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**

**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)$_3$S$_8$, chalcopyrite CuFeS$_2$, and magnetite Fe$_3$O$_4$ 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**

![Graph showing Ni-Cu production by age and deposit type]

*modified from Naldrett 2010 Econ Geol*
Age Not Important

But There Are Some Secular Variations

<table>
<thead>
<tr>
<th></th>
<th>Archean</th>
<th>Proterozoic</th>
<th>Phanerozoic</th>
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<tr>
<td><strong>Host Rock</strong></td>
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<td>dunite-gabbro</td>
<td>peridotite-gabbro</td>
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<td><strong>Host Magma</strong></td>
<td>up to 32% MgO</td>
<td>up to 22% MgO</td>
<td>up to 14% MgO</td>
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<td><strong>Ni/Cu and Ir/Pd</strong></td>
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<td><strong>Inclusions</strong></td>
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Tectonic Settings

Largest deposits are in rift-related settings

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

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)
### 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

![Mg Content / Temperature Not Important](image)

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

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
Mineralized units are enriched in olivine relative to unmineralized units.

Extrusive Host Units

Increasing Olivine Accumulation

Increasing Differentiation

Width of profiles is proportional to MgO content
Lava Channels

Chukotat Group
- Komatiitic Basalt
- Gabbro
- Pyroxenite
- Wehrlite
- Peridotite

Povungnituk Group
- Slate
- Tholeiitic Basalt
- Gabbro
- Pyroxenite
- Wehrlite/Peridotite

Channelized Sheet Flows and Sheet Sills

Cross Lake – C1-2-3 Area
Falconbridge Ltée.
### Lunnon Shoot, Kambalda

**Channelized sheet flow**

Note: All intrusive rocks omitted without subsequent thickness corrections

### Perseverance, WA

**Lava channel**

modified from Barnes et al. 1988 J Pet

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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

Subhorizontal Magma Conduits

B “Nebo-Babel (Limoeiro) Type” - tubular chonolith

D,E “Eagle/Kalatongke Type” - tube/funnel transition

Notes:
- **Marginal gabbronite**
- **Gabbro (norite)**
- **Peridotite**
- **Massive sulfide (breccia)**
- **Disseminated ore**
- **Matrix ore**
- **Semi-massive sulfide**
- **Olivine gabbronite (norite)**
- **Norite**
- **Gabbro-norite**
- **Orerite
Channelized Sheet Sills

North Rockall Trough, North Sea


Jinchuan

Cross section looks like a funnel and some authors (e.g., Tang 199 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

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**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 subhorizontal blade-shaped dike (Lesher in press *CJES*)
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*)

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.
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.

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.
**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.

**Kalatongke #2**

Clearly a chonolith in cross section.
Santa Rita (Mirabella)

Tilted chonolith

Jingbulake

Symmetrically zoned
Mineralization in gabbro, not peridotite
More like an Alaskan-Uralian intrusion
Voisey’s Bay

Ores occur within dikes (Reid Brook, NED) and in the throats of magma chambers (Ovoid, Eastern Deeps)

Ores locally injected into fractures adjacent to dikes

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Voisey’s Bay

Ovoid

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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

ALEXO KOMATITE
- 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
- Andesitic Rocks
  - Pillows with minimal hyaloclastite
  - Ameboid to irregular pillows
    with abundant hyaloclastite
  - Hyaloclastite
  - Massive
- Argilbite

Houlé et al.
2012 Min Dep

Footwall Embayments

ALEXO KOMATITE
- Coarse-grained random olivine
  spinel with arcytobasal (+ sulfides)
- Komatitite olivine-pyroxenite
  (basal unit, +/- bobbly sulfides)
- Fine-grained olivine spinel
- Komatitite (footwall) dikes

FOOTWALL ROCKS
- Net-textured to disseminated sulfides facies
- Layered net-textured sulfides facies
- Massive to semi-massive sulfides facies

Houlé et al.
2012 Min Dep
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)

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
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 interstitial 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

%S

%MgO

cumulus

intercumulus

interstitial

sulfide-saturated

sulfide-undersaturated

S addition

low $O_2/S_2$

high $O_2/S_2$

barren

Timing vs. Dynamics

Timing vs. Dynamics

Dynamic Examples

Dumont

Mt Keith

Black Swan

Jinchuan

Eagle’s Nest

Raglan

Alexo

Kambalda

Non-Dynamic Examples

Bushveld

Stillwater

Norilsk I

Pechenga

Norilsk II

Talnakh

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

*adapted from Lesher Keays 2002 CIM v54

Mineralization Types

**A: Type I (Stratiform Basal) Mineralization**

- Channel-Flow Facies
- Lava Lobe Facies
- Sheet-Flow Facies

**B: Type II (Stratabound Internal) Mineralization**

- Overbank Lava Lobe Facies
- Channel-Flow Facies
- Overbank Lava Lobe Facies

**C: Type III (Stratiform "Reef") Mineralization**

- Sheet Flow or Sill
- **PGE-(Cu)-(Ni)** sulfide reef
Type I

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

The banding in the massive ore is metamorphic.

Type I

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

PDAC – 02 Mar 2019
**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
Type IIc

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

Type III

Coarse stratiform disseminated sulfides, Murray Mine discovery site, Sudbury
**Type IV**

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

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

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

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

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

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**Controls on Ore Composition**

- Composition of magma
  - **Source composition**
  - $f_{O_2}$ and degree of partial melting
  - Residue composition
  - FC and AFC processes
- **Sulfide/silicate partition coefficients** (which vary as a function of $T$, $f_{O_2}$, and $f_{S_2}$)
- **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

![Graph showing Pd/Ir vs Ni/Cu ratios for various ore deposits.](image)

from Barnes et al. 1985 Chem Geol

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?

PDAC – 02 Mar 2019 – Lesher

data from Naldrett 2004 Springer
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

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.

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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.
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

Komatiitic deposits are derived from peridotitic mantle

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

Lu et al. in revision Ore Geol Rev
## Ore Tenor vs. Mg in Magma

Increasing Degree of Mantle Melting   
Increasing Fractional Crystallization of Magma

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### Metal Contents of Magmas

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<th></th>
<th>Ni (ppm)</th>
<th>Cu (ppm)</th>
<th>Pd (ppb)</th>
<th>Pt (ppb)</th>
<th>Ir (ppb)</th>
<th>Au (ppb)</th>
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<td>Low-Mg Komatiite</td>
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<td>10.5</td>
<td>1.7</td>
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<td>Komatiitic Basalt</td>
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Metal contents of magmas vary widely, but even a crustal impact melt can form a major deposit (e.g., Sudbury)

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

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

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Sources: High-Mg Komatiite: Lesher & Campbell 1993 Econ Geol; Crustal Impact Melt: Kayas & 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:

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.

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)

\[
Y_i^f = \frac{X_i^{0 \text{Sul/Sil}} D_i^{\text{Sul/Sil}}}{R + D_i^{\text{Sul/Sil}}} (R + 1) \quad [1]
\]

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

\[
Y_i^f = \frac{X_i^{0 \text{Sul/Sil}}}{R + D_i^{\text{Sul/Sil}}} R \quad [2]
\]

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

\[
Y_i^f = \frac{(X_i^{0 \text{Sul/Sil}} + Y_i^o D_i^{\text{Sul/Sil}})}{R + D_i^{\text{Sul/Sil}}} \quad [3]
\]

dynamic upgrading
(Brügmann et al. 1993 GCA)

\[
Y_i^f = X_i^{0 \text{Sul/Sil}} \left[ D - \left( D - 1 \right) e^{-\left(1/D \times N\right)} \right] \quad [4]
\]

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 \( R \geq 10D \), which means that when \( R \geq 10D \), the abundances are strongly controlled by the R factor (magma:sulfide ratio).
S Isotope Mixing

Modeled $\delta^{34}S$ 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

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*)

Fluid Dynamics

- **Laminar Flow Regime**
  - Planar interface,
  - low surface area,
  - low R factor

- **Transitional Flow Regime**
  - Scalloped contact with some entrained sulfides,
  - intermediate surface area,
  - intermediate R factor

- **Turbulent Flow Regime**
  - Entrained sulfides,
  - high surface area,
  - high R factor
### Decoupling with Variable R

<table>
<thead>
<tr>
<th>Extra Low R</th>
<th>High R</th>
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<tbody>
<tr>
<td>Crustal S, Se, Pb, Sr, Nd, &amp; Os</td>
<td>Crustal S &amp; Se, mantle-like Pb, Sr, Nd, &amp; Os</td>
</tr>
<tr>
<td>Very strong depletion PGE&gt;Cu&gt;Ni&gt;&gt;Co</td>
<td>Minor PGE depletion</td>
</tr>
<tr>
<td>Very high tonnage, very low tenor, Co&gt;Ni&gt;Cu&gt;PGE</td>
<td>Low tonnage, high tenor, Co=Ni=Cu=PGE</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Very Low R</th>
<th>Very High R</th>
</tr>
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<tbody>
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<td>Crustal S, Se, Pb, Sr, &amp; Nd, mantle-like Os</td>
<td>Mantle-like S, Se, Pb, Sr, Nd, &amp; Os</td>
</tr>
<tr>
<td>Strong depletion PGE&gt;Cu&gt;Ni&gt;Co</td>
<td>Negligible chalcophile element depletion</td>
</tr>
<tr>
<td>High tonnage, low tenor, Co&gt;Ni&gt;Cu&gt;PGE</td>
<td>Very low tonnage, very high tenor, Co=Ni=Cu=PGE</td>
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<th>Extremely High R</th>
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<td>Mantle-like S, Se, Pb, Sr, Nd, &amp; Os</td>
</tr>
<tr>
<td>Moderate depletion PGE&gt;Cu&gt;Ni&gt;Co</td>
<td>No metal depletion in magma</td>
</tr>
<tr>
<td>Moderate tonnage, moderate tenor, Co&gt;Ni&gt;Cu&gt;PGE</td>
<td>No tonnage</td>
</tr>
</tbody>
</table>

Lesher et al. 2001 Can Min

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### 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

PDAC – 02 Mar 2019 – Lesher
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)

Jinchuan Ni/Cu

JNMC data

Tonneller 2010 PhD Thesis
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)

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)
**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
  - Sulfdic 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)
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: $^{34}\text{S}$ only slightly greater than 0‰, but crustal source permitted by mass balance calculations
  - Babel-Nebo: very constant $^{34}\text{S}$ ~ 0‰, but nearby S source has been recently identified (Karykowski et al. 2015 Econ Geol)

- Note that near-zero $^{34}\text{S}$ 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)

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 Xiarhamu

Lu et al. in revision Ore Geol Rev
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

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

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

Inclusion sulfide ore, Voisey’s Bay

Inclusion-bearing troctolite, Voisey’s Bay

photos by C. Li

Lesher in press CJES Special Issue on LIPs (as modified from Lesher & Keays 2002 CIM Spec Vol 54)
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*
- **Voisey’s Bay**: Ripley et al. 1999 *Lithos*; Ripley & Li 2002 *Econ Geol*

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*
**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

**Kotalahti**

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?
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
Other Upward Transport Models

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

---

**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

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
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

Upward Transport: Problem 1

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**

<table>
<thead>
<tr>
<th></th>
<th>Yilgarn</th>
<th>Abitibi</th>
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<tbody>
<tr>
<td><strong>Lavas</strong></td>
<td>mineralized</td>
<td>mineralized</td>
<td>not exposed</td>
<td>barren</td>
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<td><strong>Sills/dikes</strong></td>
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</tr>
<tr>
<td><strong>Xenoliths</strong></td>
<td>rare local</td>
<td>rare local</td>
<td>underlying BIF</td>
<td>???</td>
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</tr>
<tr>
<td><strong>Contamination</strong></td>
<td>upper crust ± local rocks</td>
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</tr>
<tr>
<td><strong>S source</strong></td>
<td>local sulfidic cherts, argillites, felsic volc</td>
<td>local SUIF and argillite</td>
<td>local SUIF and an undiscovered source</td>
<td>underlying semi-pelite</td>
<td>underlying semi-pelite</td>
<td>adjacent SUIF</td>
</tr>
</tbody>
</table>

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**Upward Transport: Problems 2-3**

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

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<td>local</td>
<td>???</td>
<td>rare local</td>
</tr>
<tr>
<td><strong>Contamination</strong></td>
<td>upper and lower crust</td>
<td>adjacent petilies and OXIF</td>
<td>adjacent petilies</td>
<td>adjacent gneisses</td>
<td>upper crust</td>
<td>local marble and upper crust</td>
</tr>
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<td>not clear</td>
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</tr>
</tbody>
</table>

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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**

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Lesher in press *CJES Spec Issue on LIPs*

### 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)**

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Lesher in press *CJES Spec Issue on LIPs*
Upward Transport: Problem 4

Arndt-Lesher-Czamanske 2005 SEG100

Day et al. 2013 Lithos
Paradox

The paradox of why fine ($\leq 1$ 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

Lesher in press CJES Spec Issue on LIPs

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)
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.

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.
Mixing I.

Transferred 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)

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)
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 10⁶ (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.

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).
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 that deposits 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

Pseudoslags and Pseudolayers

Sulfides may have settled as:

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

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

Countercurrent Flow of Sulfides

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

**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
Sills in Sedimentary Basins

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

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
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

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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 \( \leq 500^\circ C \) will mobilize Ccp >> Po > Pn-Py-Mag-Chr
  
  Deformation at \( \geq 500^\circ C \) 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*)
**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)

**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
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 where 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