Nickel Sulfide Ore Deposits and Impact Melts: Origin of the Sudbury Igneous Complex

Peter C. Lightfoot - January 20, 2017
Some of the Major Debates in Sudbury Geology

1. **Timelines:**
   - Short-lived catastrophic event
   - Uniform long-lived processes

2. **Formation of the SIC and Sudbury Structure:**
   - Explosive endogenic magmatic event
   - Impact cratering
   - Impact melting and differentiation

3. **Source of the magmatic rocks:**
   - Mantle-derived melt
   - Wholesale crustal melting

4. **Formation of the Ni-Cu-PGE sulfide ores:**
   - Primary localization of dense immiscible magmatic sulfide
   - Post-magmatic processes (formation/modification)

5. **Origin of the metals:**
   - Emplacement of sulfides from depth
   - Sourced from the melt sheet

6. **Deformation history:**
   - Relatives roles of different orogenic events
   - Shape and deep configuration of the Sudbury Structure
The Sudbury Event at a 1.85Ga cratonic margin

Lightfoot (2016)
Sudbury Structure - 100+ years of terminology to describe rocks produced by impact process

Lightfoot (2016)
Sudbury Igneous Complex: distribution of Sublayer and Offset Dykes
Deep structure – a preferred model

Objectives

1. Timelines and processes:
   - Sudbury Breccia
   - Offsets
   - Main Mass
   - Sublayer

Sequence of events
1. Diversity in styles of mineralization
2. Linkages between melt sheet processes and ore deposits
   - Source of the metals
   - Thickness of melt sheet
3. Primary magmatic and post-magmatic processes
4. Place Sudbury ores in a global context: past, present, and future
Catastrophic initial impact event recorded in country rocks

Shatter cones

Sudbury Breccia
Geochemical evidence consistent with local derivation from country rocks of the matrix of Sudbury Breccia

Lightfoot (2016); and O’Callaghan et al., (2016)
Discontinuous segmented Offset in proximal Sudbury Breccia (Frood-Stobie)

Stewart and Lightfoot (2012); Lightfoot (2016)
Quartz Diorite “pod” in Sudbury Breccia (Stobie East)
Geological Relationships Within Offset Dykes (Totten)

Mineralization Styles

1. Metagabbro inclusions in mineralized VM(I)QD, some veins and patches of MASU
2. Metagabbro stockwork with veins of sulphide - rich VM(I)QD and pods of SMASU - MASU
3. Stockwork of mineralized M(I)QD veins in Sudbury gabbro megabreccia
4. M(I)QD with DISU, blebbby - disseminated and Cu - rich stringer sulphide

Legend:
- Metasedimentary rocks
- Quartz Diorite
- M(I)QD
- Metagabbro in VM(I)QD
- Sudbury Gabbro
- Halo of Cu-enrichment

Lightfoot (2016) and Lightfoot and Farrow (2002)
Geological relationships at Totten

Lightfoot (2016)
Geochemical relationships at Totten indicate that QD and MIQD were derived from a similar magma type with different sulfide saturation status and inclusion content.

Lightfoot (2016)
The Main Mass in the South Range is strongly deformed

Lightfoot (2016)
Petrography of the South Range Main Mass (Creighton Traverse)
Physical property and chemical stratigraphy of the Creighton traverse

Lightfoot (2016) and Lightfoot and Zotov (2007)
Physical property and chemical stratigraphy of the Creighton traverse

Lightfoot (2016) and Lightfoot and Zotov (2007)
One Main Mass magma type in North and South Ranges

Lightfoot (2016)
The Sublayer: inclusion-rich variably mineralized unit in troughs and embayments at the base of the SIC

Lightfoot (2016)
Distribution and geometry of Sublayer embayment's and troughs

Lightfoot (2016)
Sublayer Granite Breccia
Sublayer Norite

Lightfoot (2016)
Heterogeneity in the composition of Sublayer Norite matrix from different troughs – local inclusion populations are a dominant control on matrix composition

Lightfoot (2016) and Lightfoot et al (1997A)
Petrography of 1.85Ga (U-Pb zircon, baddeleyite) ultramafic inclusions

Lightfoot (2016) and Corfu and Lightfoot (1996)
Sequence of events

### Timeline and sequence of events at Sudbury

(a brave view)

**Lightfoot (2016)**

<table>
<thead>
<tr>
<th>Event Description</th>
<th>Time After 1850Ma Impact Event</th>
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<tbody>
<tr>
<td>Impact</td>
<td>-0 sec</td>
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<tr>
<td>Transient crater</td>
<td>10^-15</td>
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<tr>
<td>Rim collapse &amp; uplift</td>
<td>10^-14</td>
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<tr>
<td>Sudbury breccia formation</td>
<td>10^-13</td>
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<tr>
<td>Shock crystallization (shatter cones)</td>
<td>10^-12</td>
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<tr>
<td>Melt sheet initiation</td>
<td>10^-11</td>
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<tr>
<td>Injection of QD into offsets</td>
<td>10^-10</td>
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<tr>
<td>Initiation of sulfide saturation in melt sheet</td>
<td>10^-9</td>
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<tr>
<td>Injection of IQD into offsets</td>
<td>10^-8</td>
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<tr>
<td>Sublayer norite &amp; granite breccia formation</td>
<td>10^-7</td>
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<tr>
<td>Mafic norite crystallisation</td>
<td>10^-6</td>
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<tr>
<td>Norite crystallisation</td>
<td>10^-5</td>
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<td>Granophyre crystallisation</td>
<td>10^-4</td>
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<td>Gabbro crystallisation</td>
<td>10^-3</td>
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<td>Onaping fall back breccia</td>
<td>10^-2</td>
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<td>Onaping melt bodies</td>
<td>10^-1</td>
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<td>Onaping reworked sediments</td>
<td>0 Ma</td>
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<tr>
<td>Onwatin formation</td>
<td>10 Ma</td>
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<tr>
<td>VMS formation</td>
<td>100 Ma</td>
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<tr>
<td>Breccia belt ores</td>
<td>1000 Ma</td>
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<tr>
<td>Contact ores</td>
<td>10,000 Ma</td>
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<tr>
<td>Footwall ores</td>
<td>1 Ma</td>
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<tr>
<td>Crater-wall readjustment</td>
<td>10 Ma</td>
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<tr>
<td>Chelmsford formation</td>
<td>100 Ma</td>
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</tbody>
</table>
Objectives

1. Timelines and processes:
2. Diversity in styles of mineralization
   - Contact and footwall (Creighton and Victor)
   - Offsets (Copper Cliff)
3. Linkages between melt sheet processes and ore deposits
4. Primary magmatic and post-magmatic processes
5. Place Sudbury ores in a global context: past, present, and future
The Creighton Deposit

Graph showing the production of Ni and Cu in ore produced over time, with markers for discovery, shaft sinking, open pit production, and underground production.
The Creighton Deposit

Lightfoot (2016)

With permission: Archives of Ontario
Good examples of displacement of contact ores along structures (but are some of the ore bodies primary?)

Lightfoot (2016)
Creighton Deep

Contact sulfide
Transitional sulfide
Footwall sulfide
Norite
Sublayer Norite
Sudbury Breccia
Black granite porphyry
Creighton Pluton
Huronian
Fault

*Sulfide ore bodies are projected onto geological section.

400 OB: 5.7 %Ni – 3.5 %Cu – 1.1 g/t 3E over 35 m true width

461 OB: 2.1 %Ni – 5.7 %Cu – 5.3 g/t 3E over 10 m true width

310 OB: 5.2 %Ni – 2.7 %Cu – 2.5 g/t 3E over 20 m true width

320 OB: 2.6 %Ni – 4.6 %Cu – 4.8 g/t 3E over 10 m true width

Lightfoot (2016) with special thanks to Rob Pelkey
Sulfides become richer in Pn+Cpy and develop a higher Cu/(Cu+Ni) with distance down a trough.
Compositional diversity in Sulfide ores is a function of host rock

Lightfoot (2016)
East Range – Victor Mineral System

Lightfoot (2016)
Mineralogy of the Massive Sulfides at Victor
Typical contact sulfide mineralogy

Lightfoot (2016)
Transitional to Footwall Sulfide Mineralogy
Compositional diversity at Victor

Lightfoot (2016)
The Copper Cliff Deposit
Copper Cliff – relationship to the melt sheet

Interpreted base of Sudbury Igneous Complex (projected)

Contact / Funnel-style deposits now eroded away

Current erosional level

Gord’s Fault

Kelly Lake

Evans Fault

Kerry Lake Orbodies

880 Structure

Creighton Fault

Cliff Lake Fault

Looking West. Ore bodies projected onto N-S long section of Offset Dyke

Lightfoot (2016)
Styles of Mineralization at Copper Cliff
Compositional diversity

Figure A: South Range Mineral Systems

Figure B: Copper Cliff Offset

Figure C: Copper Cliff Offset

(C) Copper Cliff 790–810 Orebodies—low tenor

D Copper Cliff 790–810 Orebodies—high tenor

Lightfoot (2016)
## Generalised Paragenesis

<table>
<thead>
<tr>
<th>Minerals</th>
<th>Early magmatic</th>
<th>Intermediate magmatic</th>
<th>Post-magmatic</th>
<th>Ore deposit environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSHPM*</td>
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<td>Contact sulfides</td>
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<tr>
<td>Arsenides</td>
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<td>Transitional sulfides</td>
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<td>Granular pentlandite</td>
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<td>Footwall sulfides</td>
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<td>mss*</td>
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<td>Offset and Breccia Belt sulfides</td>
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<td>Pyrrhotite</td>
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<td>Flame pentlandite</td>
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<td>Pyrite</td>
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<td>Chalcopyrite</td>
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<td>Cubanite</td>
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<td>iss*</td>
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<td>Millerite</td>
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<td>Bornite</td>
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<tr>
<td>Native silver</td>
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<tr>
<td>Native gold</td>
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<tr>
<td>LSHPM*</td>
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<tr>
<td>Sphalerite-galena</td>
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<td>Violarite</td>
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</tbody>
</table>

LSHPM - Low sulfide high precious metals  
HSHPM - High sulfide high precious metals  
mss - Monosulfide solid solution  
iss - Intermediate solid solution
Dominant magmatic sulfide compositions at Sudbury
Compositional diversity in Sulfides explained by Fractionation and inherent “nugget effect”

Lightfoot (2016)
Objectives

1. Timelines and processes:
2. Diversity in styles of mineralization
3. Linkages between melt sheet processes and ore deposits
   - Source of the metals
   - Thickness of melt sheet
4. Primary magmatic and post-magmatic processes
5. Place Sudbury ores in a global context: past, present, and future
Distribution of ore deposits is not uniform around the basin

Lightfoot (2016)
Thickness of the Main Mass Ni-Cu-PGE-depleted norite sequence

Lightfoot (2016)
Variations in Ni, Cu, Pt, and Pd through the Main Mass (North Range)
Ni-Cu(PGE)-depleted norites occur throughout the Main Mass stratigraphy.
Relationship between melt sheet thickness and scale of mineral systems

Lightfoot (2016)

- Thick norite unit, 50 ppm missing Ni
  - 0.6 km³ magma
  - 2x10⁸ tonnes melt
  - 0.01x10⁸ tonnes Ni lost
  - At 2% Ni grade, 0.6x10⁸ tonnes ore

- Thin norite unit, 50 ppm missing Ni
  - 0.6 km³ magma
  - 2x10⁸ tonnes melt
  - 0.01x10⁸ tonnes Ni lost
  - At 2% Ni grade, 0.6x10⁸ tonnes ore

Onaping Formation  Target rocks  Large convection cell
Melt sheet  Localization of sulphide melt  Small convection cell
Offset Dykes

FS

10 km
Scale and quality of mineral system is a function of norite thickness.
Main Mass record as prospectivity tool

Lightfoot (2016)
Objectives

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4. Primary magmatic versus post-magmatic processes
5. Place Sudbury ores in a global context: past, present, and future
Low sulfide mineralization styles tend to be associated with magmatic ore systems (e.g. Nickel Rim).
Deformation undoubtedly modifies and re-distributes contact ores (e.g. Garson Deposit)

Lightfoot (2016) and Mukwakwami et al (2012)
Understanding displacement on structures is critical to future discovery

Lightfoot (2016)
Objectives

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Despite being eclipsed by the Noril’sk Camp, Sudbury remains the second largest resource of magmatic Ni sulfide.
History of sulfide nickel discovery

Lightfoot (2016)
Historic production at Sudbury

- Contained Ni in ore
- Average Cu grade (wt%)
- Average Ni grade (wt%)

Historical Events:
- 1866 First Sudbury Mine
- 1914-1918 WWI
- 1926 Start of Flood Mine
- 1929 Depression
- 1938-1945 WWII
- Cold war nickel demand
- 1959 Mining at Tahanco Hills
- 1978 Strike
- 1981-2 Recession
- 2010 Strike

Lightfoot (2016)
Effective exploration is required to populate the project pipeline and secure new mines at Sudbury.

<table>
<thead>
<tr>
<th>Concept inception</th>
<th>Regional exploration</th>
<th>Discovery</th>
<th>Exploration to confirm potential scope</th>
<th>Discovery shown to have potential economic significance</th>
<th>Definition of ore body (resources)</th>
<th>Pre-feasibility study</th>
<th>Delineation (reserves)</th>
<th>Feasibility study</th>
<th>Mine development</th>
<th>Near-mine exploration to sustain production</th>
</tr>
</thead>
</table>

**Graphical Representation**

- **Project Risk**
  - High
  - Low

- **Expenditure**
  - High
  - Low

- **Time**

*Lightfoot (2016)*
The Sudbury sulfide ores have a competitive advantage in grade as well as metal value over laterites

Lightfoot (2016)
Thank you

- Students (Sudbury projects): Mark Cooper, James Darling, Keith Farrell, Kathy Hattie, Grant Mourre, Mars Napoli, Jon O’Callaghan, Kostas Papapavlou, Aaron Venables, and Yu-Jian Wang
- Co-investigators: Reid Keays, Chris Hawkesworth, Tony Naldrett, Mike Lesher, Steve Barnes, Ed Ripley, Ulrich Riller, Dan Kontak, Gord Osinski, Bob Linnen, Fernando Corfu, Will Doherty, Steve Prevec, Mei-Fu Zhou, Igor Zotov
- Industry: Vale (special recognition to the many exploration staff)
- Graphic design: Alex Gagnon
- Preparation and photography of samples: Ben Vandenburg