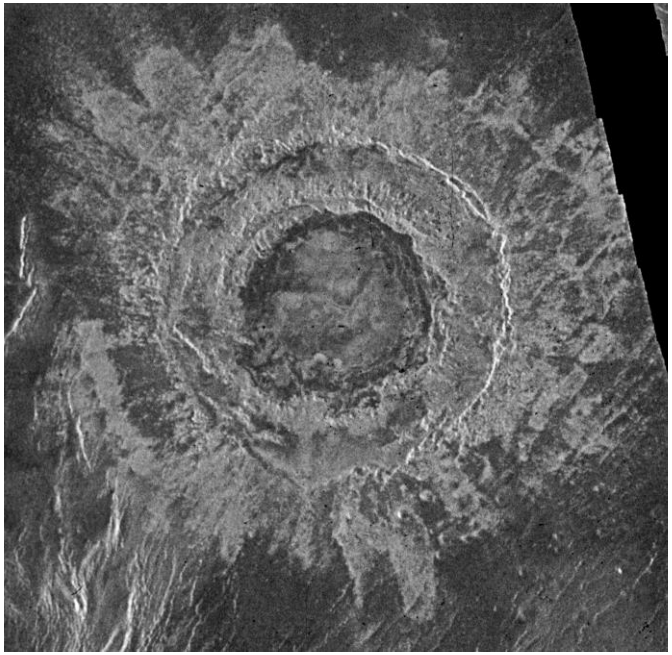
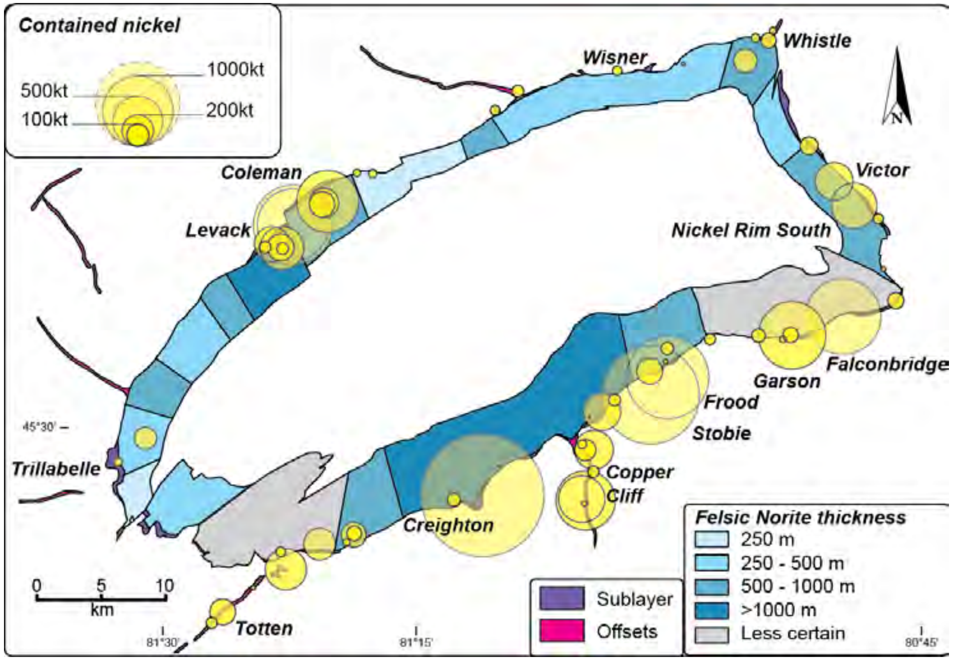




Nickel Sulfide Ore Deposits and Impact Melts: Origin of the Sudbury Igneous Complex

Peter C. Lightfoot - January 20, 2017

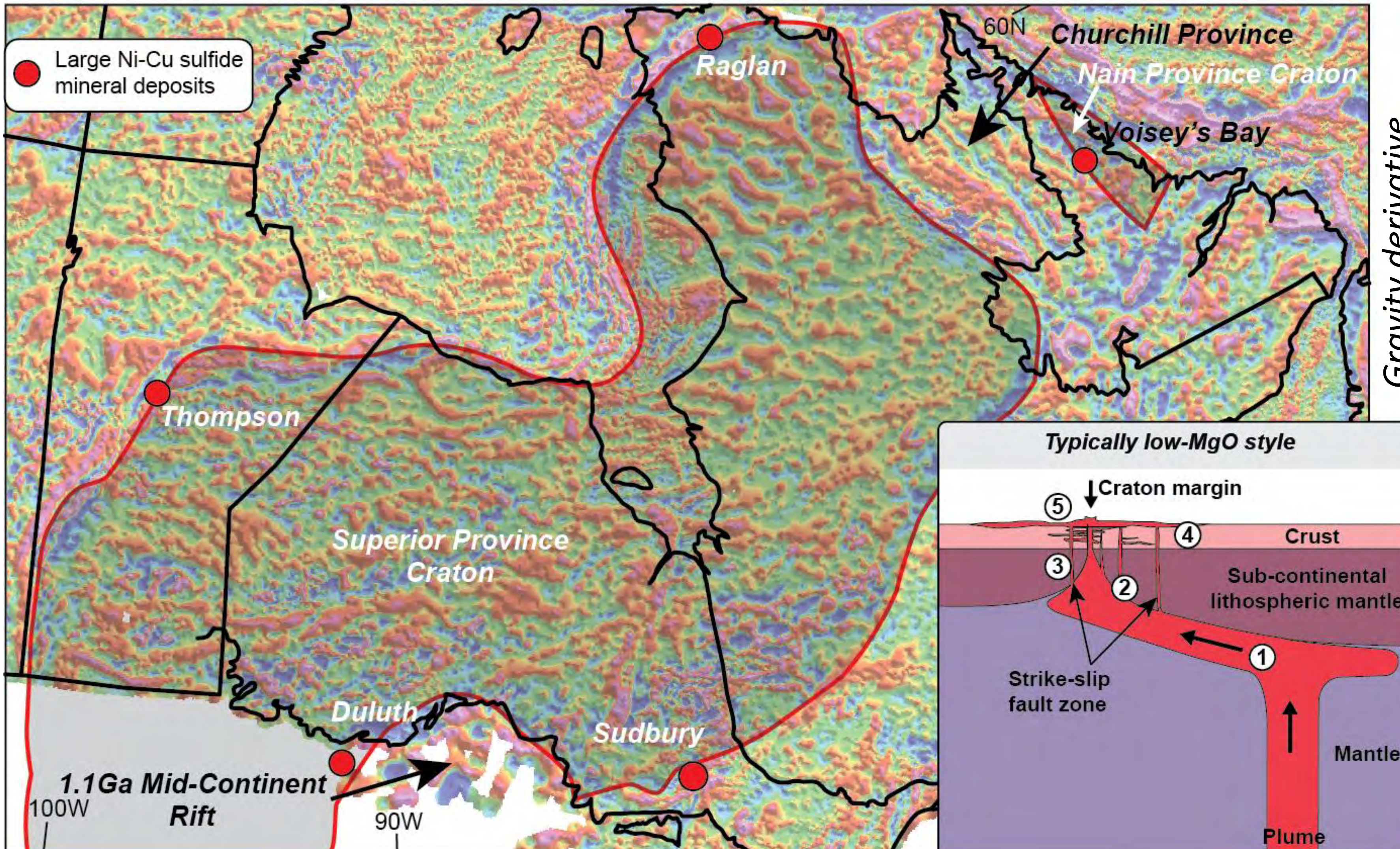
Lightfoot GEOSCIENCE

Project review | Interpretation | Strategy | Training

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

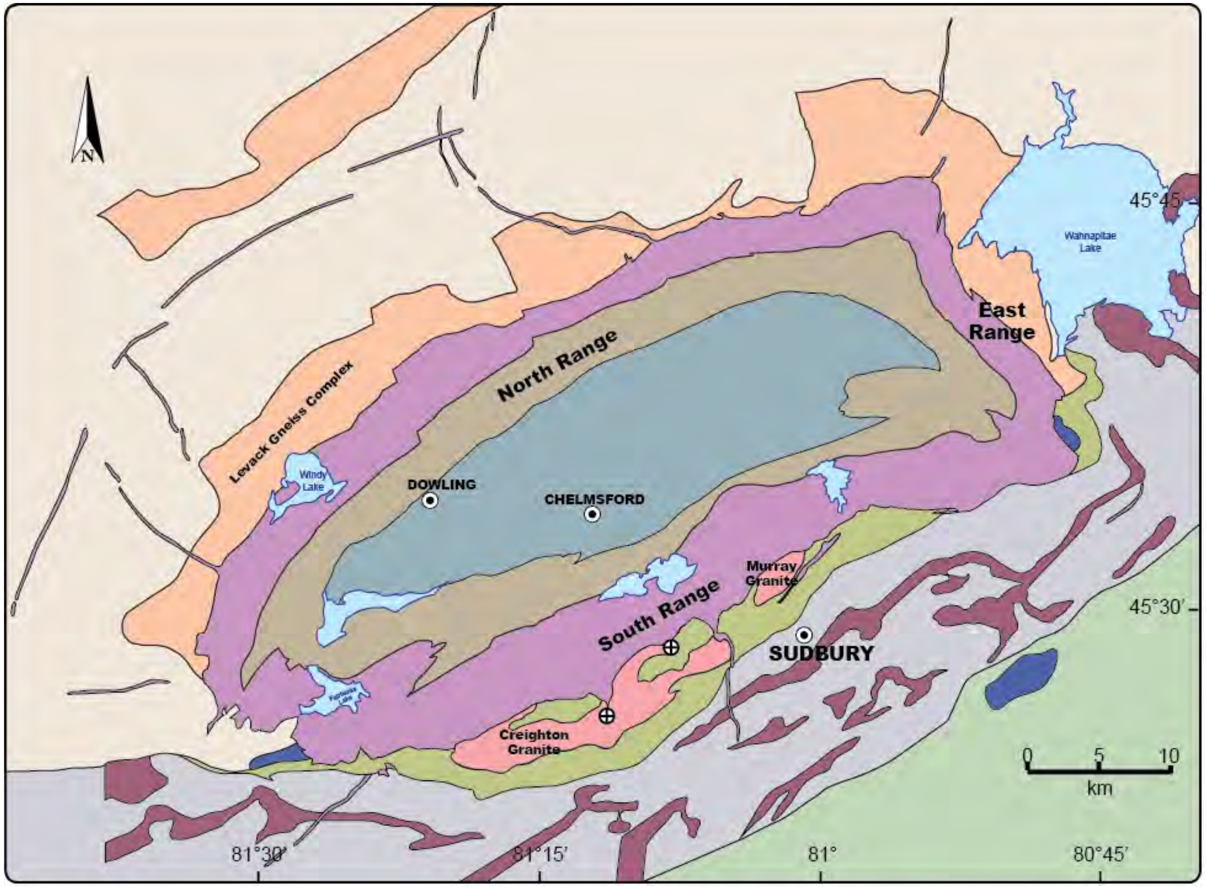
The Sudbury Event at a 1.85Ga cratonic margin

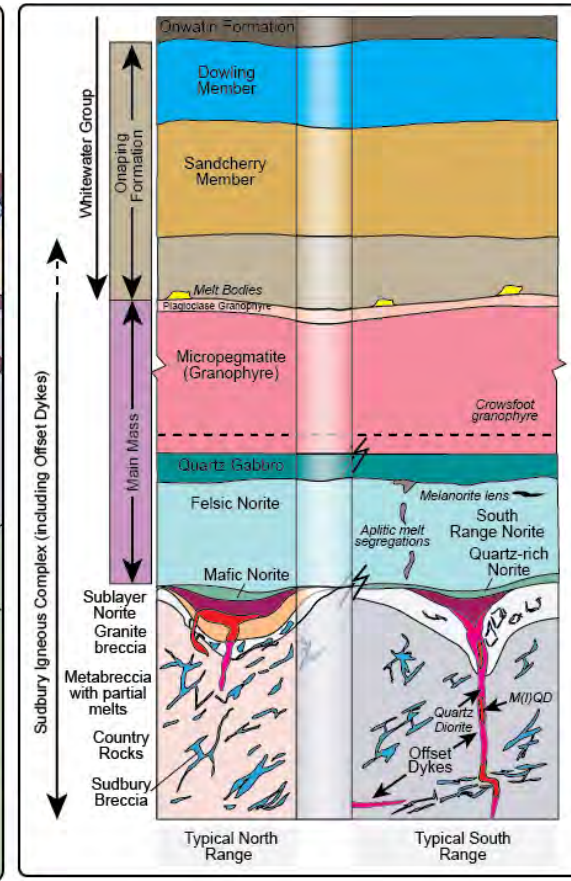


Gravity derivative

Lightfoot (2016)

Sudbury Structure - 100+ years of terminology to describe rocks produced by impact process

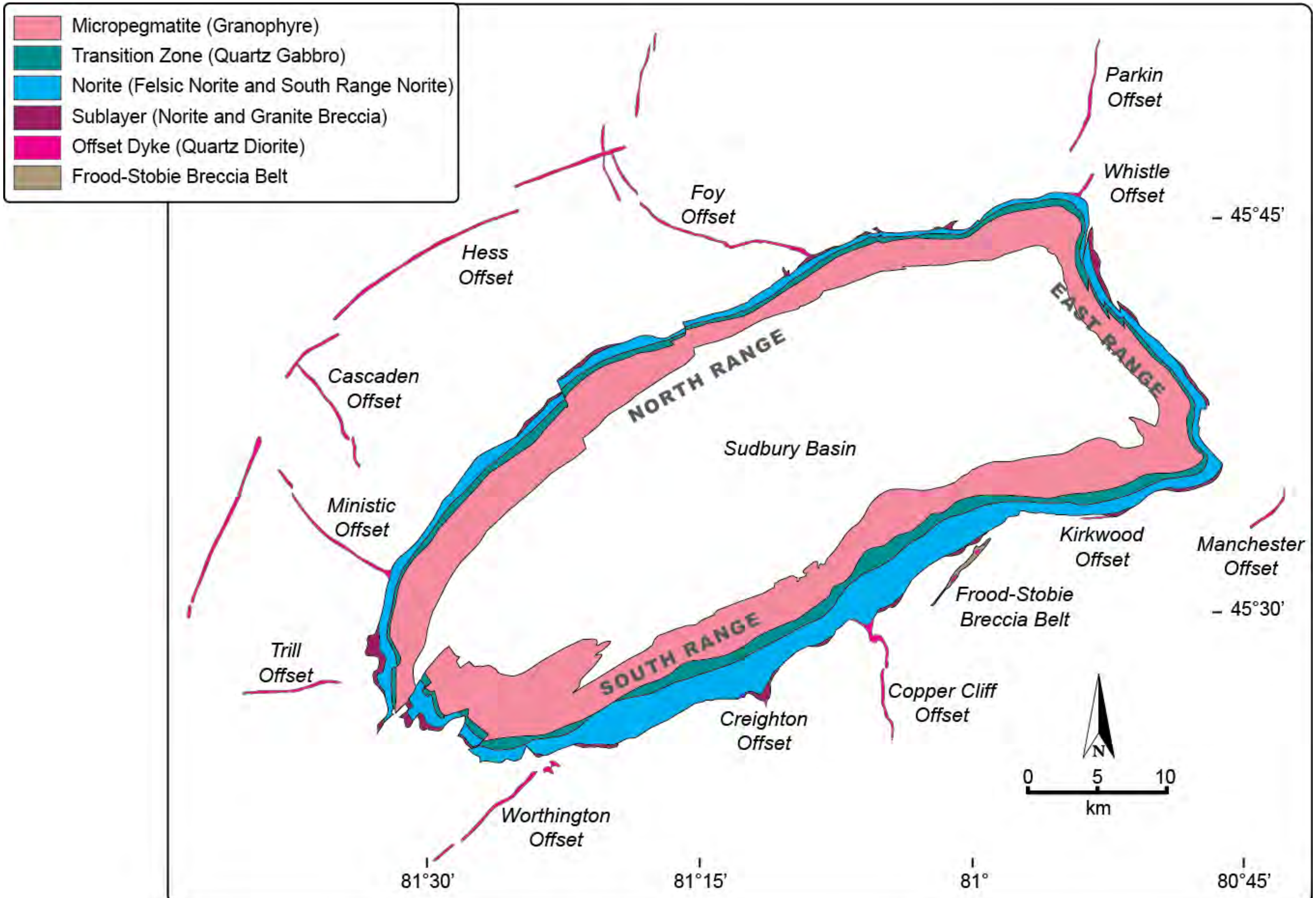




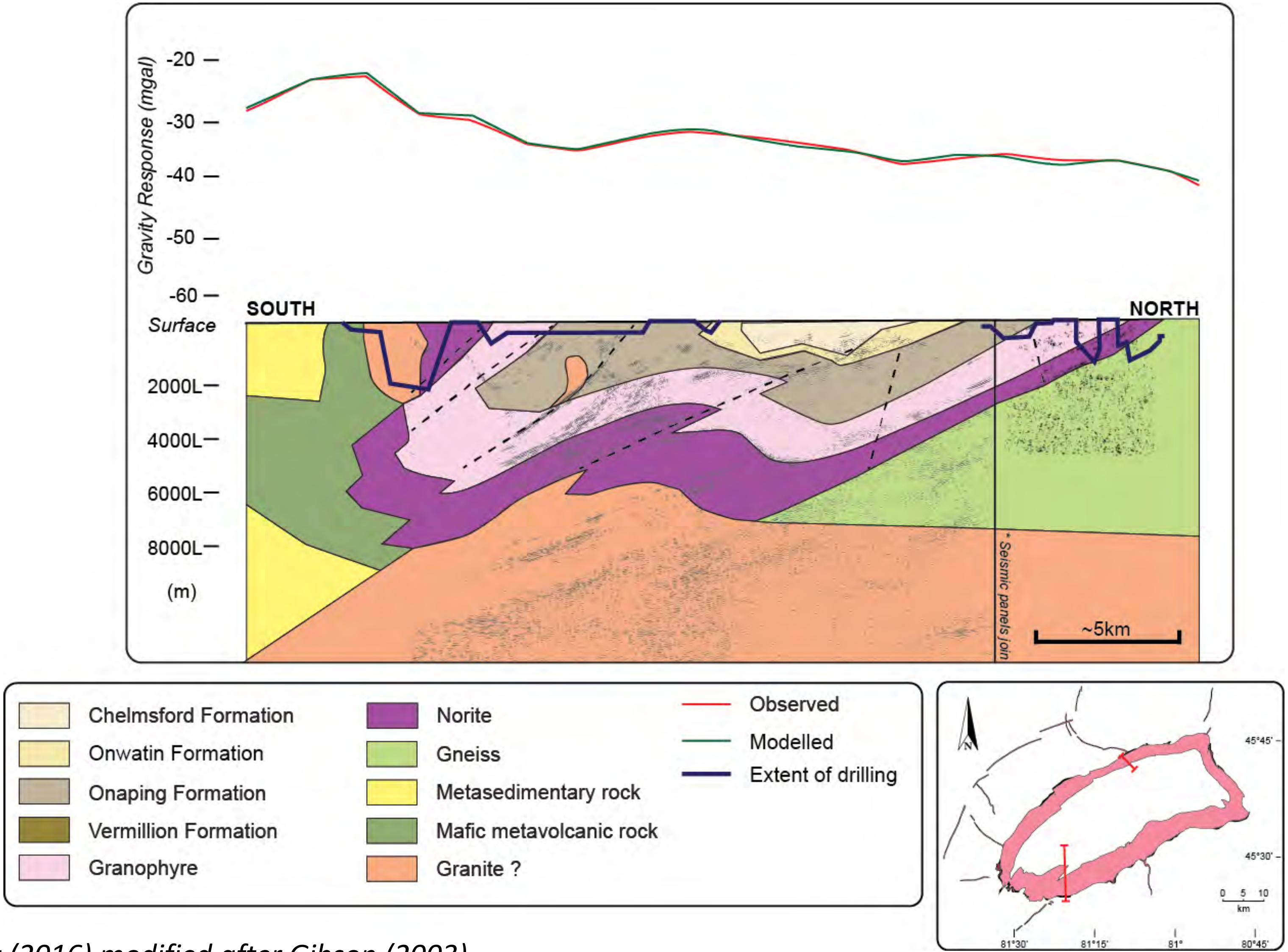
- Grenville gneiss
- Onwatin and Chelmsford Formation
- Onaping Formation
- Sudbury Igneous Complex
- Nipissing diabase and Sudbury Gabbro
- Metasedimentary rock
- Mafic and felsic volcanic rock
- Mafic and intermediate gneiss
- Creighton and Murray granite
- Early Proterozoic Mafic intrusions
- Archean granitoid rocks and gneisses
- ⊕ Inclusions of gneiss in Sudbury Breccia (South Range)

Lightfoot (2016)

Sudbury Igneous Complex: distribution of Sublayer and Offset Dykes



Deep structure – a preferred model



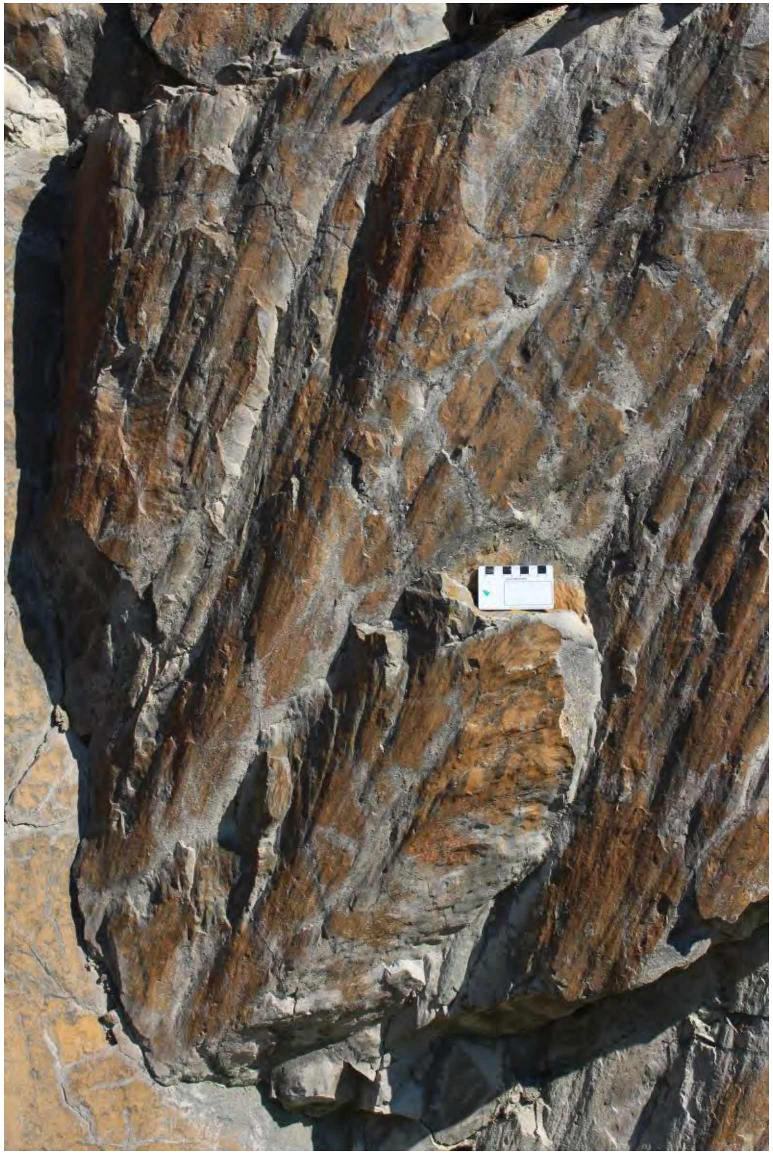
Lightfoot (2016) modified after Gibson (2003)

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

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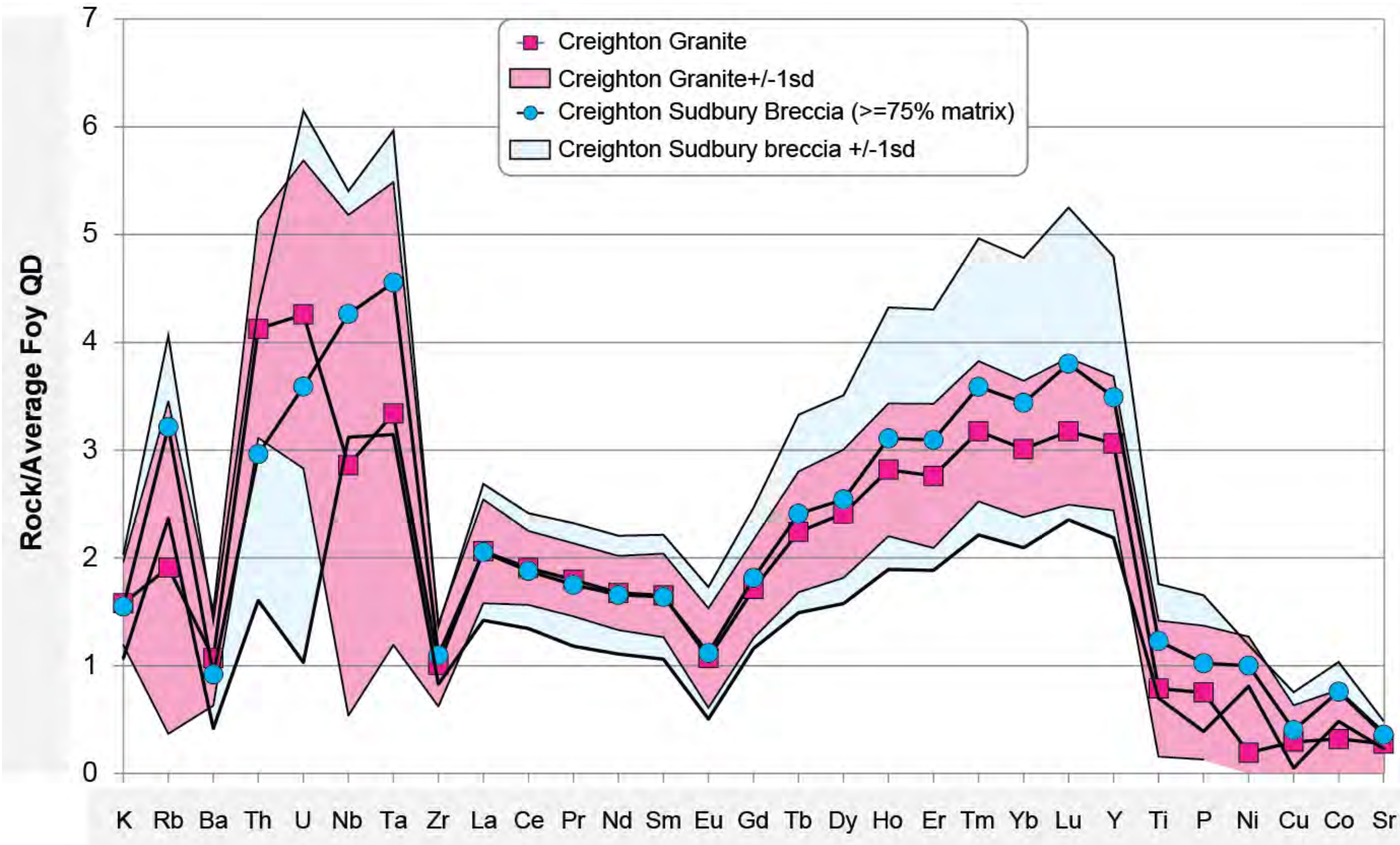
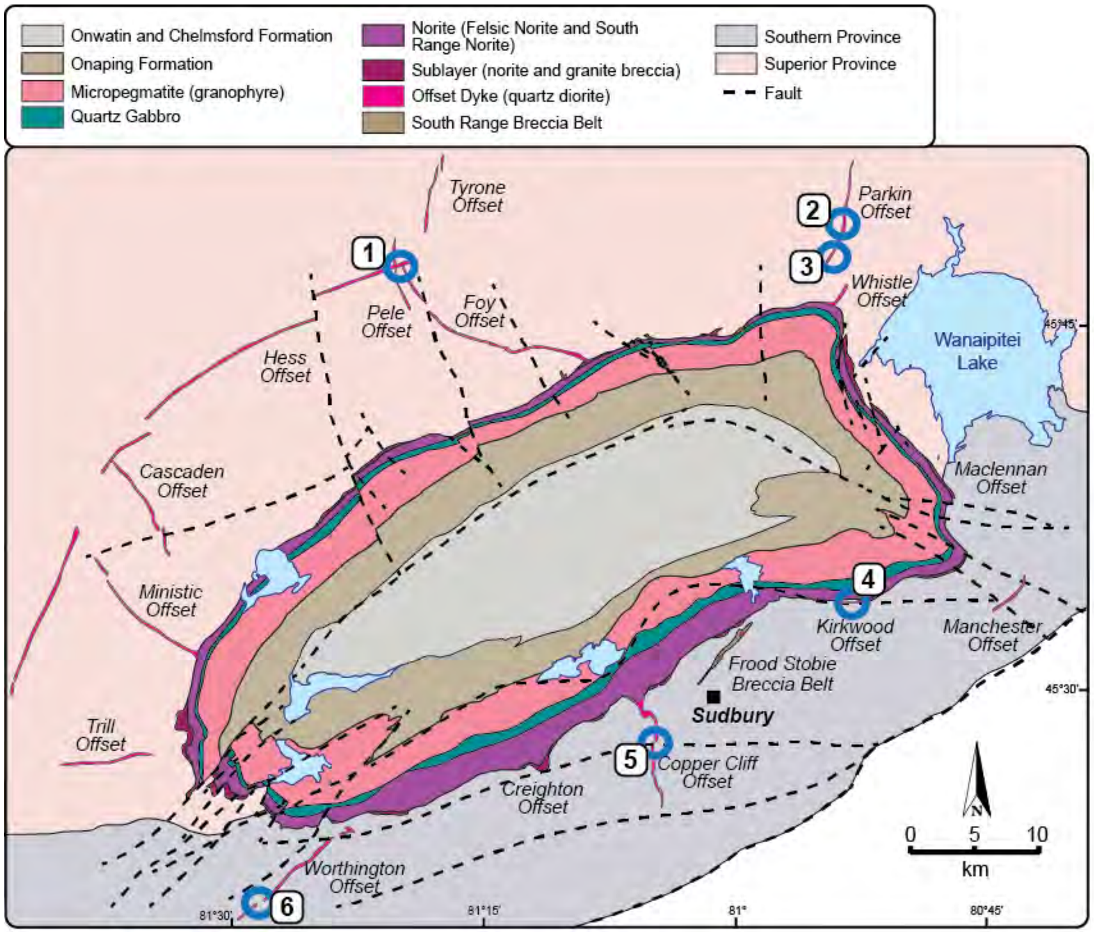
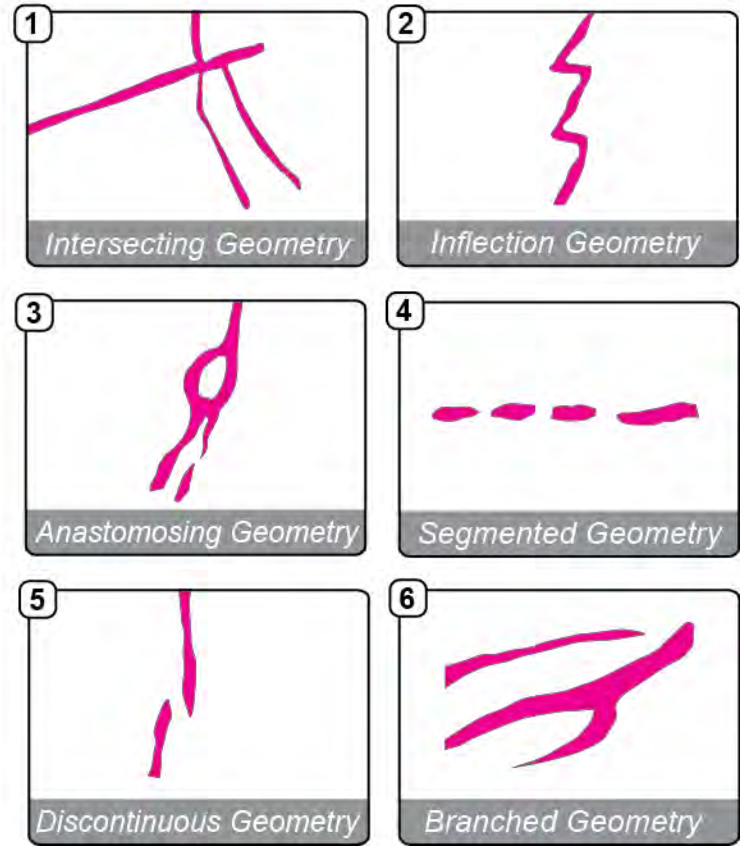


Lightfoot (2016); and O'Callaghan et al., (2016)

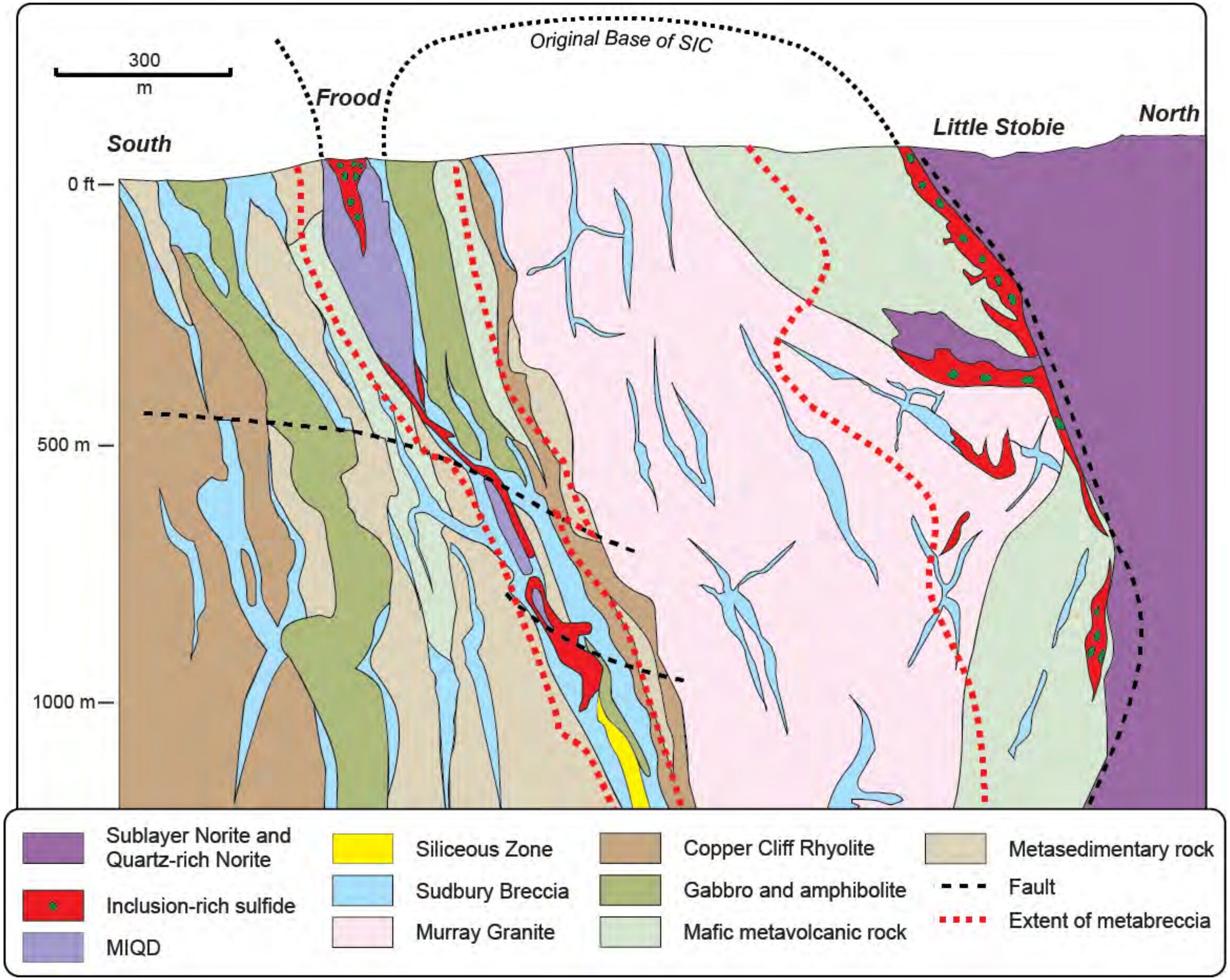
Quartz Diorite Offset Distribution and Configuration





Lightfoot (2016)

Discontinuous segmented Offset in proximal Sudbury Breccia (Frood-Stobie)



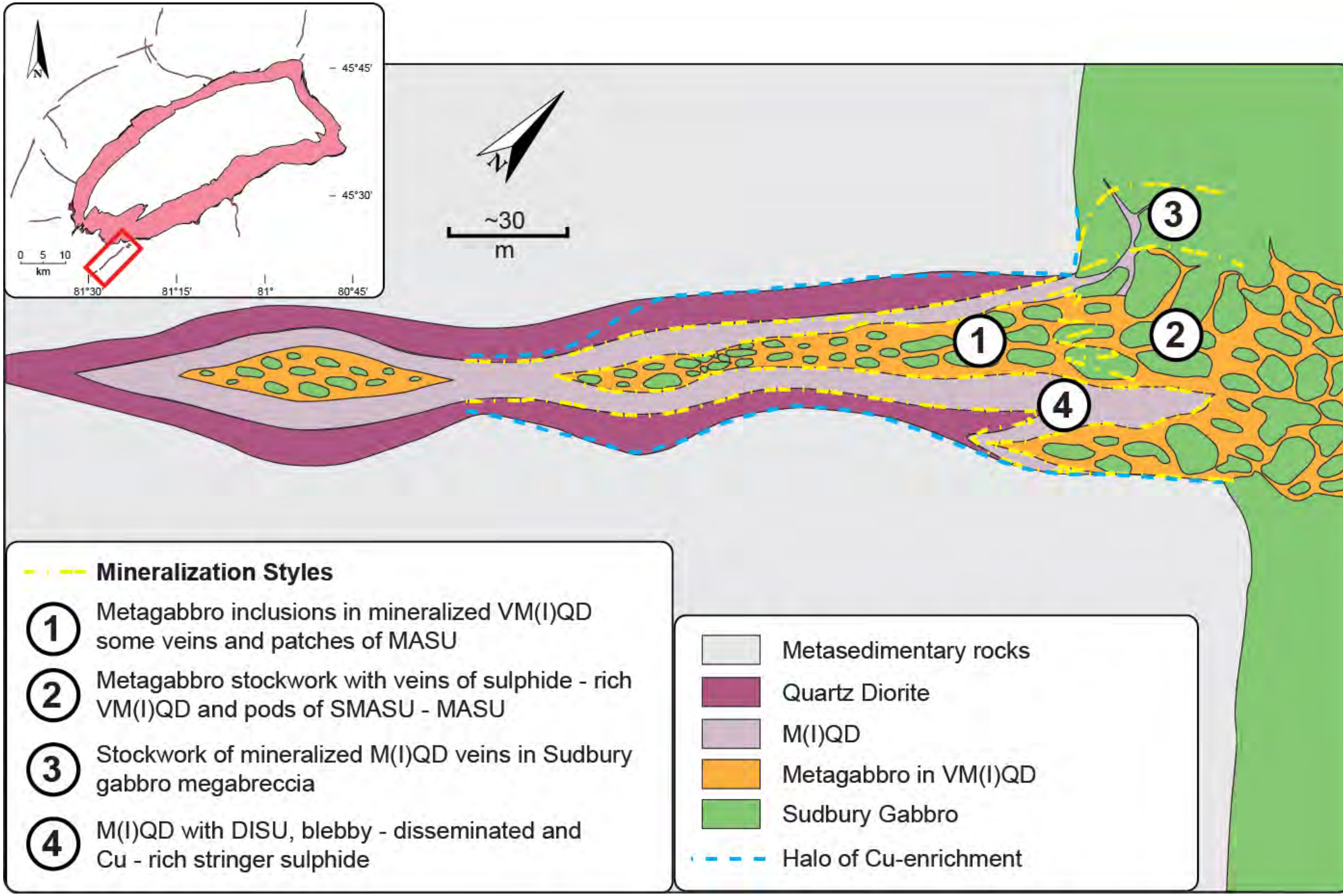
Stewart and Lightfoot (2012); Lightfoot (2016)

Quartz Diorite “pod” in Sudbury Breccia (Stobie East)

Lightfoot GEOSCIENCE

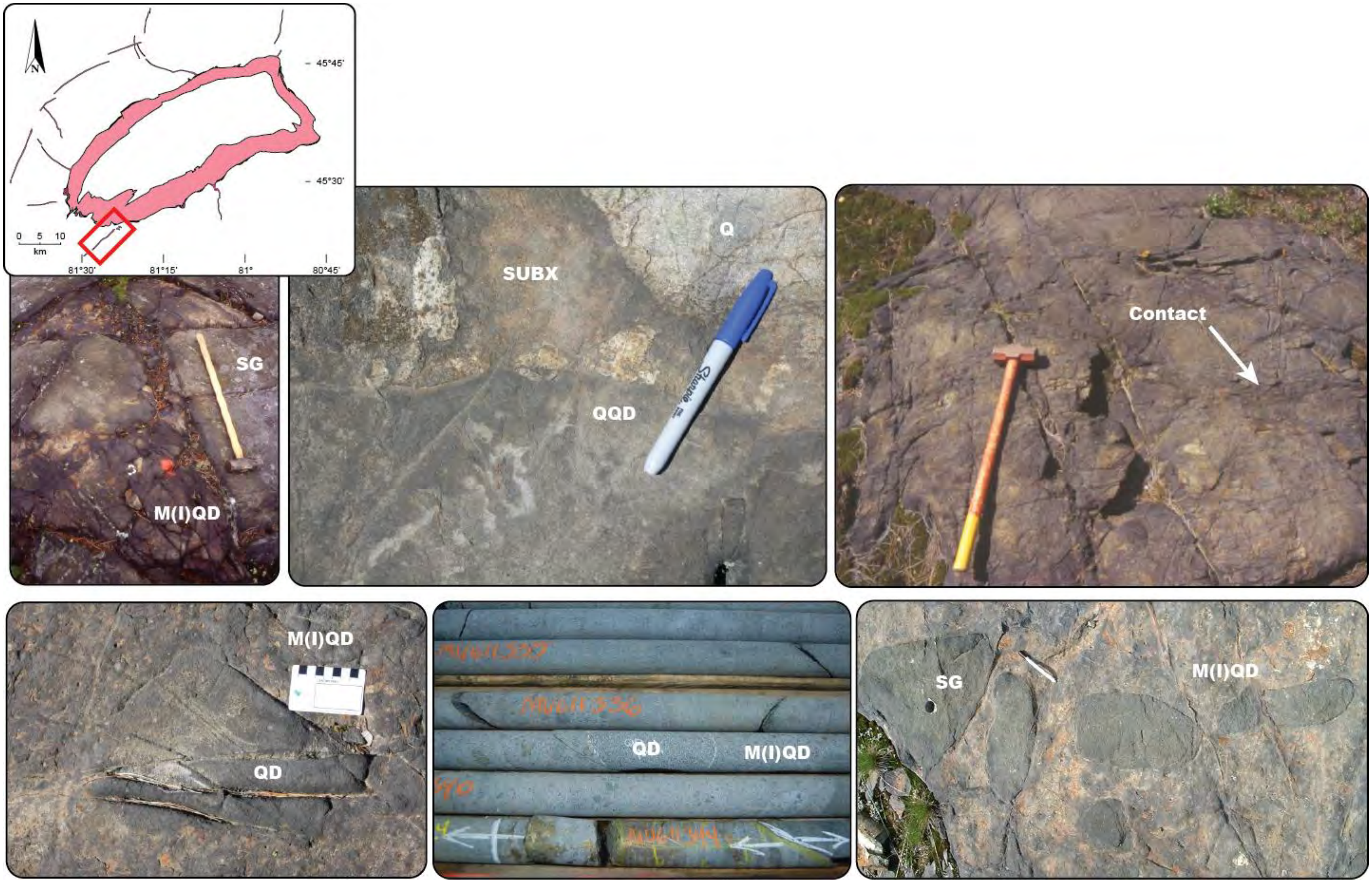
Geological Relationships Within Offset Dykes (Totten)

Lightfoot GEOSCIENCE



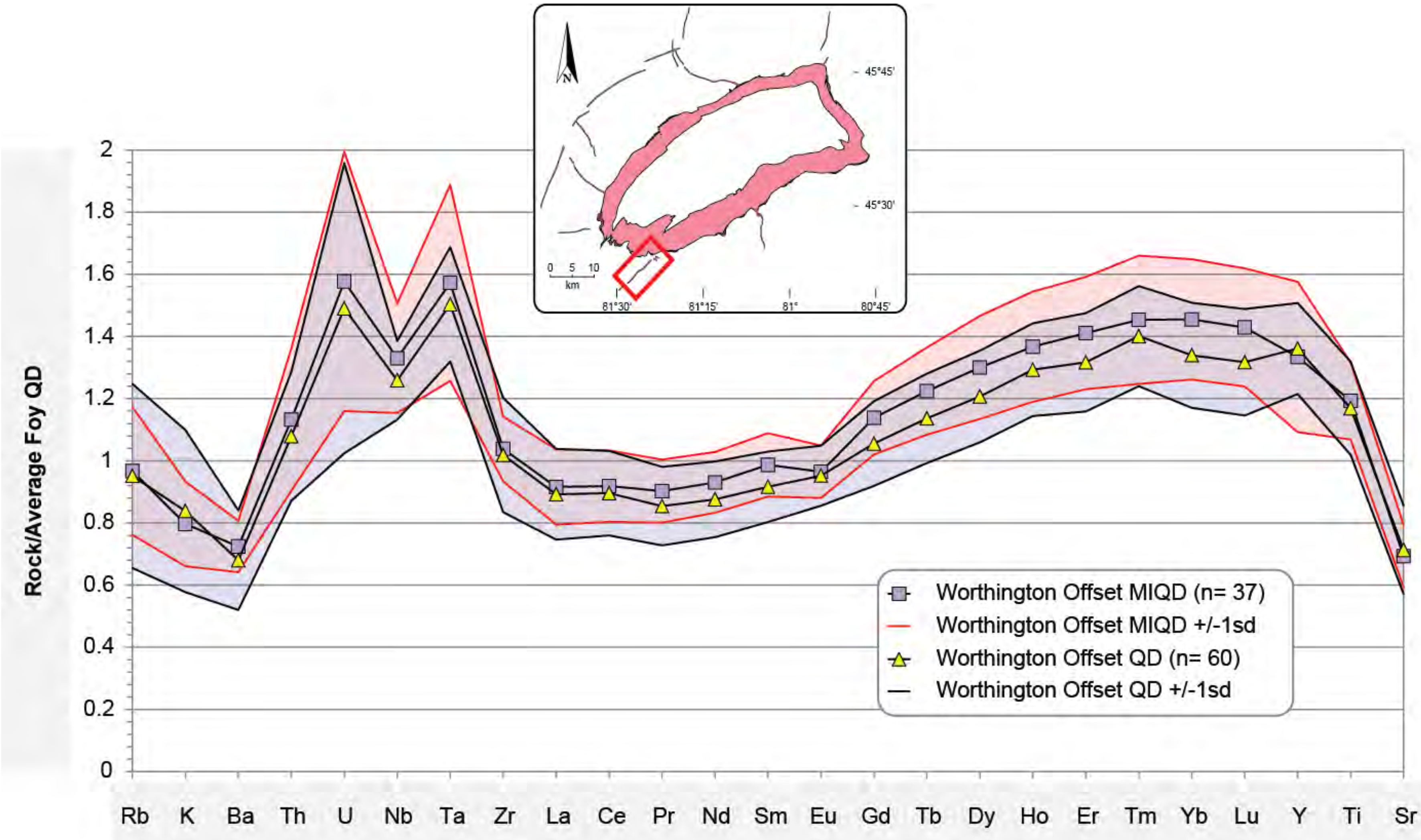
Lightfoot (2016) and Lightfoot and Farrow (2002)

Geological relationships at Totten



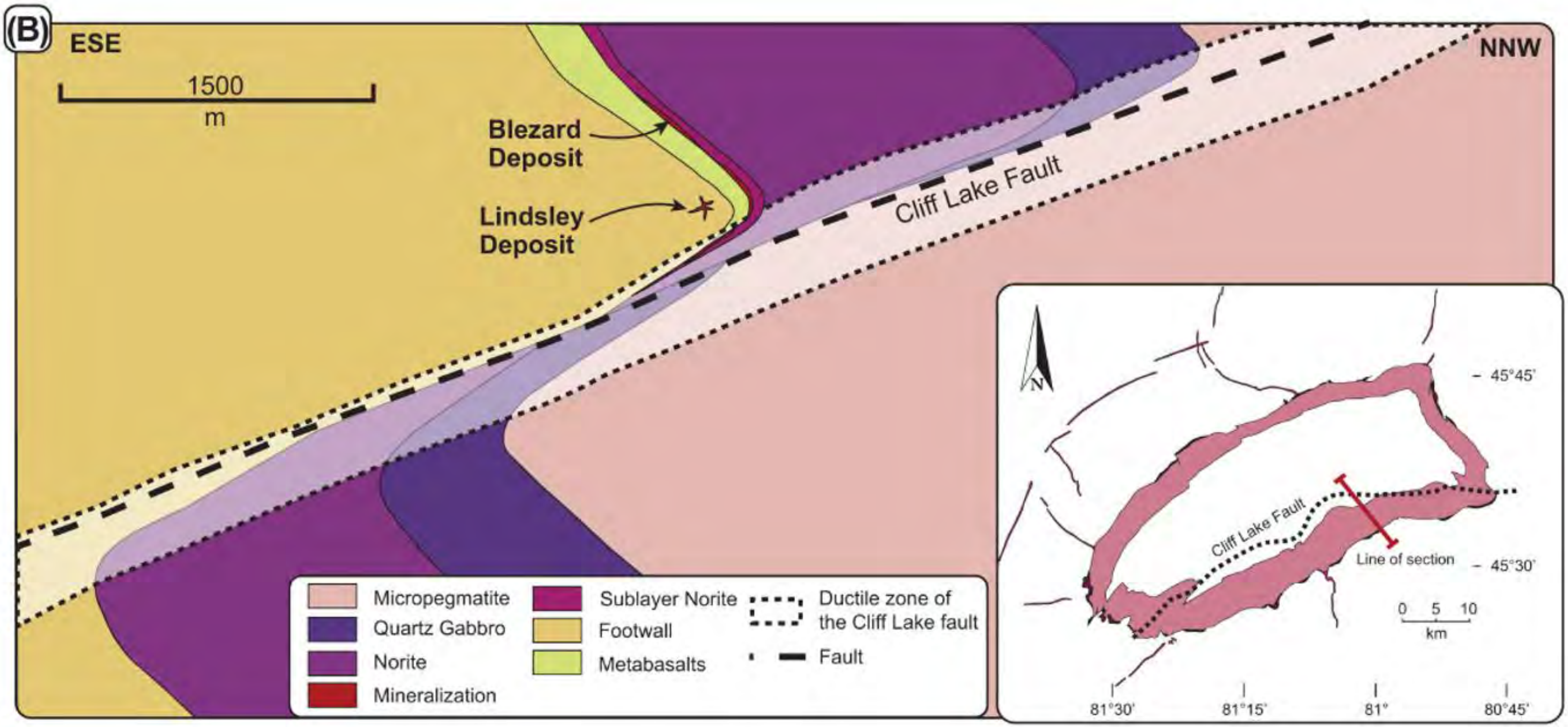
Lightfoot (2016)

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



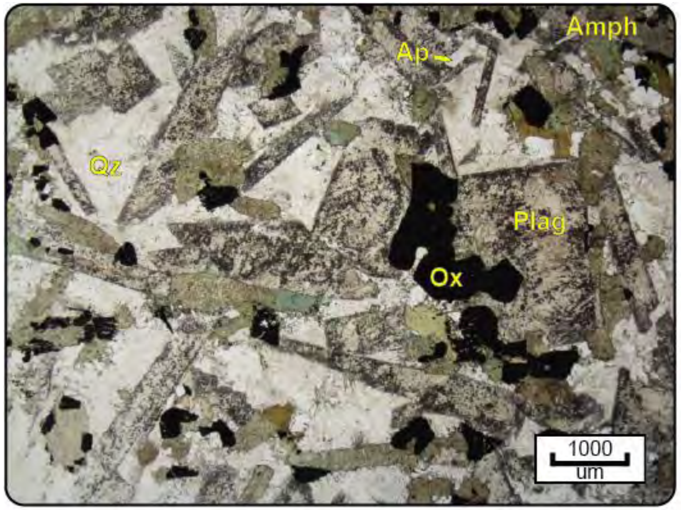
Lightfoot (2016)

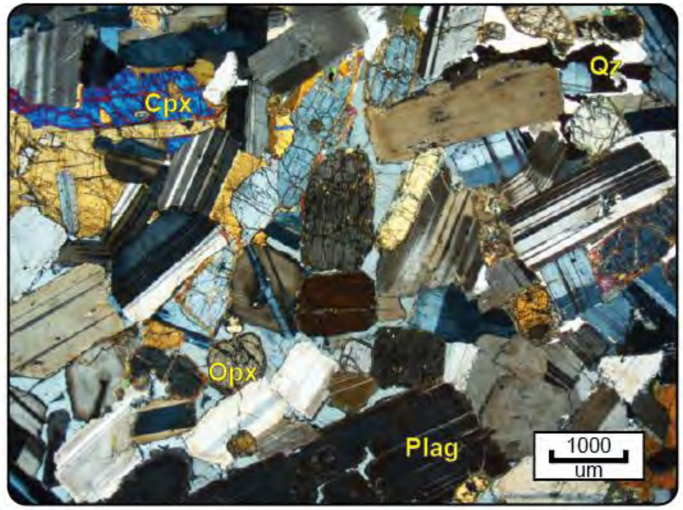
The Main Mass in the South Range is strongly deformed

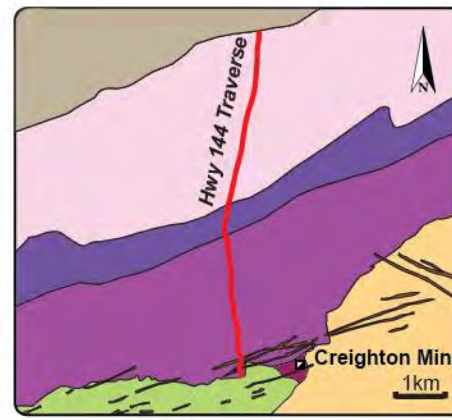


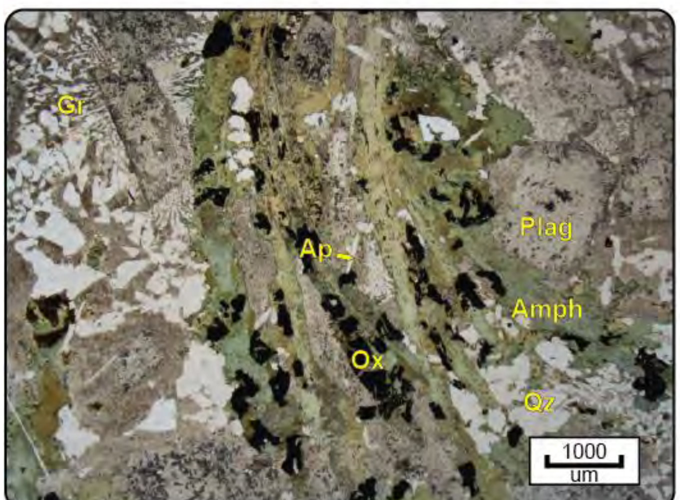
Lightfoot (2016)

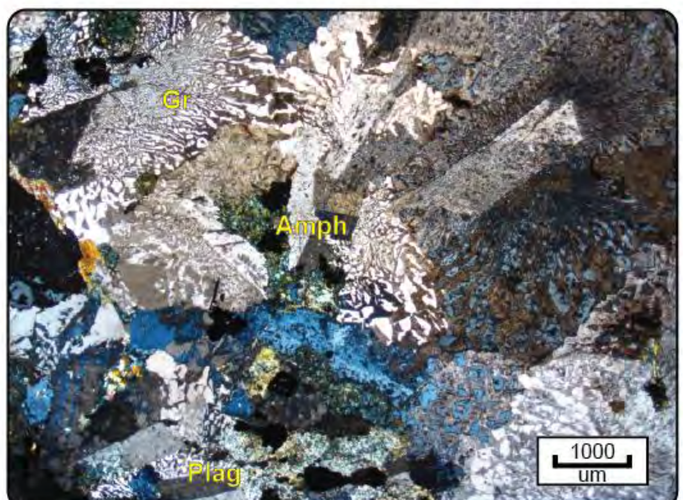
Petrography of the South Range Main Mass (Creighton Traverse)





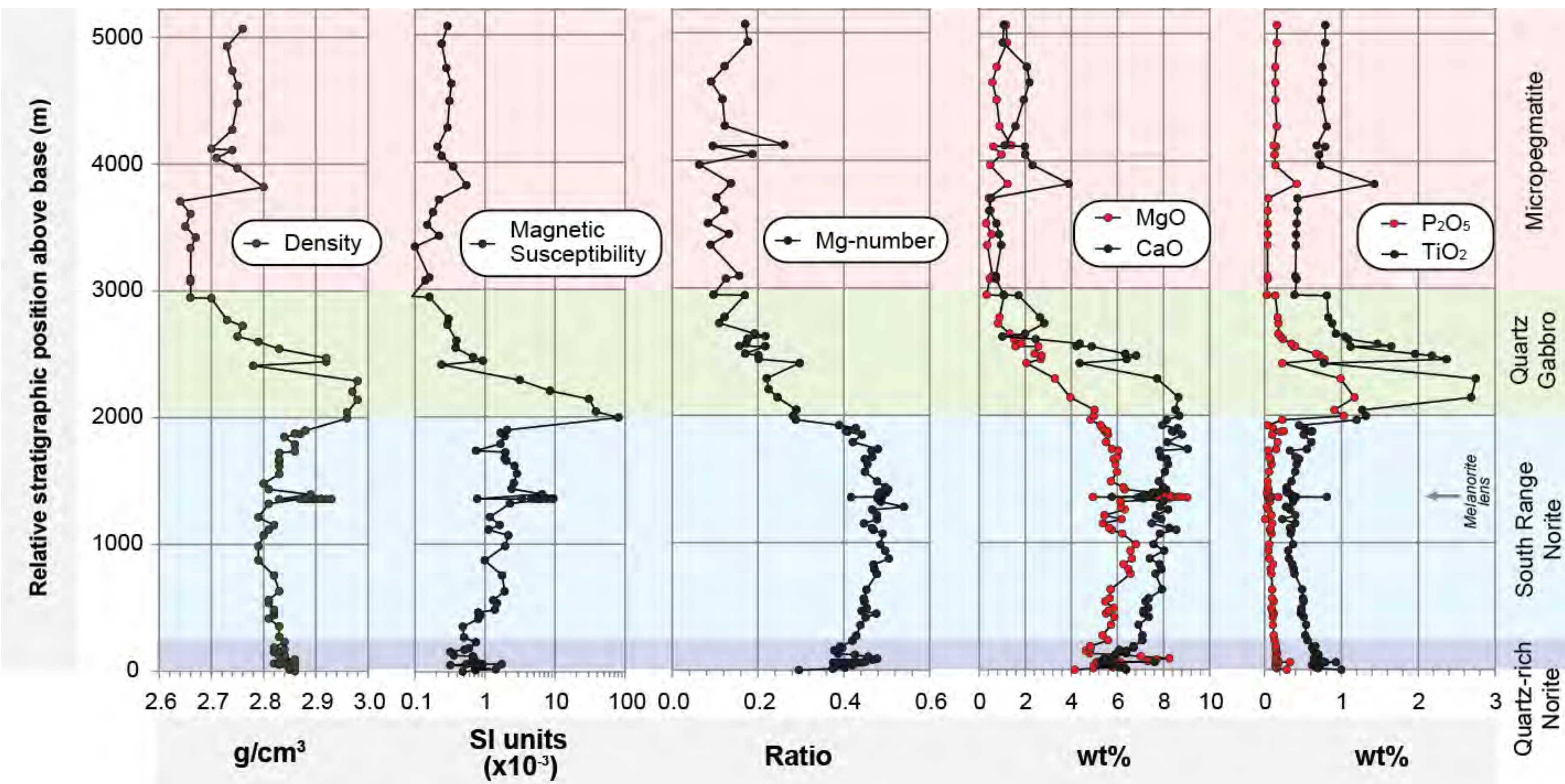






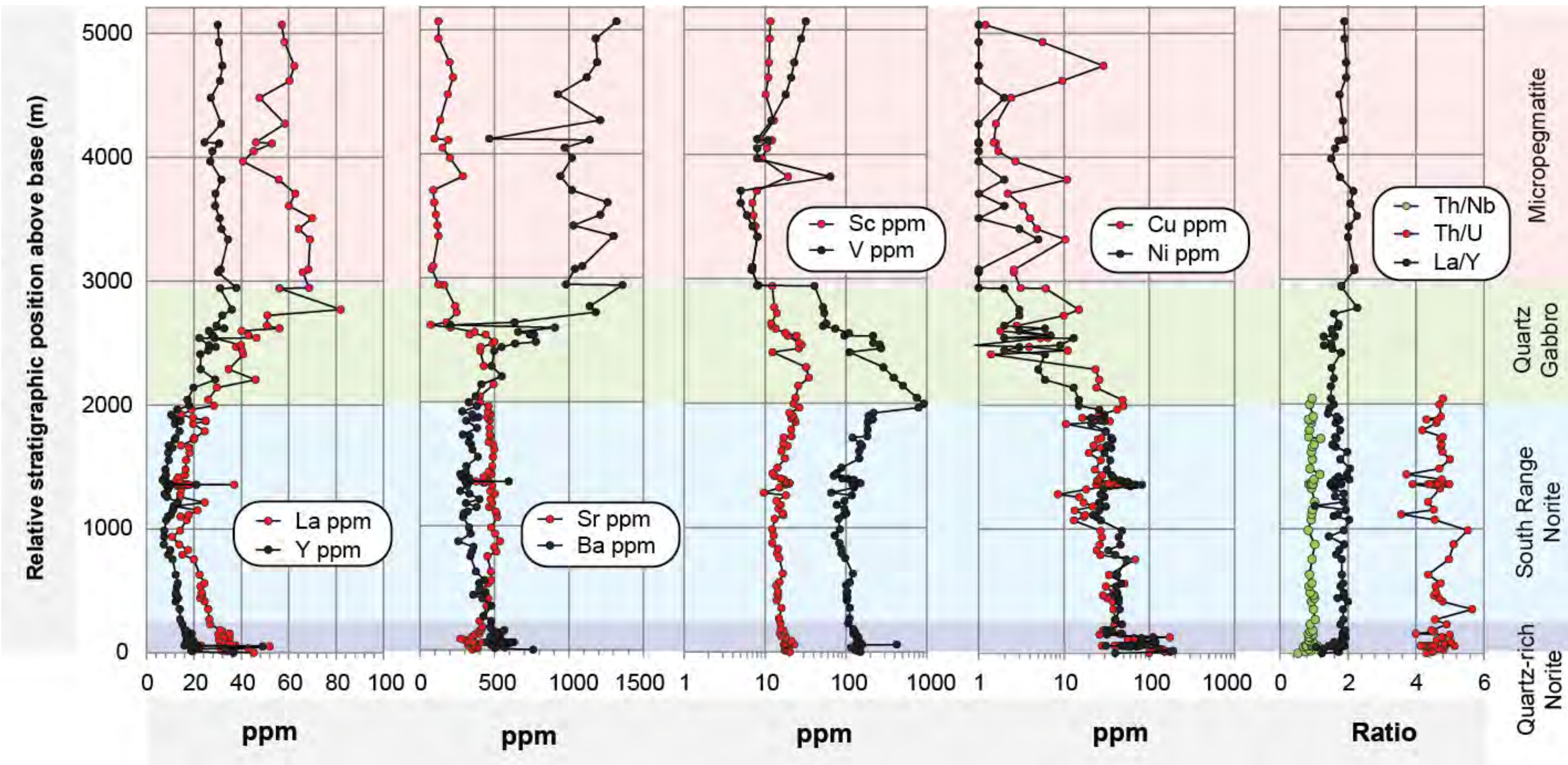
Lightfoot (2016)

Physical property and chemical stratigraphy of the Creighton traverse



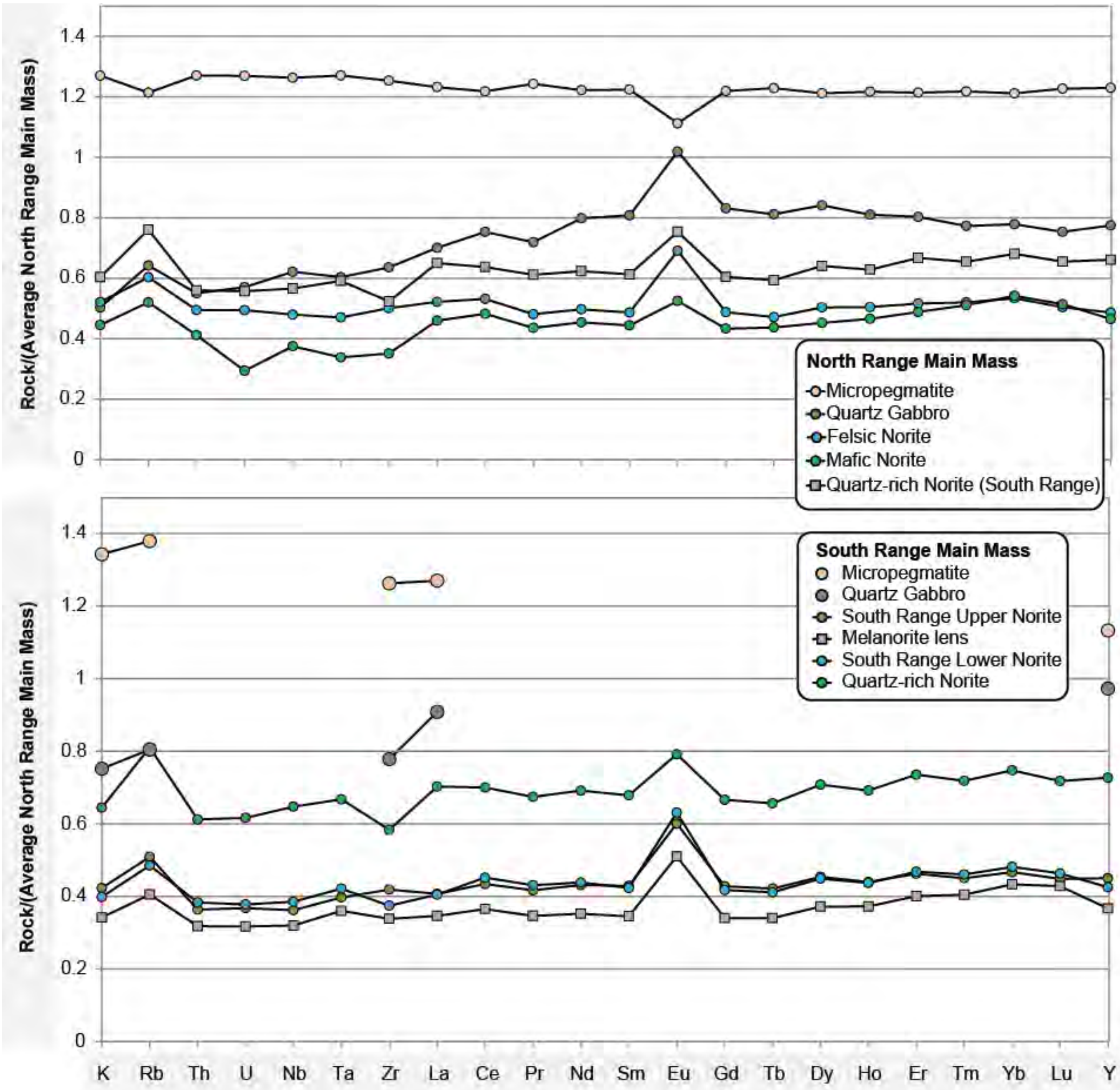
Lightfoot (2016) and Lightfoot and Zotov (2007)

Physical property and chemical stratigraphy of the Creighton traverse



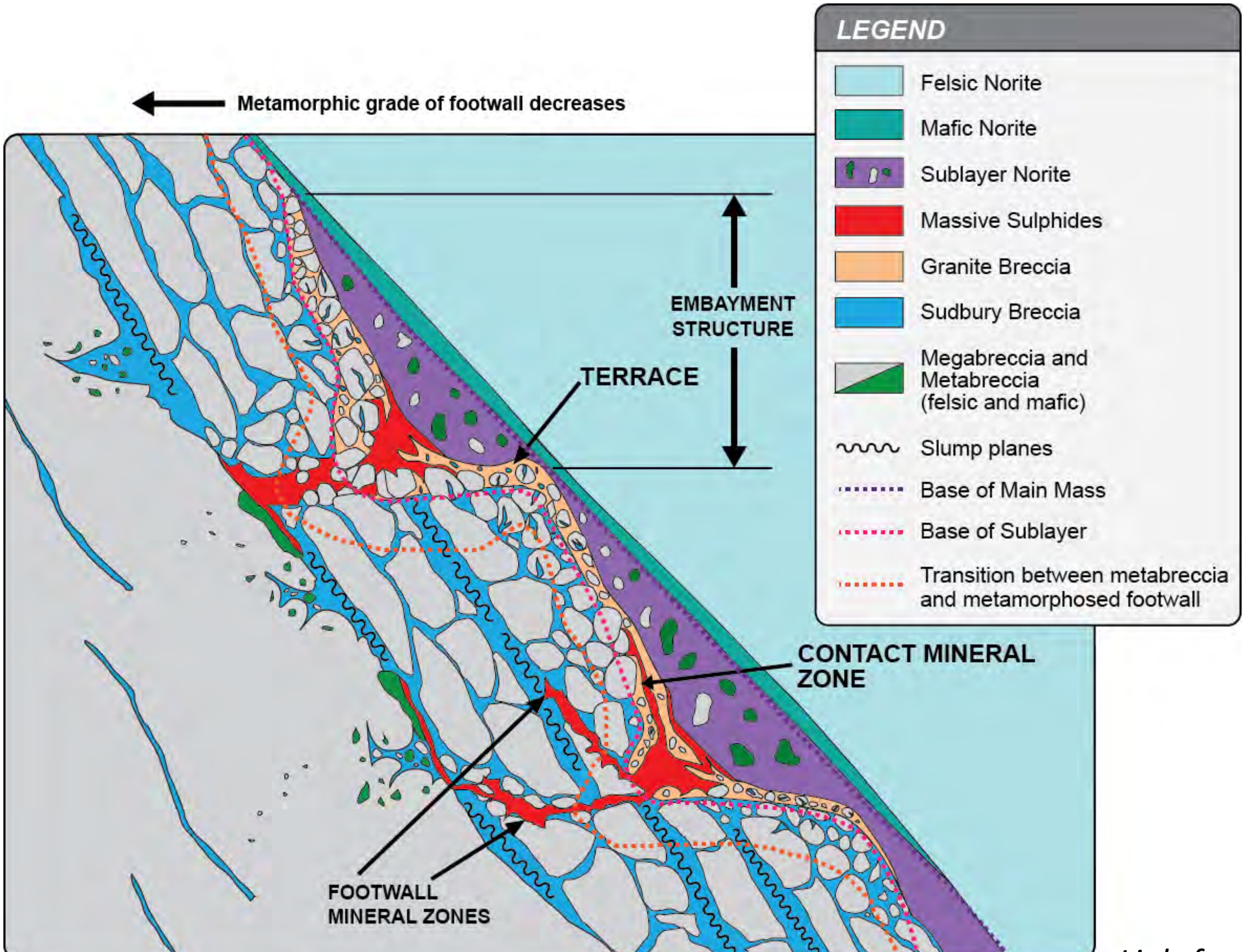
Lightfoot (2016) and Lightfoot and Zotov (2007)

One Main Mass magma type in North and South Ranges



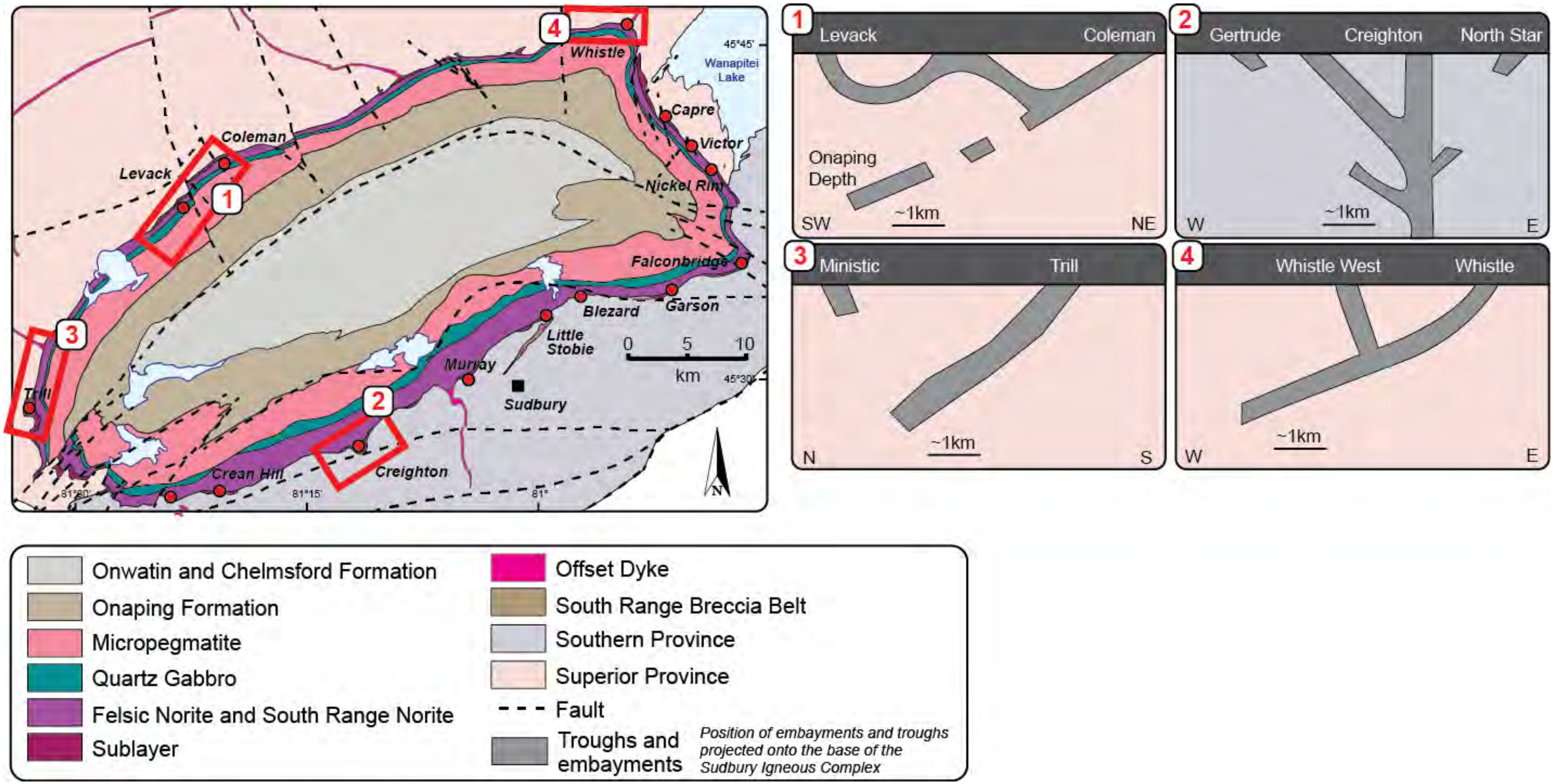
Lightfoot (2016)

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



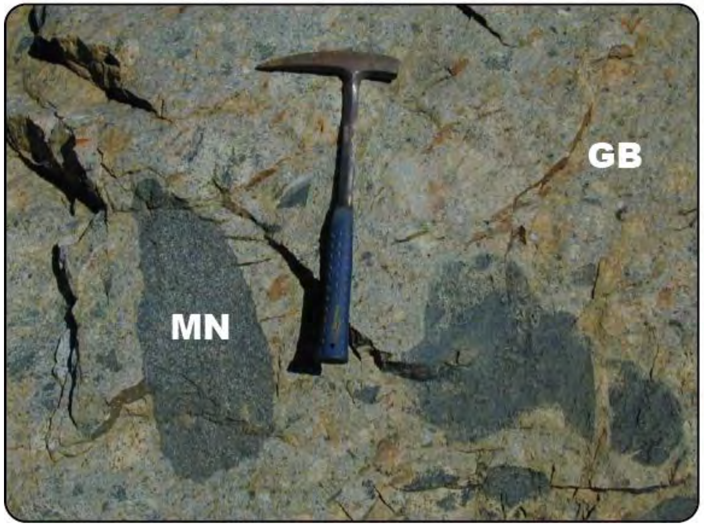
Lightfoot (2016)

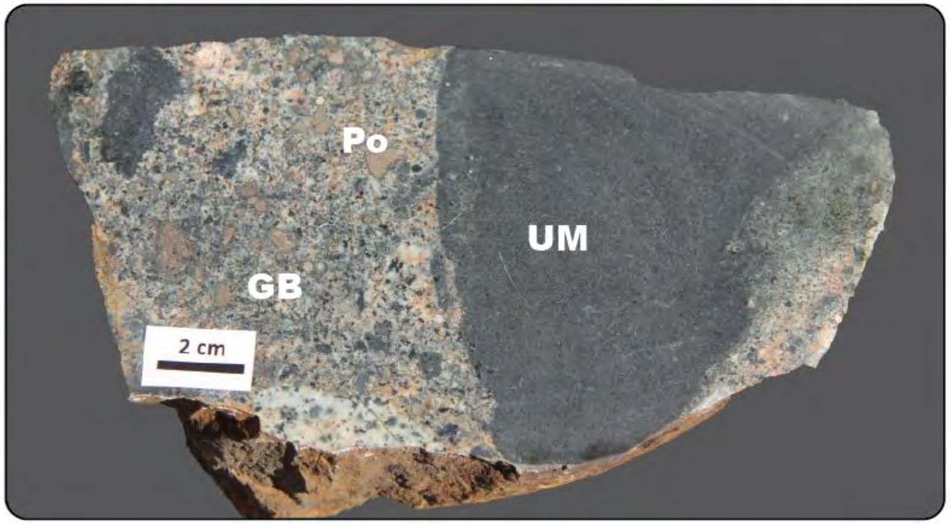
Distribution and geometry of Sublayer embayment's and troughs



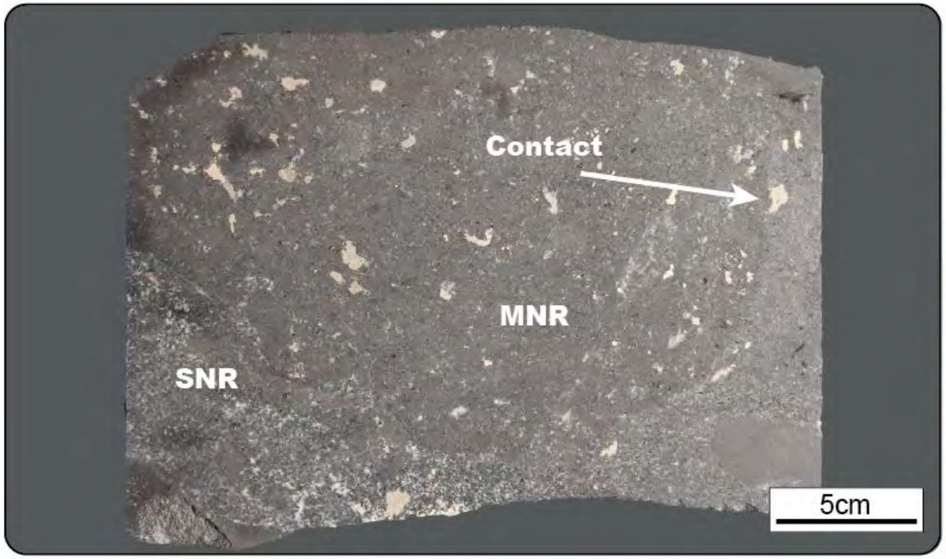
Lightfoot (2016)

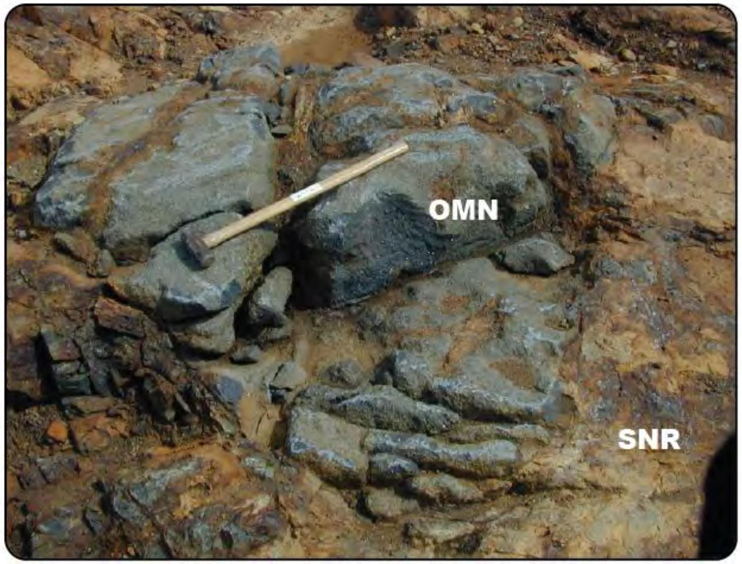
Sublayer Granite Breccia

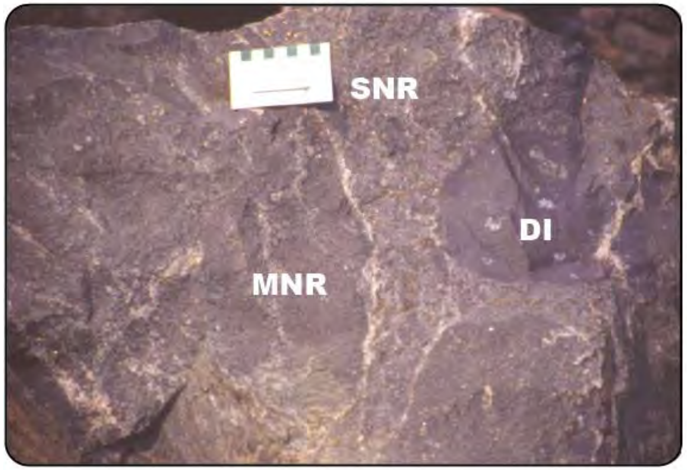


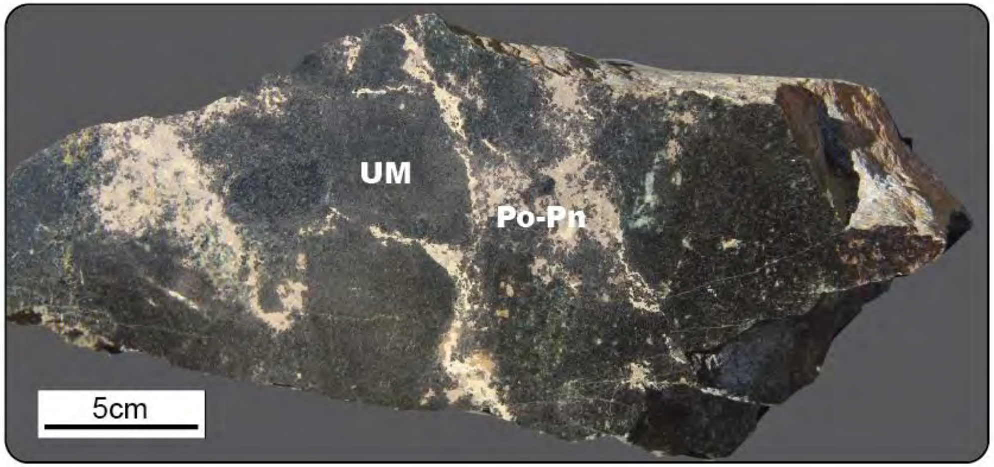


Sublayer Norite



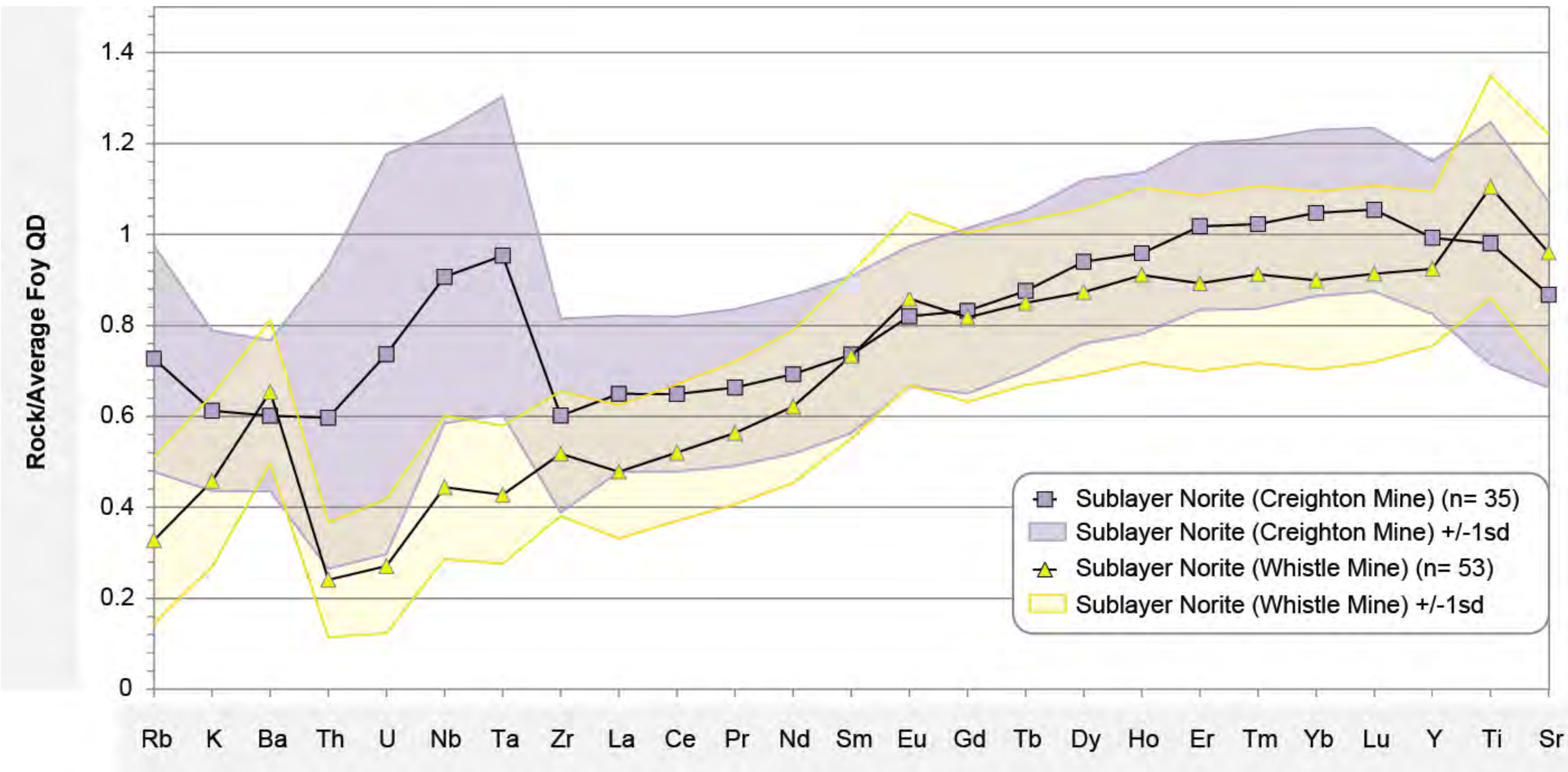






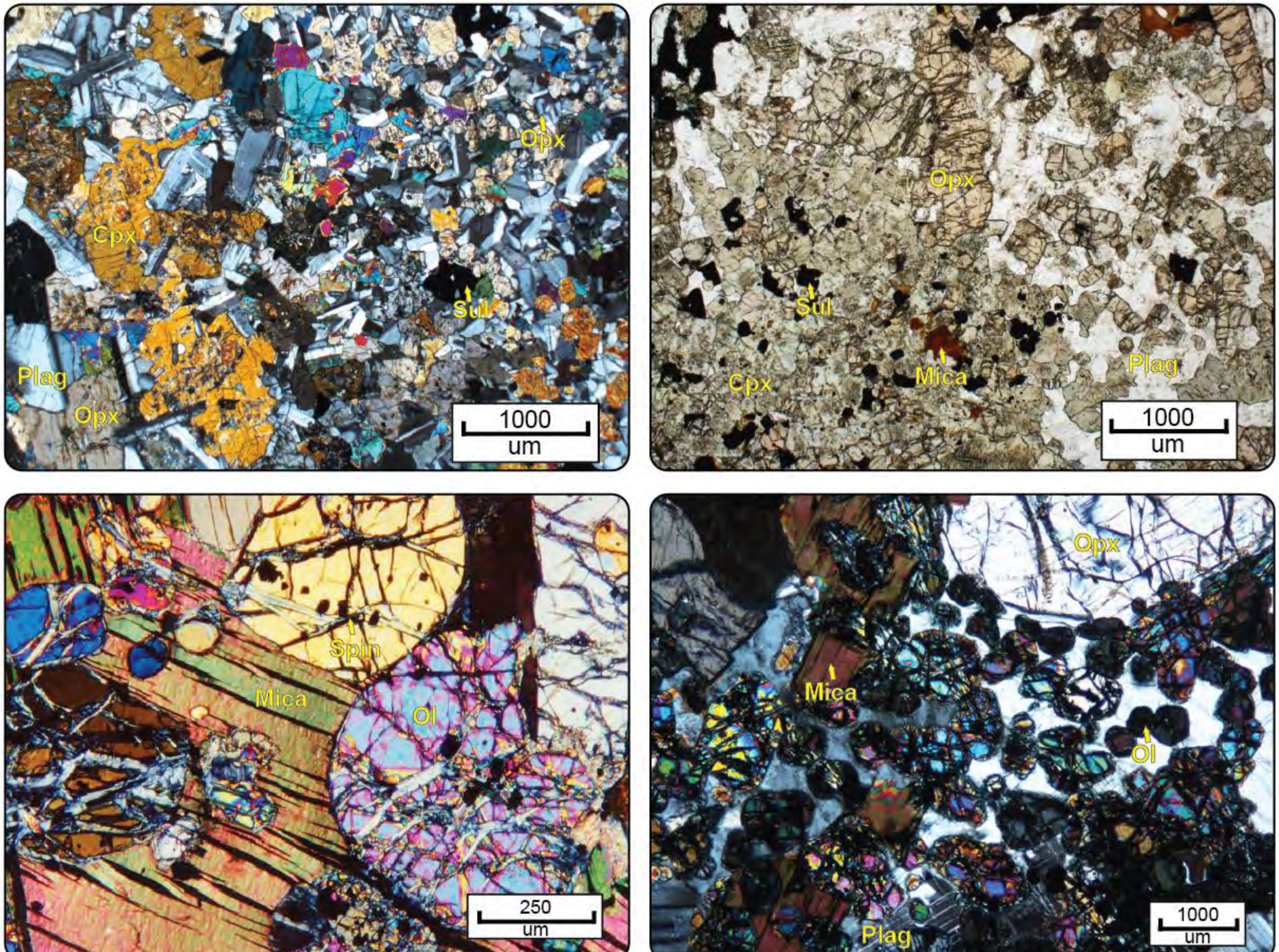
Lightfoot (2016)

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



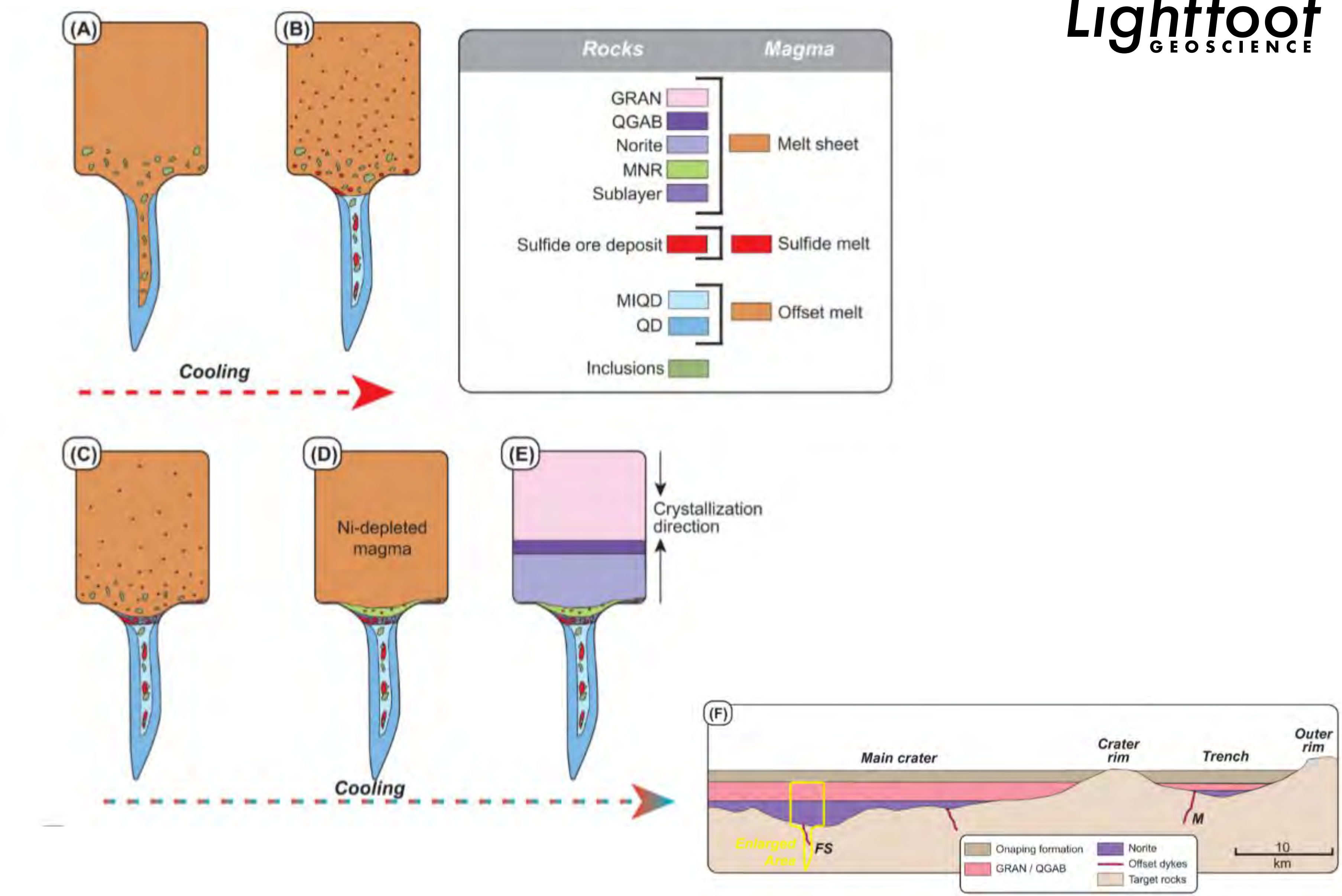
Lightfoot (2016) and Lightfoot et al (1997A)

Petrography of 1.85Ga (U-Pb zircon, baddeleyite) ultramafic inclusions



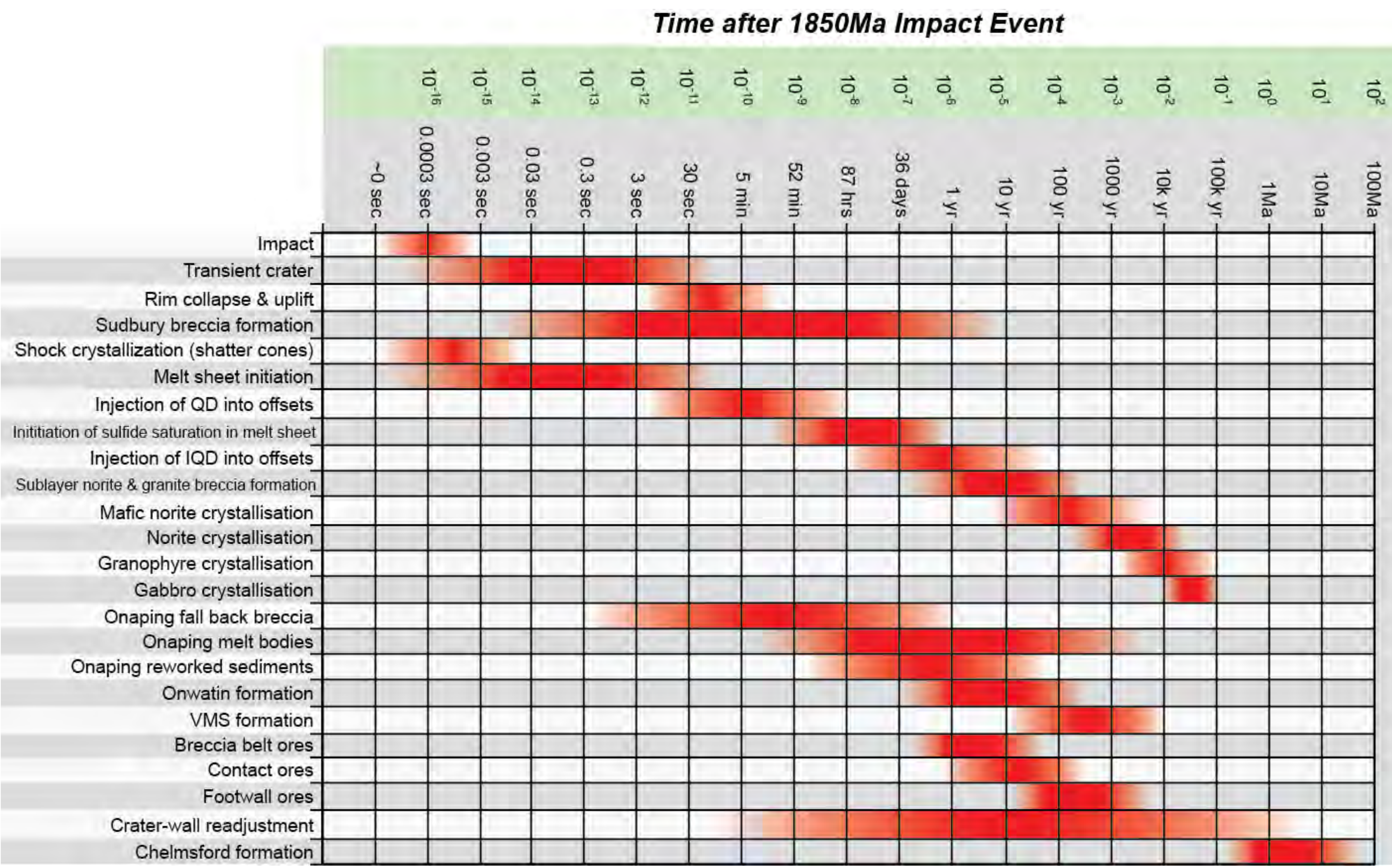
Lightfoot (2016) and Corfu and Lightfoot (1996)

Sequence of events



Lightfoot (2016) and Keays and Lightfoot (2004)

Timeline and sequence of events at Sudbury (a brave view)

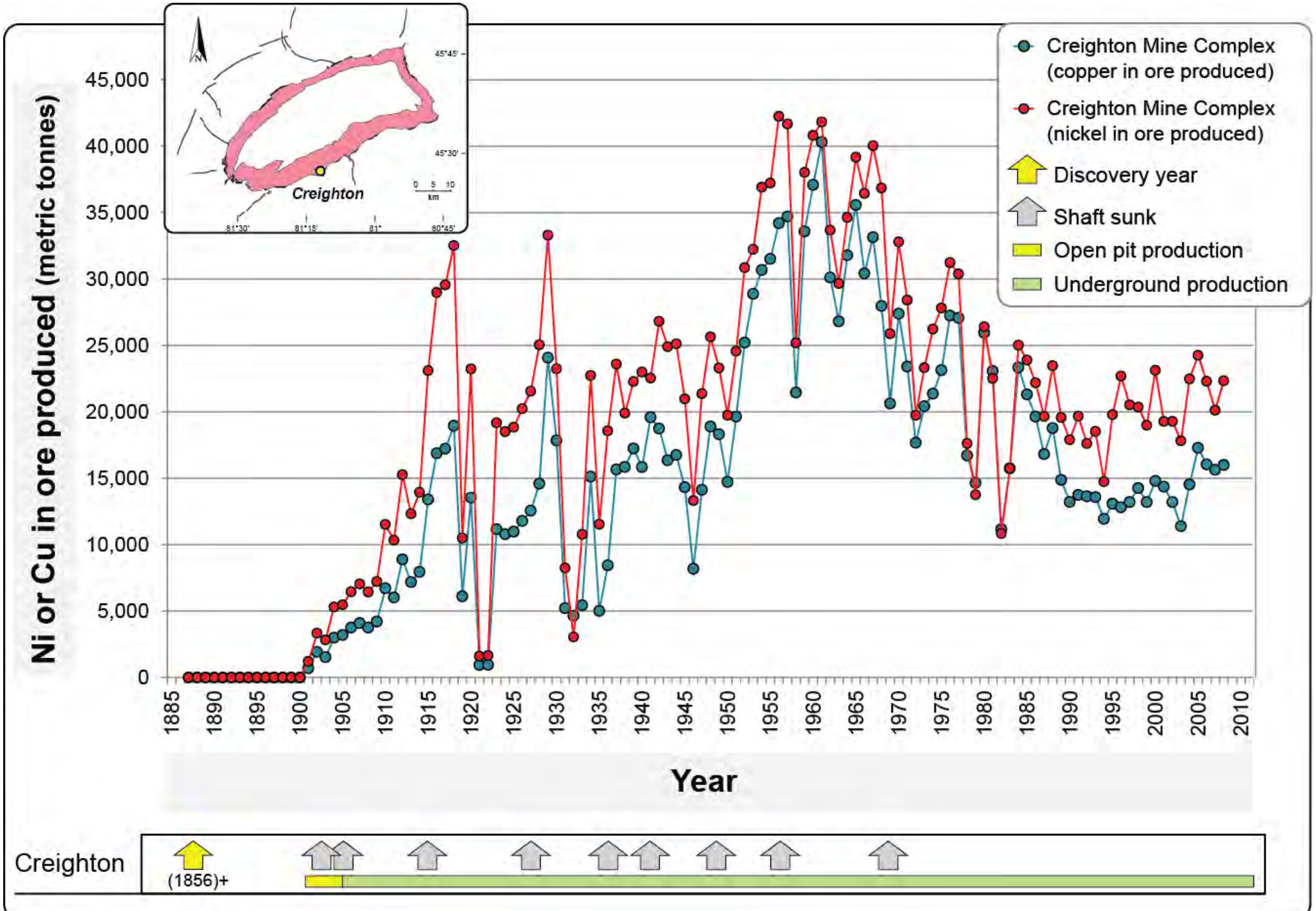


Lightfoot (2016)

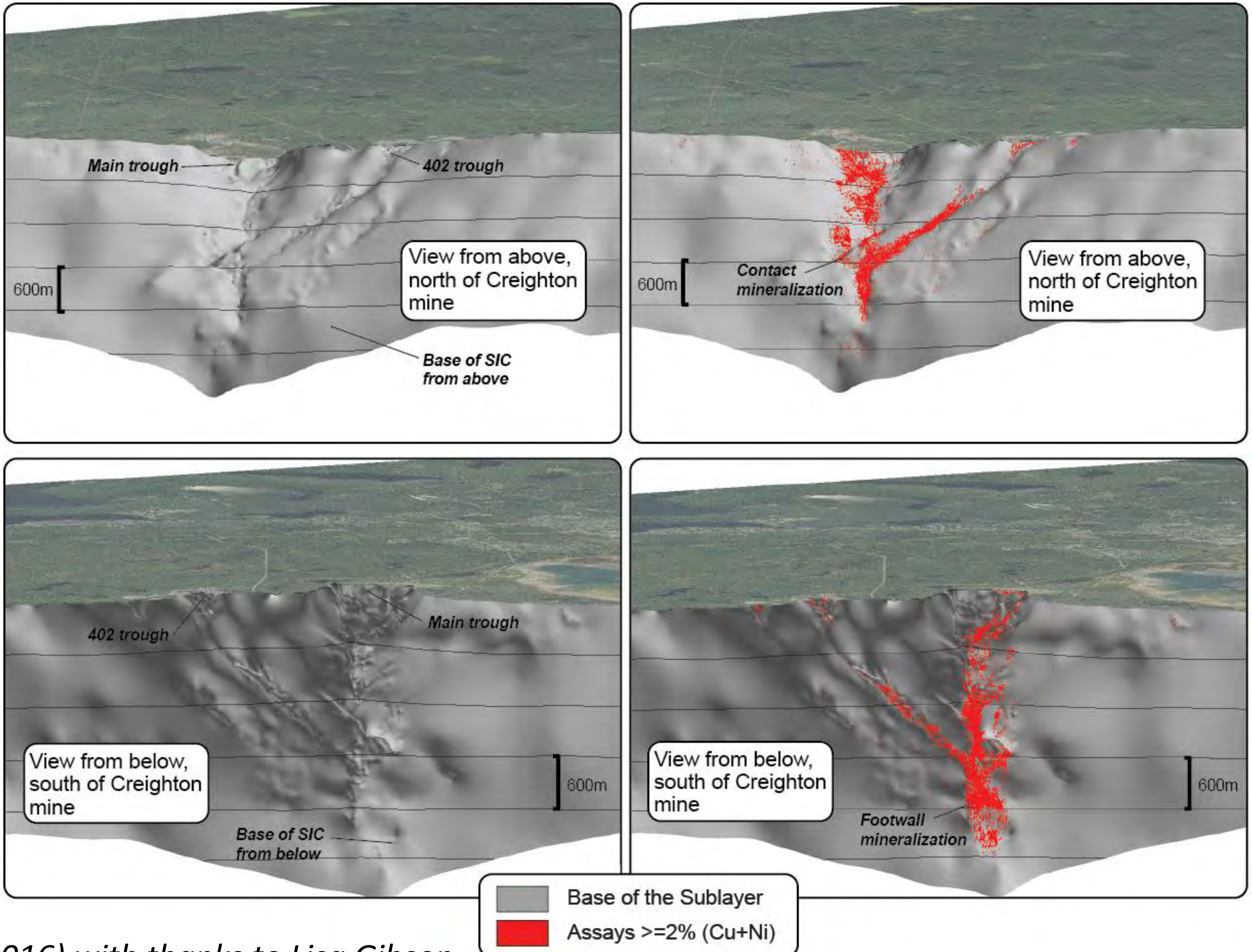
Objectives

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



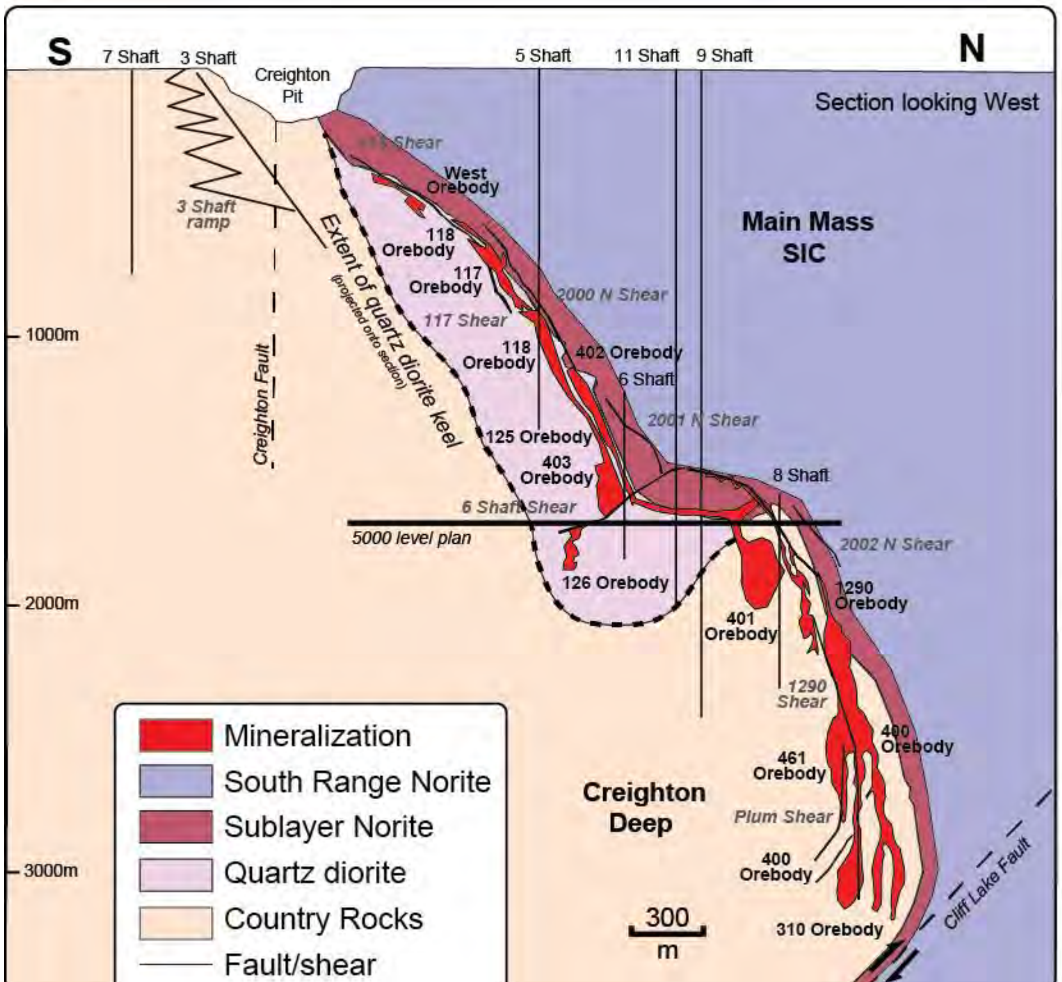
The Creighton Troughs

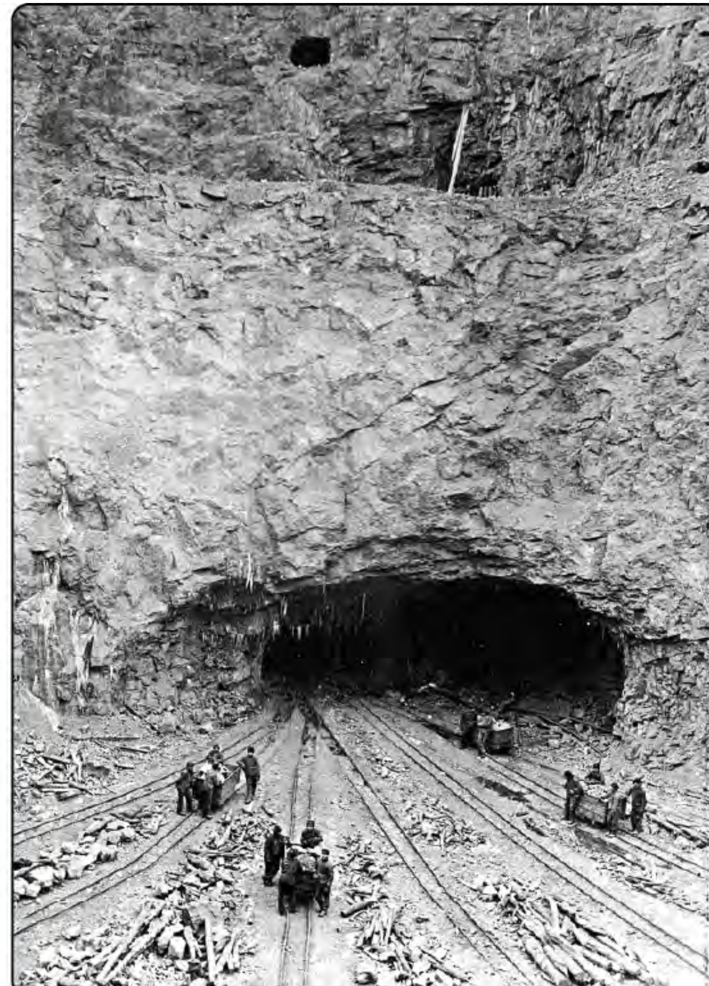


Lightfoot (2016) with thanks to Lisa Gibson

The Creighton Deposit

Lightfoot
GEOSCIENCE

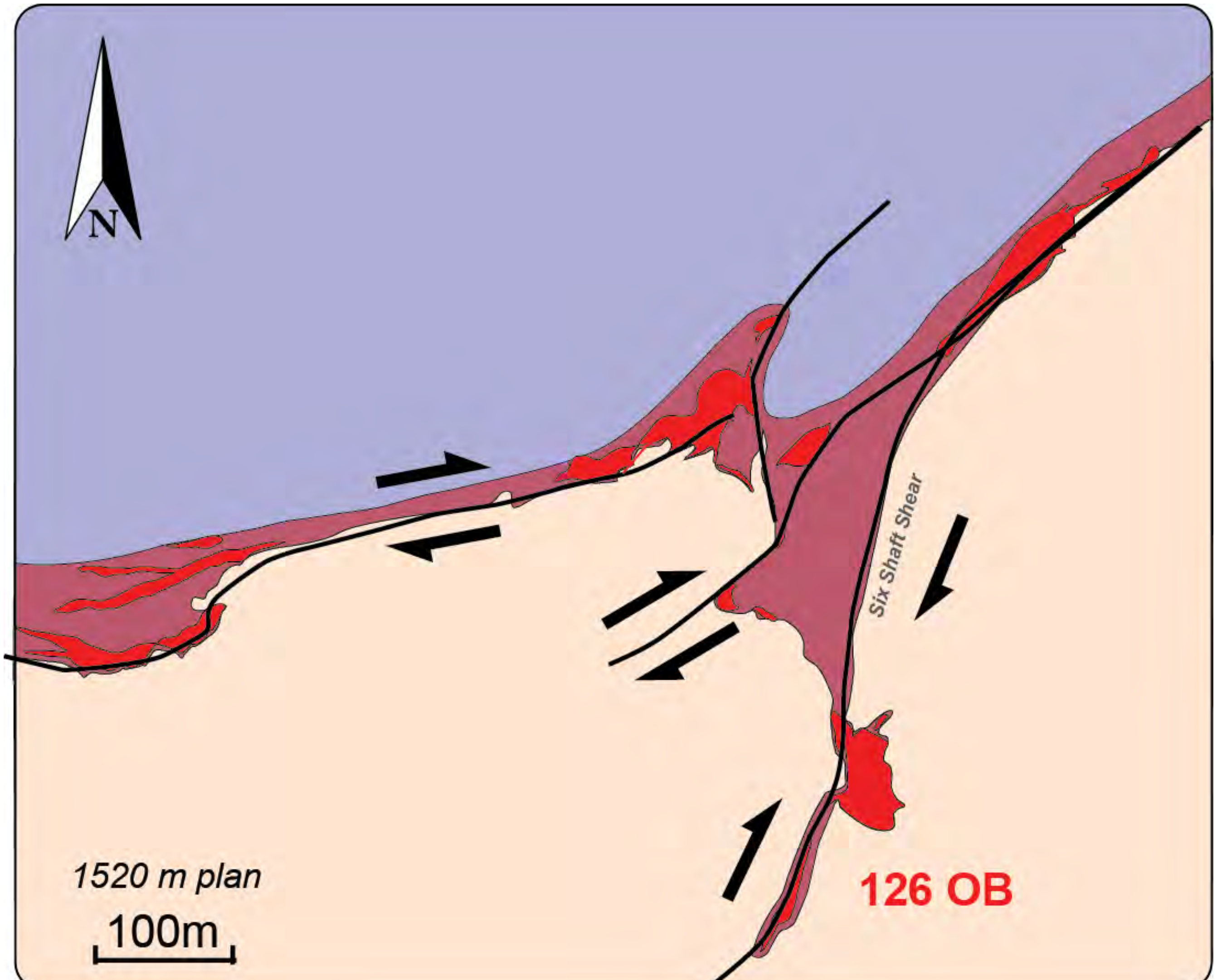




With permission: Archives of Ontario

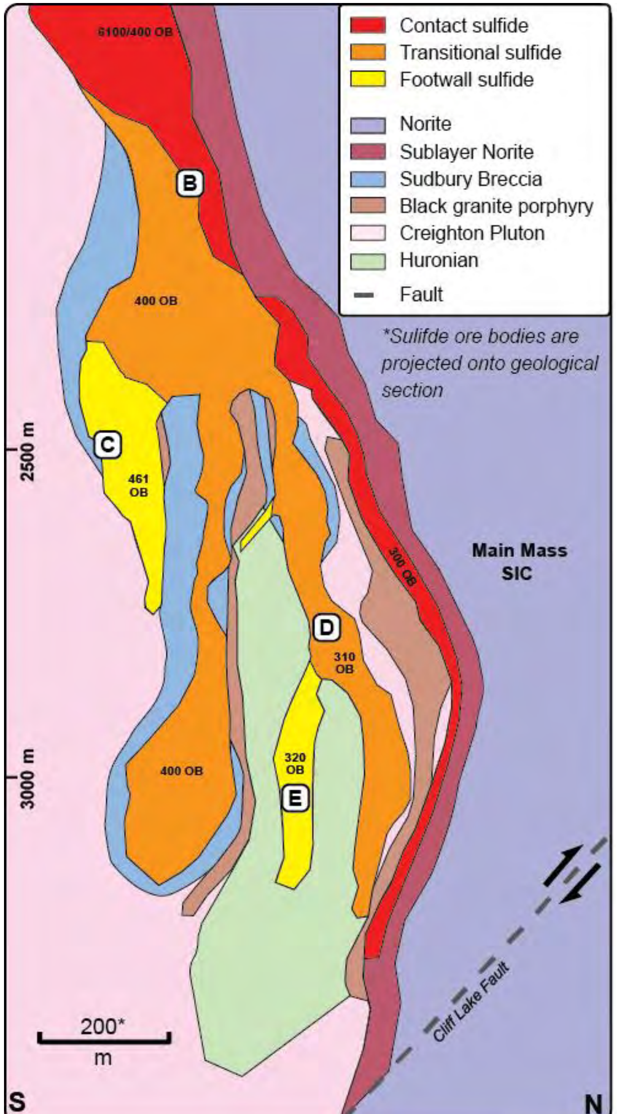
Lightfoot (2016)

Good examples of displacement of contact ores along structures (but are some of the ore bodies primary?)



Lightfoot (2016)

Creighton Deep



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

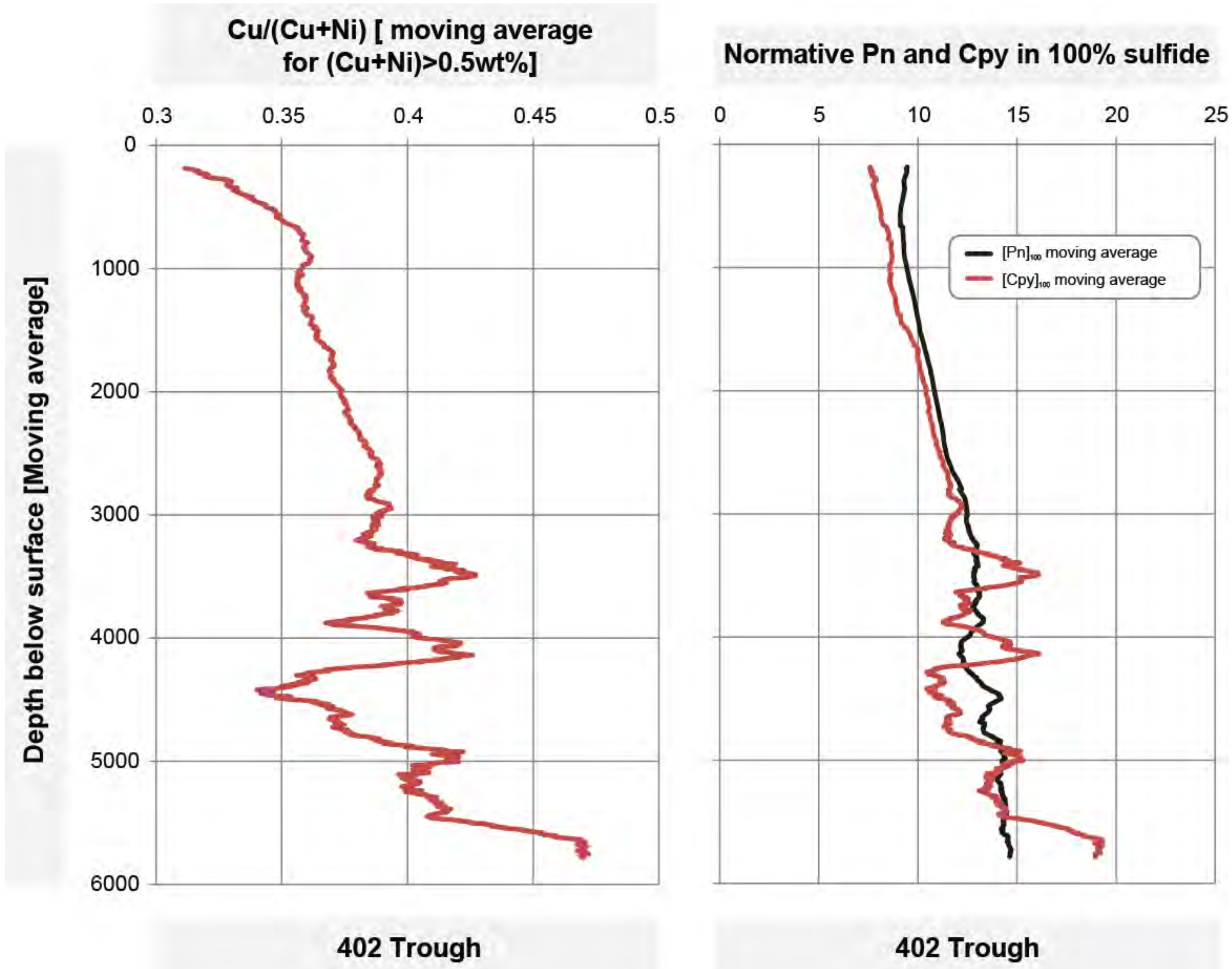
461 OB: 2.1 %Ni – 5.7 %Cu – 5.3 g/t 3E over 10 m true width

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

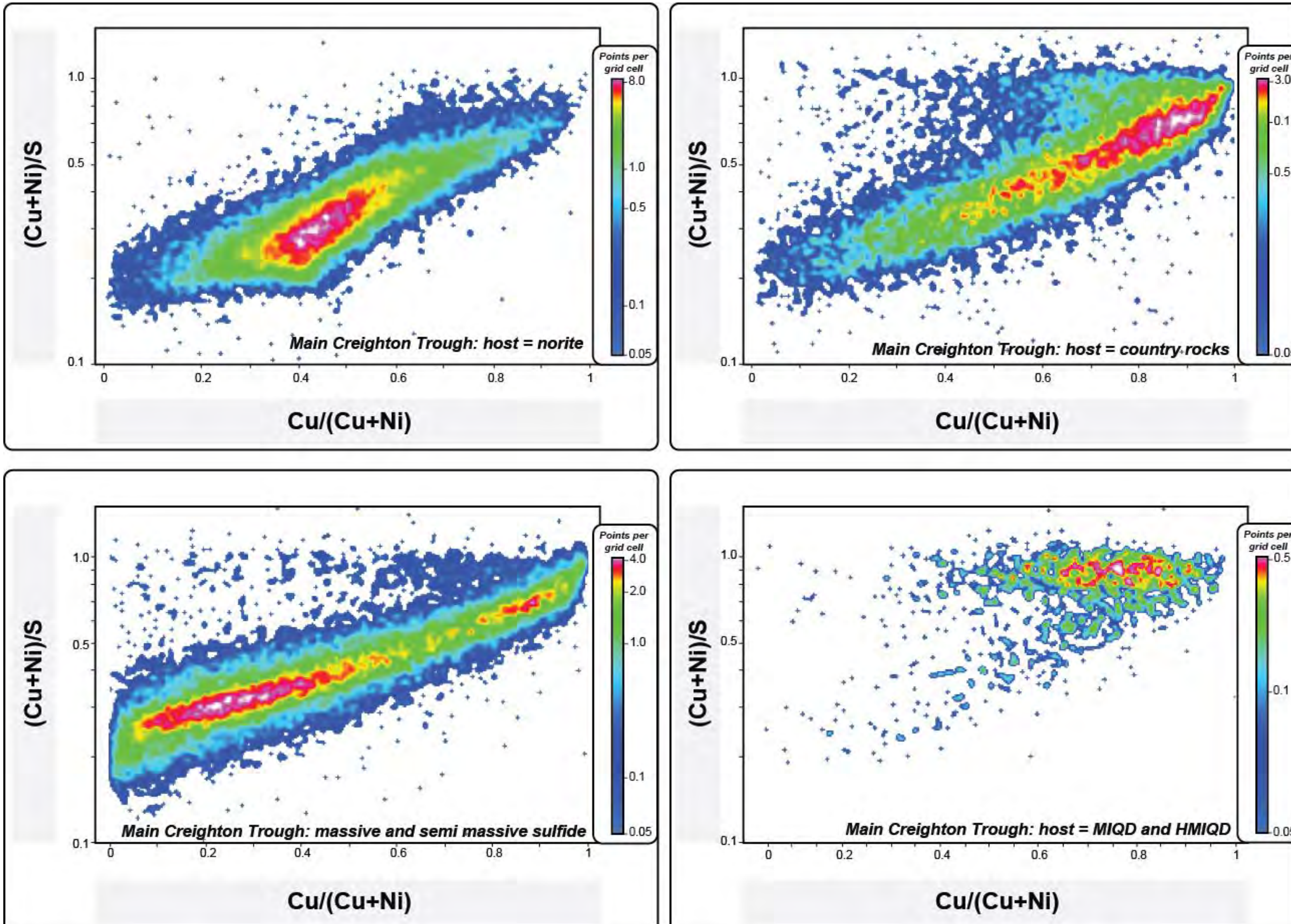
Lightfoot (2016) with special thanks to Rob Pelkey

Sulfides become richer in Pn+Cpy and develop a higher Cu/(Cu+Ni) with distance down a trough



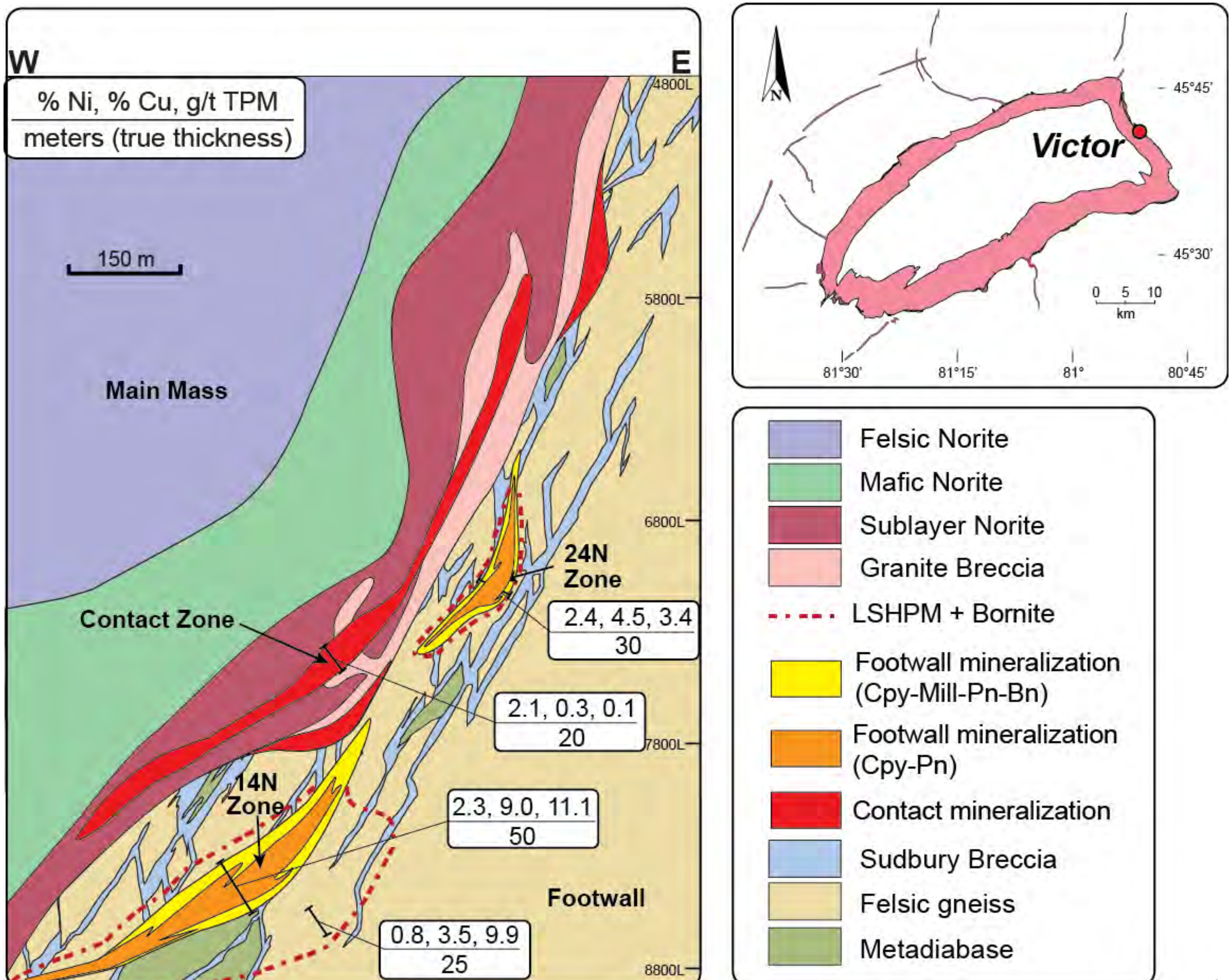
Lightfoot (2016)

Compositional diversity in Sulfide ores is a function of host rock



Lightfoot (2016)

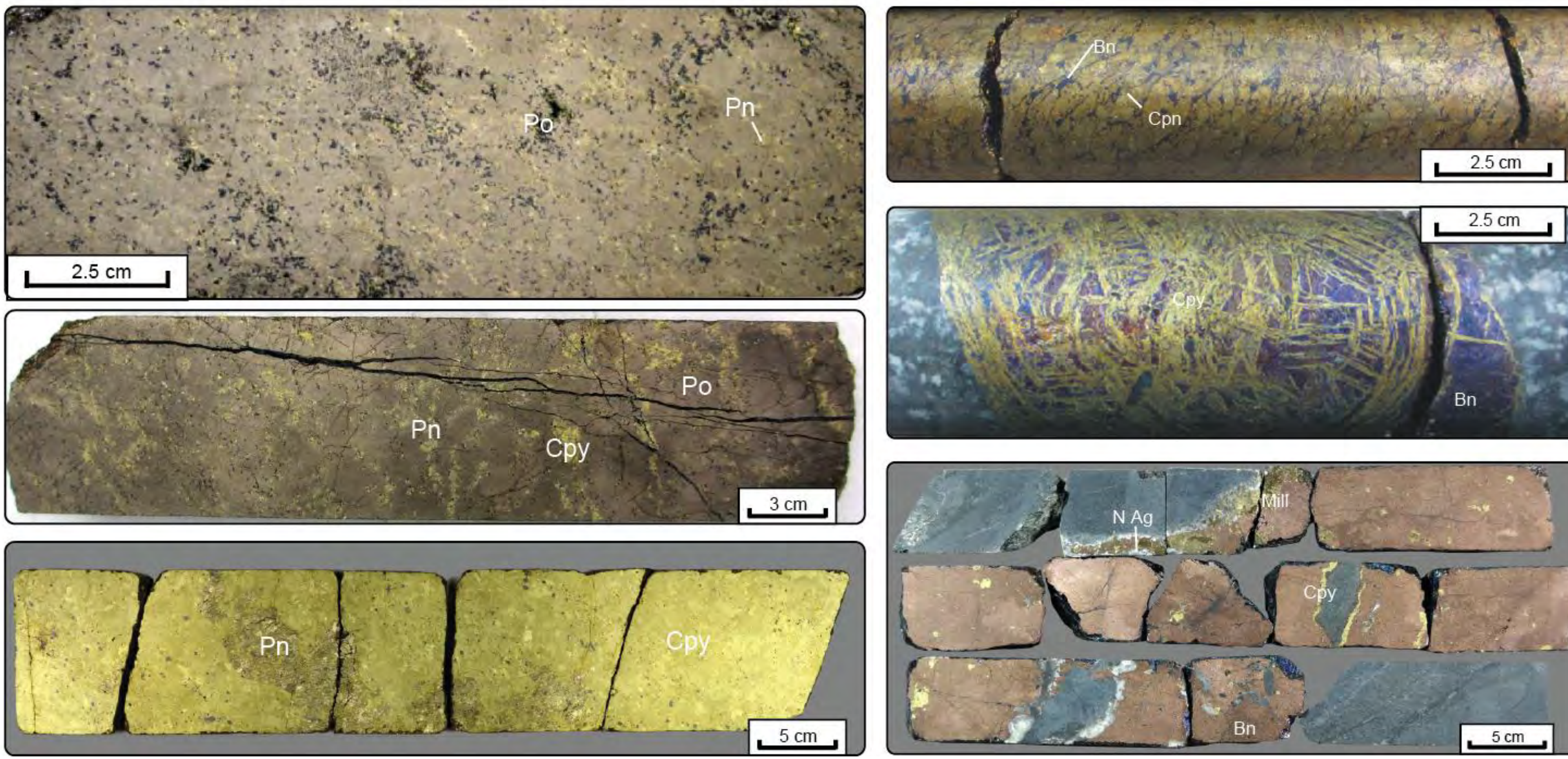
East Range – Victor Mineral System



Lightfoot (2016)

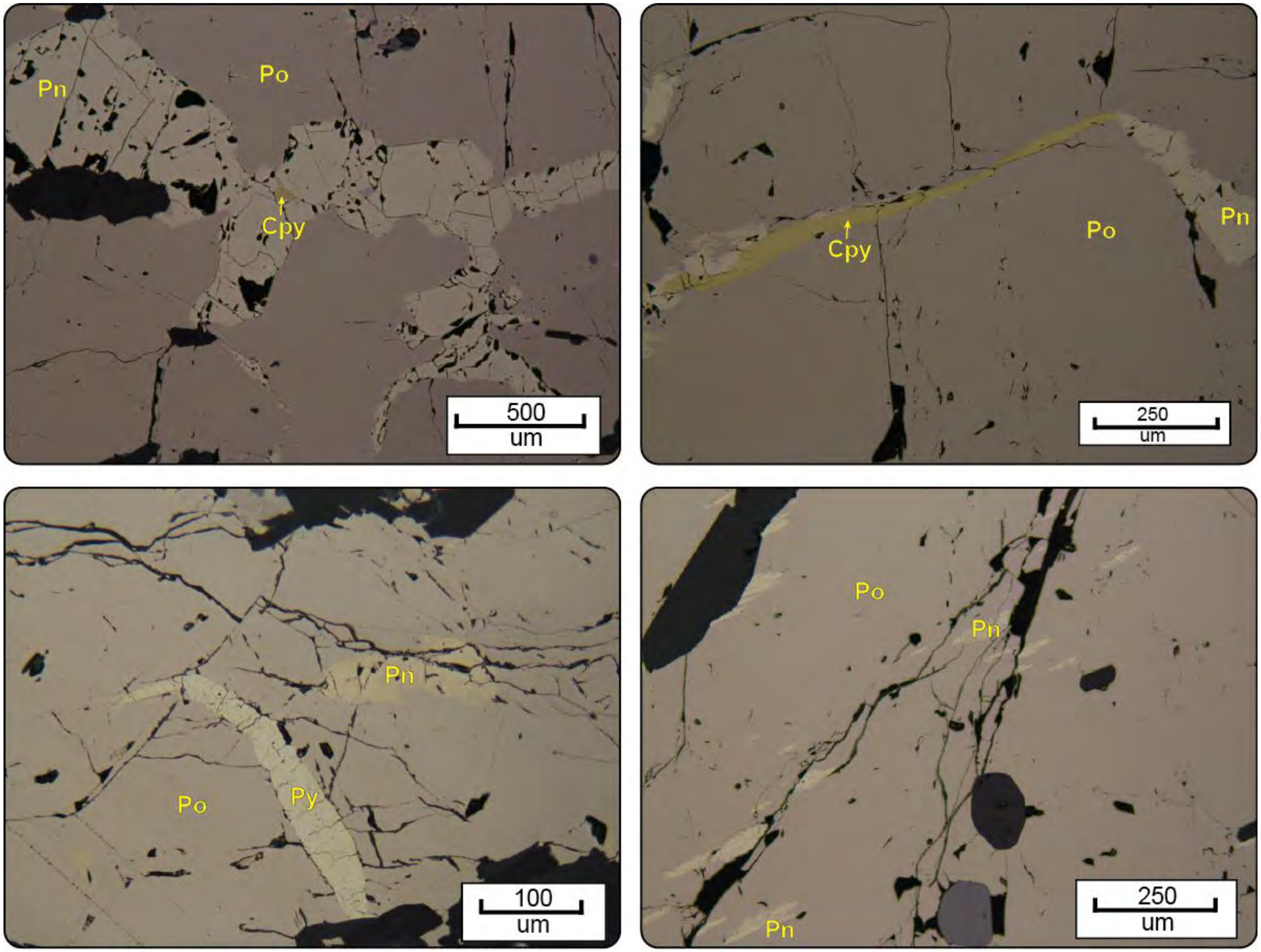
Mineralogy of the Massive Sulfides at Victor

Lightfoot GEOSCIENCE



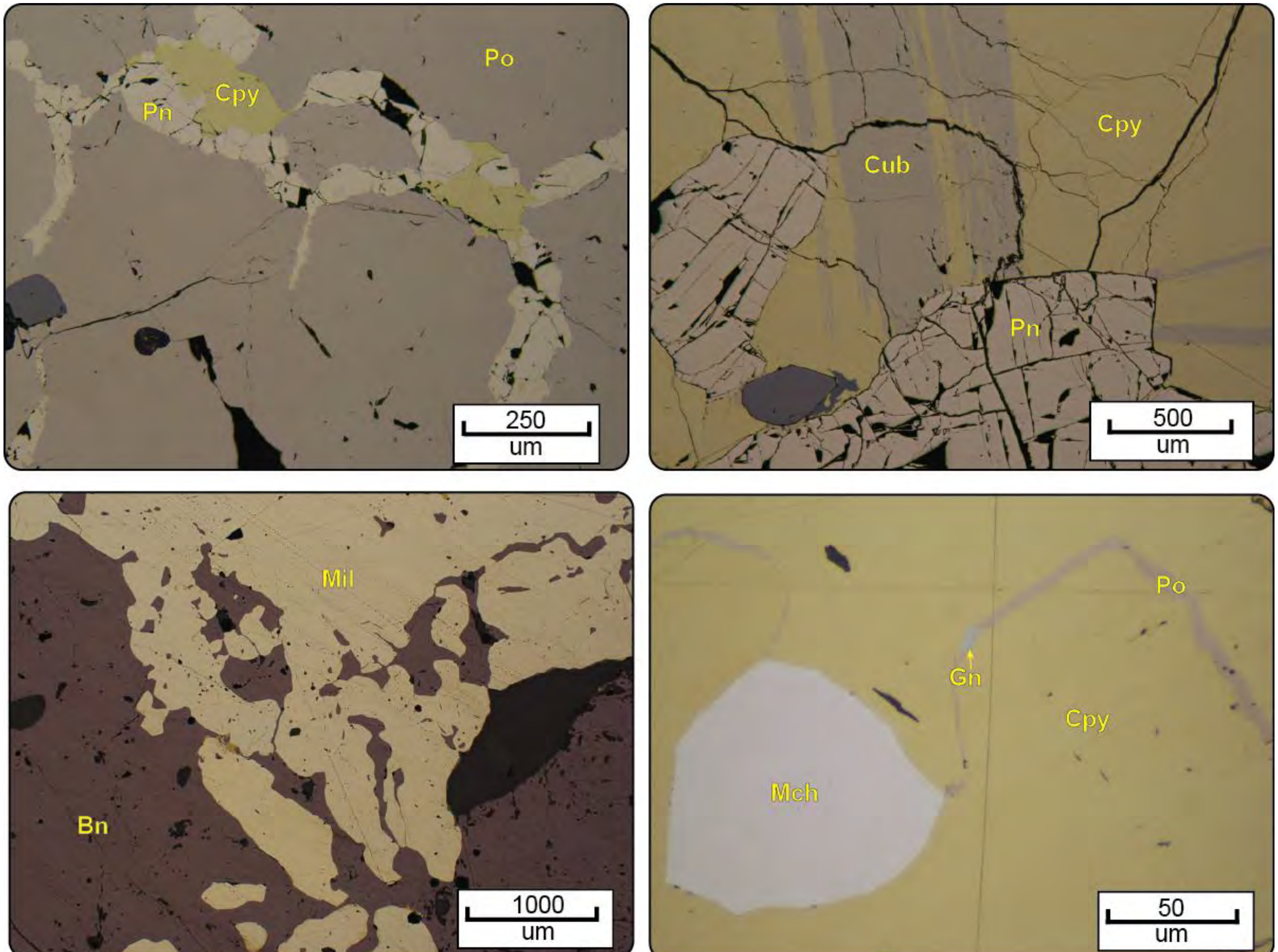
Lightfoot (2016)

Typical contact sulfide mineralogy



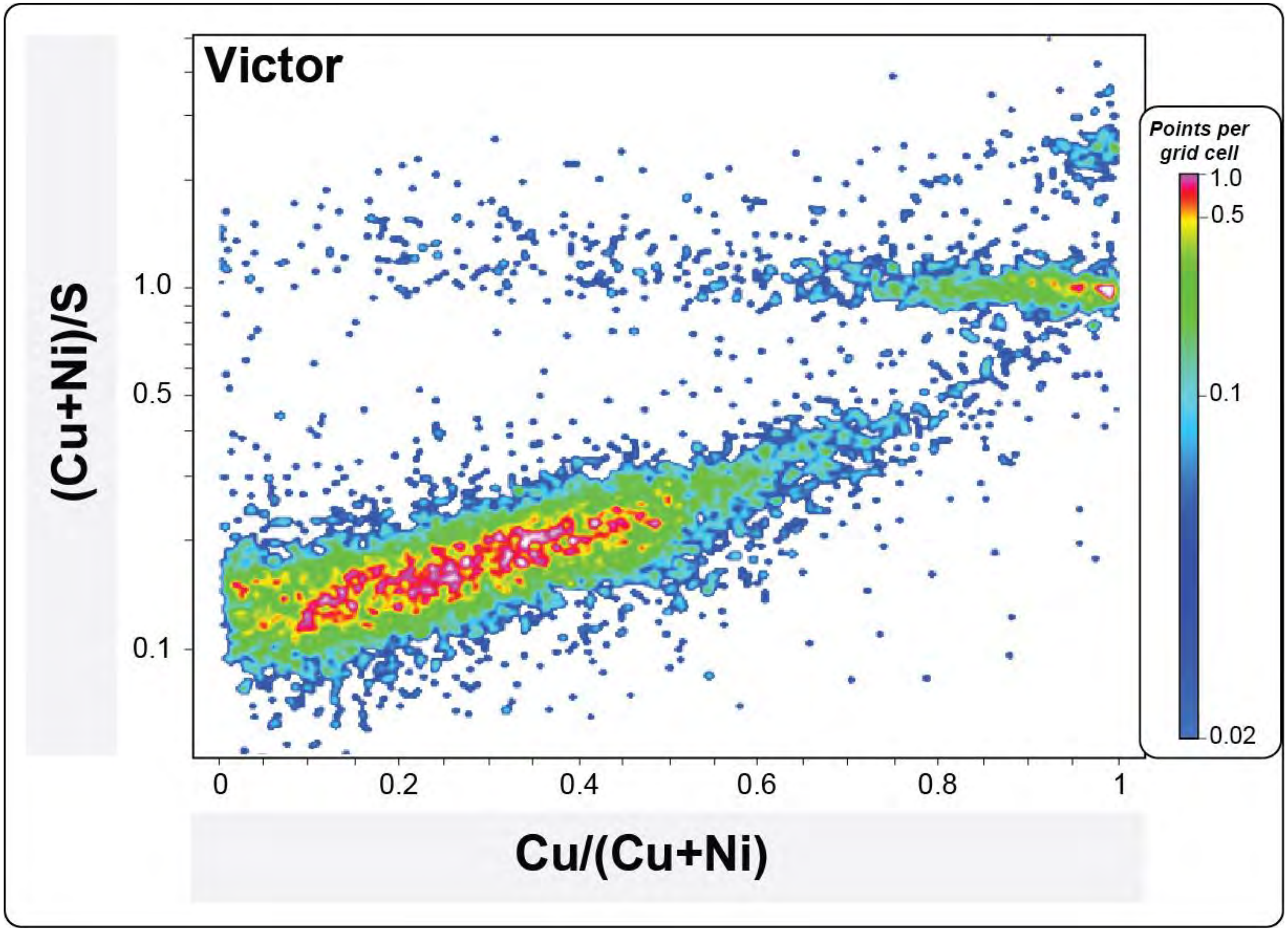
Lightfoot (2016)

Transitional to Footwall Sulfide Mineralogy



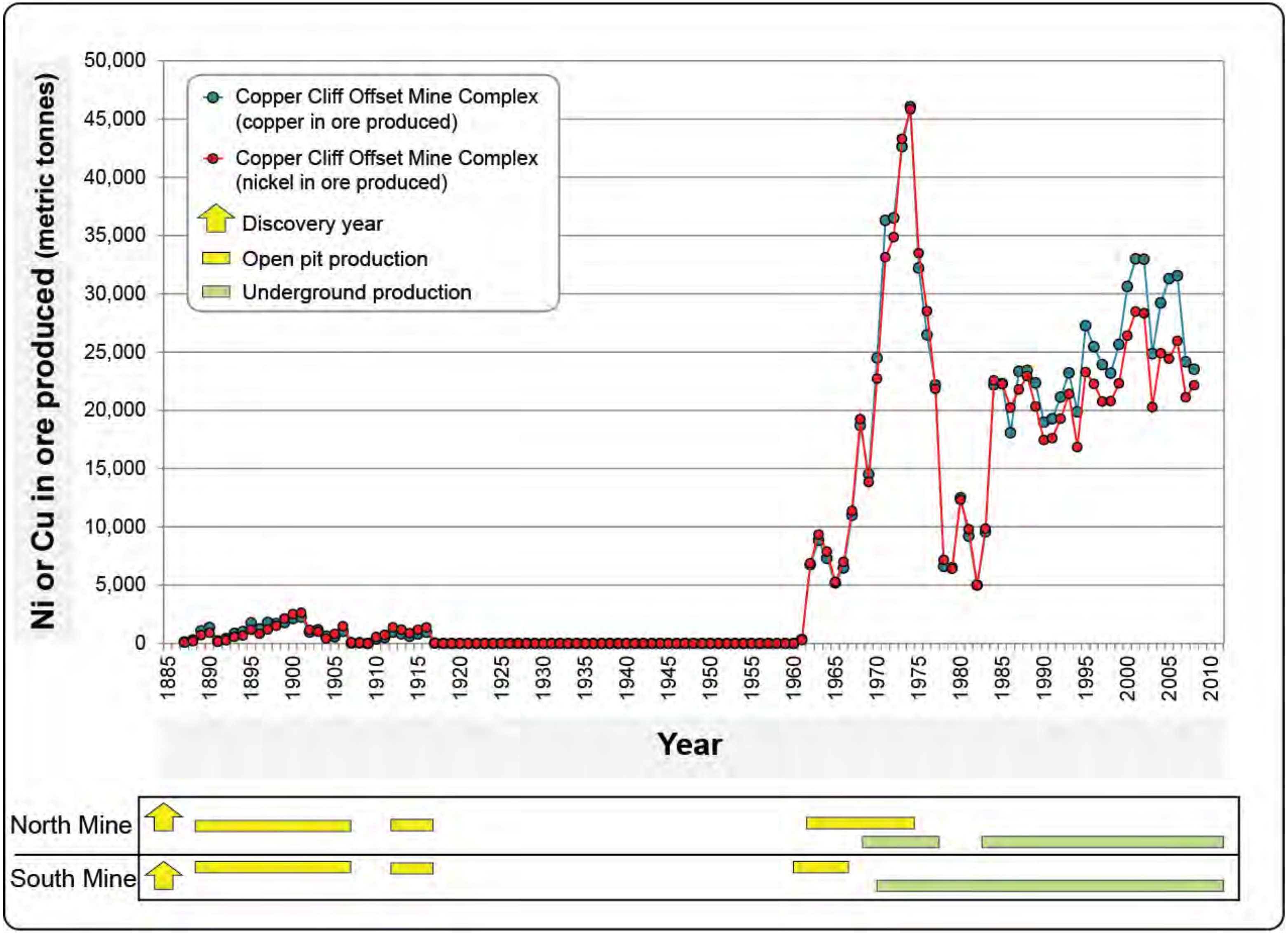
Lightfoot (2016)

Compositional diversity at Victor

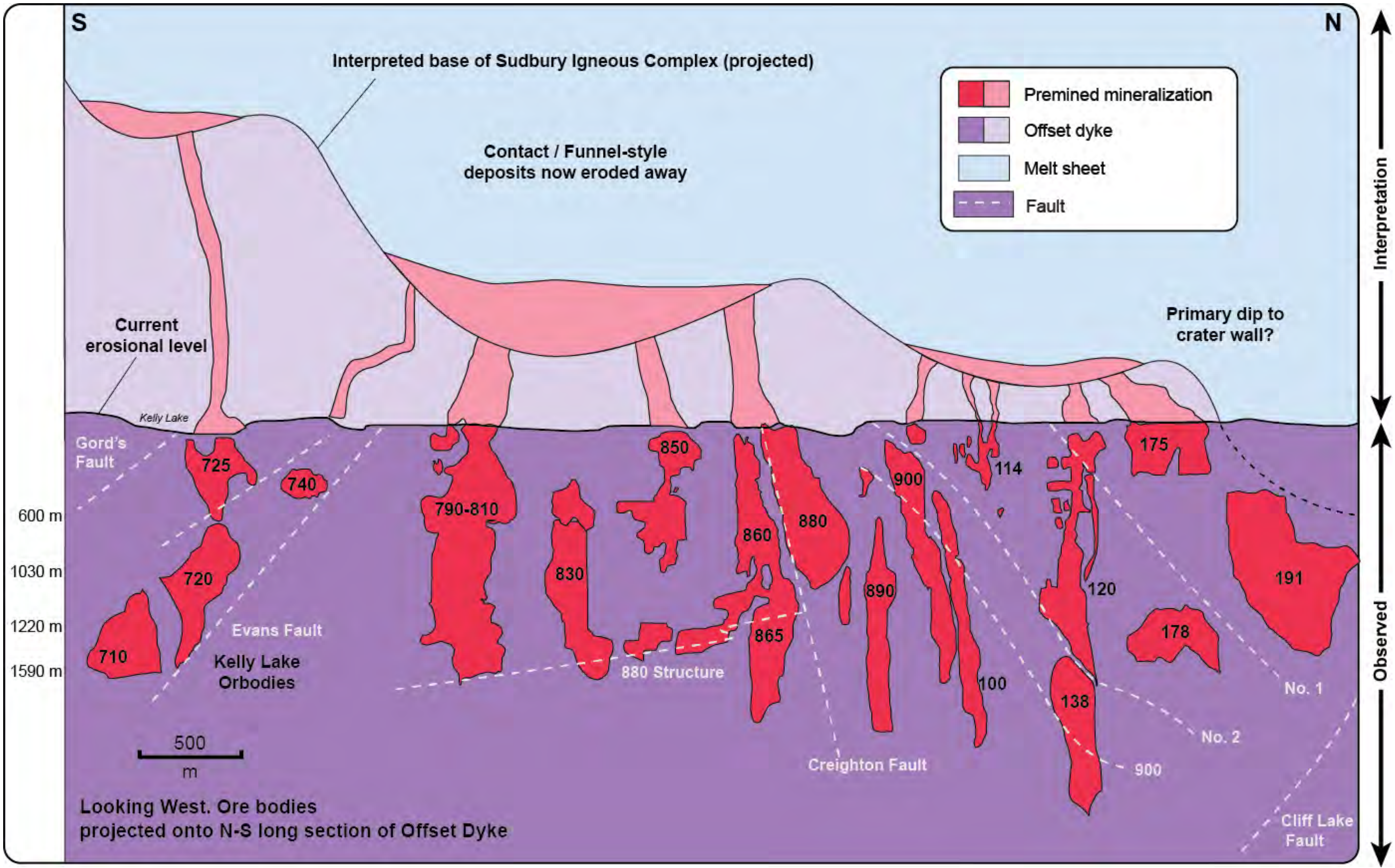


Lightfoot (2016)

The Copper Cliff Deposit

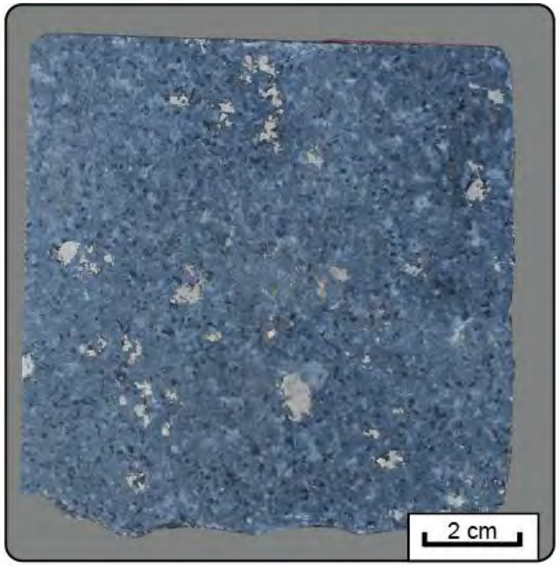


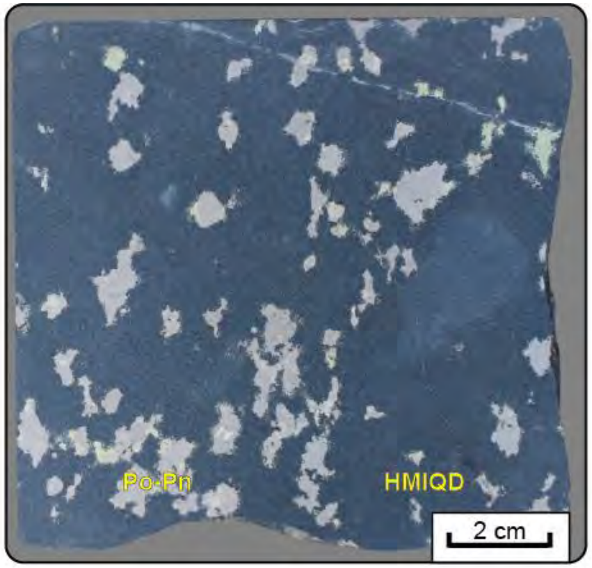
Copper Cliff – relationship to the melt sheet

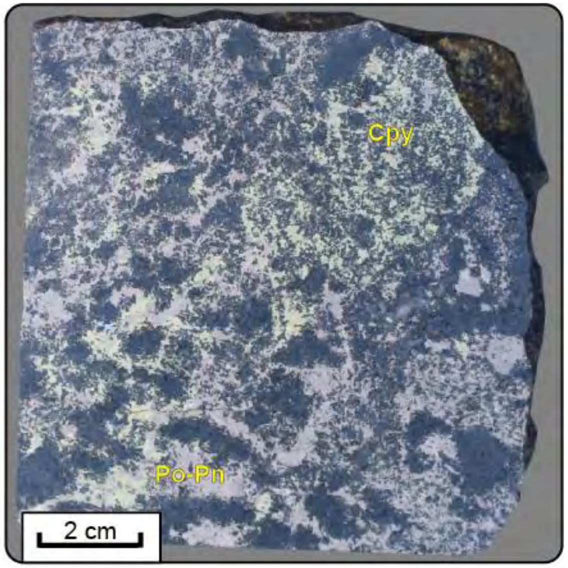


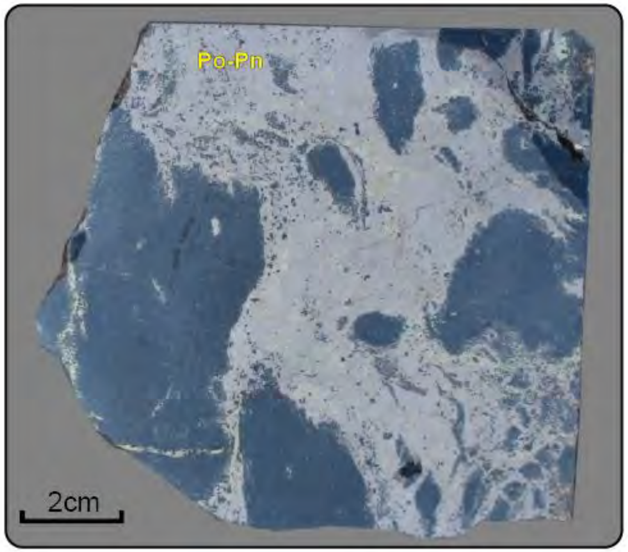
Lightfoot (2016)

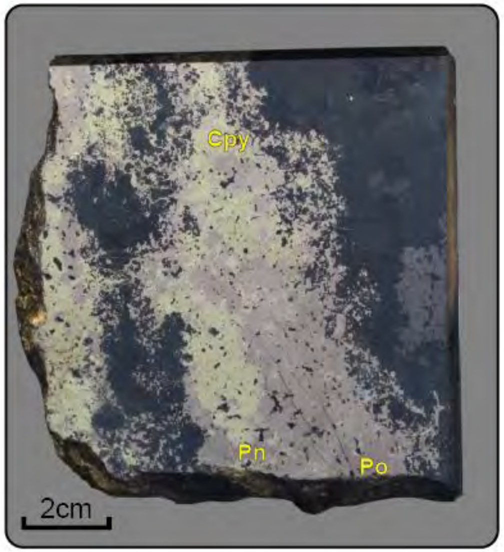
Styles of Mineralization at Copper Cliff

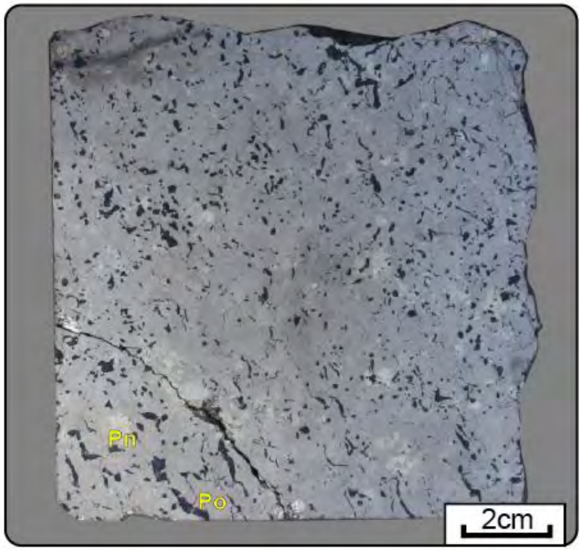




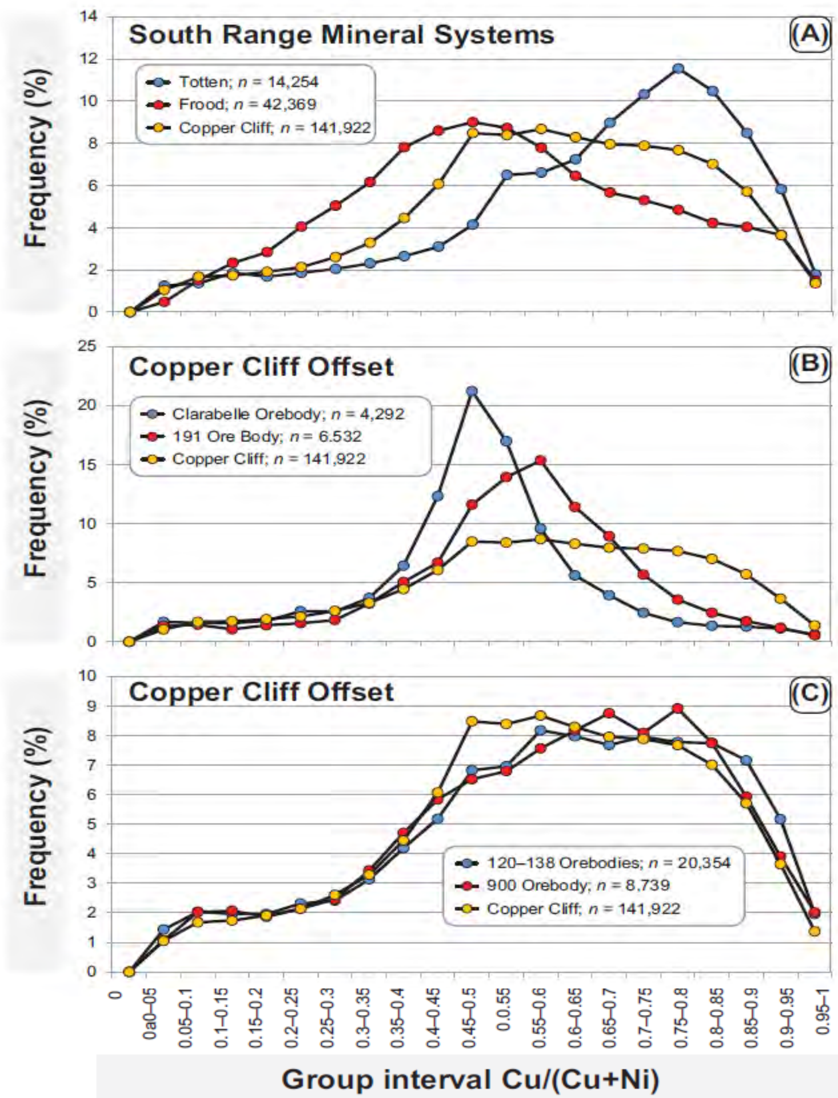


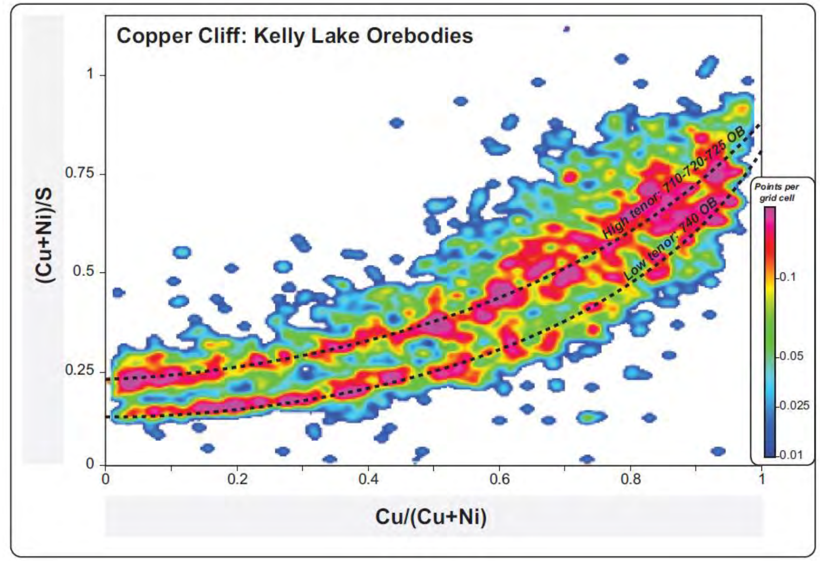


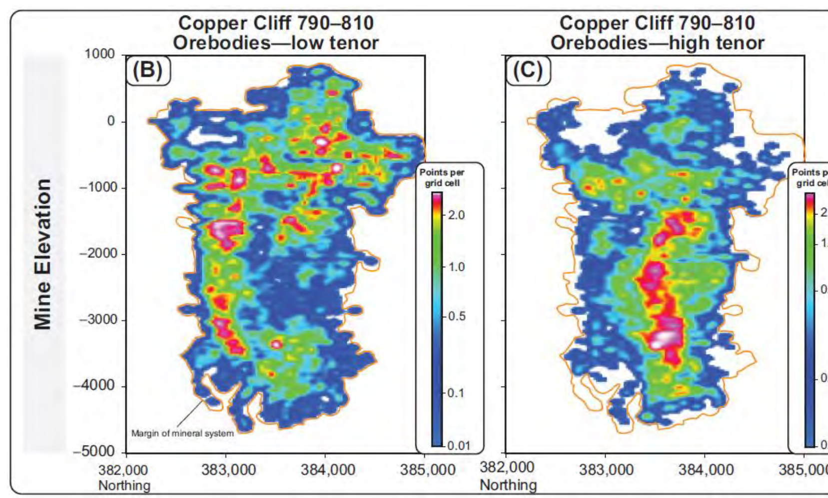




Compositional diversity

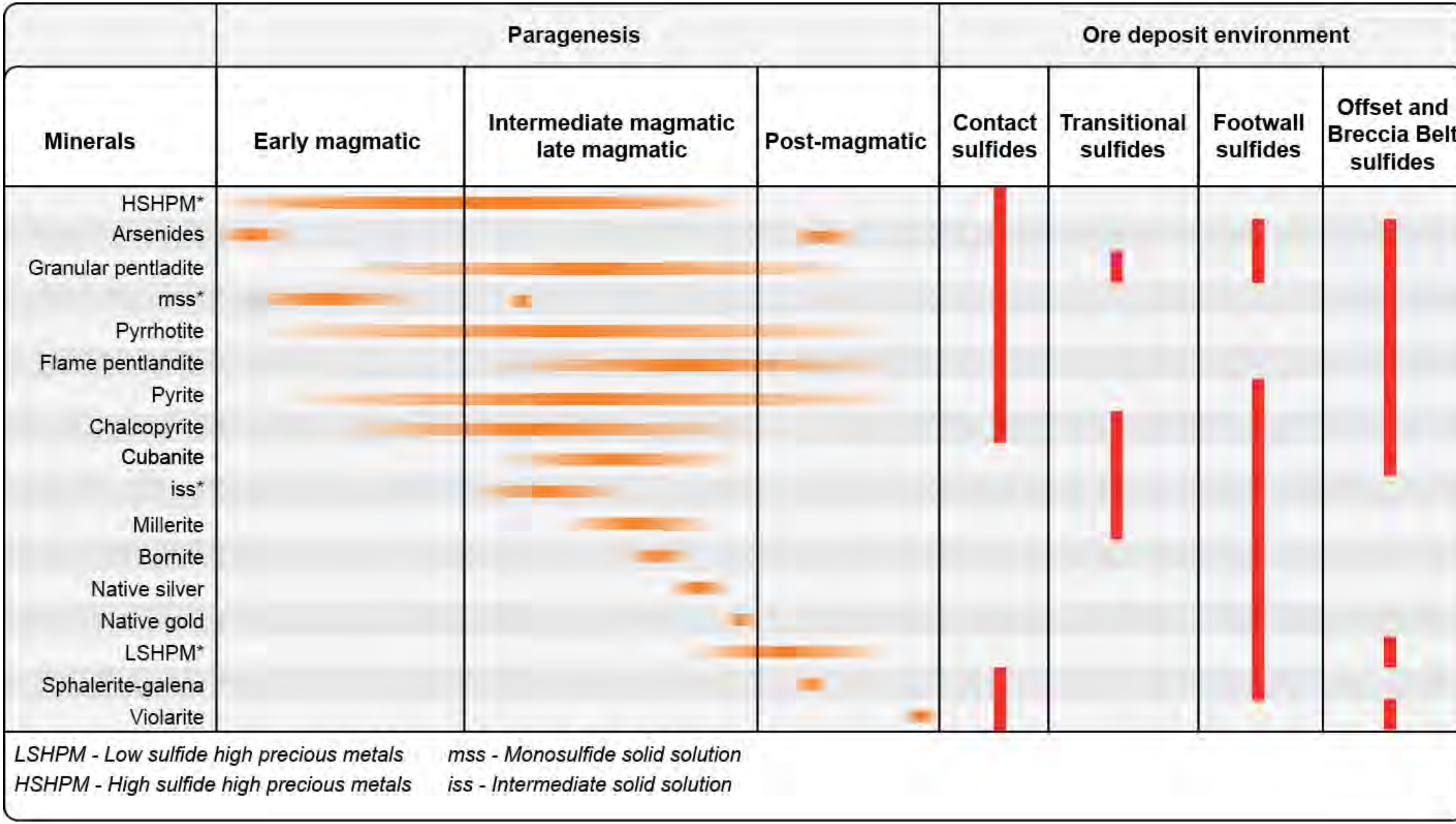






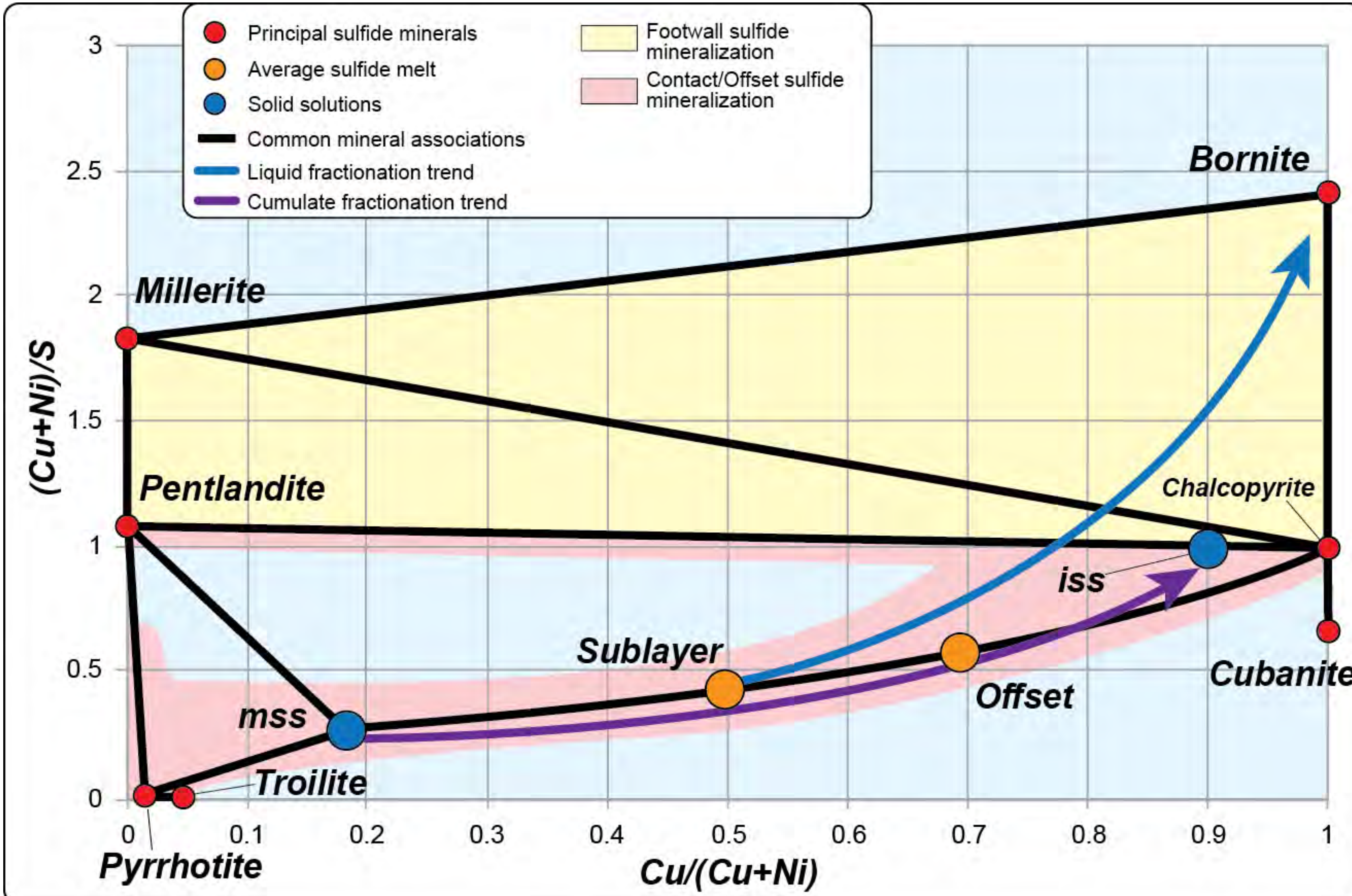
Lightfoot (2016)

Generalised Paragenesis



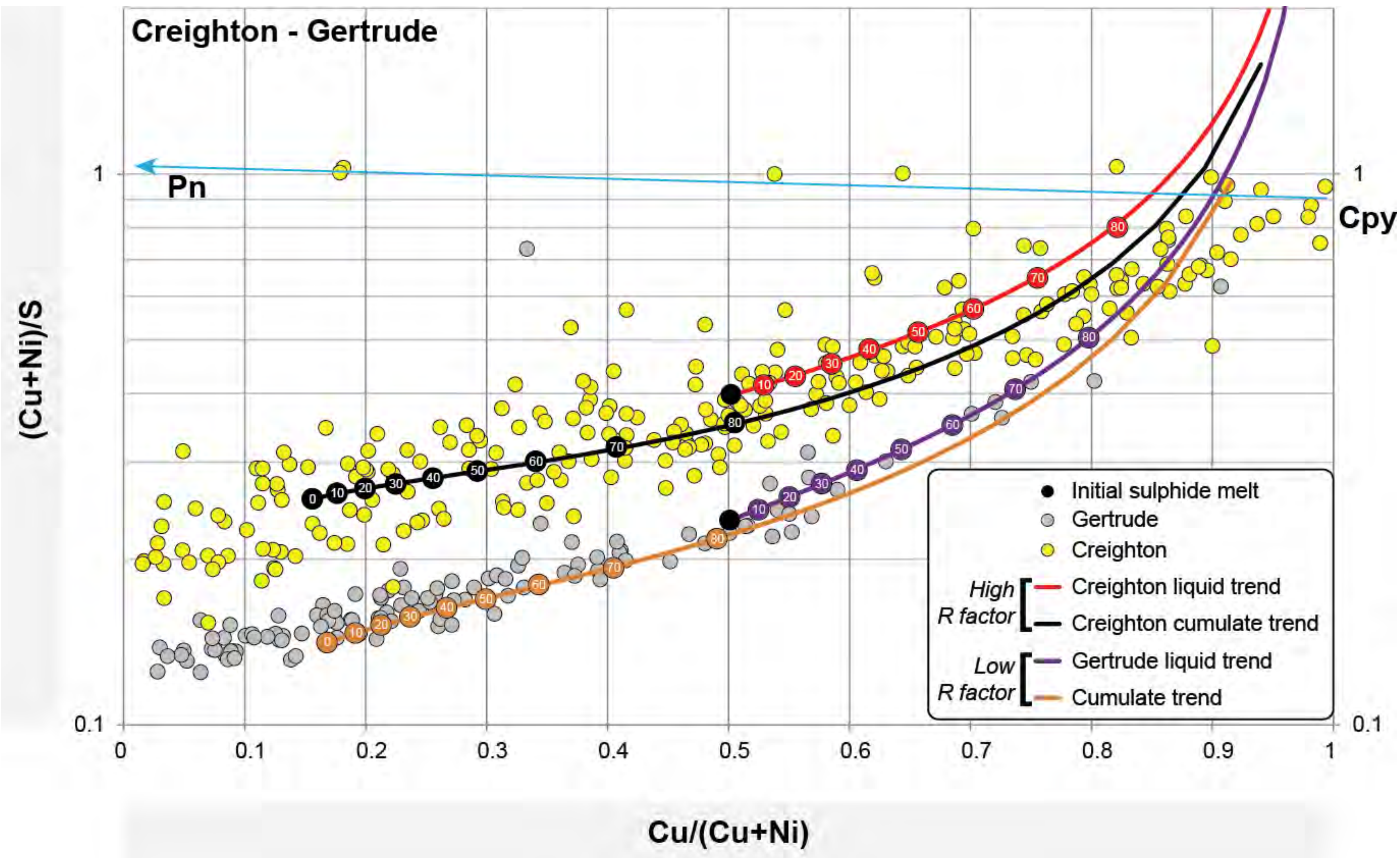
Lightfoot (2016)

Dominant magmatic sulfide compositions at Sudbury



Lightfoot (2016)

Compositional diversity in Sulfides explained by Fractionation and inherent "nugget effect"

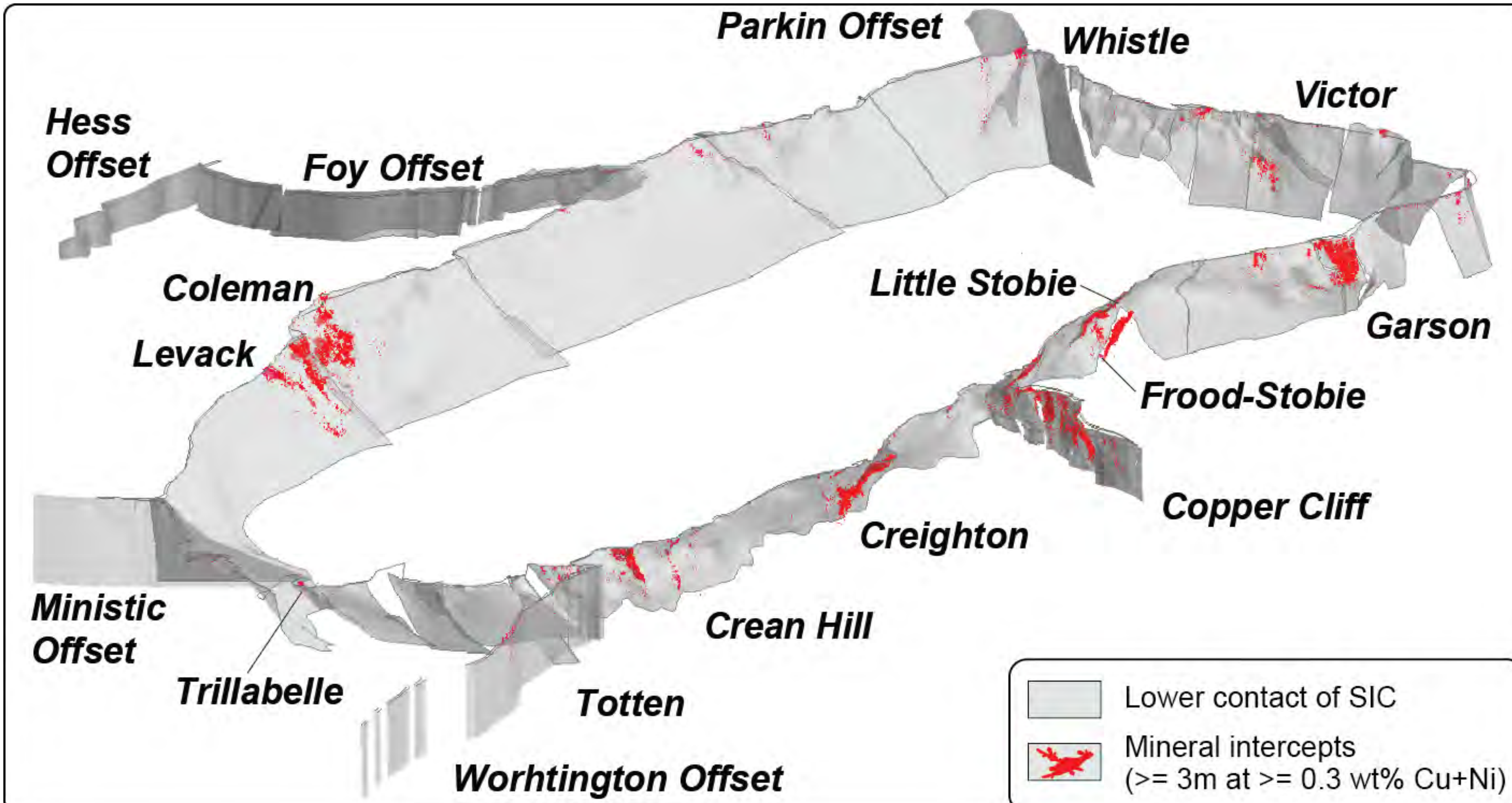


Lightfoot (2016)

Objectives

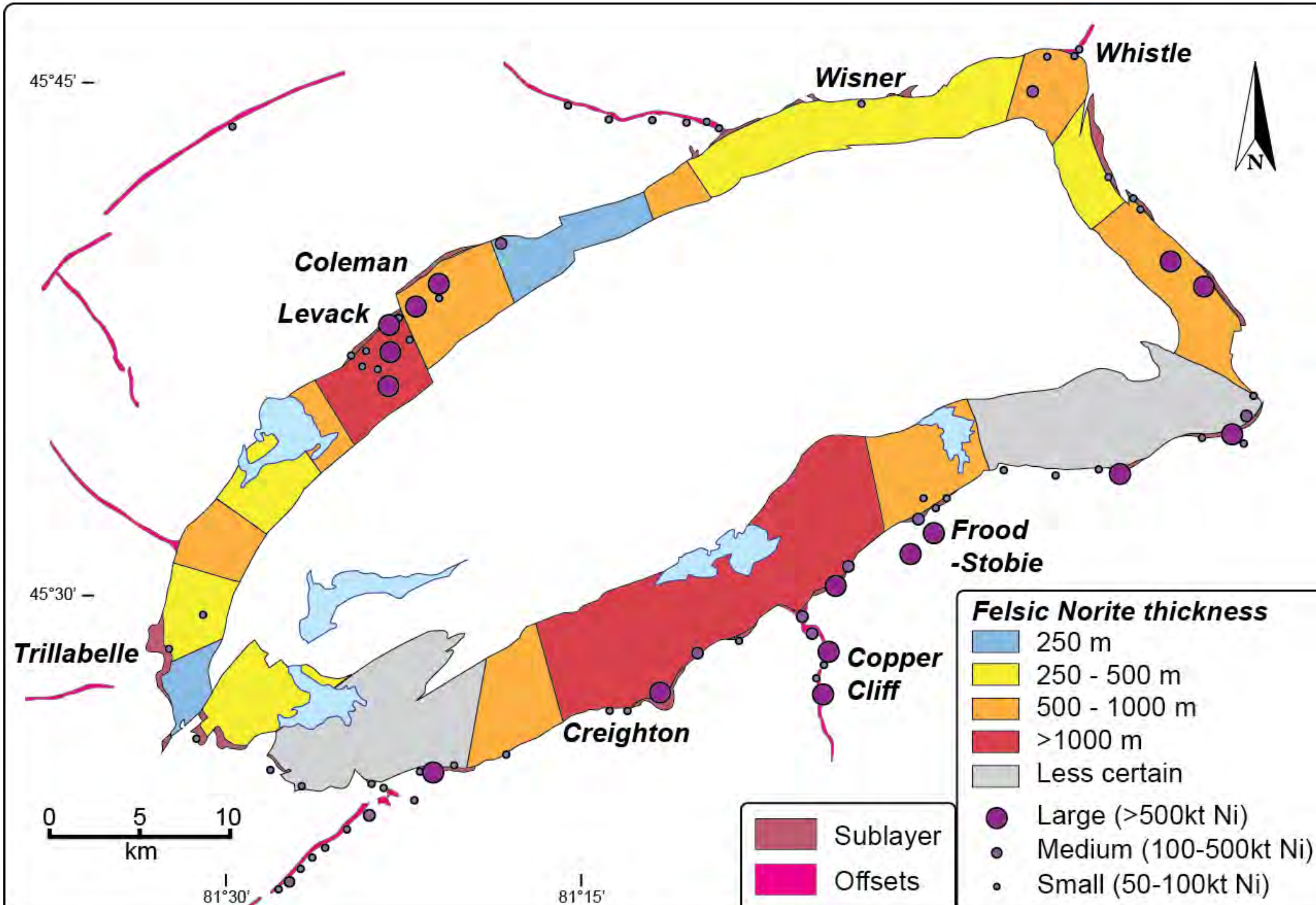
1. Timelines and processes:
2. Diversity in styles of mineralization
3. Linkages between melt sheet processes and ore deposits
    - Source of the metals
    - Thickness of melt sheet
4. Primary magmatic and post-magmatic processes
5. Place Sudbury ores in a global context: past, present, and future

Distribution of ore deposits is not uniform around the basin



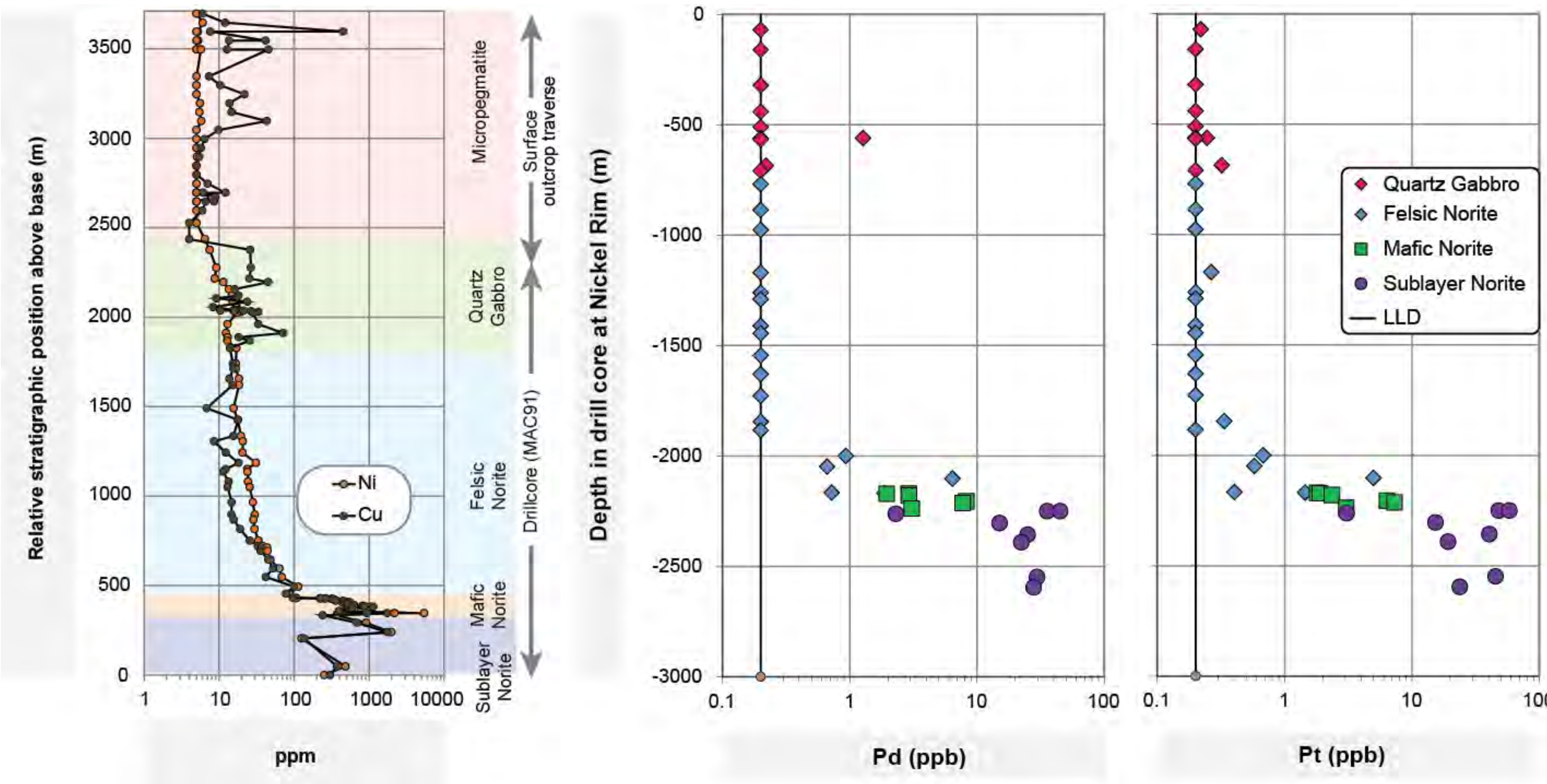
Lightfoot (2016)

Thickness of the Main Mass Ni-Cu-PGE-depleted norite sequence



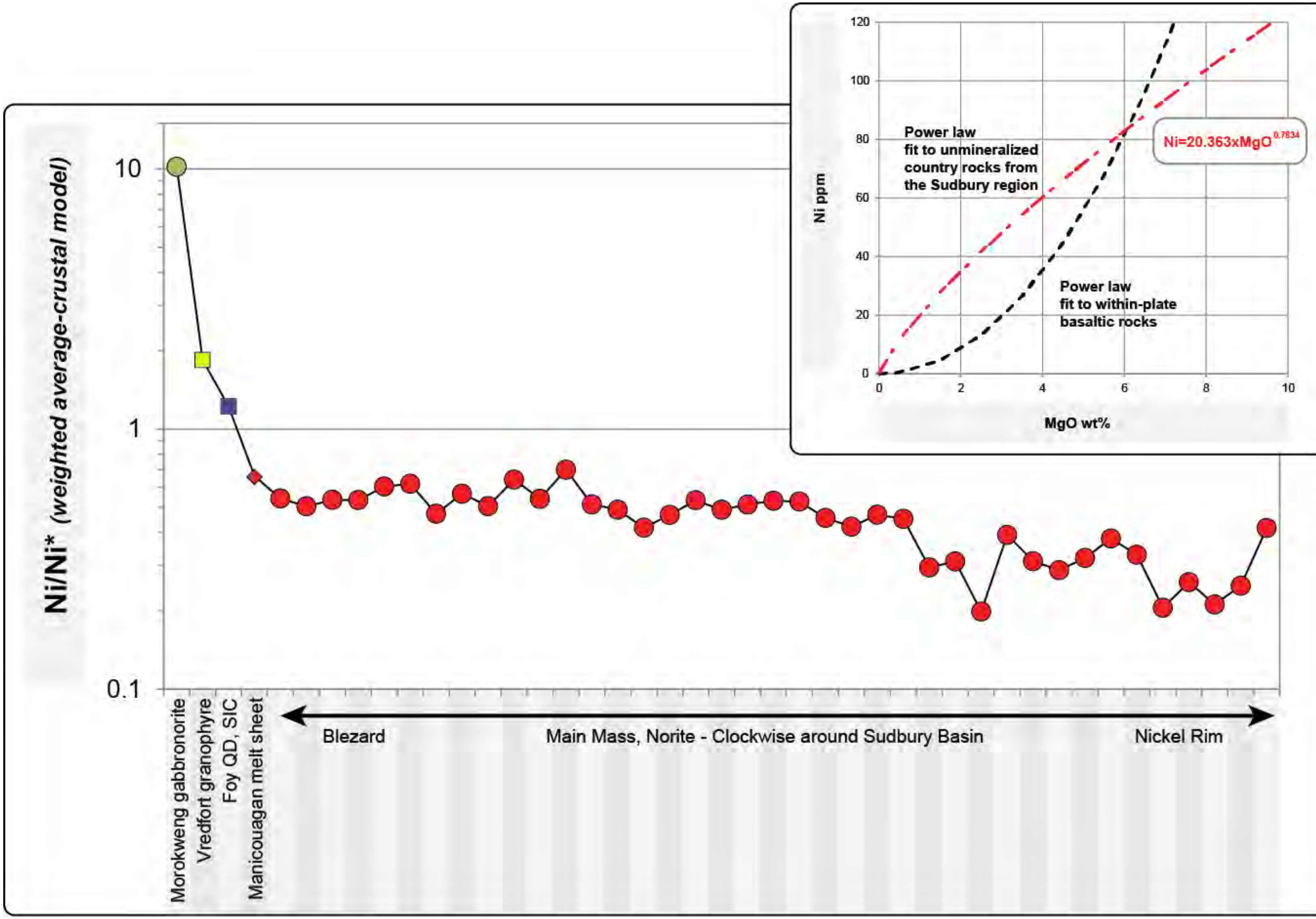
Lightfoot (2016)

Variations in Ni, Cu, Pt, and Pd through the Main Mass (North Range)



Lightfoot (2016)

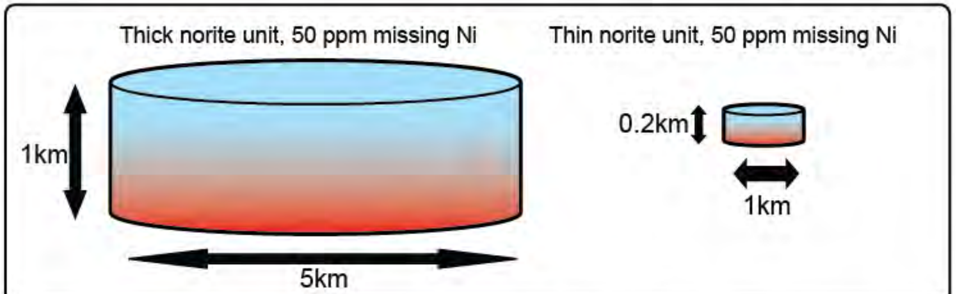
Ni-Cu(PGE)-depleted norites occur throughout the Main Mass stratigraphy



Lightfoot (2016)

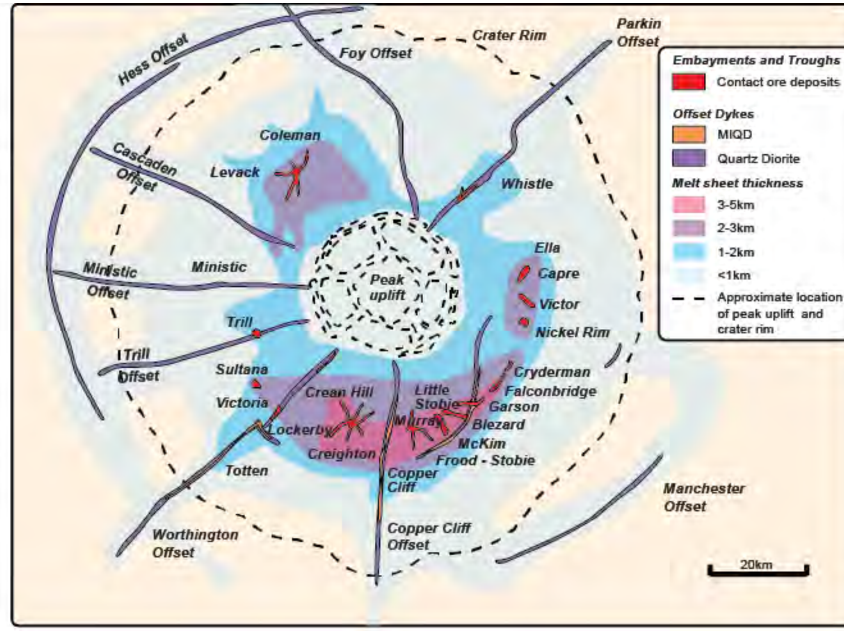
Relationship between melt sheet thickness and scale of mineral systems

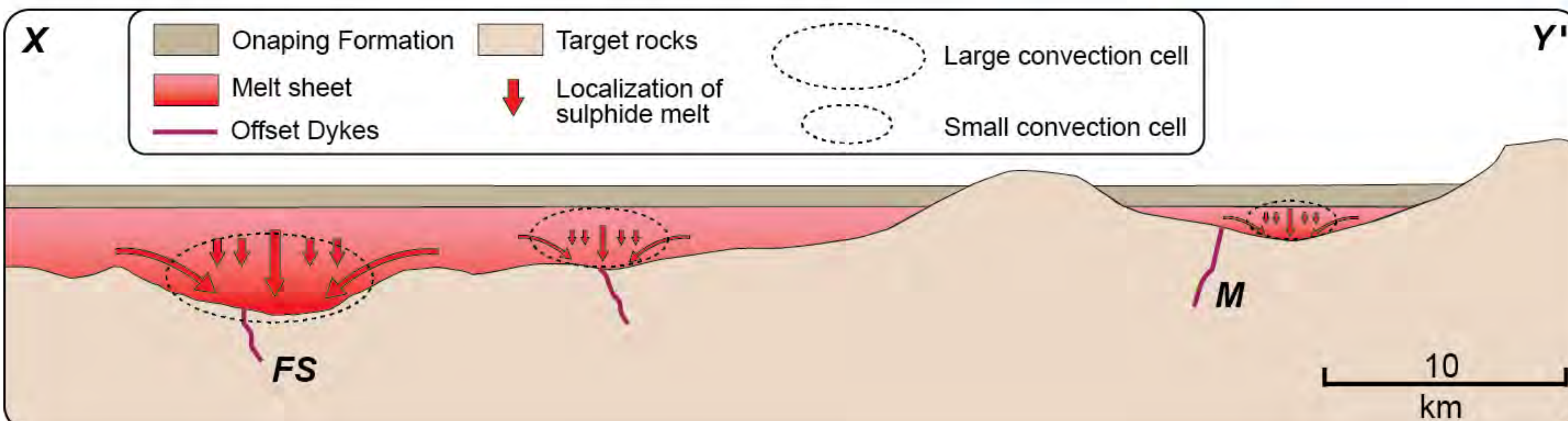
Lightfoot (2016)



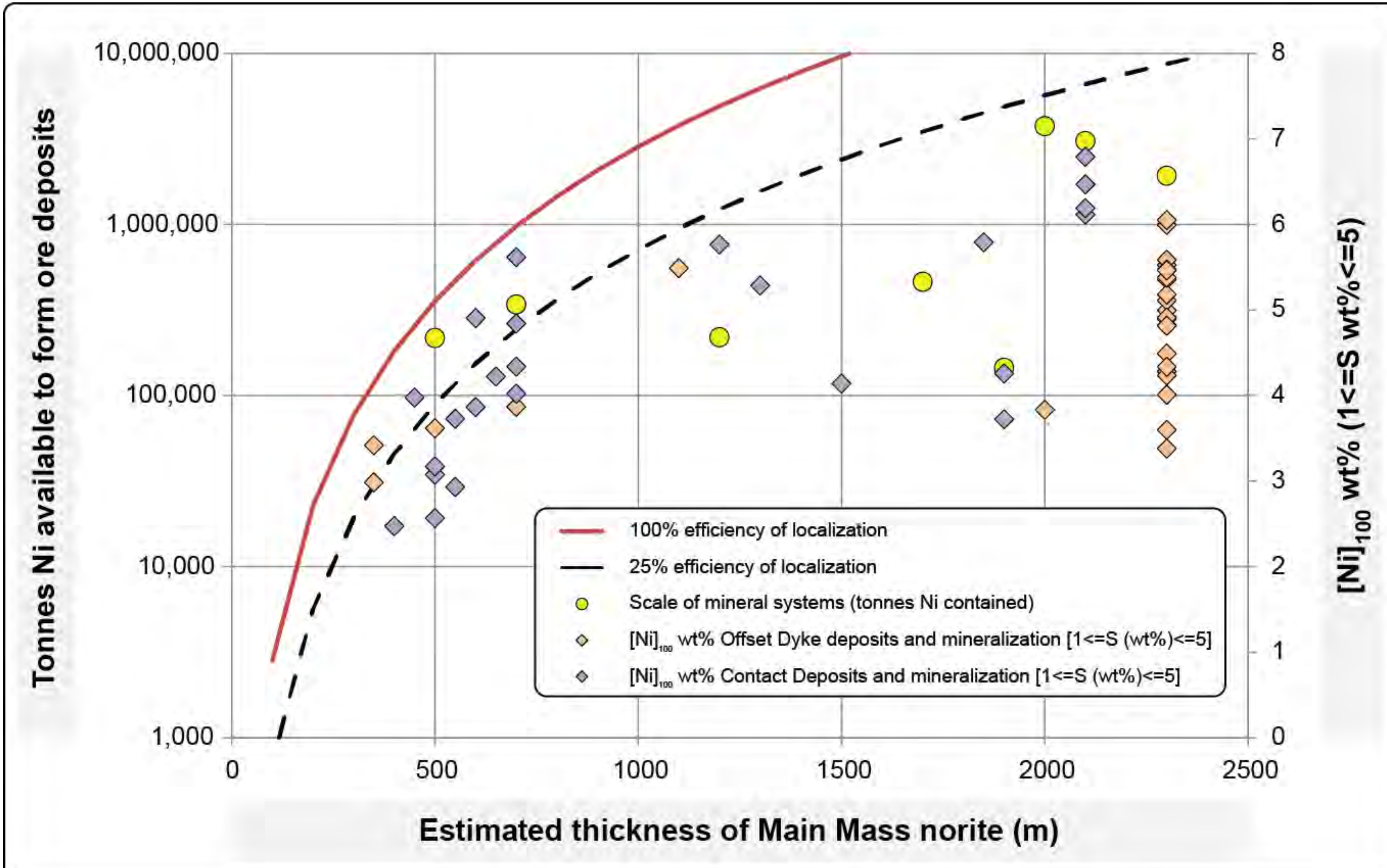
- 78 km^3 magma
- 251x10^9 tonnes melt
- 12x10^6 tonnes Ni lost
- At 2 % Ni grade, 157x10^6 tonnes ore

- 0.6 km^3 magma
- 2x10^9 tonnes melt
- 0.01x10^6 tonnes Ni lost
- At 2 % Ni grade, 0.6x10^6 tonnes ore



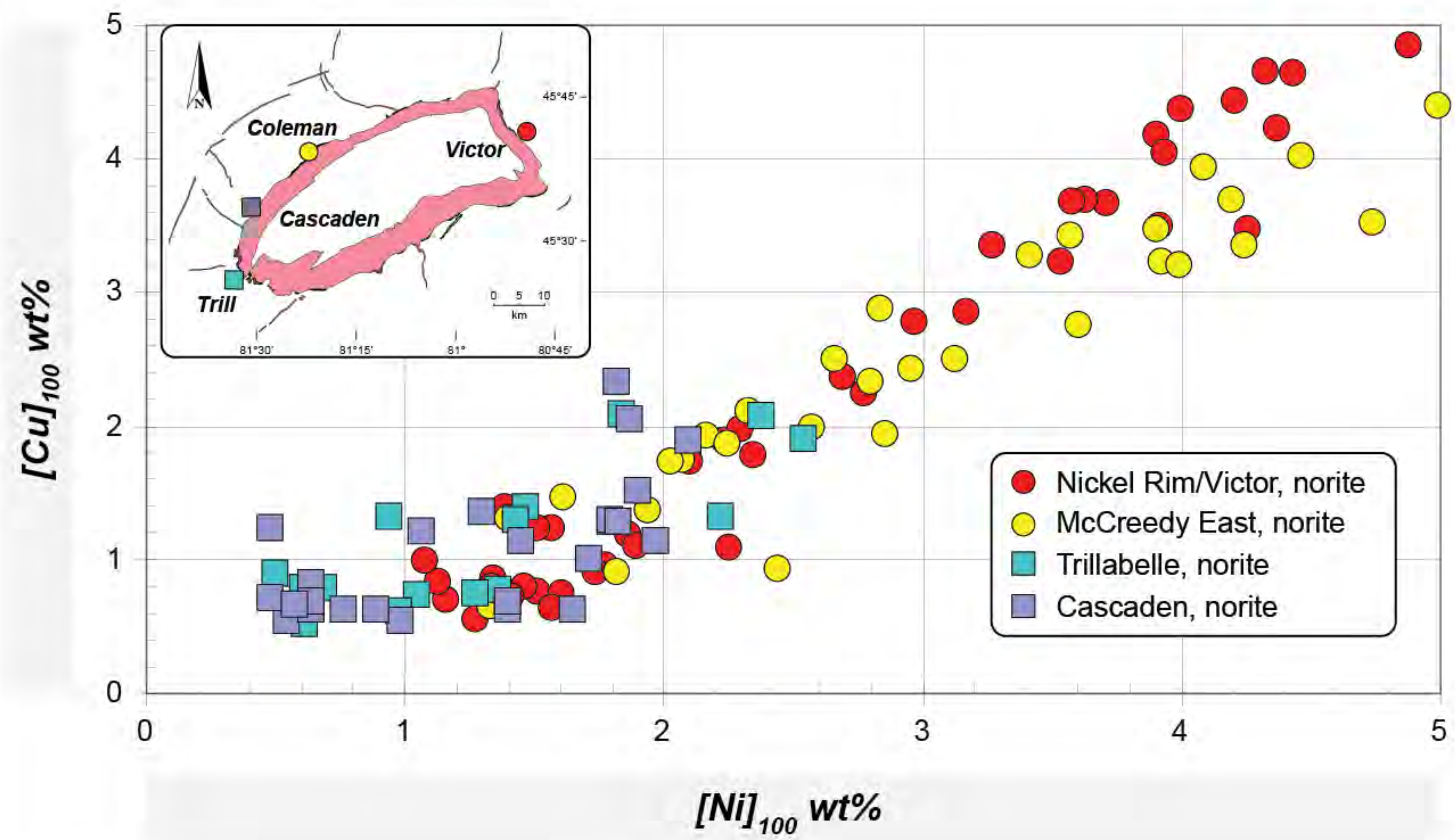


Scale and quality of mineral system is a function of norite thickness



Lightfoot (2016)

Main Mass record as prospectivity tool



Lightfoot (2016)

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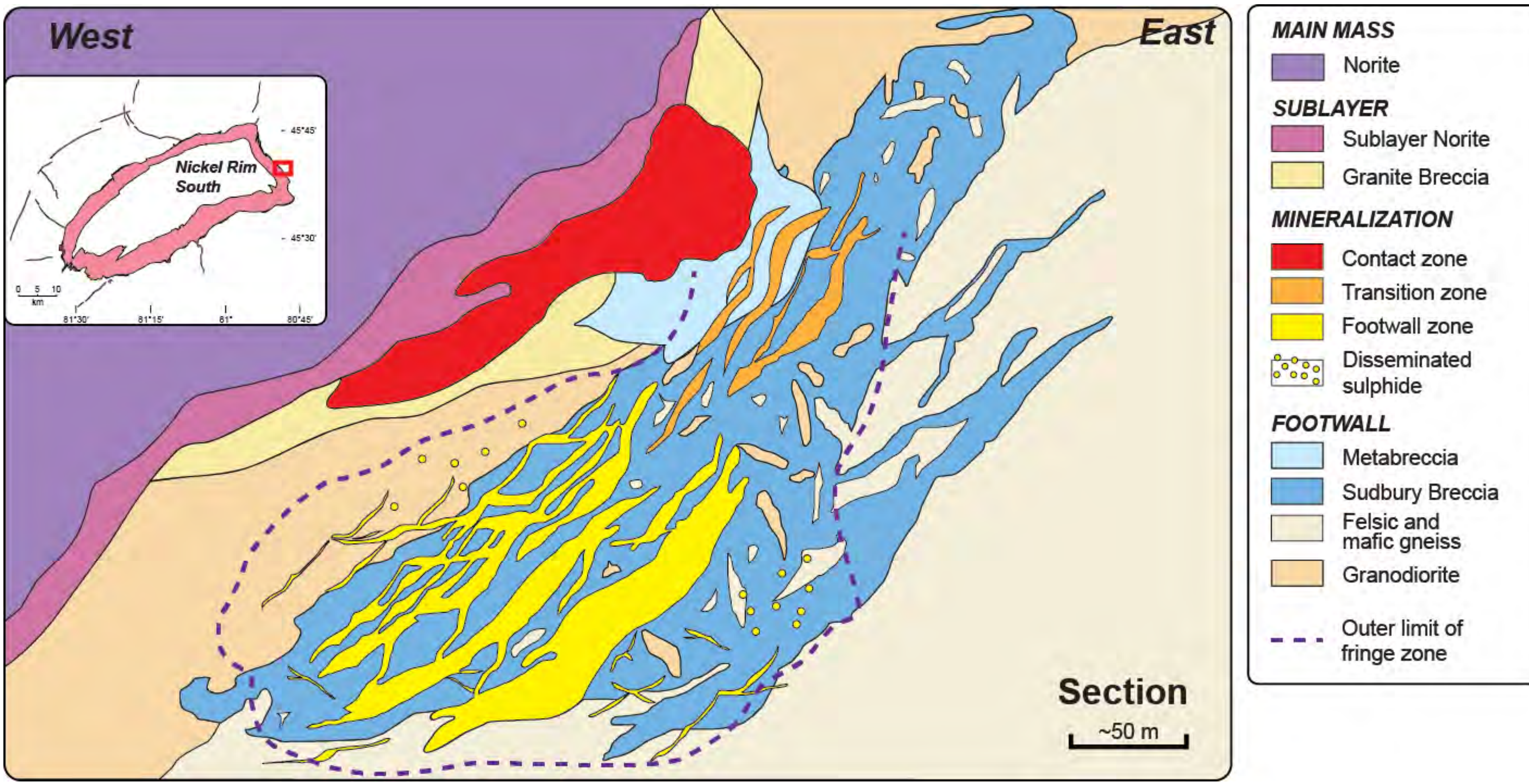
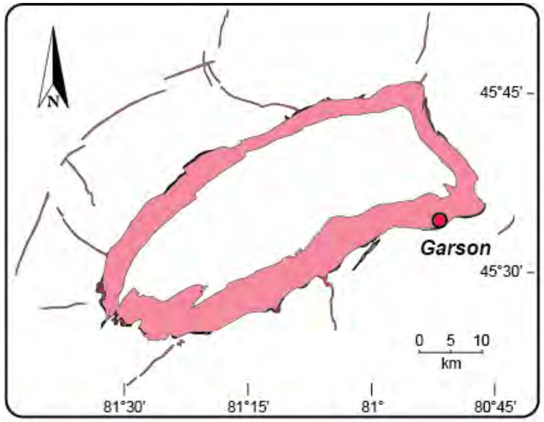
Low sulfide mineralization styles tend to be associated with magmatic ore systems (e.g. Nickel Rim)

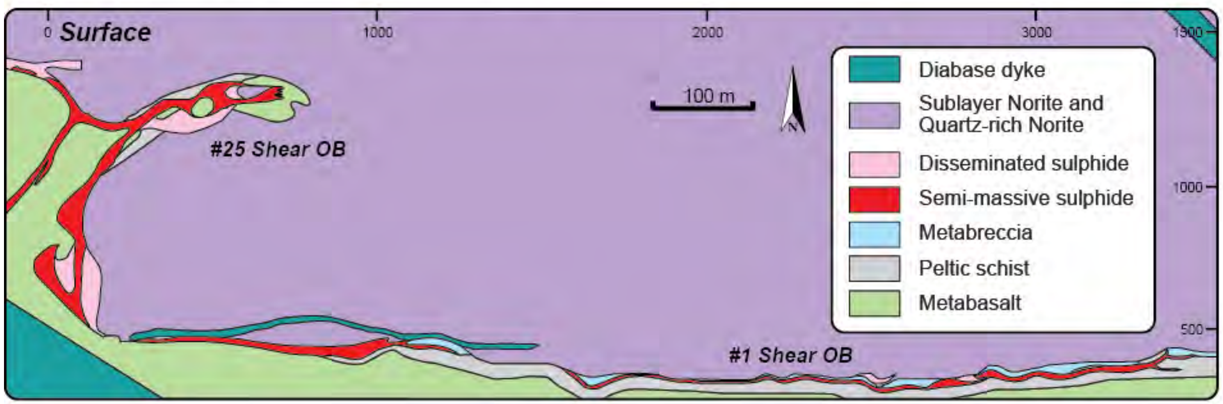


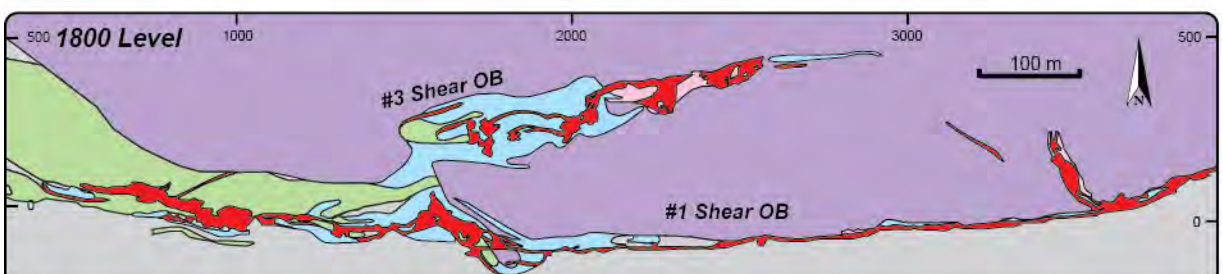
Lightfoot (2016) and McLean et al. (2006)

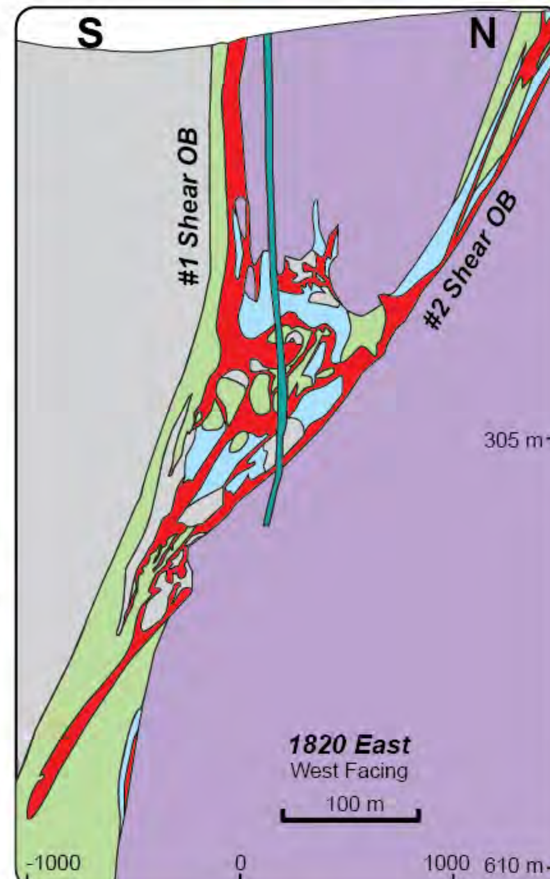
Deformation undoubtedly modifies and re-distributes contact ores (e.g. Garson Deposit)

Lightfoot (2016) and Mukwakwami et al (2012)



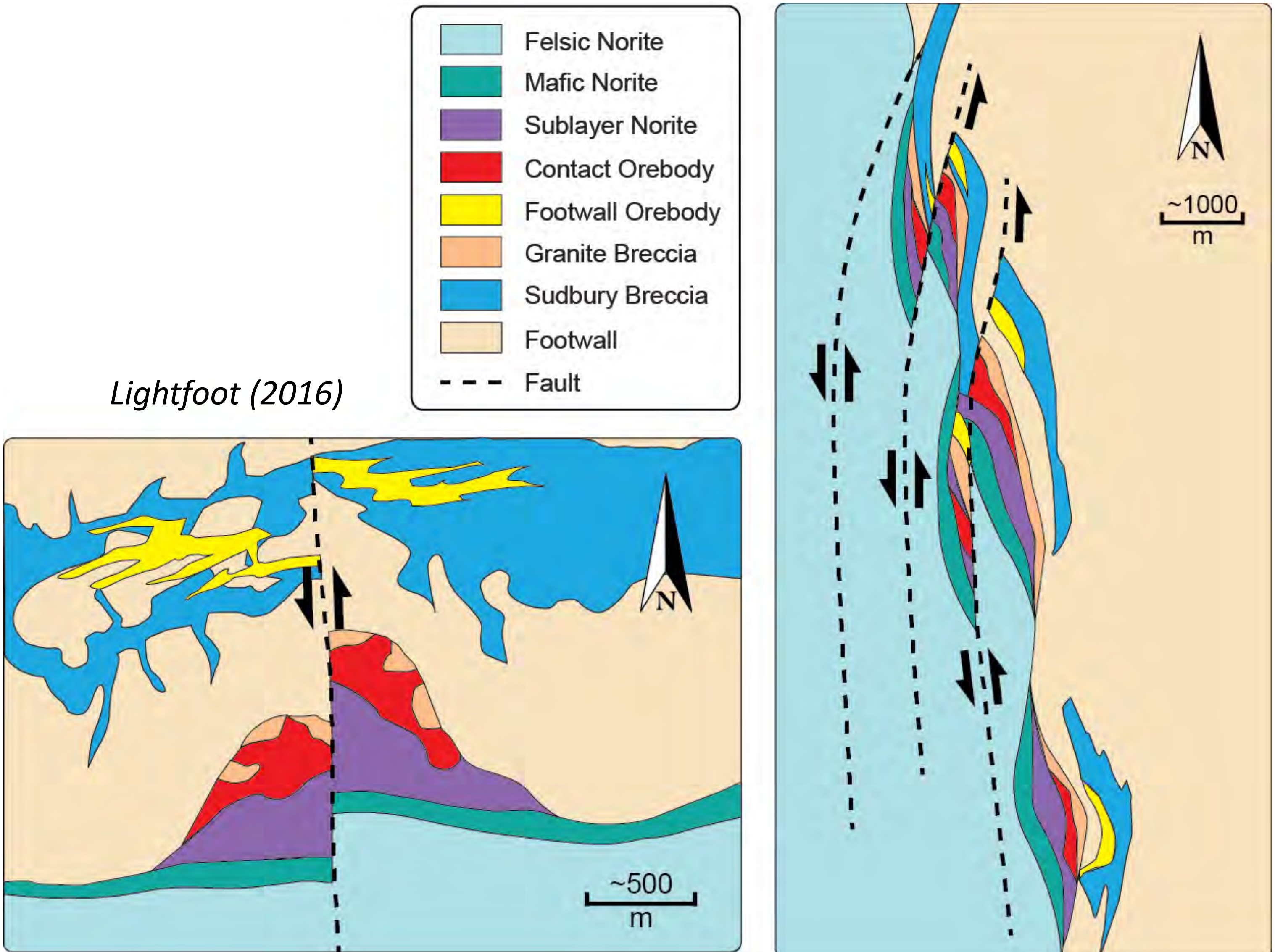






Understanding displacement on structures is critical to future discovery

Lightfoot (2016)



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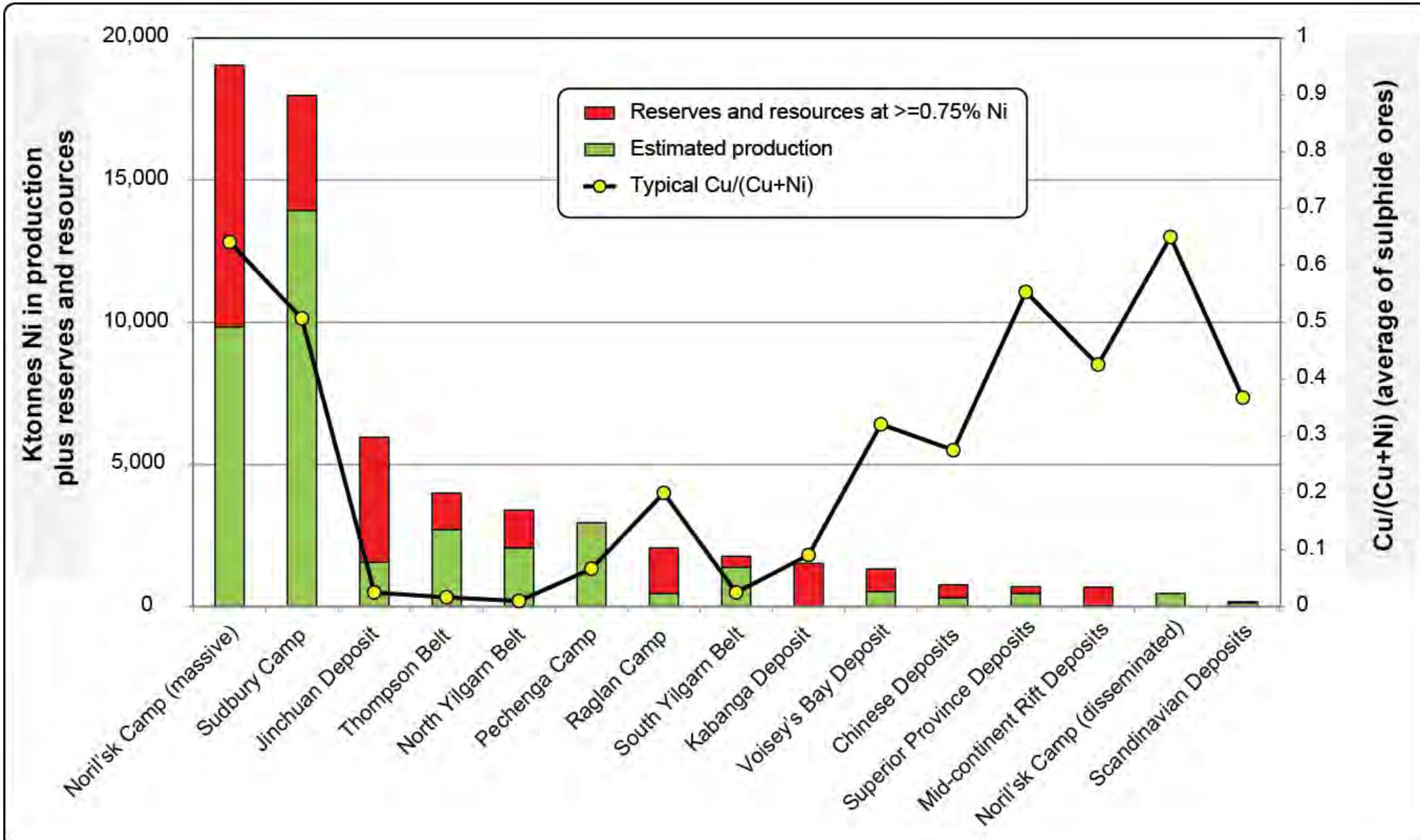
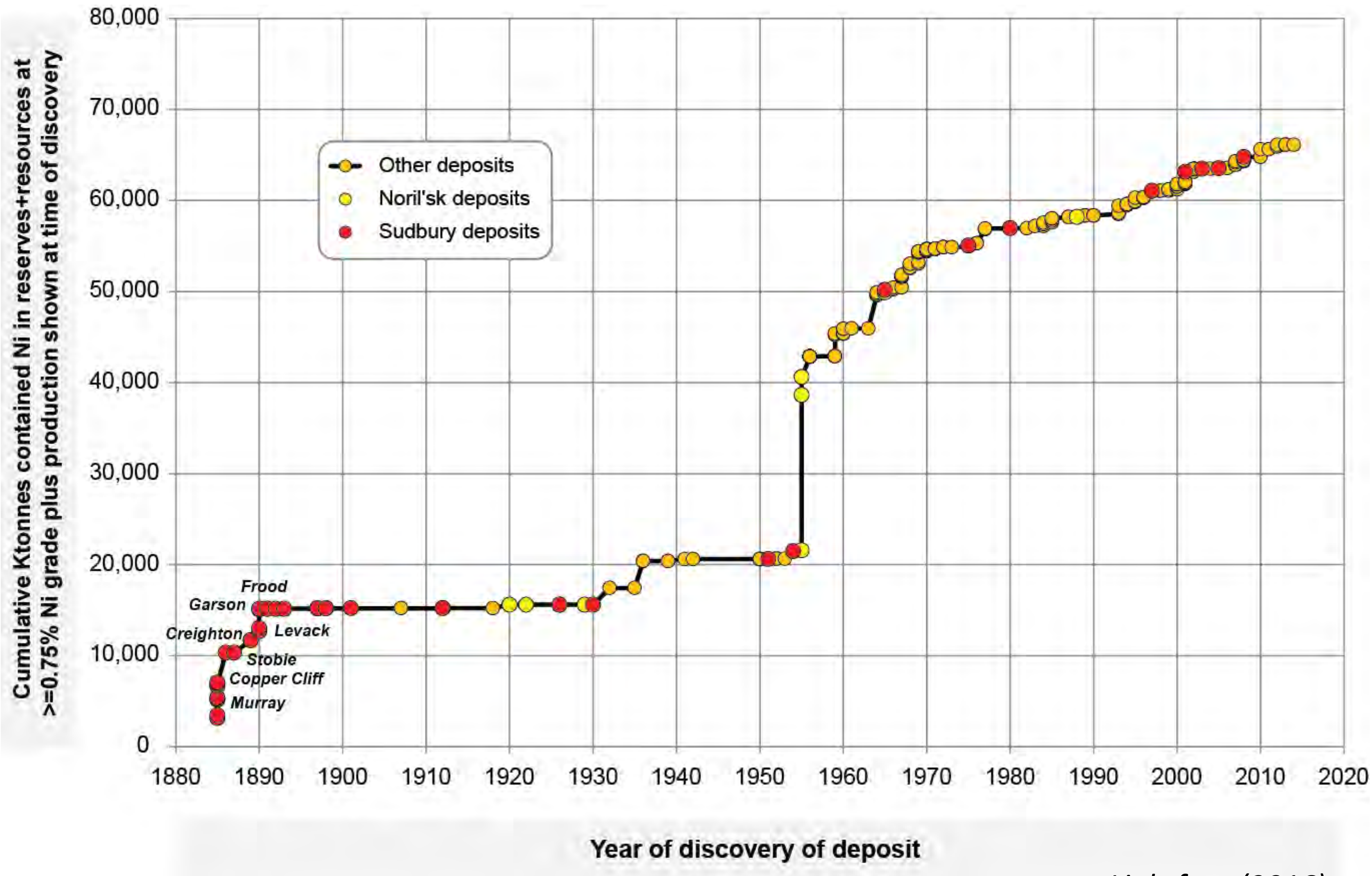
Despite being eclipsed by the Noril'sk Camp, Sudbury remains the second largest resource of magmatic Ni sulfide



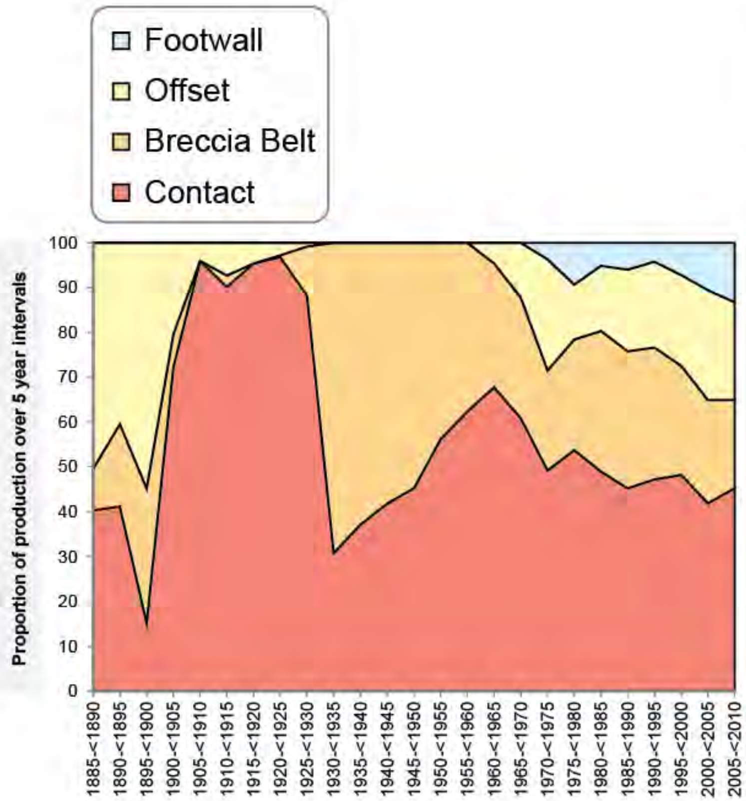
Lightfoot (2016)

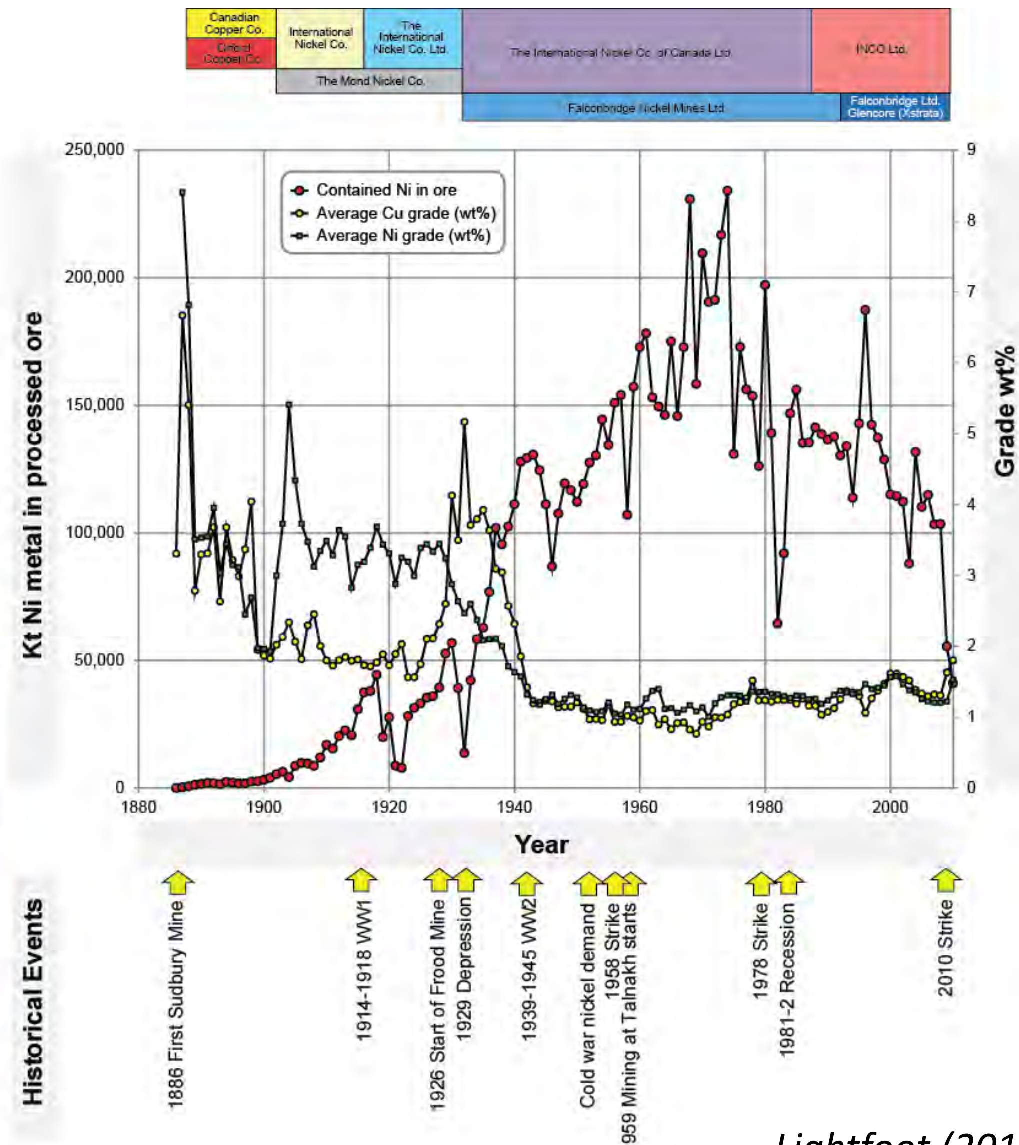
History of sulfide nickel discovery



Lightfoot (2016)

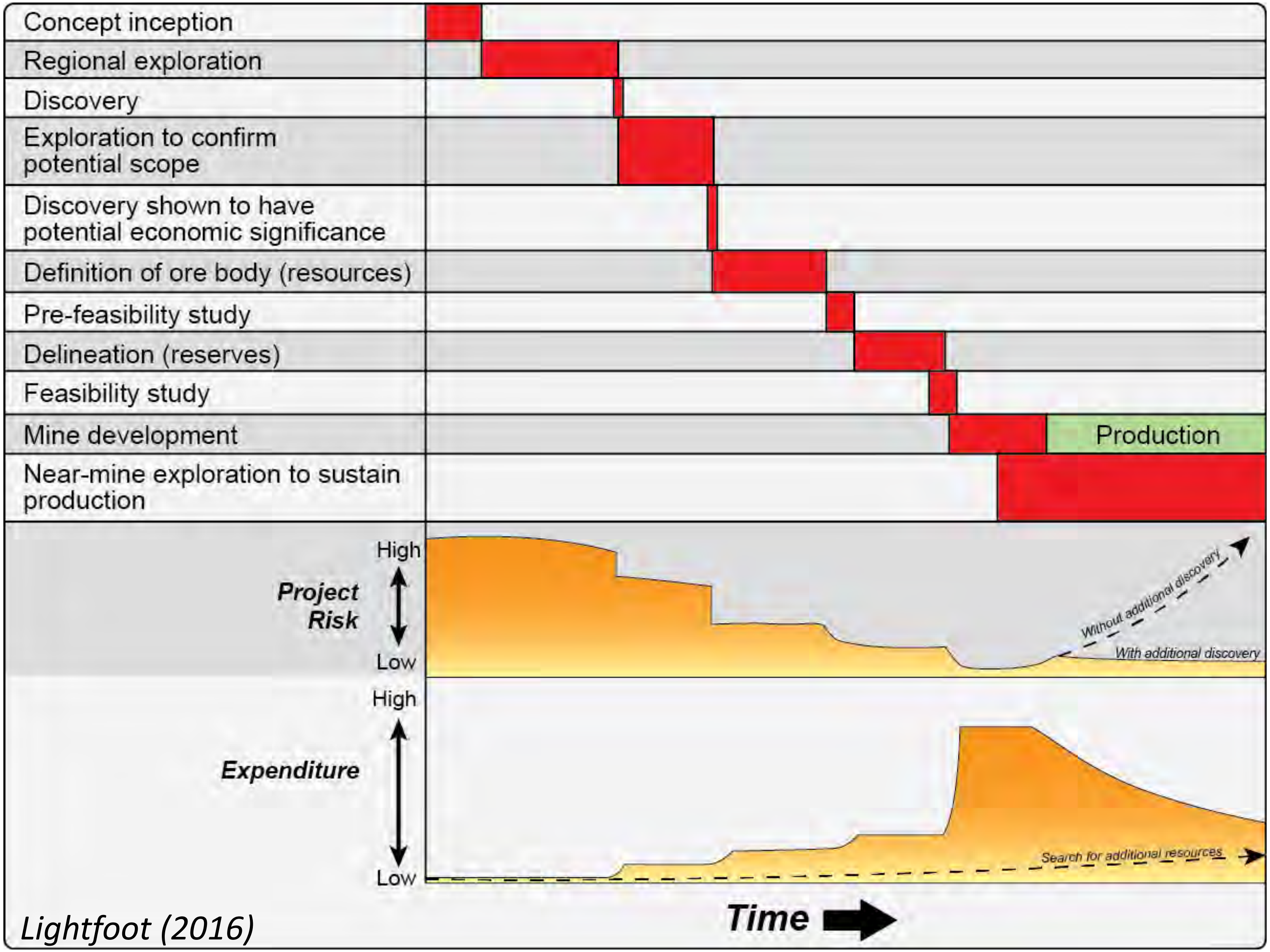
Historic production at Sudbury



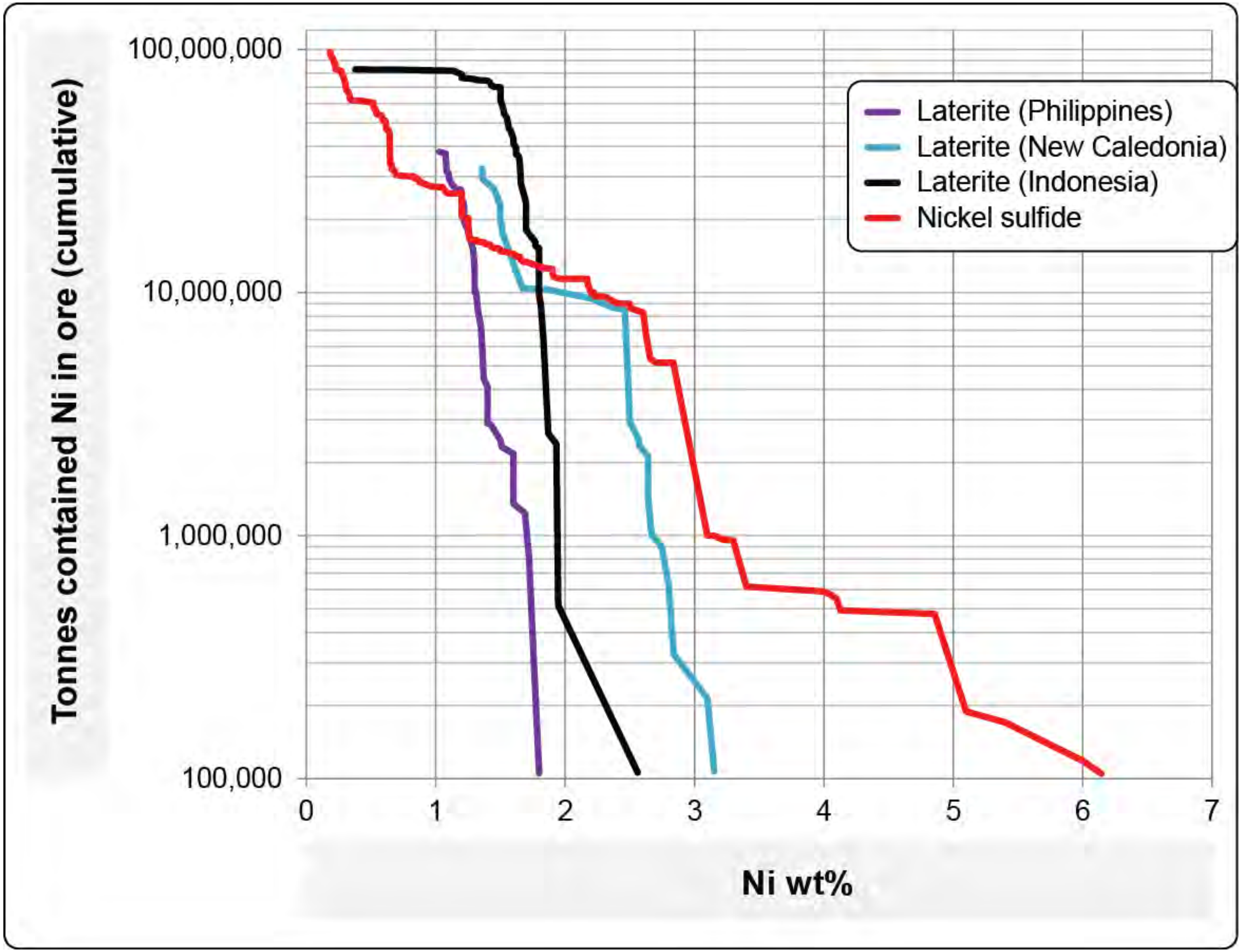


Lightfoot (2016)

Effective exploration is required to populate the project pipeline and secure new mines at Sudbury



The Sudbury sulfide ores have a competitive advantage in grade as well as metal value over laterites



Lightfoot (2016)

Thank you

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