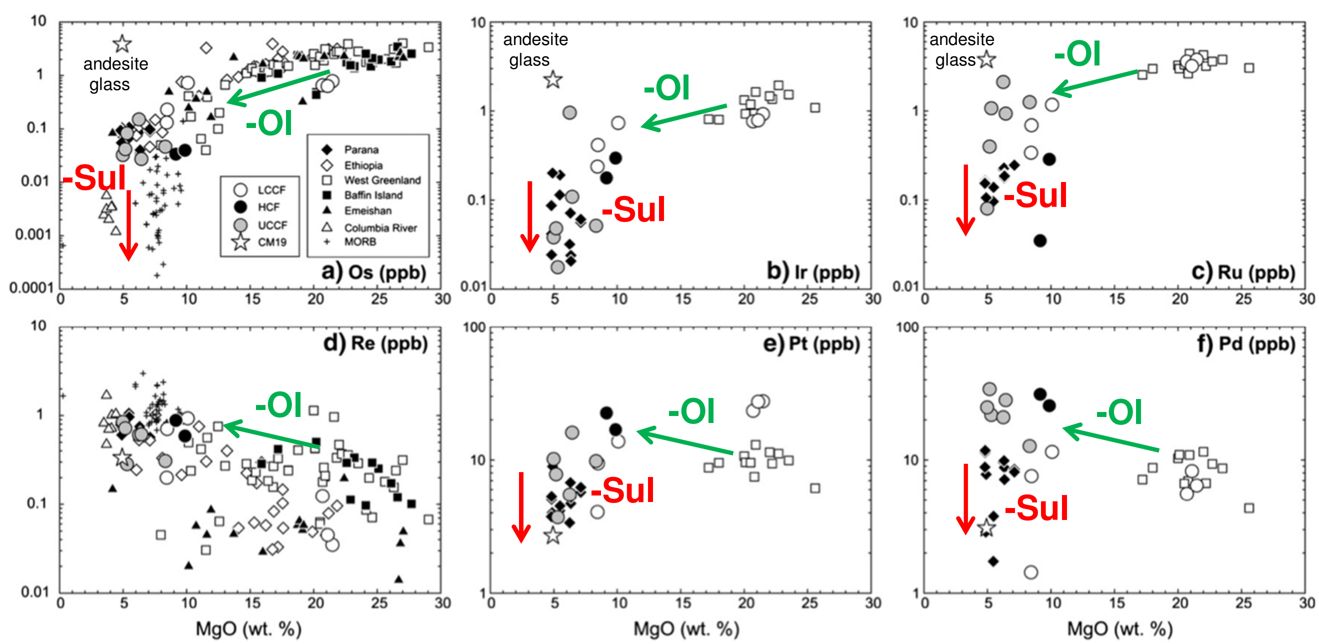
Upward Transport: Problem 4



Arndt-Lesher-Czamanske 2005 *SEG100*

Upward Transport: Problem 4



Day et al. 2013 *Lithos*

Paradox

The paradox of why fine (≤ 1 cm) **Fe-Ni-Cu-PGE sulfide droplets should be transportable at normal magma ascent rates and occur so often in subvolcanic intrusions, but almost never** (if ever) **occur in the thick sequences of rapidly erupted volcanic rocks that overlie the intrusions may have several explanations:**

1) **Mineralized intrusions may have intruded after the volcanic rocks**
2) **Mineralized intrusions may correlate with unexposed and/or unsampled volcanic rocks**
3) **Transported sulfide droplets may have dissolved by mixing sulfide-saturated, metal-depleted ore-forming magmas with later sulfide-undersaturated, metal-undepleted magmas**
4) **Sulfide droplets may have been lost due to degassing**
5) **Sulfide droplets may have collected on olivine or xenoliths**
6) **Surfactants lowered the interfacial tension of sulfide droplets, allowing them to coalesce more readily than predicted from experiments**
7) **Sulfides settled as slugs, pseudoslugs, or slurries/pseudolayers**

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Intrusions Postdate Volcanic Rocks

- **This occurred in a few cases** (e.g., Duluth: Paces and Miller 1993 *JGR*)
- **However, it unlikely to have occurred in all cases, particularly Noril'sk where the mineralized intrusions have been geochemically and geochronologically linked to overlying volcanic rocks** (e.g., Burgess and Bowring 2015 *Sci Adv*; Czamanske et al. 1994 *OGS Spec Vol*; Czamanske et al. 1995 *Res Geol*; Fedorenko 1994 OGS *Spec Vol*)

RESEARCH ARTICLE

EARTH SCIENCE

High-precision geochronology confirms voluminous magmatism before, during, and after Earth's most severe extinction

Seth D. Burgess*† and Samuel A. Bowring

10.1126/sciadv.1500470

The end-Permian mass extinction was the most severe in the Phanerozoic, extinguishing more than 90% of marine and 75% of terrestrial species in a maximum of 61 ± 48 ky. Because of broad temporal coincidence between the biotic crisis and one of the most voluminous continental volcanic eruptions since the origin of animals, the Siberian Traps large igneous province (LIP), a causal connection has long been suggested. Magmatism is hypothesized to have caused rapid injection of massive amounts of greenhouse gases into the atmosphere, driving climate change and subsequent destabilization of the biosphere. Establishing a causal connection between magmatism and mass extinction is critically dependent on accurately and precisely knowing the relative timing of the two events and the flux of magma. New U/Pb dates on Siberian Traps LIP lava flows, sills, and explosively erupted rocks indicate that (i) about two-thirds of the total lava/pyroclastic volume was erupted over ~300 ky, before and concurrent with the end-Permian mass extinction; (ii) eruption of the balance of lavas continued for at least 500 ky after extinction cessation; and (iii) massive emplacement of sills into the shallow crust began concomitant with the mass extinction and continued for at least 500 ky into the early Triassic. This age model is consistent with Siberian Traps LIP magmatism as a trigger for the end-Permian mass extinction and suggests a role for magmatism in suppression of post-extinction biotic recovery.

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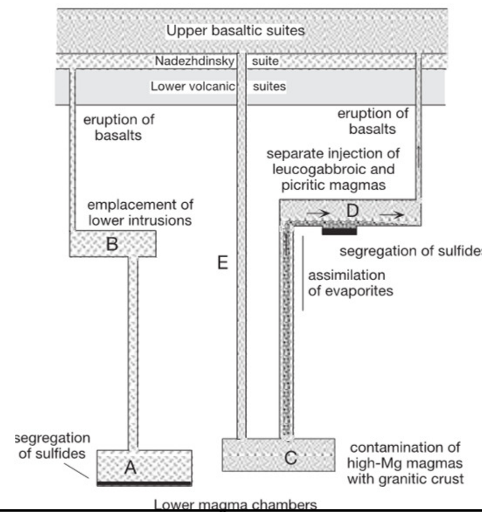
Unsampled Volcanic Rocks

- **This is always possible and there have been arguments made at Noril'sk, based on S isotopes** (Ripley et al. 2003 GCA) and **phase equilibria** (Latypov 2007 IMM) **that the lavas are not related to the mineralized intrusions**
- **However, other studies link them and it seems beyond coincidental that the extremely PGE-depleted Nadezhdinsky lavas just happen to overlie the world's largest Ni-Cu-PGE deposits**
- **In any case, many LIPs are well exposed and well studied, so it seems unlikely that no sulfide- or PGE-enriched lavas would be sampled**



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Exposure/Preservation

Mineralized intrusions may correlate with unexposed and/or unsampled volcanic rocks

- **This is always possible, as several authors have argued against links between the mineralized intrusions at Norilsk and immediately overlying lavas** (e.g., Latypov 2002 *CMP*; Ripley et al. 2003 *GCA*)
- **However, many LIPs are well exposed in multiple river sections, are well studied, and calculated magma:sulfide ratios** (R factors) **for related mineralization are commonly in the range 100-1100, so not an insignificant amount of magma/lava, yet none contain sulfide**

Lesher in press *CJES Spec Issue on LIPs*

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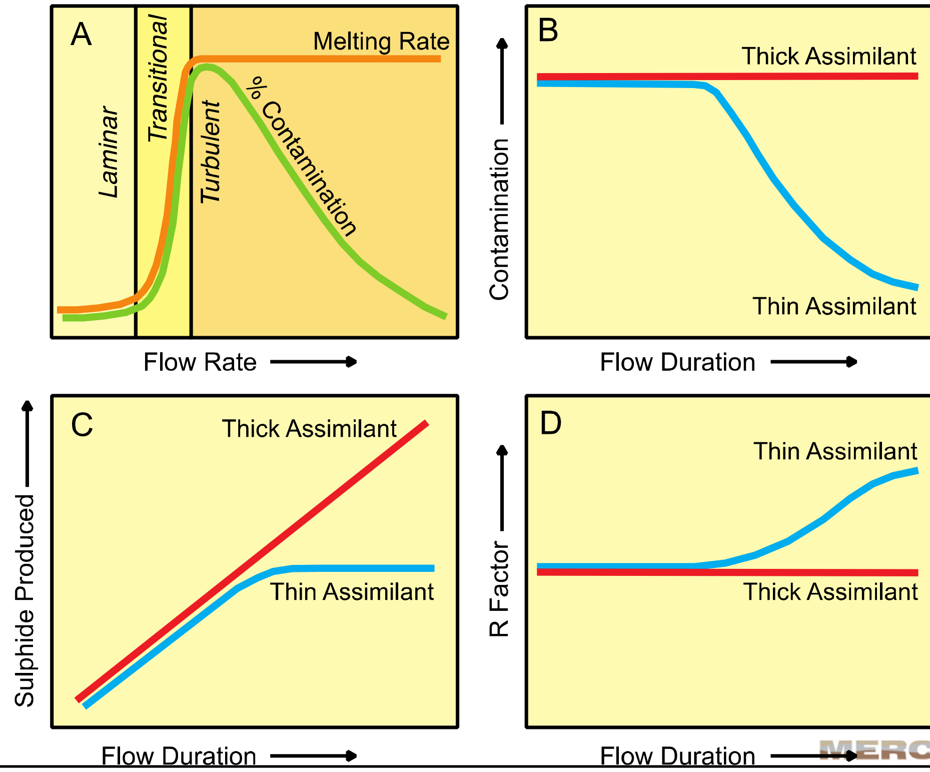
Mixing I.

Transported sulfide droplets may have dissolved by mixing sulfide-saturated, metal-depleted ore-forming magmas with later sulfide-undersaturated, metal-undepleted magmas

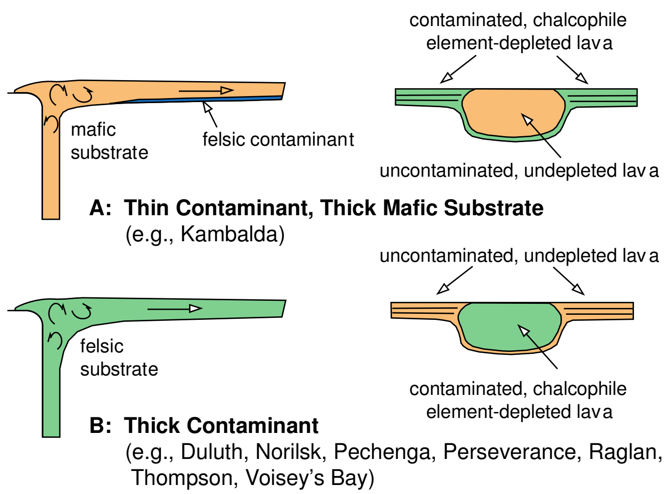
- **If the S source was thin and was eventually completely eroded upstream** (blue line on B-D and as in A on next page)**, uncontaminated lavas in the channel-flow facies would flush out any evidence of contamination or metal depletion** (Lesher & Arndt 1995 Lithos; Lesher et al. 2001 Can Min)



Lesher 2001 *Can Min*

Mixing II.

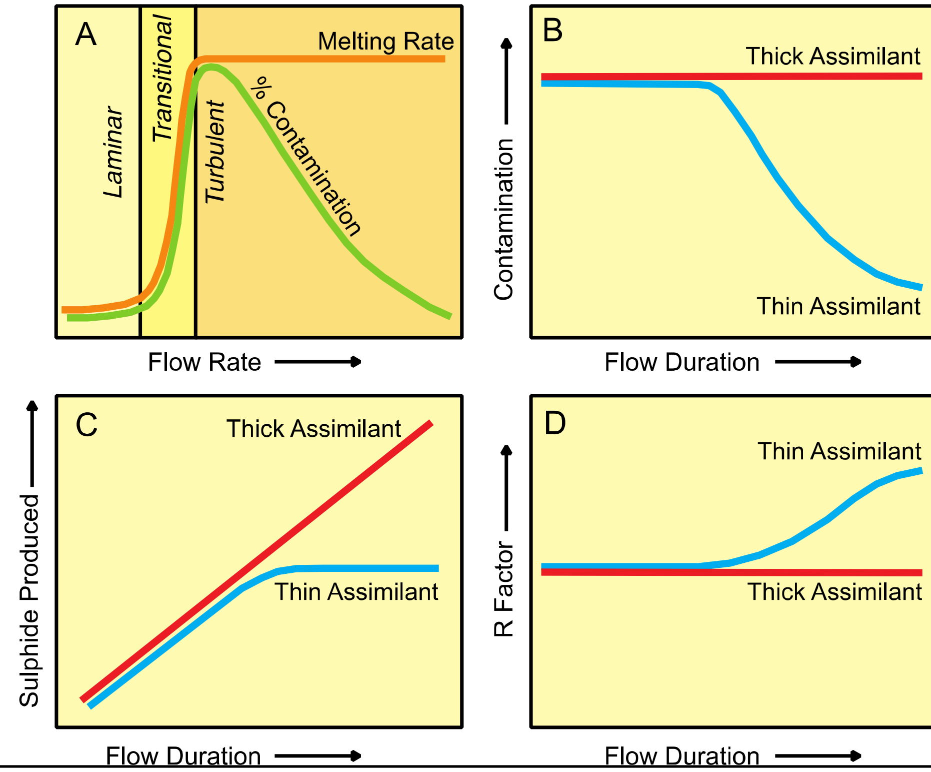
- **If magma flux after ore deposition was similar to that during ore formation, which is consistent with the large amount of overlying in situ crystallized olivine accumulation** (Lesher 1989 *Rev Econ Geol*)**, the dilution factor can be estimated to be 6000-30,000 using:**
  - **Magma:sulfide ratios calculated from PGE contents** (100-500: Lesher and Campbell 1993 *Econ Geol*)
  - **Olivine cumulate:sulfide ratios in the host units** (ave. 60:1: Lesher et al. 1981 *Econ Geol*)
- **This level of dilution in downstream lavas would dissolve any suspended sulfides and erase any metal depletion signature** (as in A)



modified from Lesher & Arndt 1995 *Lithos*

Mixing III.

- **However, many systems had access to thicker S sources** (as for red lines and in B on previous page) **and would have remained sulfide saturated during the replenishment process and contain ubiquitous sulfides in the overlying host unit**
- **Thus, even if the magma fluxes were similar, the downstream** (upsystem) **equivalents of these should also contain sulfides**



Lesher et al. 2001 *Can Min*

Sulfide Degassed

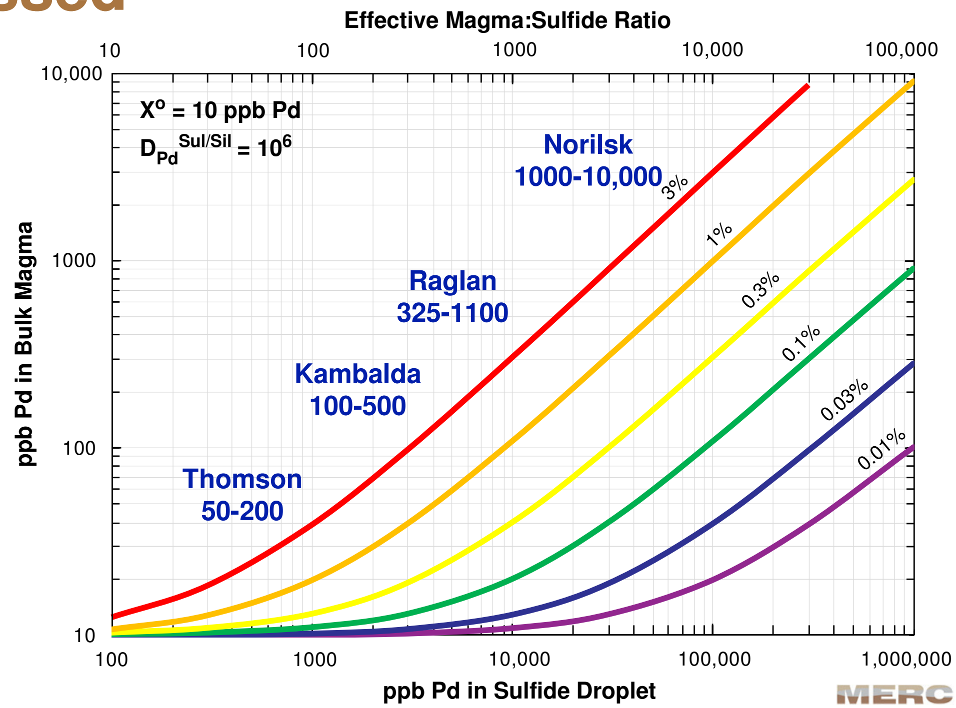
This is unlikely for two reasons:

1) **In the absence of a strong oxidant – as added during smelting – the rate of sulfide** (rather than dissolved HS^-) **dissolution** (and presumably volatilization) **is slow** (SJ Barnes and Robertson 2018 *Geosci Front*)
2) **Ni-Co-Cu-PPGE and especially IPGE are much less volatile than S** (Lodders 2003 *Astr J*)

Sulfide/silicate partition coefficients for the PGE are up to 10^6 (Mungall and Brenan 2003 *GCA*), so **even if S was lost, the lavas should contain anomalous abundances of chalcophile elements**

Sulfide Degassed

PGE contents of magmas carrying 0.01-3% sulfide droplets showing strong degrees of enrichment, even if very small amounts are present and if S is devolatilized



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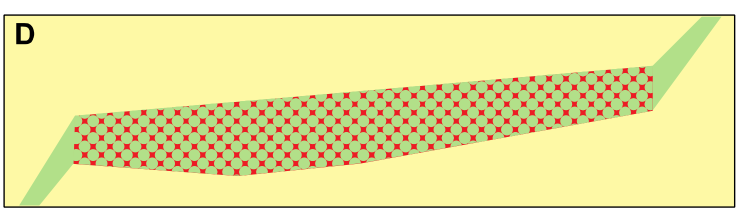
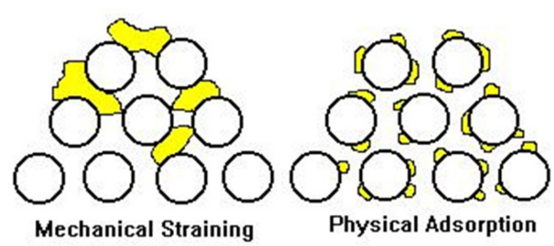
Filter Beds

- **Small droplets** (<0.1 cm) **are easily transported, but are very difficult to separate/segregate because the buoyancy forces acting on the droplets are of the same magnitude as the flow resistance forces acting on the droplets** (Robertson et al. 2015 *J Pet*)
- **By analogy with industrial filter beds, segregation of fine emulsions might require the presence of a breccia or cumulate filter bed into which droplets may collect and coalesce** (Lesher 2017 *Ore Geol Rev*)



Lesher 2017 *Ore Geol Rev*



D. Schmidt, VTI

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Surfactants

- **There may have been surfactants present in nature that lowered the interfacial tension of sulfide droplets, allowing them to coalesce more readily than predicted from experiments in surfactant-free** (Mungall and Su 2005 *EPSL*; Su et al. 2005 *Earth Sci China*) **and analog** (de Bremond d'Ars et al. 2001 *EPLS*) **experiments, facilitating downward countercurrent flow**

- **Many of magmas tha ... osits interacted with their wall rocks, some of which were unconsolidated** (e.g., Alexo-Dundonald, Kambalda, Perseverance, Raglan) **or semi-consolidated** (e.g., Duluth) **and contained saline to hypersaline and sometimes carbonaceous fluids that may have modified interfacial tensions**
- **Others** (e.g., Norilsk) **may have produced similar fluids when devolatilized**

Lesher in press *CJES Spec Issue on LIPs*

Pseudoslugs and Pseudolayers

Sulfides may have settled as:

- **Slugs** (domains of sulfide melt larger than droplets or globules)
- **Pseudoslugs** (hydrodynamically-coherent domains containing both sulfide and silicate melts)
- **Slurries/pseudolayers** (layers containing both sulfide and silicate melts)

as suggested by Arndt et al. 2013 *SGA,* Lesher 2013 *SEG,* Barnes et al. 2016 *J Pet*; Lesher 2017 *Ore Geol Rev*; Barnes and Robertson 2019 *GeoSci Front;* Lesher in press *CJES*

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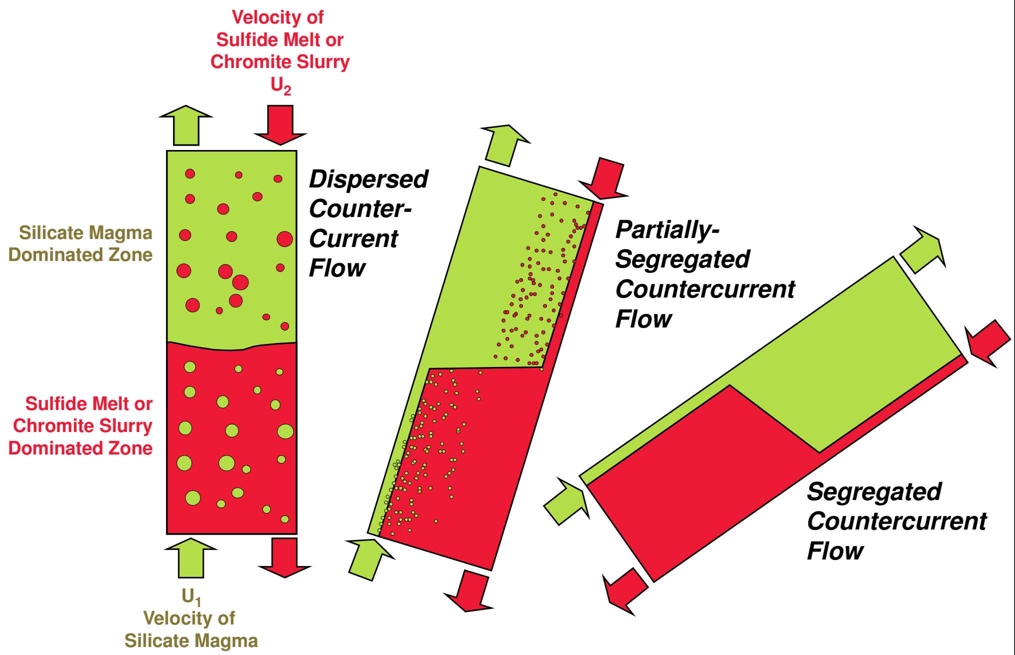
Countercurrent Flow of Sulfides

Under normal circumstances (buoyancy-driven magma flow)**, dense sulfides** (or agglomerated oxides) **will sink against the upward flow of magma, especially if the conduit is inclined**



Lesher 2017 *Ore Geol Rev*, as adapted from Ullmann et al. 2001 *ICMF*

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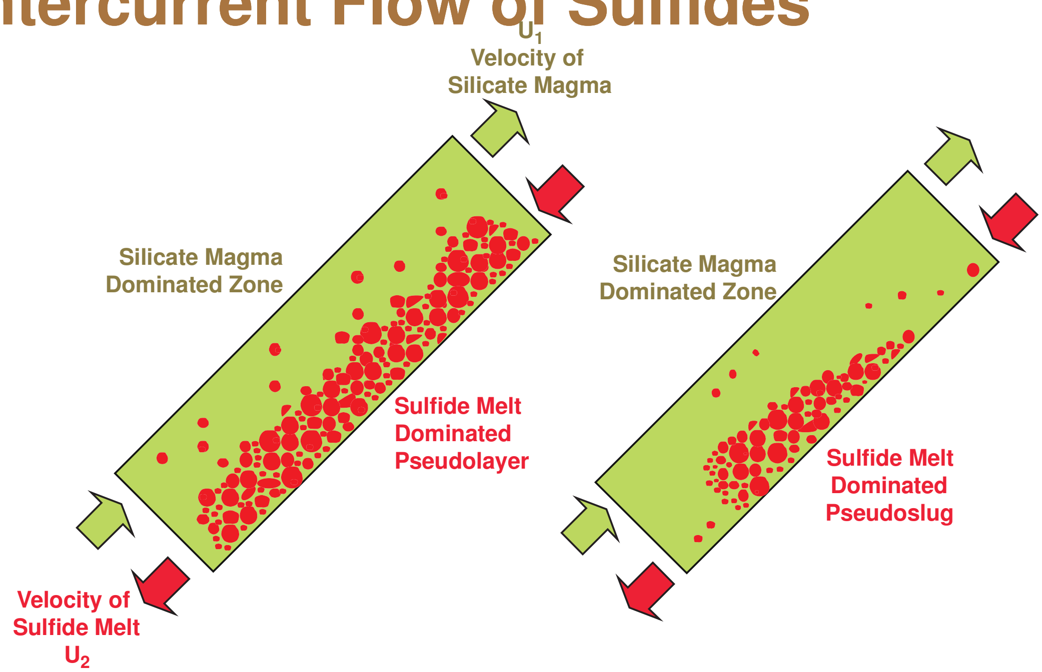
Countercurrent Flow of Sulfides



Lesher 2019 *CJES*, as adapted from Zhu et al. 2014 *Petrol Sci*

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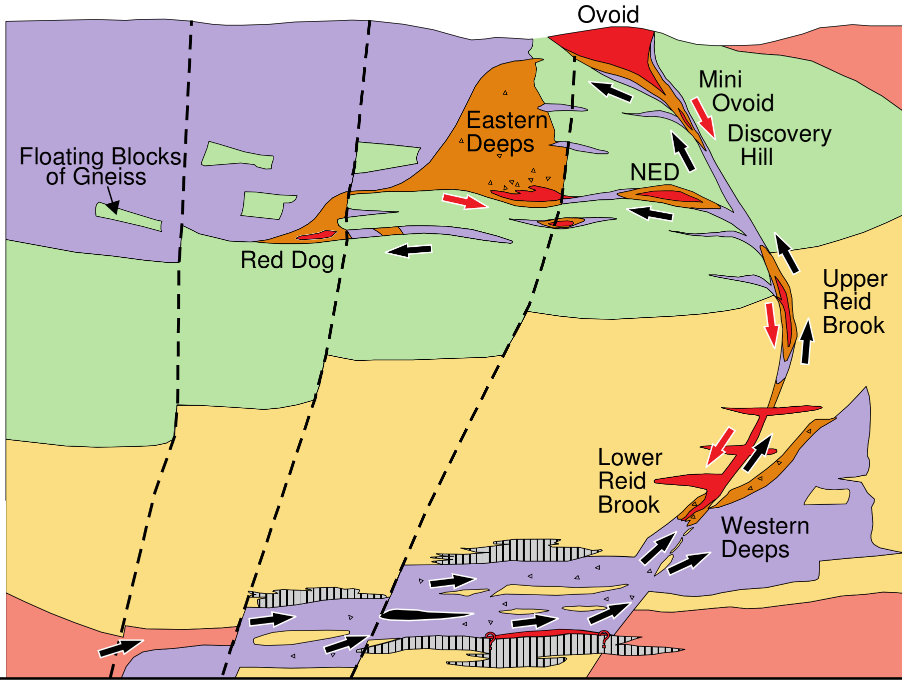
Countercurrent Flow of Sulfides?



Equally consistent with fluid dynamics

Better explains variations in S isotopes

adapted from Lightfoot et al. 2001 *Min Dep; Lightfoot & Evans-Lamswood Ore Geol Rev 2015*

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Implications

- **This means that in most situations dense sulfide melts remain at the same stratigraphic where they are generated or, if mobilized, likely settled in magmatic plumbing systems**
- **This means that we need to focus on subhorizontal rather than subvertical magmatic plumbing systems**
- **Although dike swarms are common, it sill systems that are preferentially mineralized**

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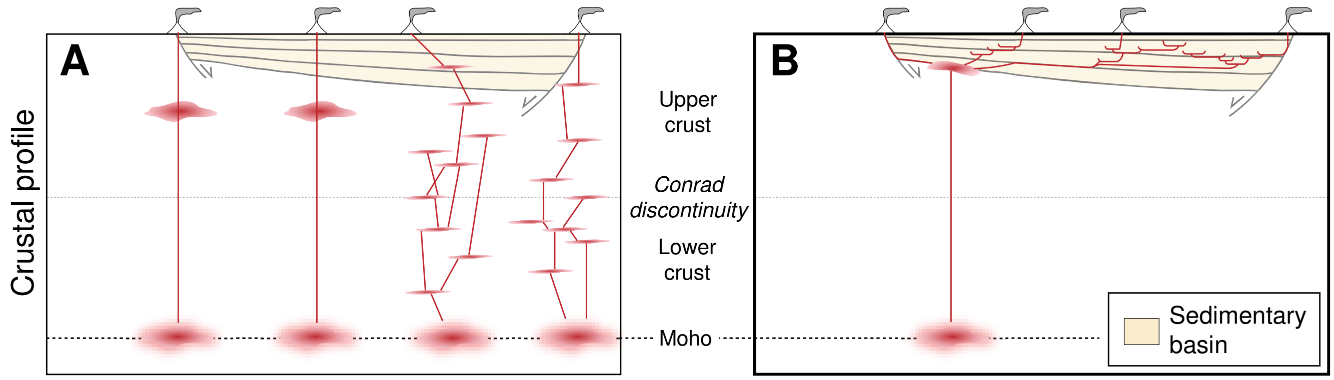
Sills in Sedimentary Basins



Magee et al. 2016 *Geosphere*

A) Traditional perspective in which subvertical dikes feed multiple intermediate reservoirs (“staging chambers”) **above the melt sources**

B) More recent perspective in which a laterally extensive sill complex feed volcanoes that may be laterally offset considerable distances from the melt source

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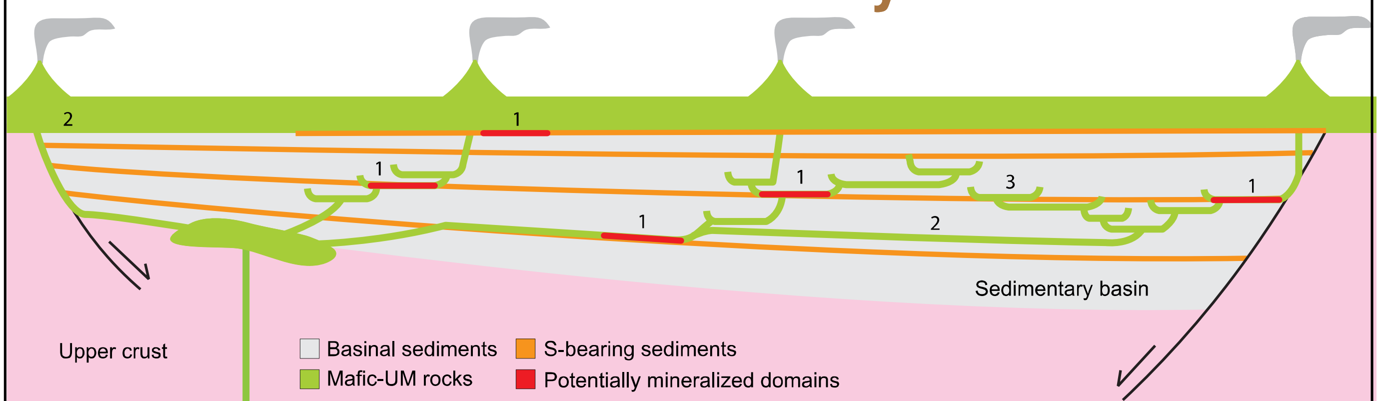
Ore Genesis in a Sedimentary Basin



Mineralization should be localized in the most dynamic parts of the system that intrude or flow along S-rich horizons: 1) mineralized lava channels, channelized flows/sills, bladed dikes, and chonoliths flowing over/along S-bearing horizons, **not 2) barren lava channels, channelized flows/sills, bladed dikes, and chonoliths** flowing over/along S-poor horizons **or 3) barren unchannelized sheet flows/sills/dikes** flowing over/along S-bearing or S-poor horizons

Lesher in press *CJES Special Issue on LIPs* as adapted from Magee et al. 2016 *Geosphere*

Ore Localization

A: Generation and collection more-or-less *in situ*: e.g., Thompson, Sudbury contact ores?

B: Riffling into embayments at the bases of volcanic or subvolcanic channels: e.g., Alexo, Kambalda, Norilsk, Pechenga, Raglan, Sudbury contact ores?

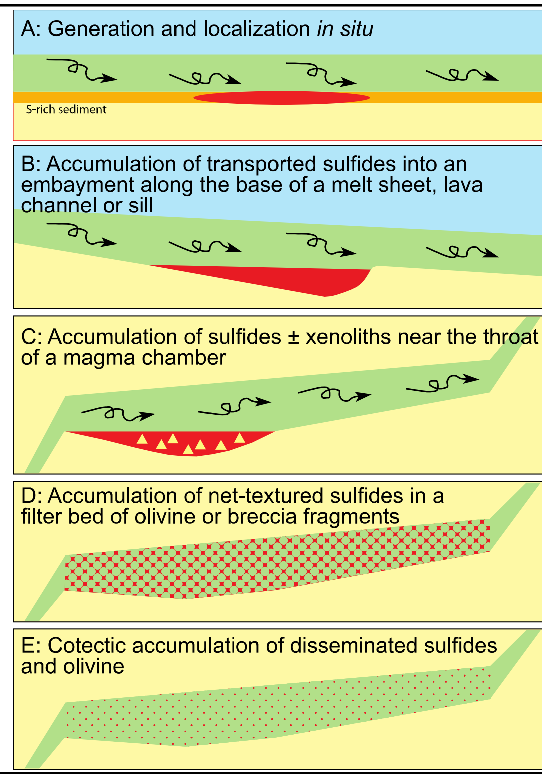
C: Collection in less dynamic parts of magma conduits: e.g., parts of Voisey's Bay?

D: Collection on olivine ± inclusion filter beds: e.g., Jinchuan?, Voisey's Bay?

E: *In situ* segregation: e.g., Dumont, Mt Keith

So, may form in situ (A, E) **or may be transported and then deposited** (B, C, D)

The ores are typically localized in subhorizontal fluid dynamic traps – footwall embayments, keels of dikes, and throats of magma chambers – in both extrusive and intrusive environments



Lesher 2017 *Ore Geol Rev*

Alteration, Deformation, and Metamorphism

- **Deuteric** (late magmatic) **fluids can mobilize Pd** (e.g., Hinchey & Hattori 2005 *Min Dep*) **and Pd–Pt–Cu > Au >> Rh–Ir–Os–Ni > Ru** (e.g., Su & Lesher 2011 *Min Dep*)
- **Metamorphism increases grain sizes, facilitates exsolution and segregation of Ni housed in Po, and facilitates exsolution and segregation of PGE housed in sulfides**
- **Deformation at ≲ 500°C will mobilize Ccp >> Po > Pn-Py-Mag-Chr**
  Deformation at ≳ 500°C will mobilize MSS > Mag-Chr
- **Metamorphic-hydrothermal fluids can mobilize Au > Cu >> Pt–Pd >> Ni >> Co–Rh–Ru–Ir >> Cr** (e.g., Lesher & Keays 1984 *IMM*, 2002 *CIM v54*; Layton-Matthews et al. 2010 *SEG*)

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Exploration: Critical

- **Source of large amounts of sulfide-undersaturated magma over a short time period:** mantle plumes appear to be most favourable
- **Craton margins and/or crustal-scale faults:** to focus magma migration
- **Environment of emplacement containing an external source of S:** sediments, volcanic rocks, or VMS mineralization
- **High-flow, dynamic environment:** lava channel or magma conduit to facilitate thermomechanical erosion and high metal tenors
- **Favourable site for ore deposition:** horizontal parts of magmatic systems (lava channels, channelized sheet flows/sills, blade-shaped dikes, chonoliths)

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Exploration: Non-Critical

- **Magma composition:** does not matter as long as moderate amounts of Ni-Cu-(PGE) are present
- **Mode and depth of partial melting:** do not appear to be important as long as most or all of the sulfides are consumed
- **Degree of partial melting:** not important as long as sulfides are consumed, degree of melting must be 10% if magma is reduced, but can be lower if magma is oxidized (e.g., alkali basalts and picrites)
- NB. retention of sulfides in the source or exsolution of sulfides prior to ore formation will lower PGE >>> Cu > Ni > Co, but will not eliminate the possibility of Ni-Cu-Co ore formation
- **Magmatic/volcanic setting**: may form in volcanic, subvolcanic, or plutonic environments
- **Stratigraphic level**: may occur at multiple levels whenever and wherever critical features (high magma flux and external S source) are favourable

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Exploration: Remaining Problems

- How far can mineralization form from a craton margin?
- How far can sulfides be transported?
- How can we identify the subvolcanic parts of magmatic plumbing systems when they are not exposed?
  - Seismic has the greatest potential, but is expensive
- How can we identify the places were sulfides are actually localized?
  - Magnetics and gravity are only useful for shallow massive ores
  - Fluid dynamic modelling can provide only very general constraints given the wide range of geometries of mineralized bodies

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