

# EARTH 471

# Mineral Deposits

## Magmatic Ore Deposits

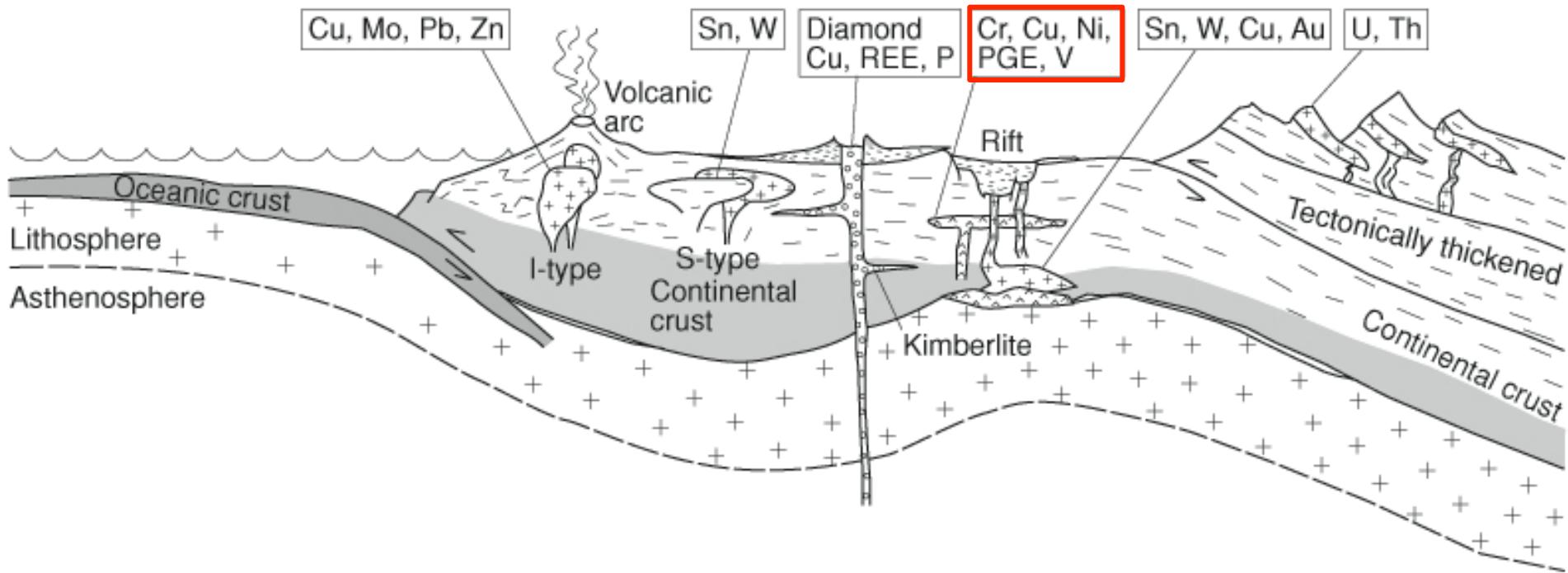
## Magmatic mineral deposits

- Also known as orthomagmatic
- Typically associated with the physical concentration of ore minerals through magmatic process
- Important elements: Ni, Cr, Cu, Ti, V, Fe, PGE
- Important minerals: **pentlandite**, chromite, chalcopyrite, ilmenite, platinum, palladium, magnetite, apatite, rutile

### Examples:

- 1) Cu–Ni (komatiites, impact melting, mafic intrusive)
- 2) PGE (stratiform in mafic intrusions, magmatic breccias)
- 3) Diamond (kimberlite, lamprophyres)
- 4) Cr (layered intrusion, ophiolite)
- 5) U, REE (Granite pegmatites)

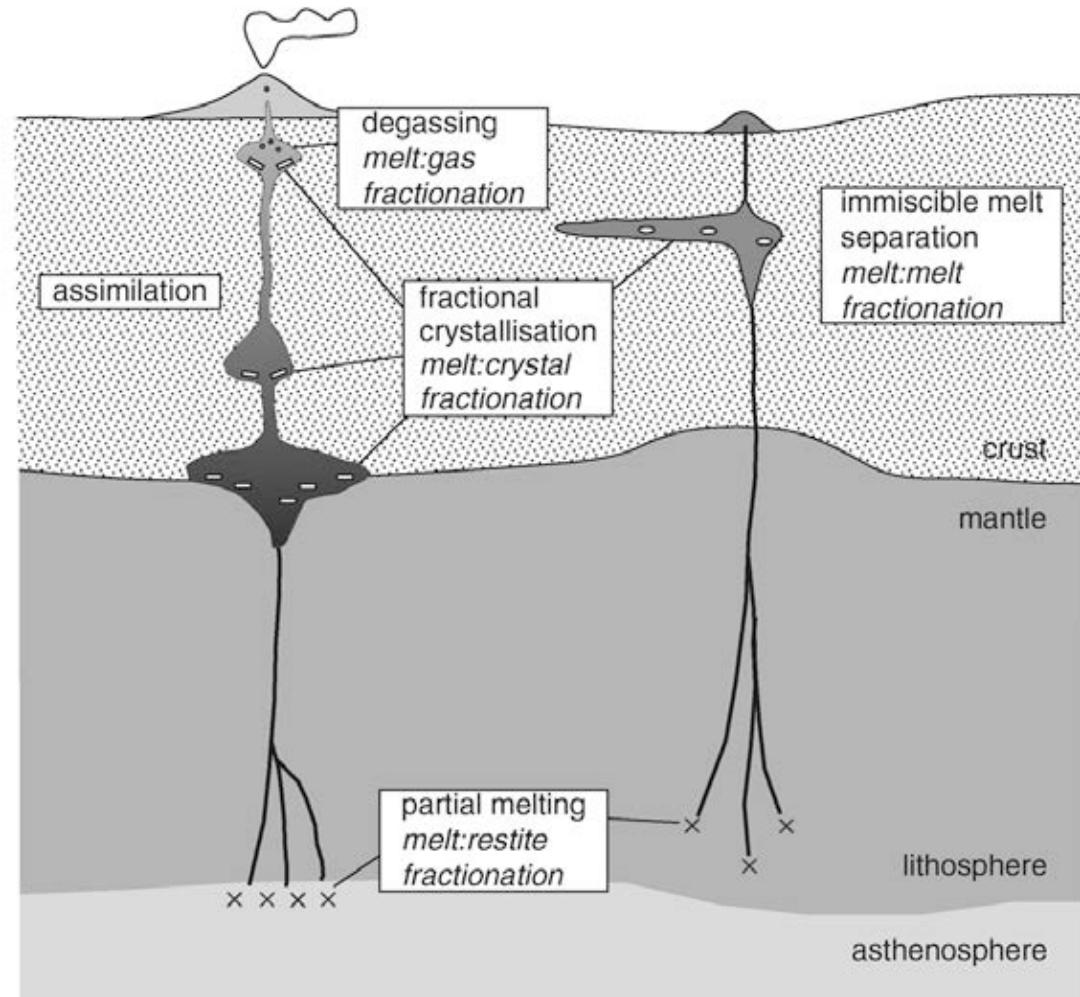
# Tectonic setting of magmatic ore deposits



Ridley (2013)

# Magmatic processes:

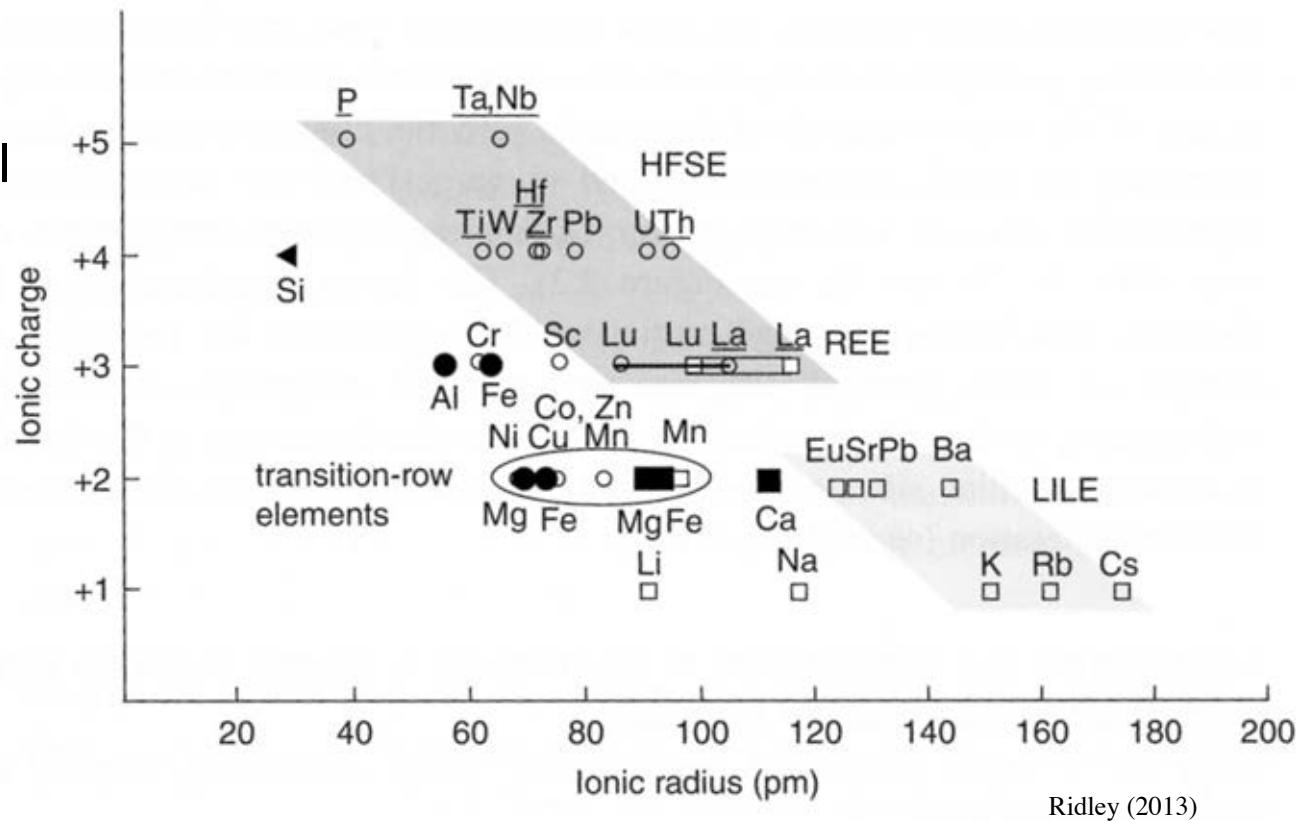
1. Very low degrees of partial melting
2. Fractional crystallization
3. Crystallization of the last increments of melt
4. Separation of two immiscible liquids
5. Physical incorporation of minerals



Ridley (2013)

# Compatible and incompatible elements

- Incompatible elements generally do not substitute well into the minerals present in the system due differences of the ionic radii and charge of the mineral-forming elements of the system.



- Compatible elements generally substitute well into the minerals present in the system due to similarities in ionic radii and charge of the mineral-forming elements of the system

# Compatible and incompatible elements

## Incompatible elements:

### HFSE:

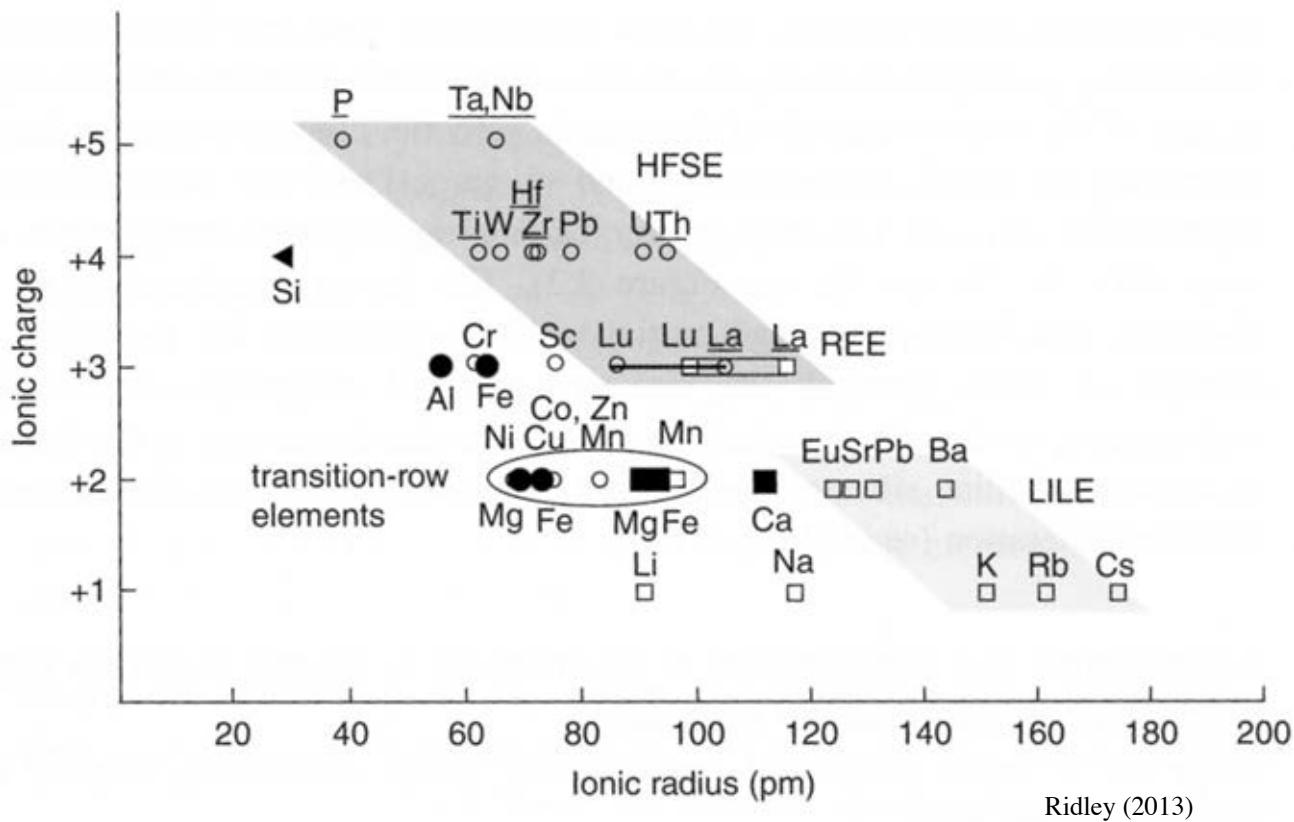
High field strength elements (high ionic charges; Ti, Zr, Hf, Nb, Ta)

### REE

Rare Earth elements (La–Lu)

### LILE

Large ion lithophile elements (large ionic radii; K, Rb, Cs, Sr, Ba, Pb, Eu<sup>2+</sup>)



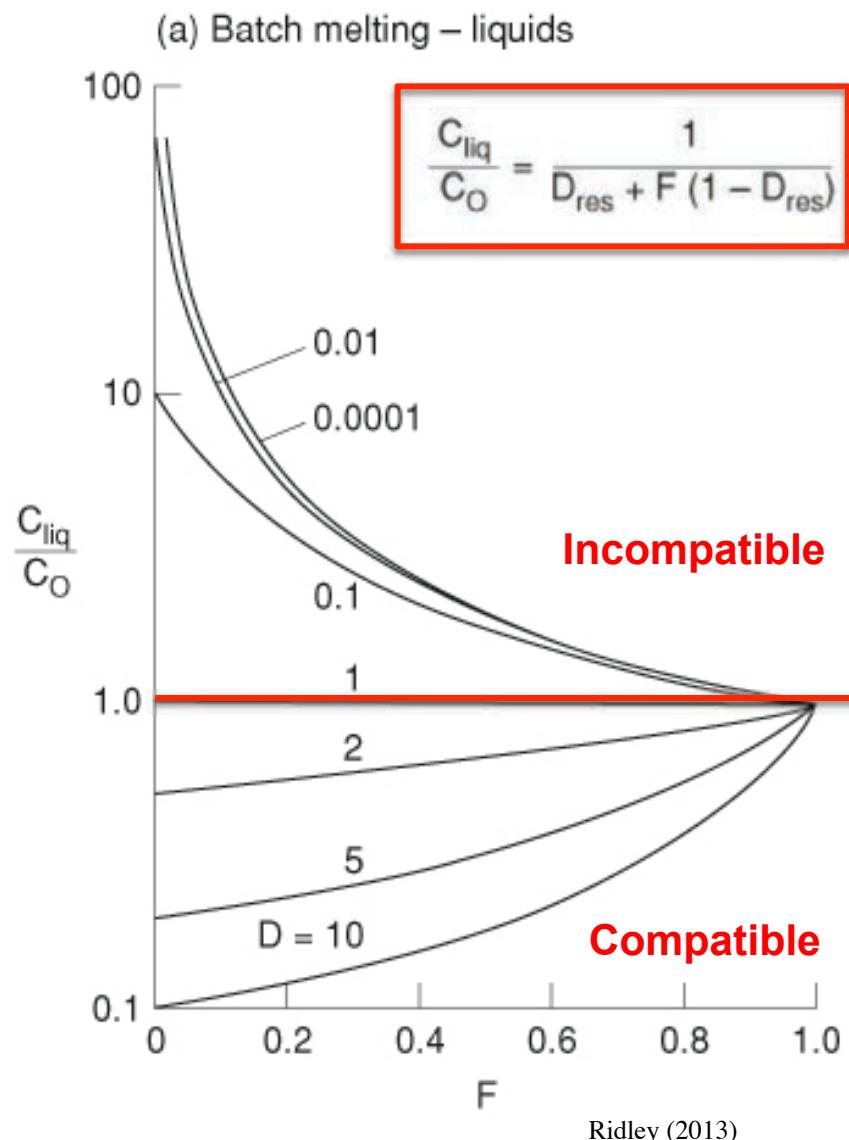
Ridley (2013)

# Compatible and incompatible elements

During partial melting and fractional crystallization, some elements will preferentially partition into the melt phase (incompatible elements) whereas others will go into the solid phase (compatible elements).

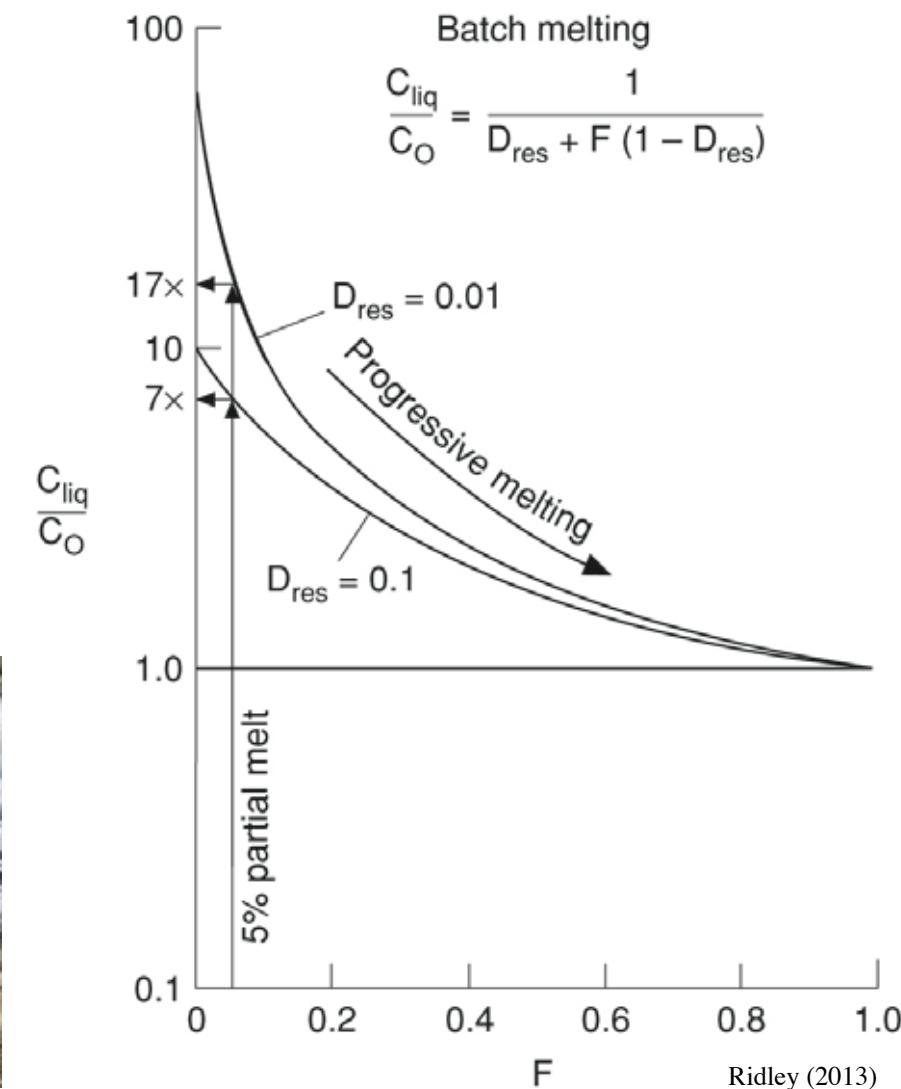
Compatibility is a function of  $P$  (pressure),  $T$  (temperature) and  $X$  (concentration)

During partial melting, incompatible elements will preferentially partition into the melt and, therefore, the first increments of melt will have high concentrations of these elements.

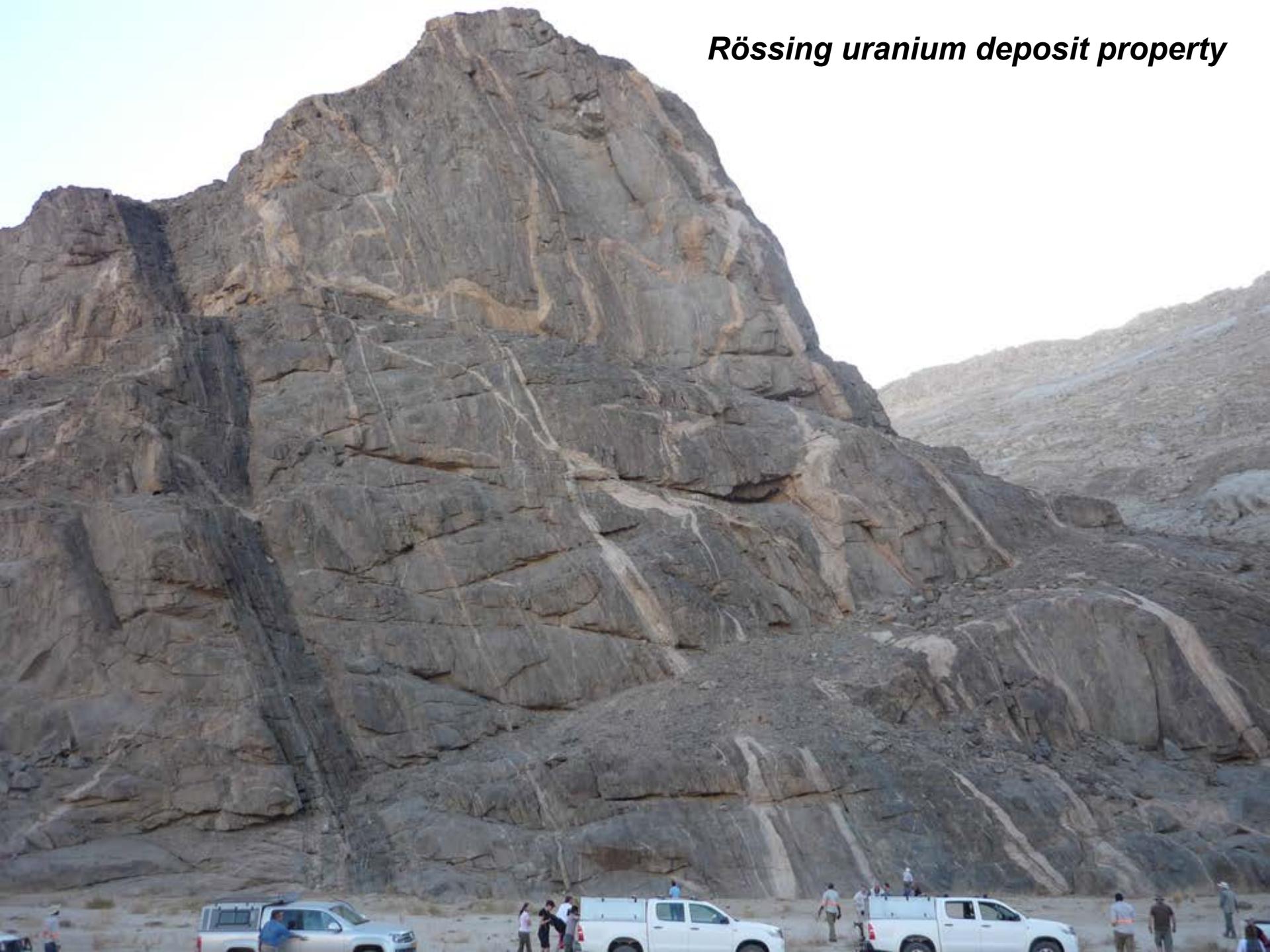


# (1) Low degrees of partial melting

- Incompatible elements enriched in the melt
- *Rössing uranium deposit (Namibia)*
  - Minor partial melting of metasediments generated melts enriched in U
  - Accumulation of leucogranite dykes makes the deposit economic (310 ppm  $\text{U}_3\text{O}_8$ )



*Rössing uranium deposit property*





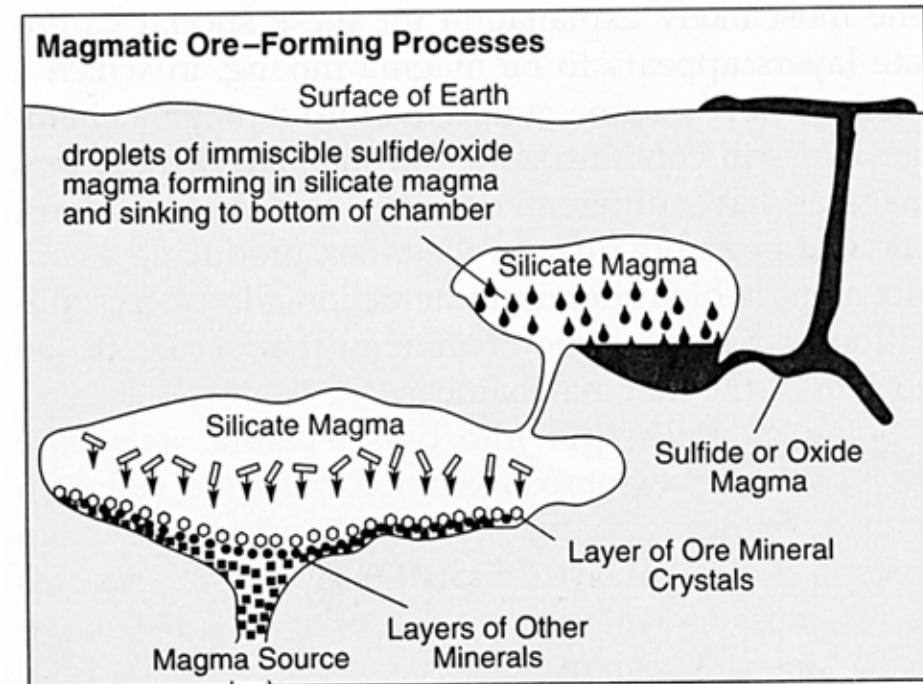
## (2) Fractional crystallization

### Melt crystallization

- Compatible elements will become concentrated in the solid phase (minerals)
- The physical segregation of minerals due to sinking or floating in the magma can lead to economic concentrations.

### Chromite ( $\text{FeCr}_2\text{O}_4$ ) deposits:

- Chromite crystallizes during cooling of mafic magmas
- Denser than silicate magma, so crystals settle to the bottom of the magma chamber
- \*\*This is a simplified model—in nature it is more complicated.



Kessler (1994)

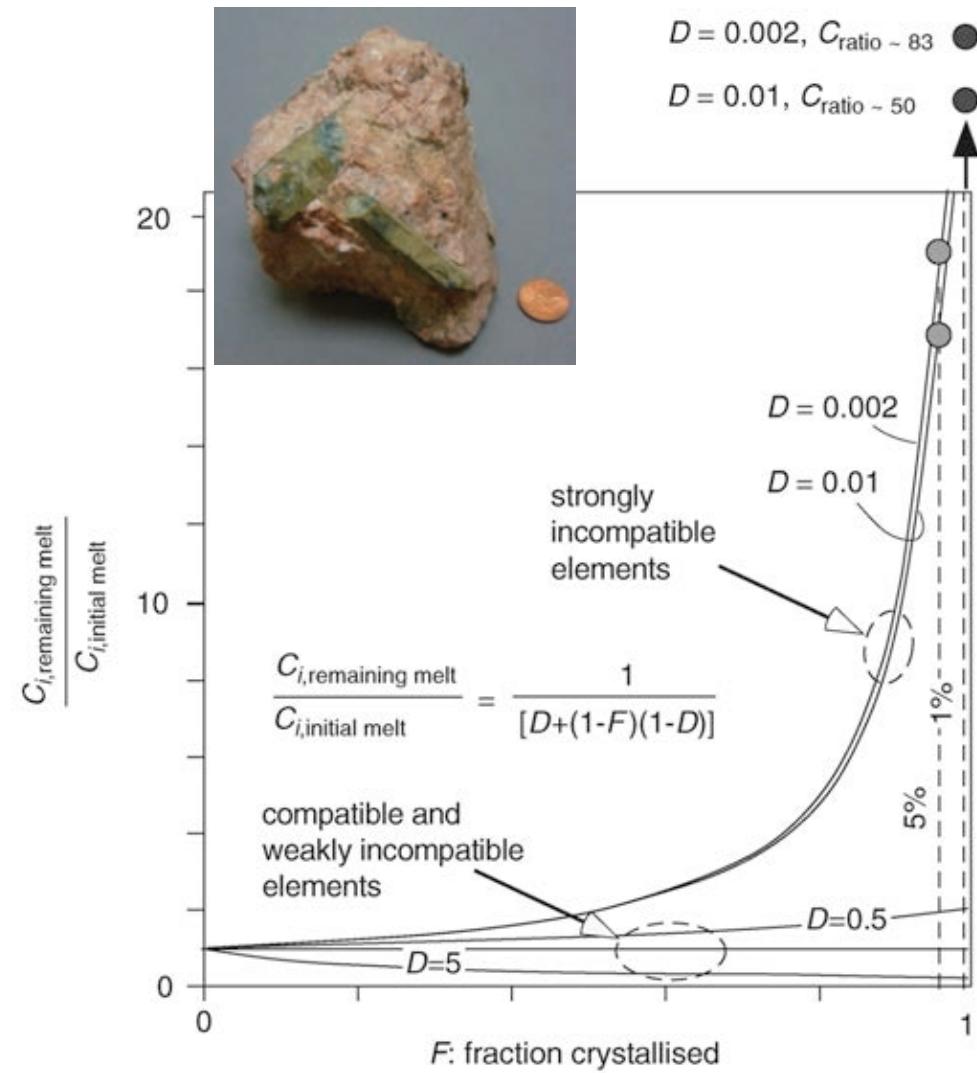
### (3) Crystallization of the last increments of melt

#### Final stages of melt crystallization

- the last increments of melt will have high concentrations of the incompatible elements

#### Pegmatites

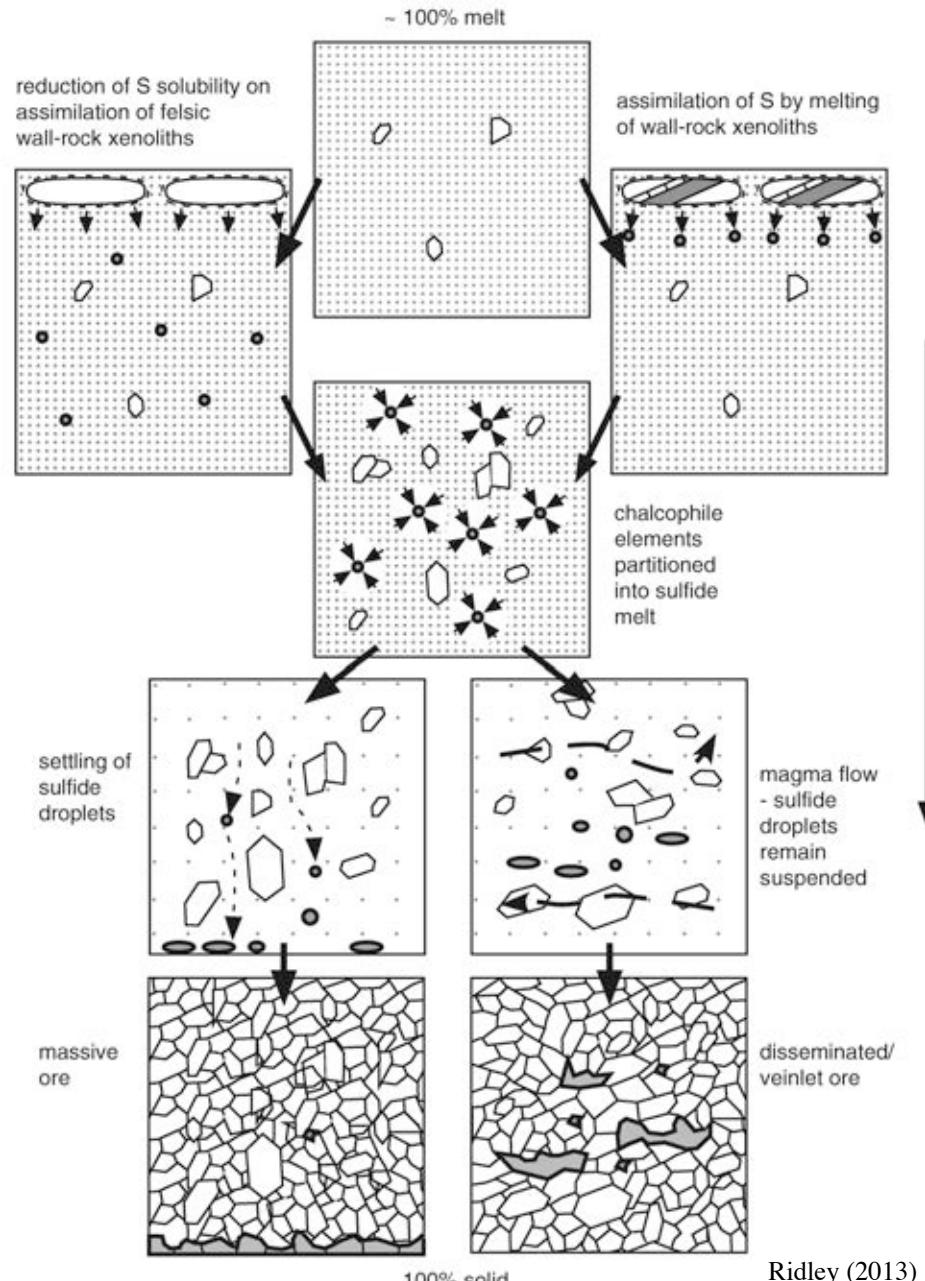
- During melt crystallization of a pluton, the last remnants of melt will be enriched in the LILEs, HFSEs, and fluid-mobile elements B and F
- Migration and crystallization of this fractionated magma will result in further fractional crystallization and potential enrichment in LILEs and HFSEs



Ridley (2013)

## (4) Separation of two immiscible liquids

- Immiscible: two phases (e.g. liquids) that coexist stably
- Particularly important for sulfide minerals
- When the concentration of dissolved sulfide reaches saturation in a silicate magma, sulfide droplets become physically separable (representing another *phase*) and may form droplets that concentrate at the bottom of a magma chamber
- Sulfide liquid may crystallize, resulting in a sulfide melt
- Chalcophile and siderophile elements (e.g. Cu, Ni, Pt) will partition into a sulfide melts instead of a silicate liquid
- Similarly (but more rarely) oxide-rich melts may concentrate Fe and Ti

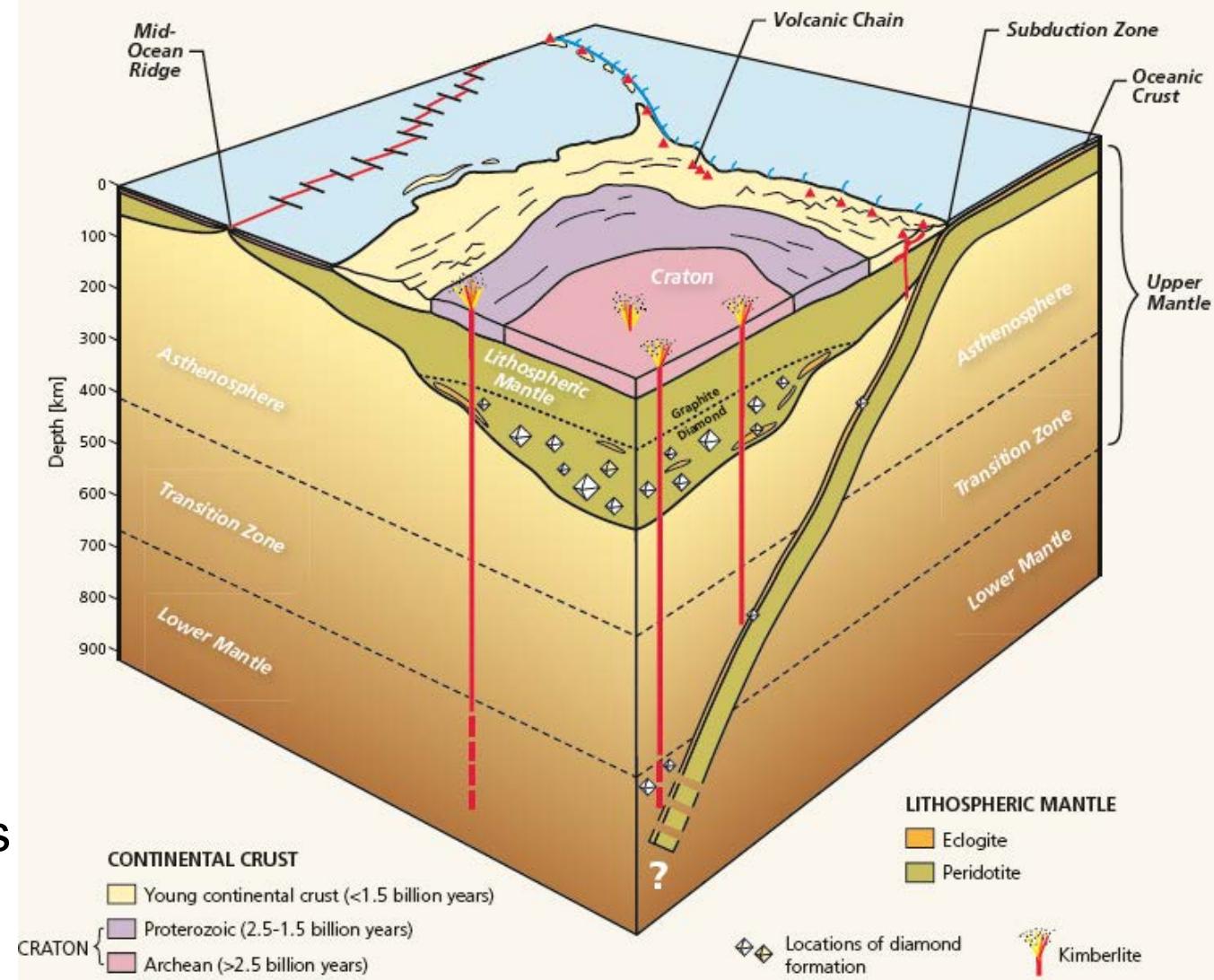


Ridley (2013)

## (5) Physical incorporation of minerals

Minerals from wall rock are physically incorporated into the ascending magma

Diamonds are xenoliths from the mantle that are brought to the surface by ascending kimberlitic magmas

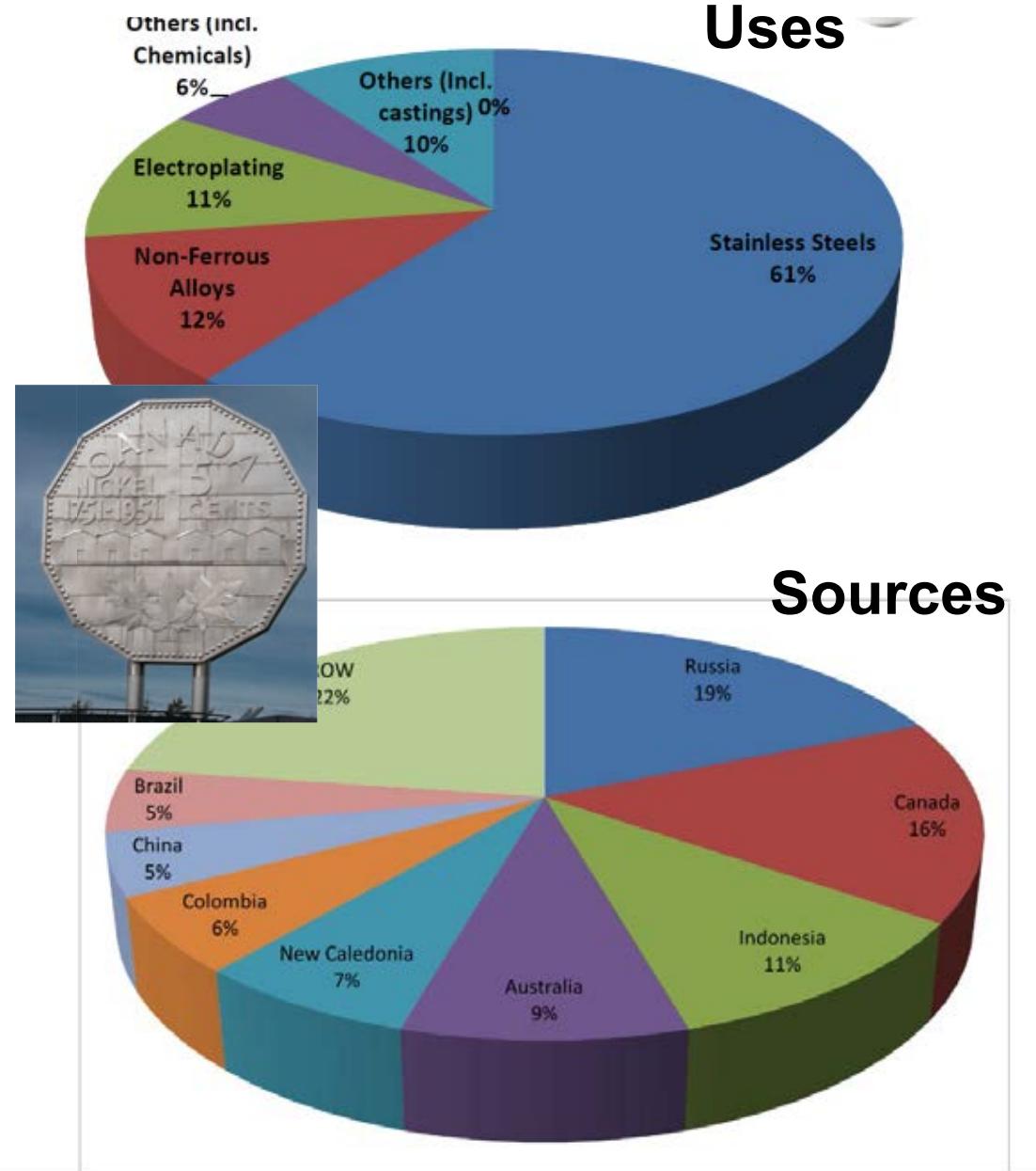


Tappert & Tappert (2011)

# **Magmatic sulfide deposits (Ni–Cu and PGE)**

# Nickel

- 1751, medieval eastern Germany – Kupfernickel, toxic gangue within copper and silver (cobalt) ores.
- 1848, 1<sup>st</sup> large scale production in Norway
- 1865, New Caledonia, Supplied world until 1815
- 1883, Sudbury (mostly copper at first)
- 1920's, Norilsk-Talnakh, Russia in 1920
- 1924, Merensky Reef, Bushveld, South Africa



# Platinum

## 1500's Spanish Conquistador's

- Alluvial Placer in Colombia
- *Platina*, Spanish “little silver”

## 1820's Ural Mountains, Russia

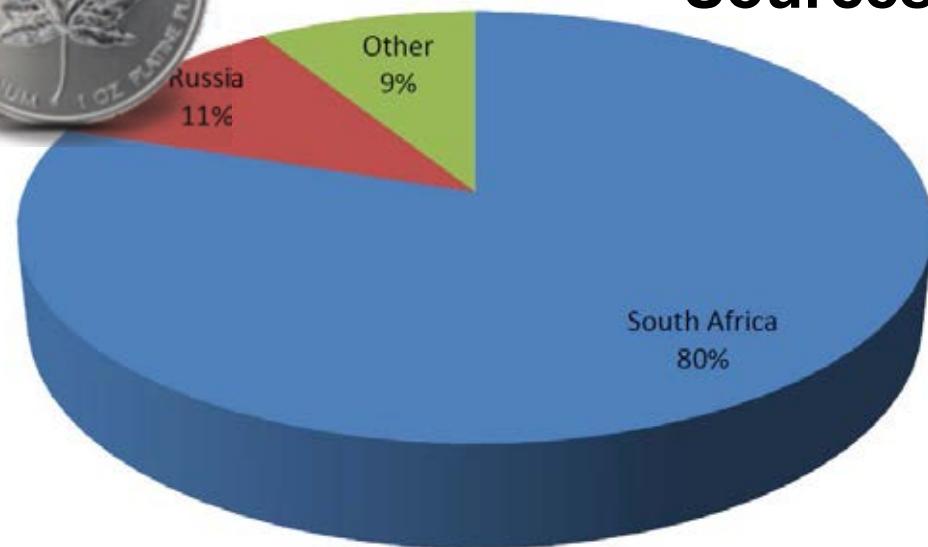
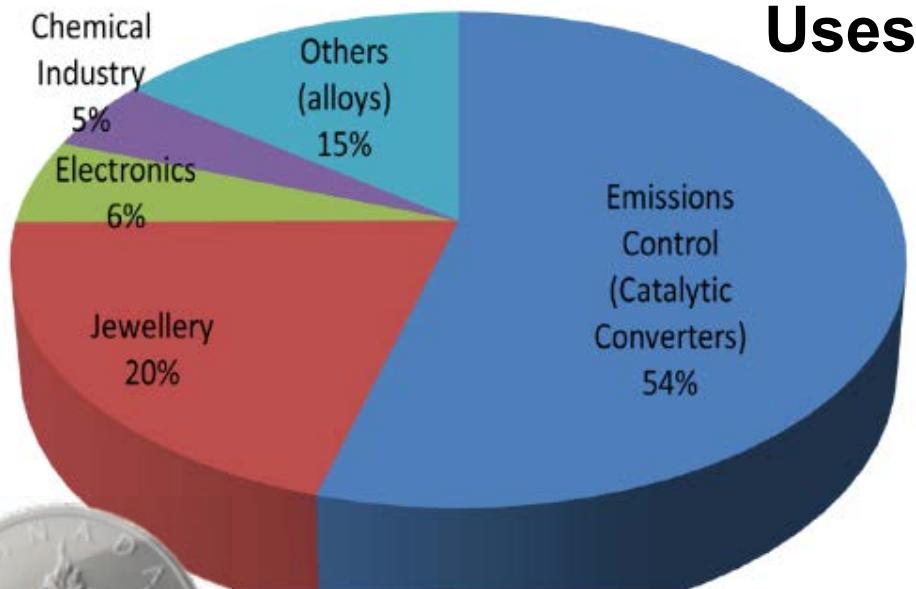
- Alluvial Placer, principal supply for 100 years

## 1886 Sudbury

- Magmatic Ni-Cu-PGE sulfide, principal supply 1920's-1950

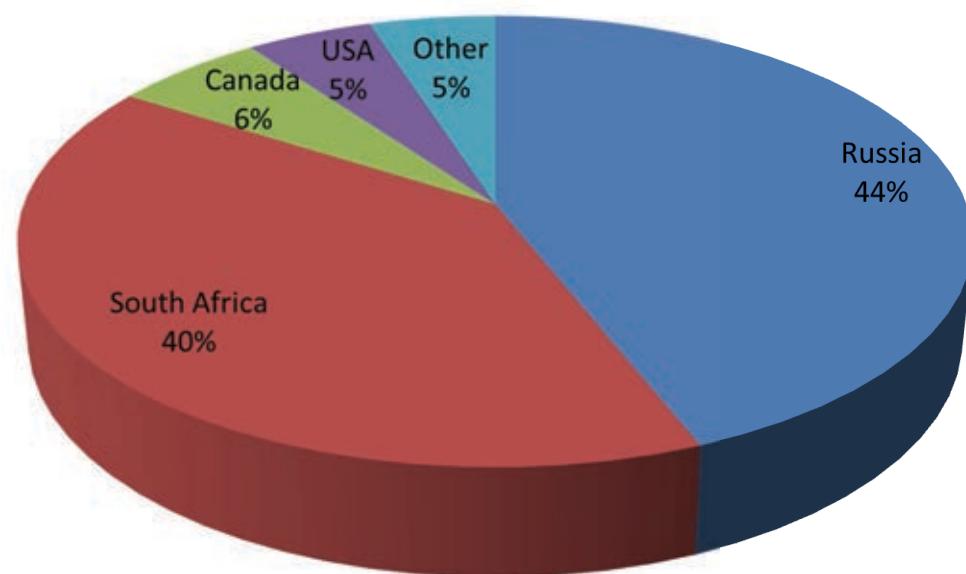
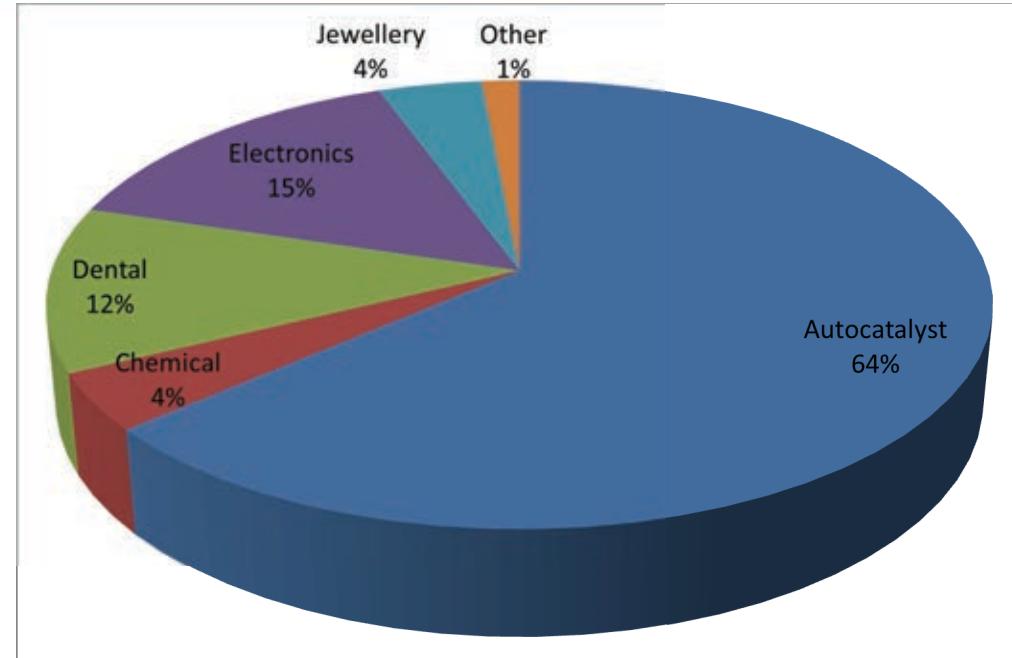
## 1920's Bushveld, South Africa

- Dominates world supply since 1950



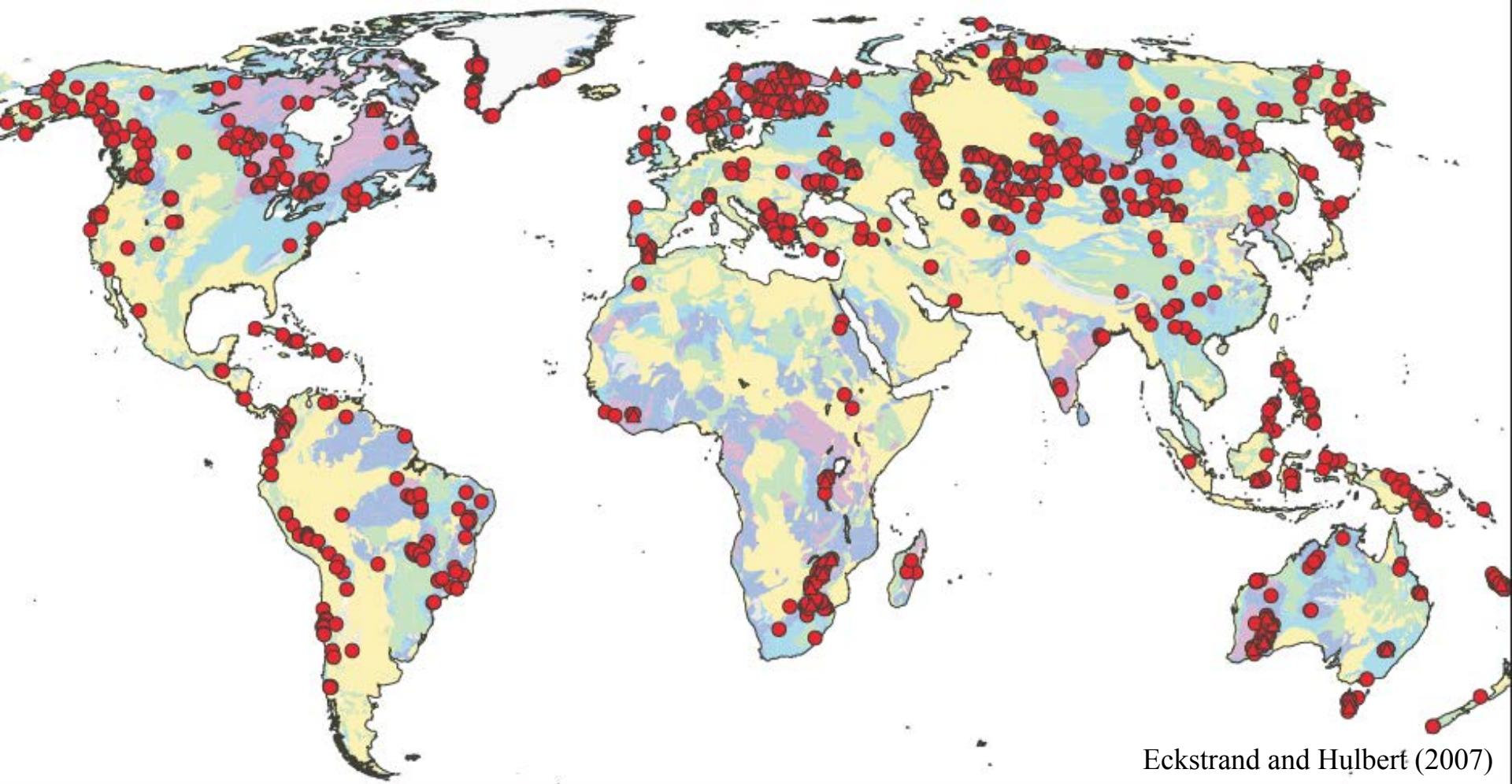
# Palladium

- 1803, first refined from Platinum
- No significant use until the 1950's

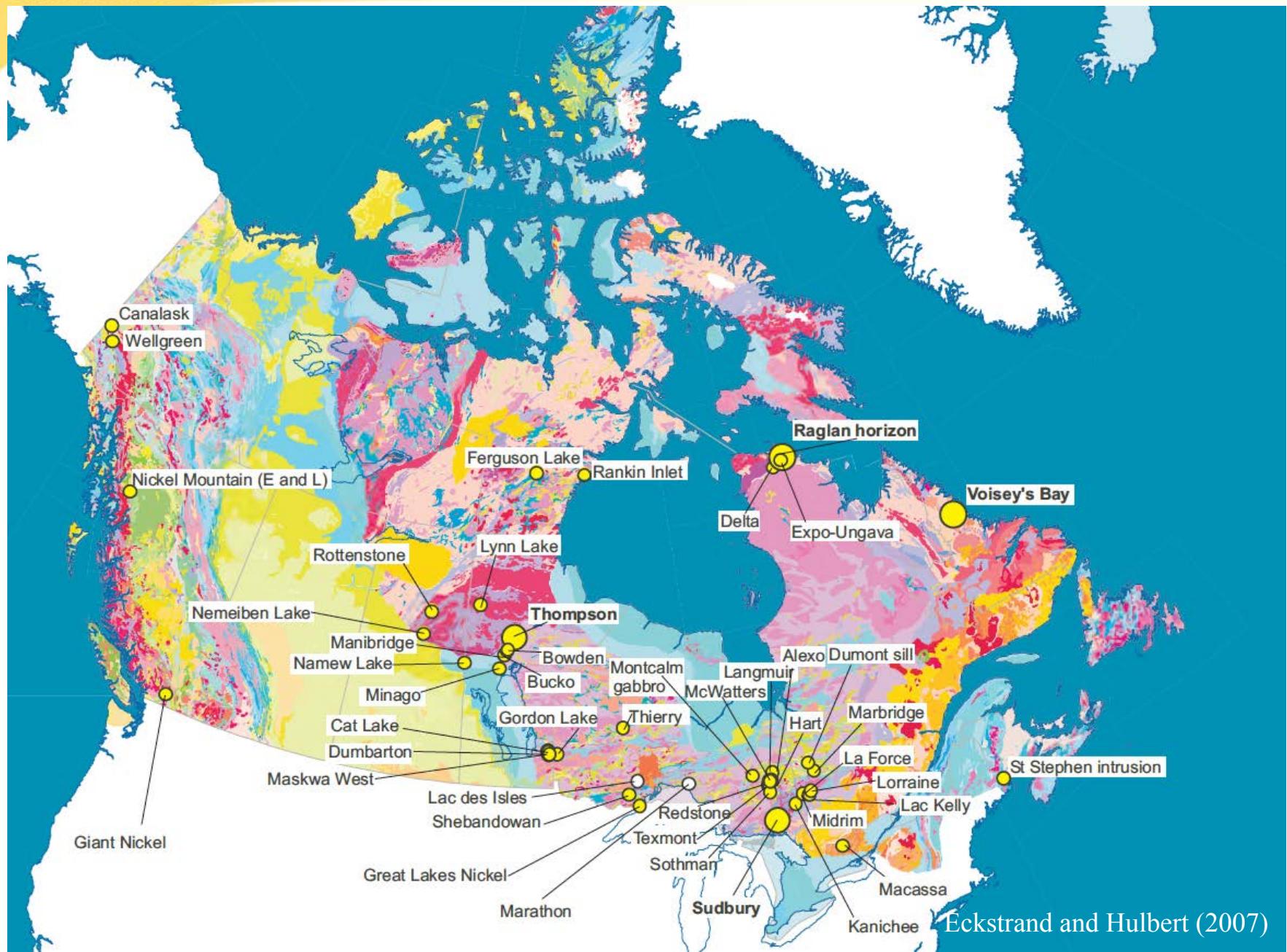




## Lots of deposits worldwide



Eckstrand and Hulbert (2007)



## Two subtypes of Ni–Cu–PGE deposits

Ni–Cu deposits – four main types based on magmatic environment

1. Meteorite impact
2. Rift and continental flood basalt
3. Komatiites
4. Other mafic/ultramafic bodies

PGE deposits – two magmatic types

1. Reef-type or stratiform
2. Magmatic breccia type

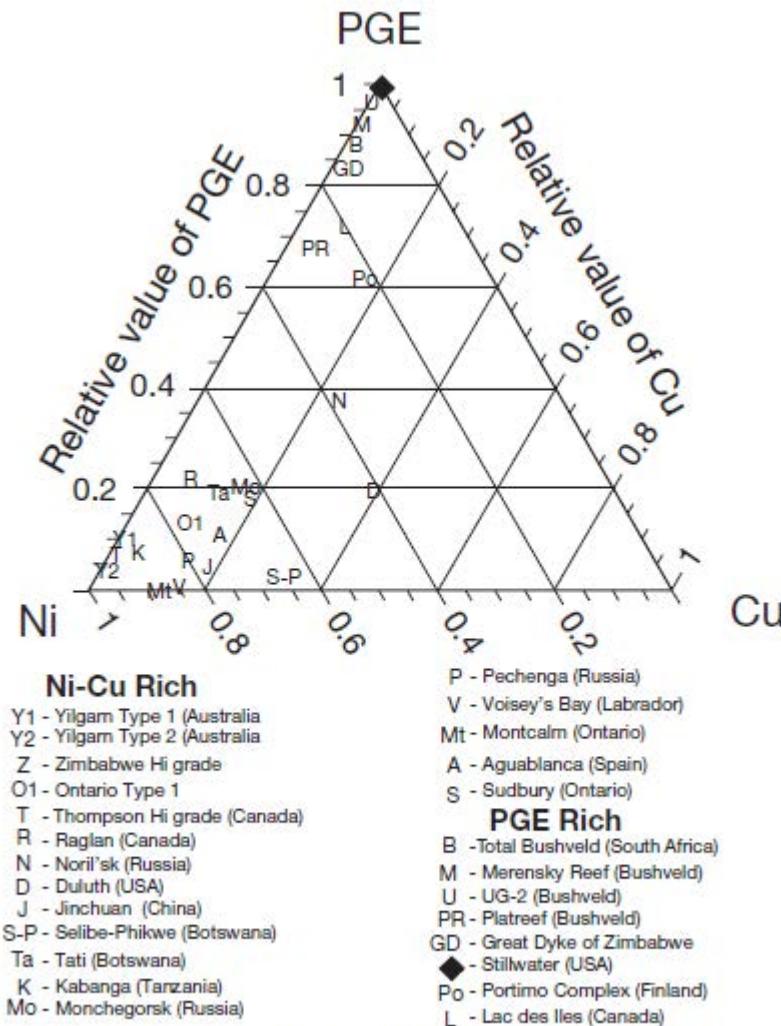
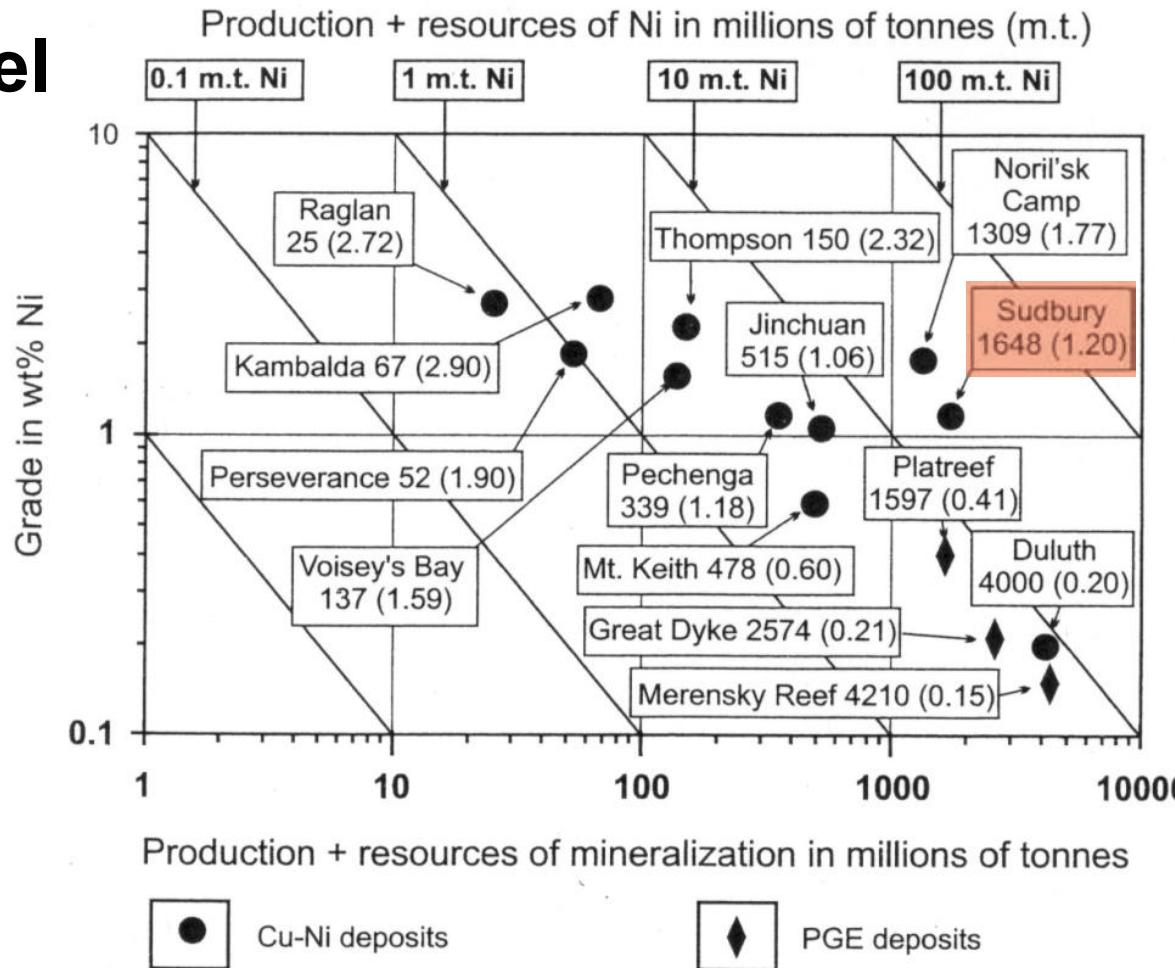


FIG. 2. Relative value of the contributions of Ni, Cu, and PGE to magmatic sulfide deposits. Data from Table 1.

Naldrett (2010)

# Nickel

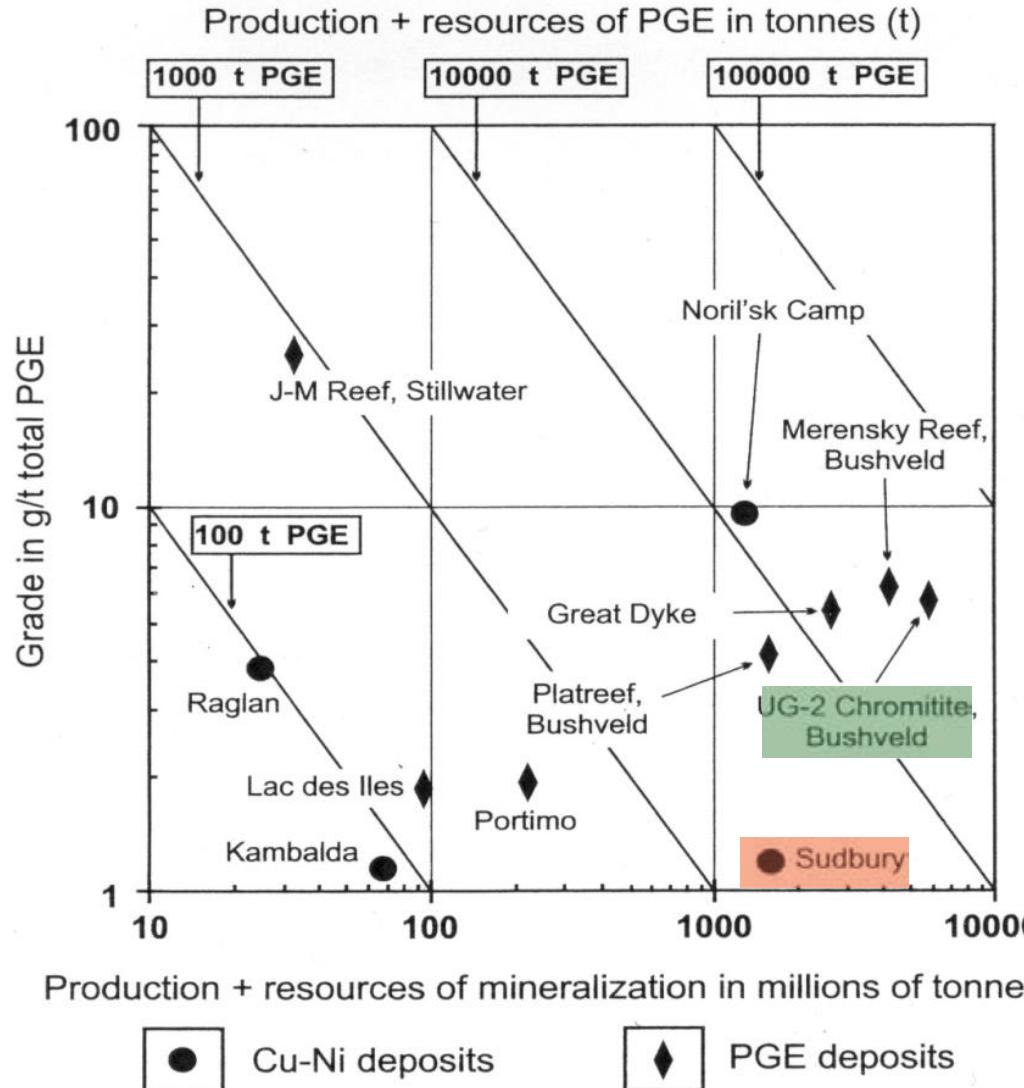


**Fig. 1.3.** Plot of grade in wt% Ni versus production + resources of mineralization in millions of tonnes for major Ni and PGE sulfide deposits of the world. Data are from Table 1.1

Naldrett (2010)



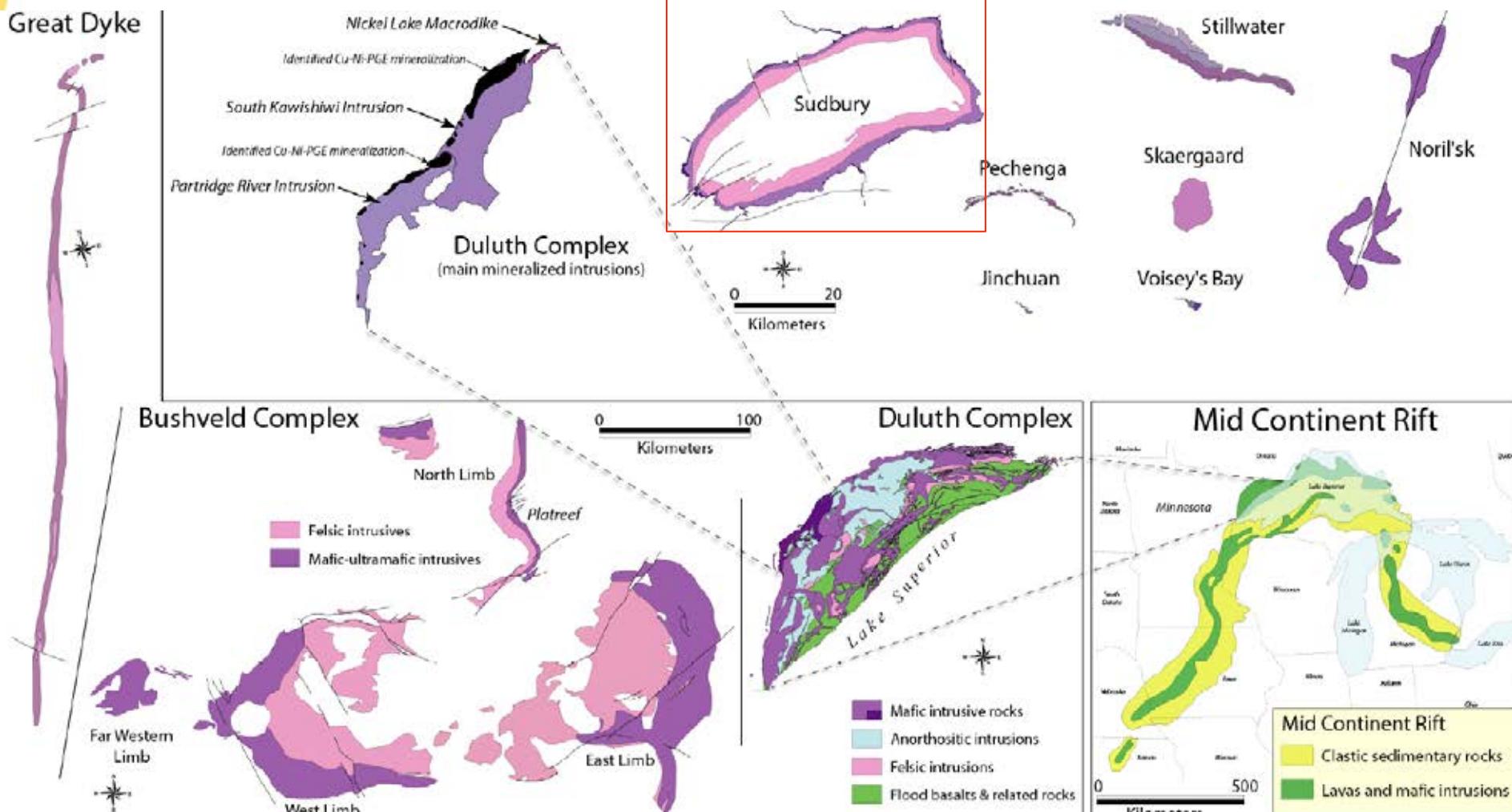
# PGEs



**Fig.1.4.** Plot of grade in g/t total PGE versus production + resources of mineralization in millions of tonnes for major PGE-containing deposits. Data are from Table 1.1

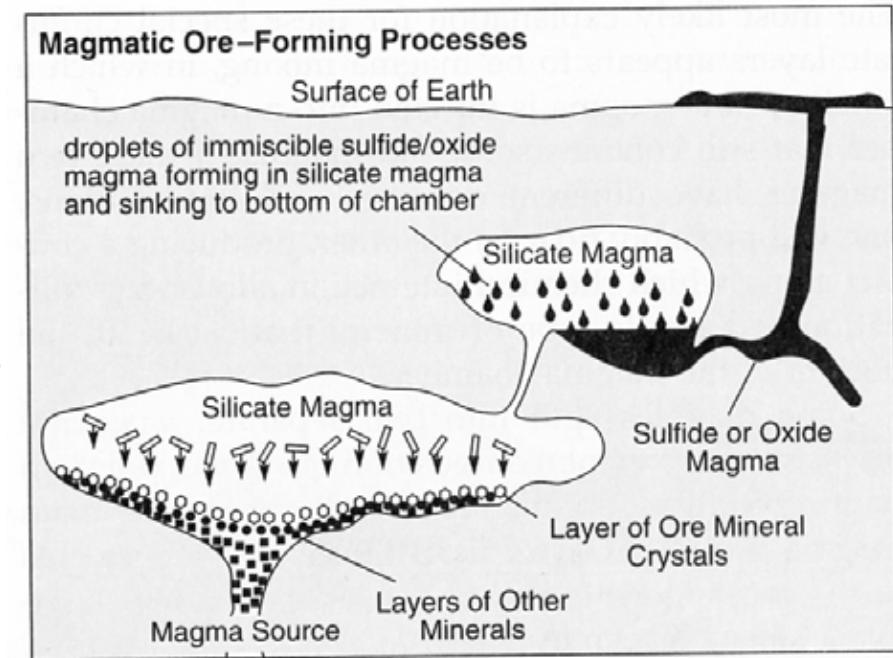
Naldrett (2010)

# Scale of Cu–Ni–PGE deposits



# Magmatic sulfide deposits (Ni–Cu and PGE)

- Magmas derived from the mantle (basalts and ultramafic magmas)
- 0.25 wt% Ni in mantle
- Ni substitutes well into olivine and pyroxene:
  - ~0.1 wt% in basalt
- To be economic, need 0.7–3 wt% Ni (or 0.2–2% Cu)



Kessler (1994)

## Ore minerals:

- Pentlandite  $(\text{Fe}, \text{Ni})_9\text{S}_8$
- Chalcopyrite  $\text{CuFeS}_2$

**Source:** Mantle melting  
**Transport:** Magma migration  
**Trap:** Sulfide precipitation...

## Source: Melt the mantle (not too little and not too much...)

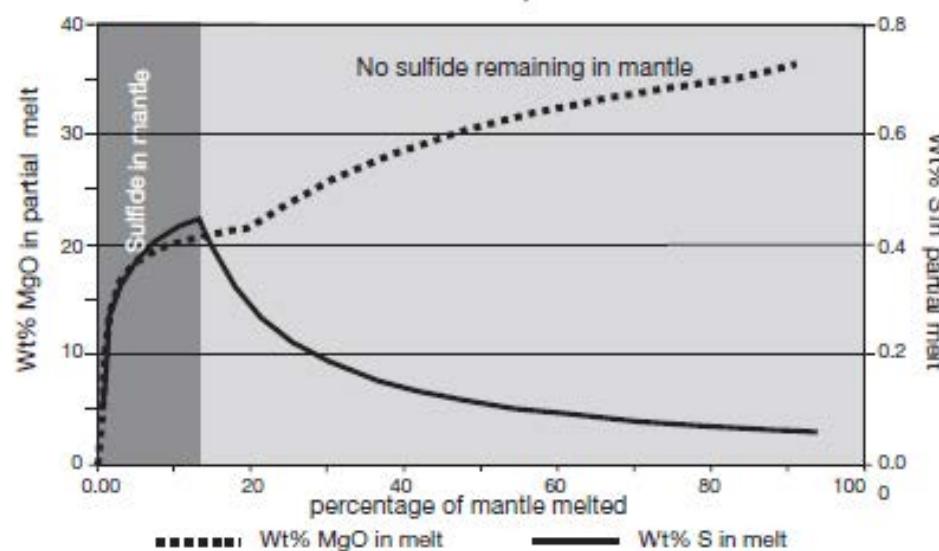
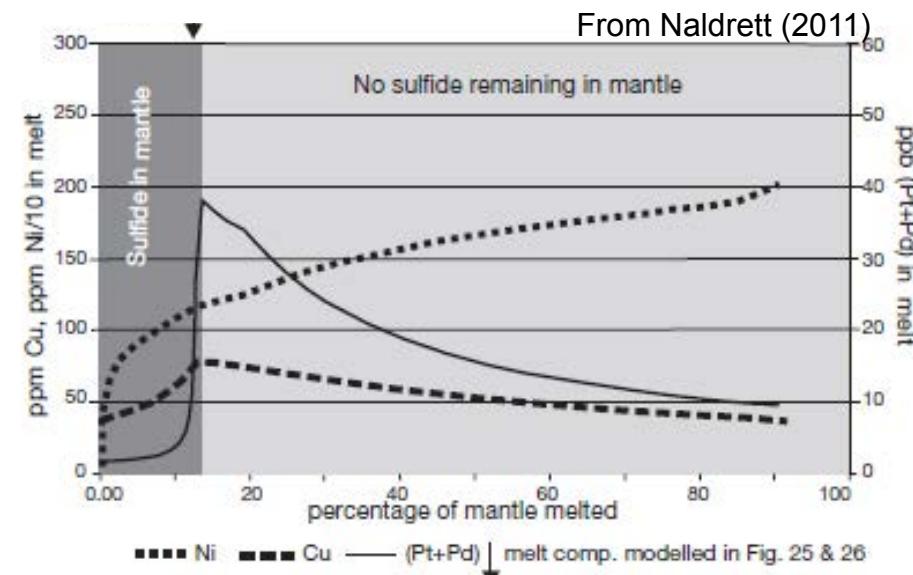
0–5% Sulfur is quickly dissolved in the melt, Ni-Cu-PGE as well.

5–13% Remaining sulfur dissolves in the melt, Cu-PGE follow.

>13% There is no more sulfur in the residual mantle. All PGEs and Cu are in melt. There is still Ni in Olivine.

Past this point, any additional melting dilutes S, Cu and PGEs, but enriches Ni.

The best magma would be a primitive magma (13% partial melting) at 40 ppb PGE, 75 ppm Cu, 1200 ppm Nickel.



## Transport: magma ascension

- Ascension is needed to move the magma from the mantle to the crust
- Magma does not precipitate sulfides during ascension because lowering P increases sulfide solubility

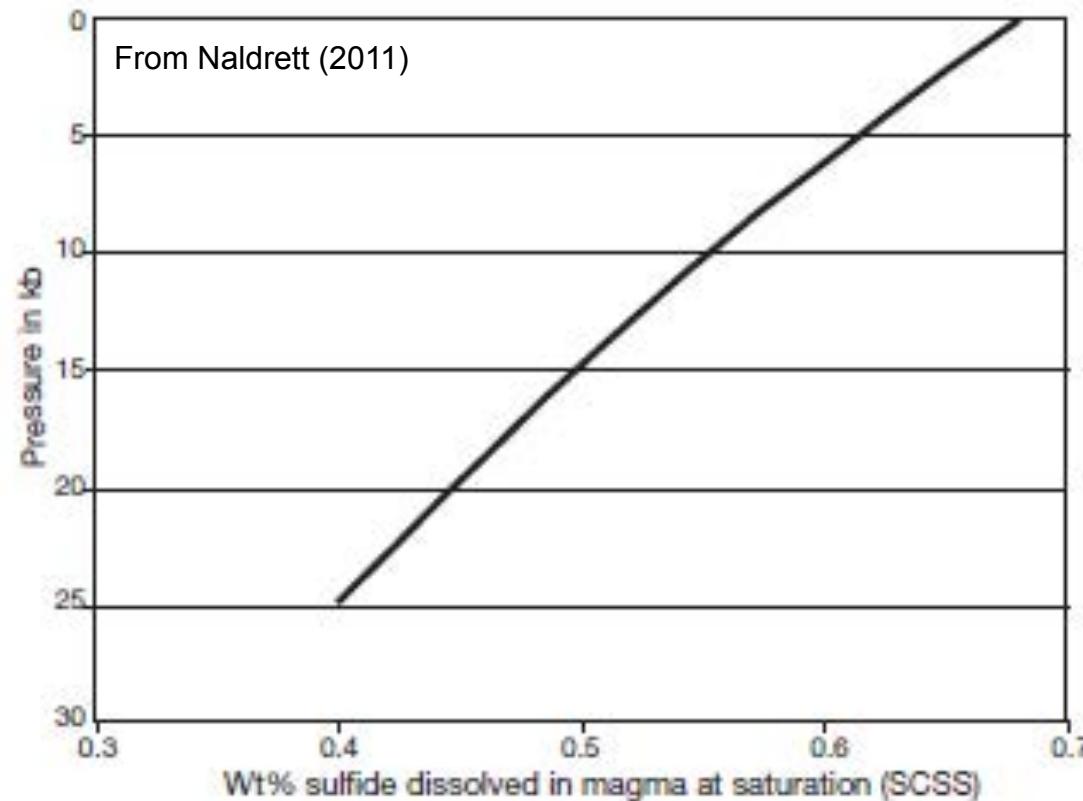


FIG. 16. The effect of pressure on the solubility of sulfide in the 13.5 percent partial melt illustrated in Figure 15. The solubility increases from 0.4 percent sulfide at 25 kbars to 0.68 percent at 0 kbar (using the equation of Li and Ripley, 2009).

Naldrett (2010)

# Trap: sulfide precipitation during cooling

Sulfur becomes immiscible after 46% fractional crystallization

At that time, there is 60 ppb PGE, 100 ppm Cu and 121 ppm Ni.

Good for PGE!

Bad for Ni and Cu

Something else needs to happen to make the sulfide immiscible early in the fractional crystallization process.

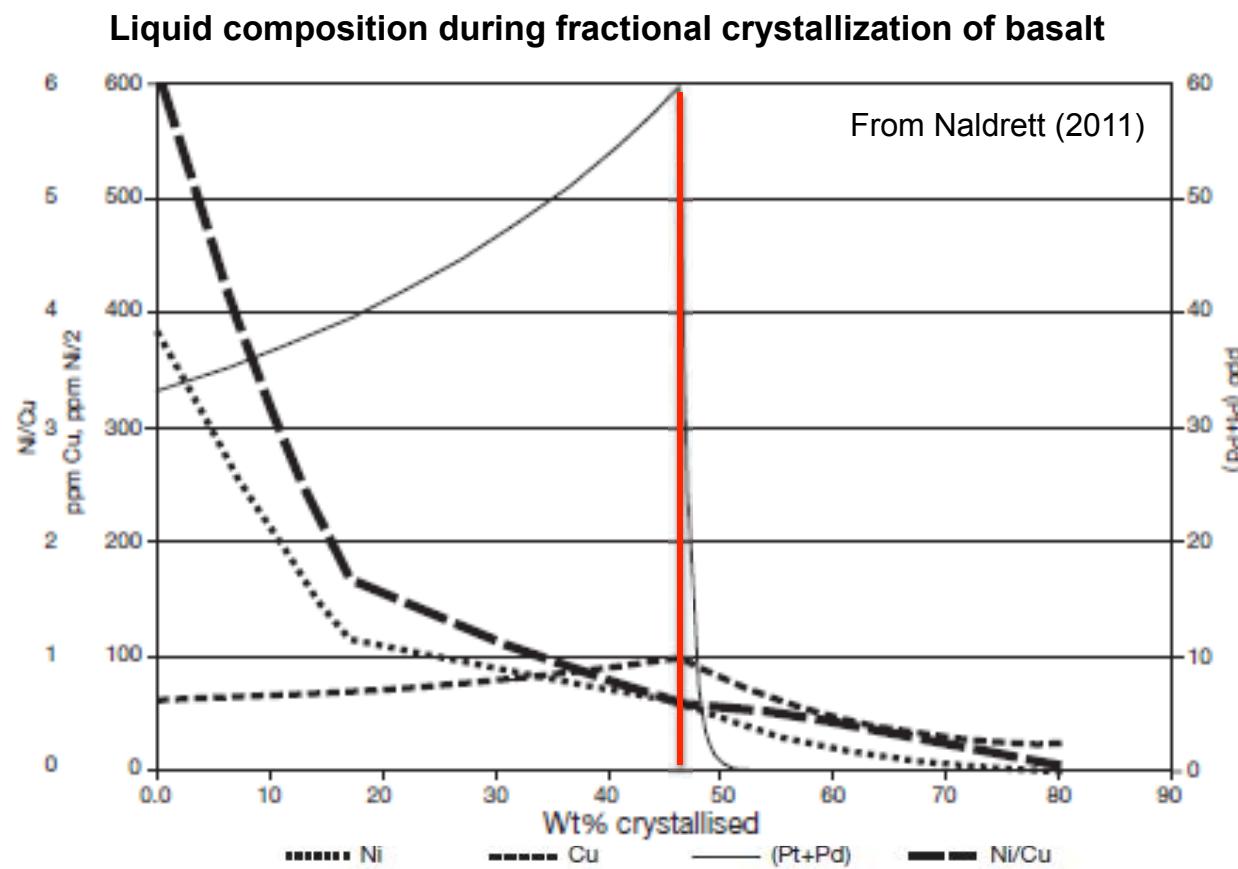


FIG. 17. Variation in Ni, Cu, (Pt + Pd) and Ni/Cu with fractionation of a typical basaltic magma at 2-kbars pressure. In this case the magma is a 20 percent partial melt of the Hart-Zindler mantle (Table 6) at 15 kbars. Note that sulfide liquid immiscibility does not occur until 46 percent crystallization. Thereafter Cu and (Pt + Pd) decrease sharply. Ni decreases continuously from the start of crystallization and is about 62 ppm by the time that sulfide saturation occurs. The Ni/Cu also decreases sharply to about 0.6 at sulfide saturation.

## Trap: sulfide precipitation

A major control on the deposition of sulfide minerals are changing conditions leading to sulfide saturation:

Solubility a function of:  $P$ ,  $T$ ,  $X$  and  $f(O_2)$ :

$$\ln(X_{\text{sulfur}}) \text{ content at sulfide saturation} = 1.229 - 0.74(104/T) - 0.021(P) - 0.311/\ln X_{\text{FeO}} + 6.594X_{\text{FeO}} - 6.6166X_{\text{SiO}_2} - 9.153X_{\text{Na}_2\text{O} + \text{K}_2\text{O}} - 1.914X_{\text{MgO}}$$

– from Li & Ripley (2009)

In general:

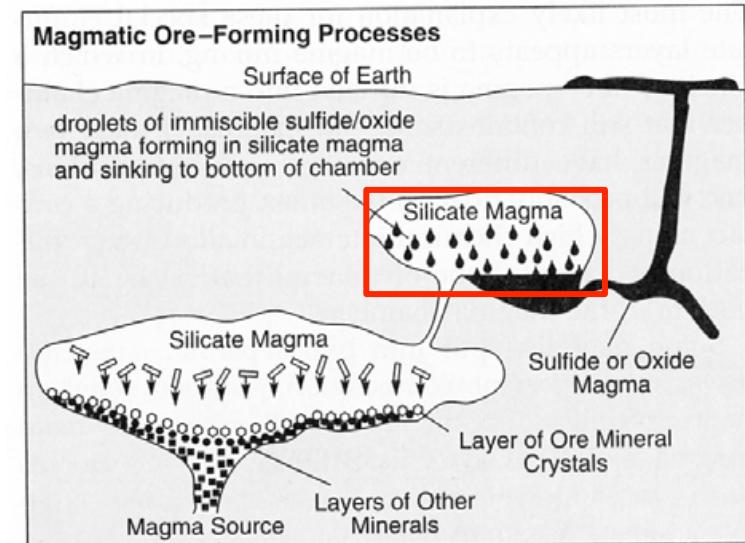
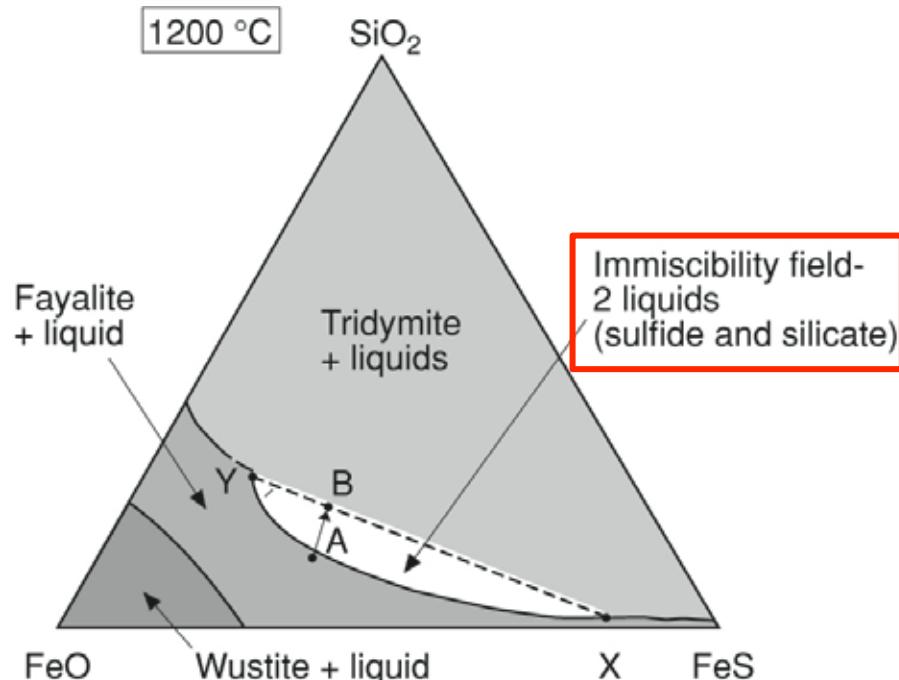
Solubility drops during cooling

Solubility increases during decompression

Solubility drops by adding  $\text{SiO}_2$

## Trap: sulfide melt droplets

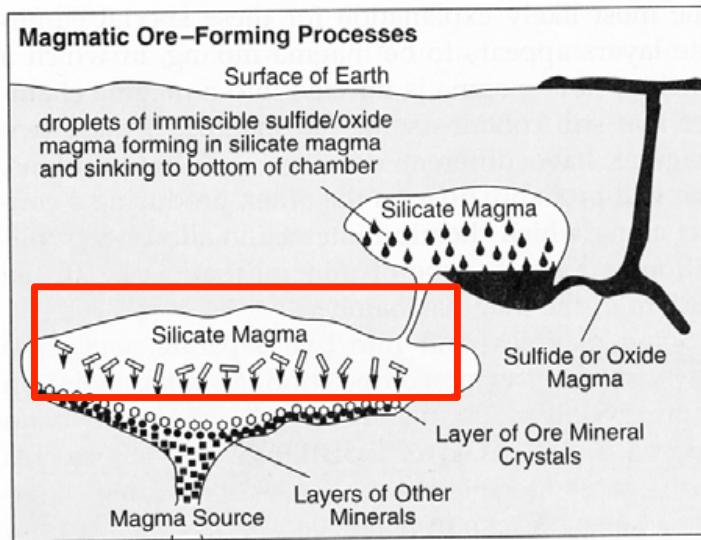
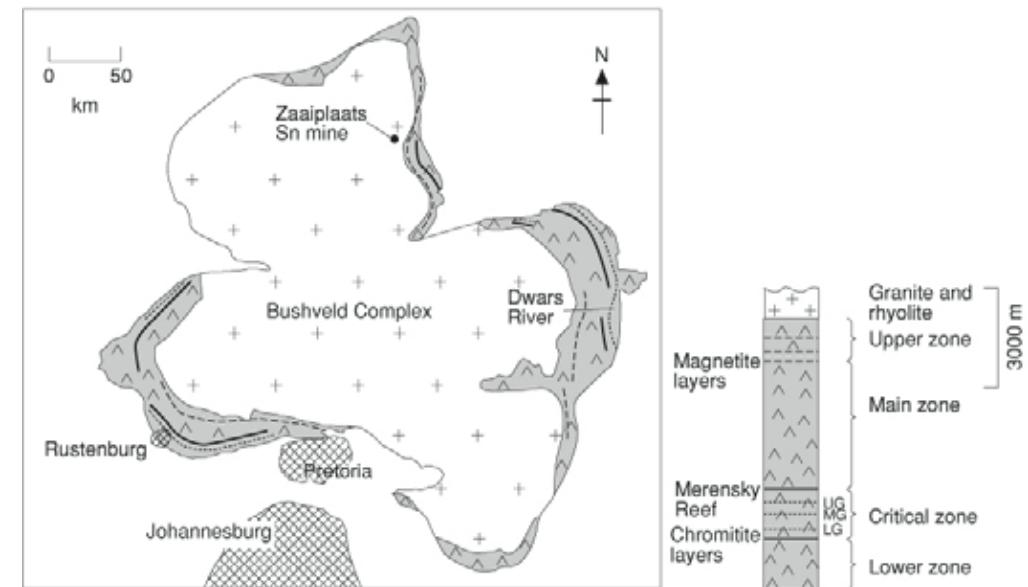
1. Start with sulfide undersaturated magma (A)
2. Add  $\text{SiO}_2$  (e.g. wall rock assimilation)
3. Magma composition will shift towards the 2 liquid field (B)
4. Sulfide liquid scavenges Ni–Cu–PGEs and sinks





# Crystal fractionation: Bushveld chromitite seams

- World's largest layered mafic intrusion (~67,000 km<sup>2</sup>)
- ~80% of world's PGE reserves in the Bushveld
- Major source of chromite ( $\text{FeCr}_2\text{O}_4$ )

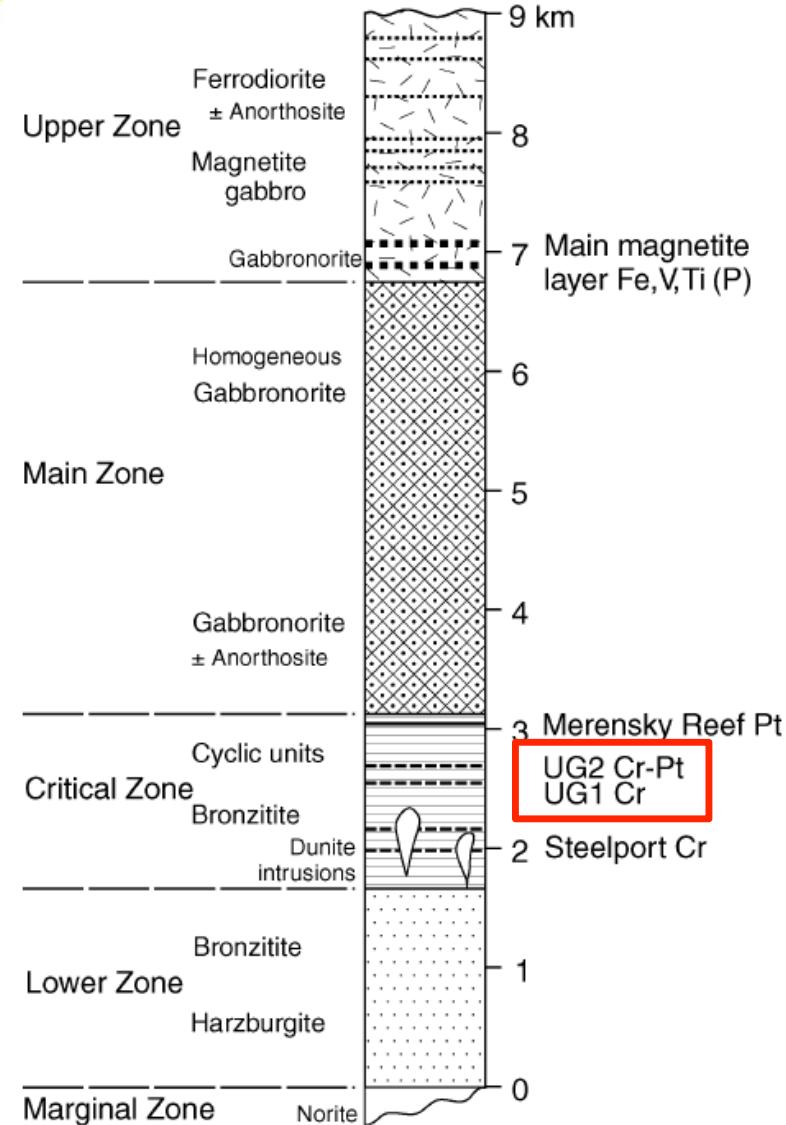


# Chromitite seams

- Stratiform
- Chromite is platiniferous
- Occur at base of mafic–ultramafic magma chamber
- Cyclic units: chromitite, dunite, harzburgite, bronzitite
- Chromitite seams (~14) given names based on position in sequence (e.g. UG1, LG2, MG1)
- UG1 and UG2 chromite layers are only ~60 cm thick, but are very famous

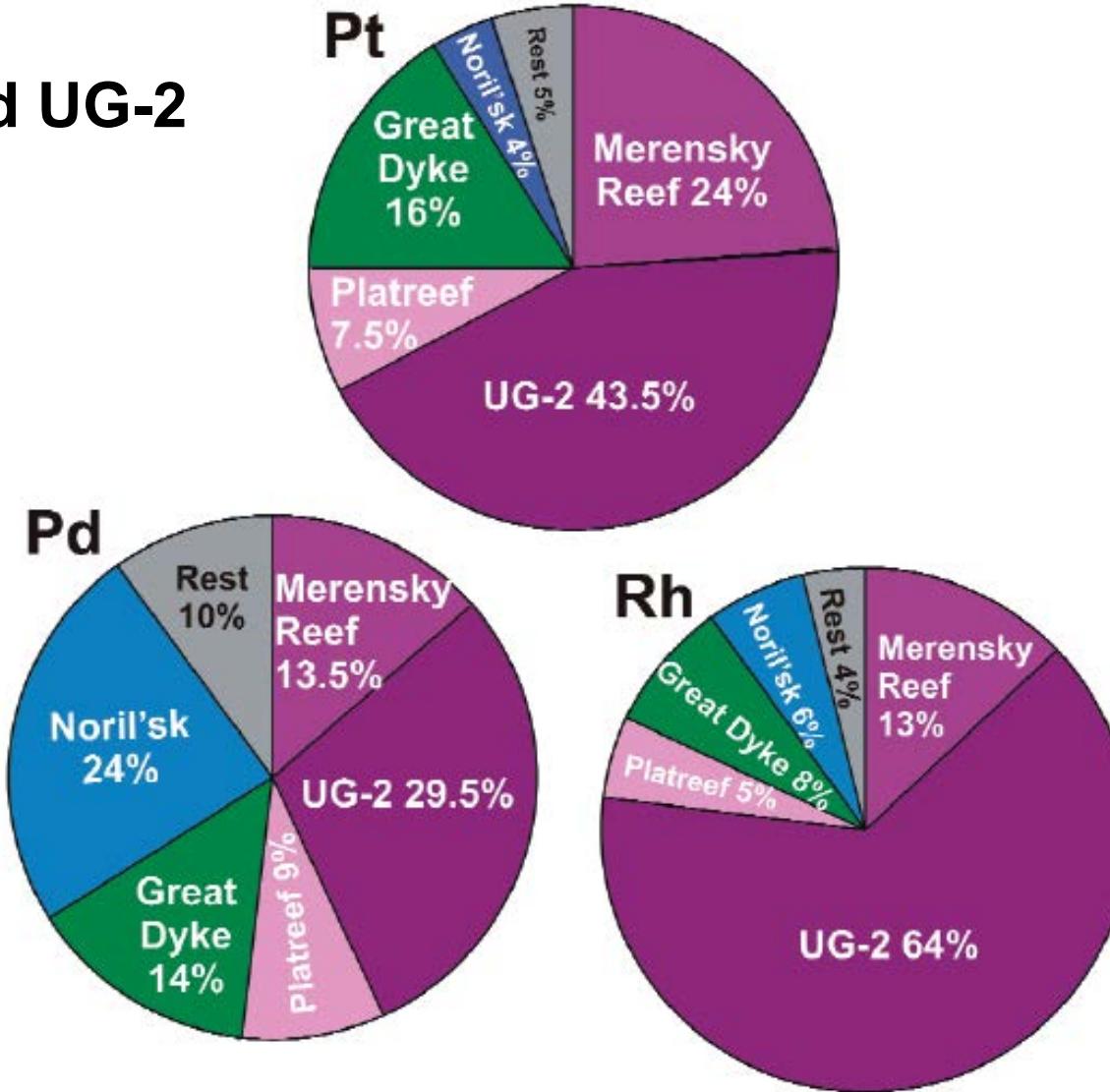


UG1



**Figure 1.5** Simplified lithostratigraphic column of the mafic Rustenburg Layered Suite in the Eastern Bushveld, South Africa, with major ore horizons.

## Bushveld UG-2



**FIGURE 3** Contributions of different ore deposits to global production and reserves of Pt, Pd, and Rh



## Chromitite seam genesis

- Deposition of Cr-oxide melt unlikely due to high melting T of chromite
- Chromite ( $\text{FeCr}_2\text{O}_4$ ) solubility in basalt melt decreases with:
  - $\downarrow T$
  - $\uparrow \text{fO}_2$
  - $\uparrow \text{SiO}_2$

$T$ : As basalt crystallizes,  $\text{Olv}+\text{Cr}+\text{Py}$  will crystallize together and cannot make monomineralic chromite layers

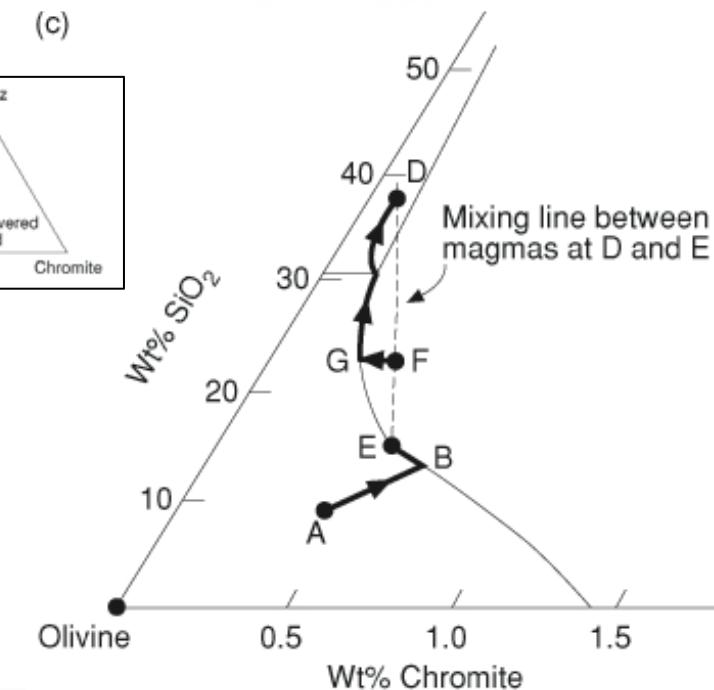
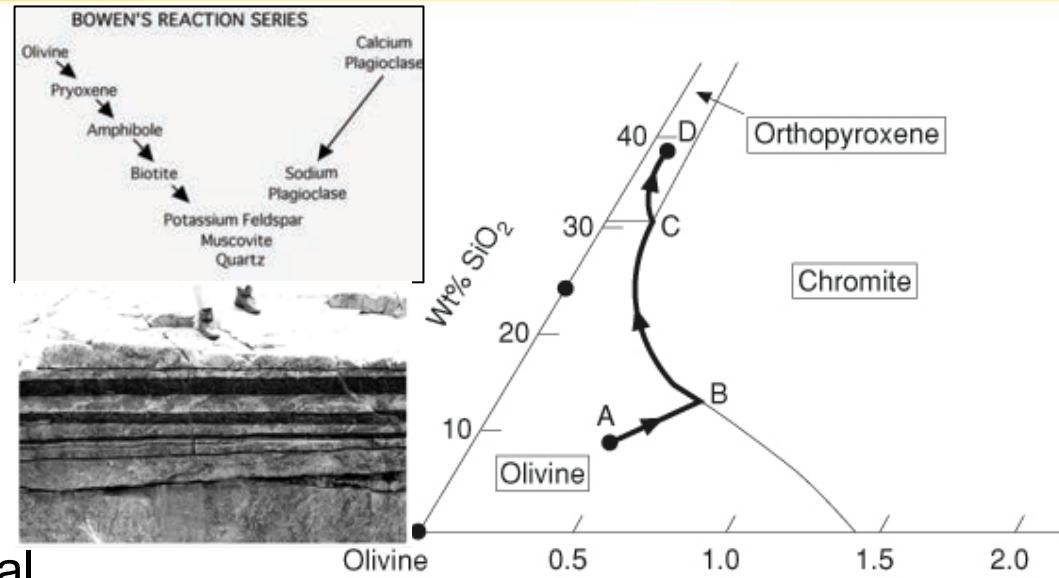


$\text{fO}_2$ : cannot be changed throughout an entire magma body because it is essentially buffered

This leaves  $\text{SiO}_2$ ...

# 'Irvine' model of chromitite genesis

- Episodic filling of magma chambers results in magma mixing
- Typical basalt will crystallize chromite as an accessory mineral (~1 vol.%) with olivine (B->C)
- Mixing two magmas with different  $\text{SiO}_2$  compositions (reflecting their crystallization history) may allow chromite to crystallize (F->G) and sink to the bottom of the magma chamber
- Potential for chromite deposits when large volumes of magmas are involved



# Komatiite Ni–Cu–PGE deposits

## Locations:

Abitibi  
Yilgarn  
Barberton  
Thompson

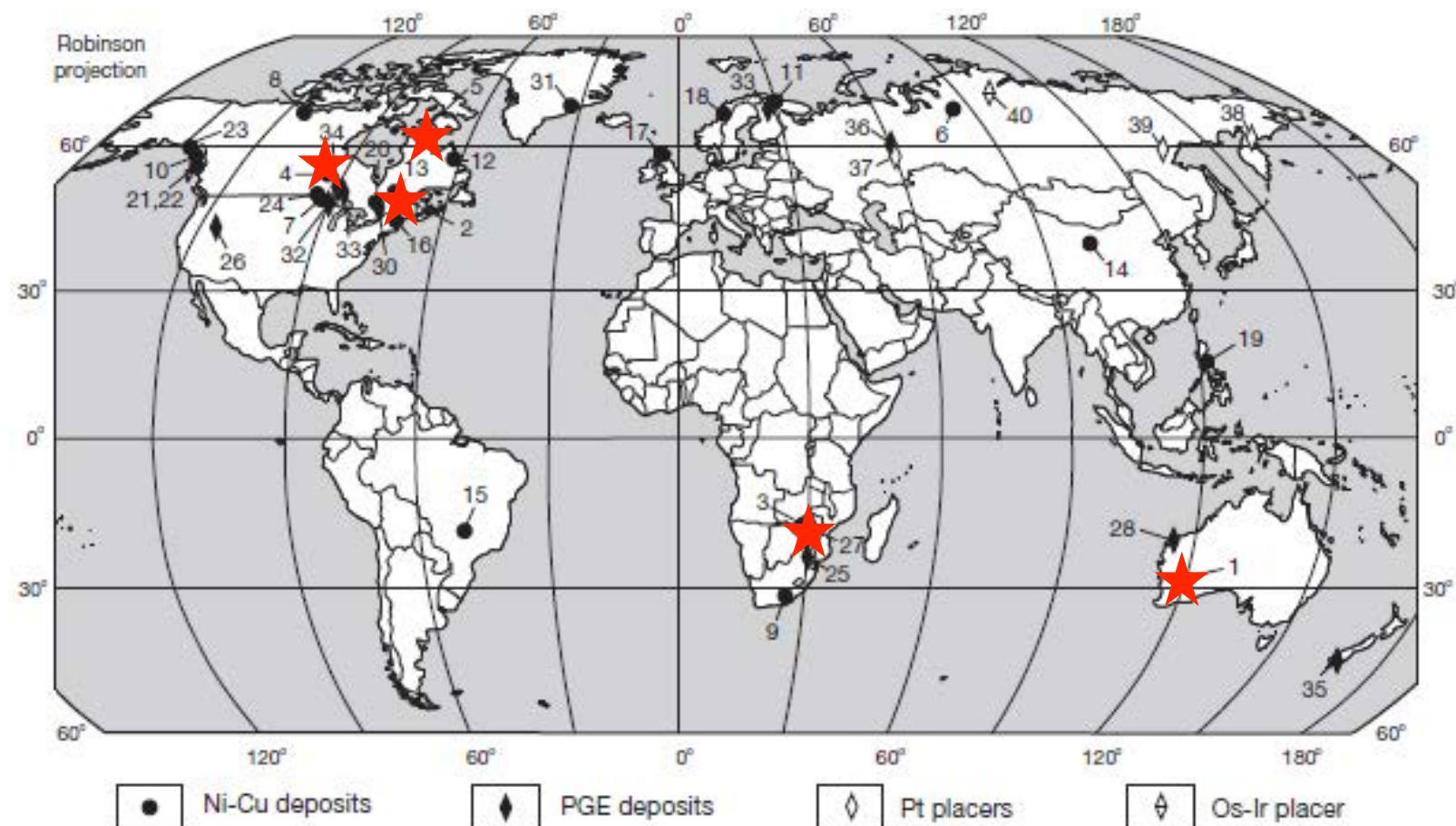
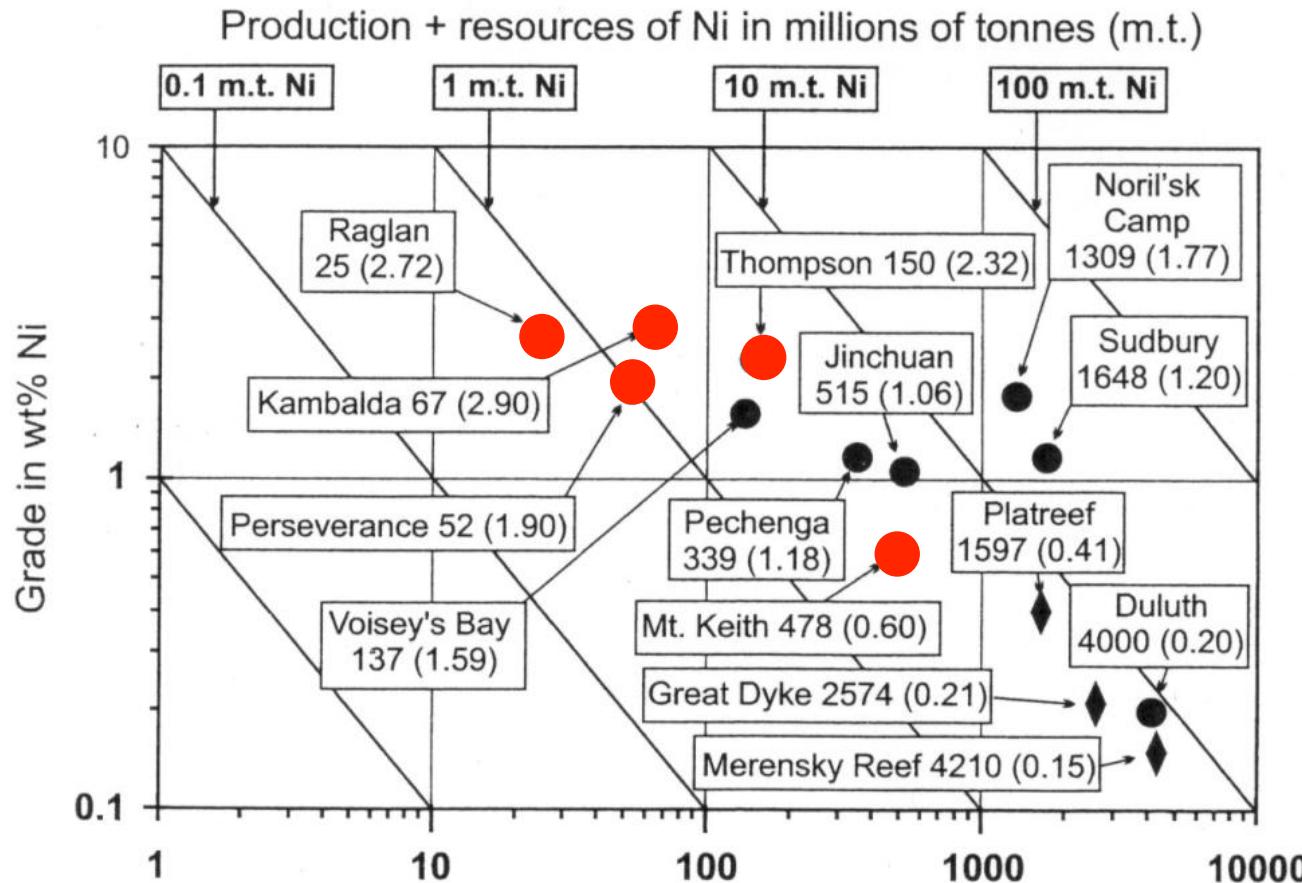


FIG. 3. Geographic distribution of the world's most important magmatic sulfide Ni-Cu and PGE deposits. The numbers attached to the deposits correspond to those given in Tables 2 and 3.

# Komatiite Ni–Cu–PGE deposits



# Komatiites (extrusive rocks)

## Komatiite:

- Archean ultramafic lava flows
- $T \sim 1700^\circ\text{C}$
- $>18$  wt% MgO
- 30–50% partial melting of the mantle
- High T and low viscosity (similar to water) lavas
- Can erode and/or melt the footwall rocks – called “thermochemical erosion” and “footwall melting”
- Diagnostic “spinifex” textures (olivine blades produced through supercooling at surface of flow)



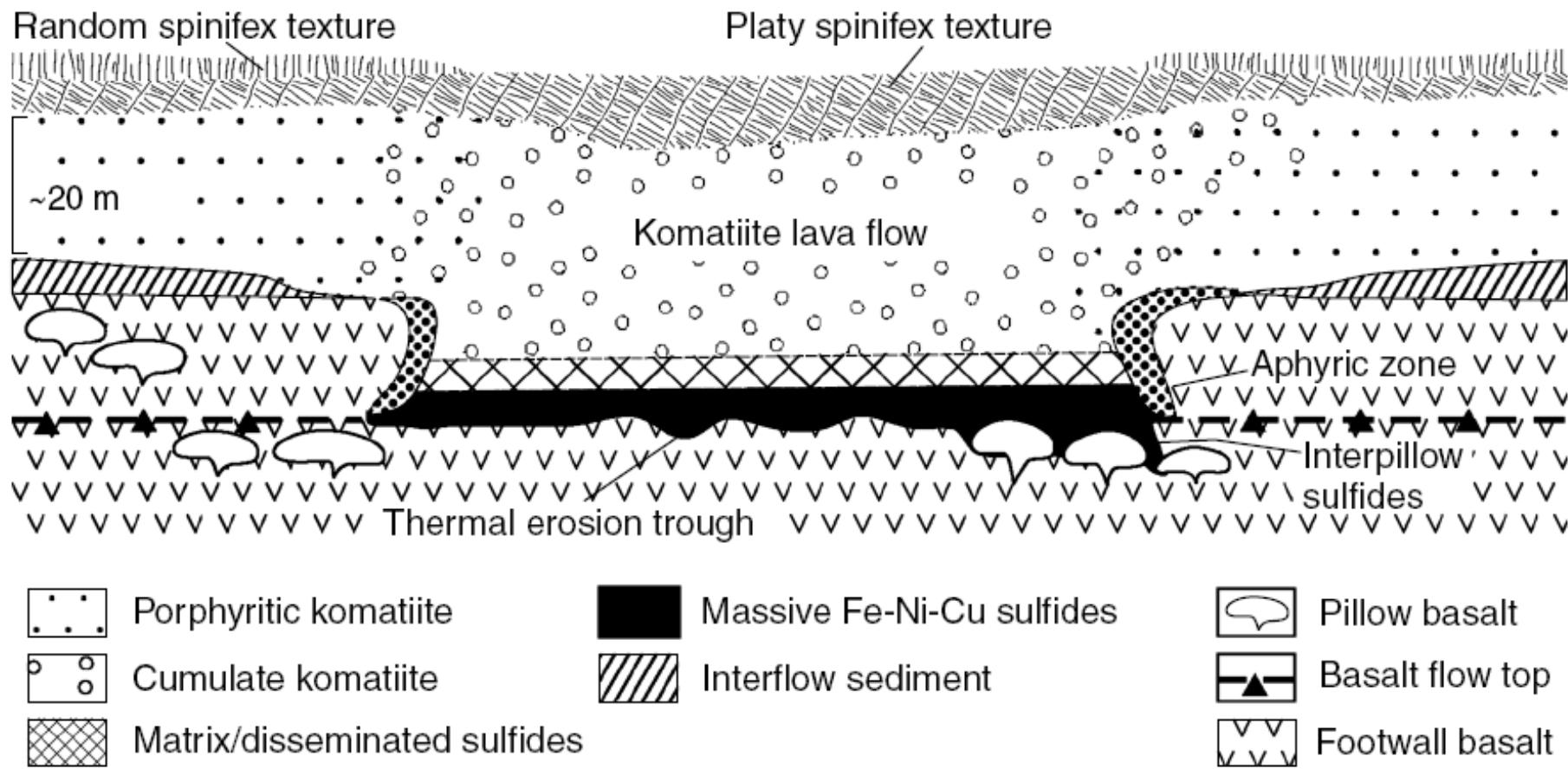
From Houle and Lesher (2011)

Spinifex: Texture after a grass in the Yilgarn Archean Craton of Australia



[http://en.wikipedia.org/wiki/File:Spinifex\\_grass.jpg](http://en.wikipedia.org/wiki/File:Spinifex_grass.jpg)

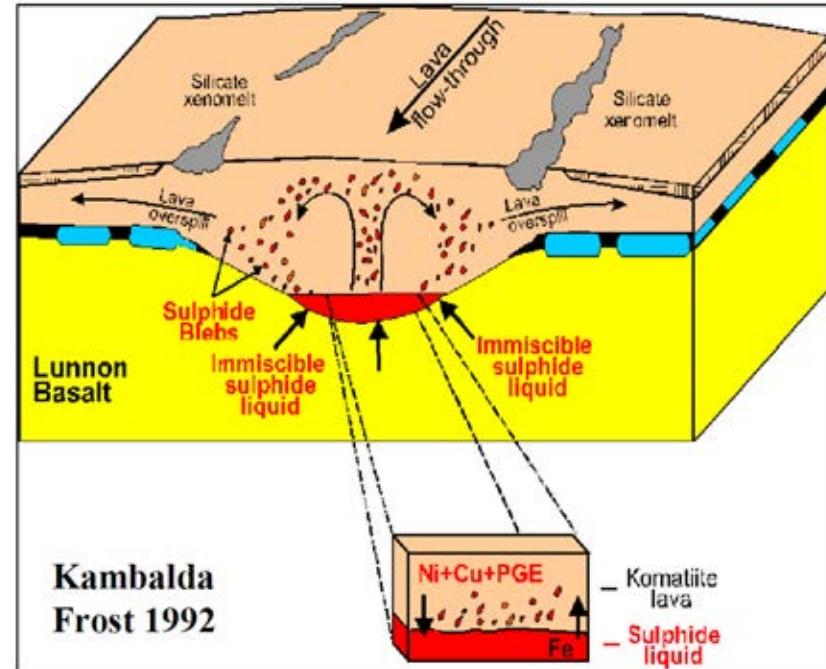
# Komatiite ore bodies



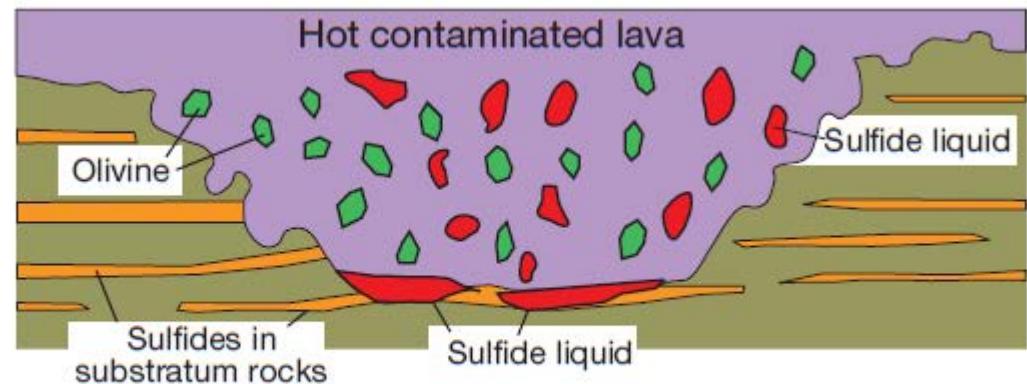
Pohl (2012)

# Komatiite Ni–Cu: Genetic model

- Komatiites initially undersaturated in sulphur
- Lava flow thermally eroded the base rock
- S incorporated from thermochemical erosion of sulfur-rich sediments (shale, BIF, chert)
- Sulfide saturation occurs and a sulfide liquid precipitates



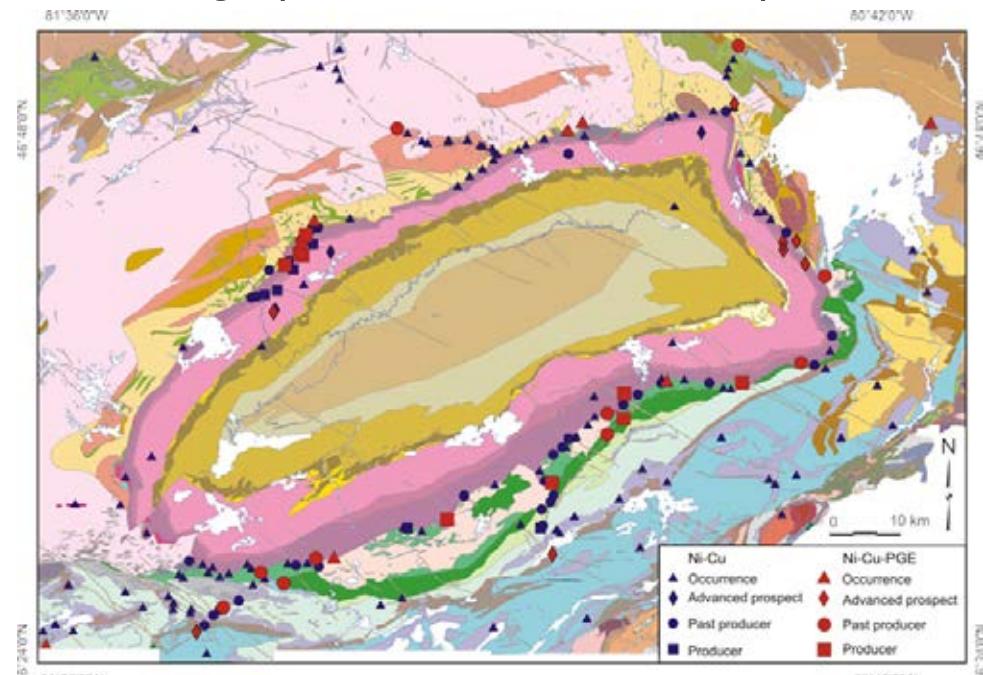
Vertical scale is exaggerated



Cross-section through mineralised lens

# Case study in Ni–Cu: Sudbury (a unique deposit)

- 77 producing and past producing Ni–Cu–PGE sulfide deposits
- 1.655 Gt past production, reserve and resource
- \$330 billion of metal produced in last 100 years
- World class!!
- >50% located in the Sudbury Igneous complex
- Supergiant Ni–Cu–PGE discovered during CPR construction in 1883



Ames and Farrow (2007)

# Before 1850 Ma

Continental margin of Nuna (supercontinent)

Boundary between:

1. Archean tonalite gneiss (Levack Gneiss Complex; Superior Province)
2. Paleoproterozoic metasedimentary Huronian supergroup (intracontinental rift basin sediments)

All was well in this quiet rift basin until 1850 Ma...

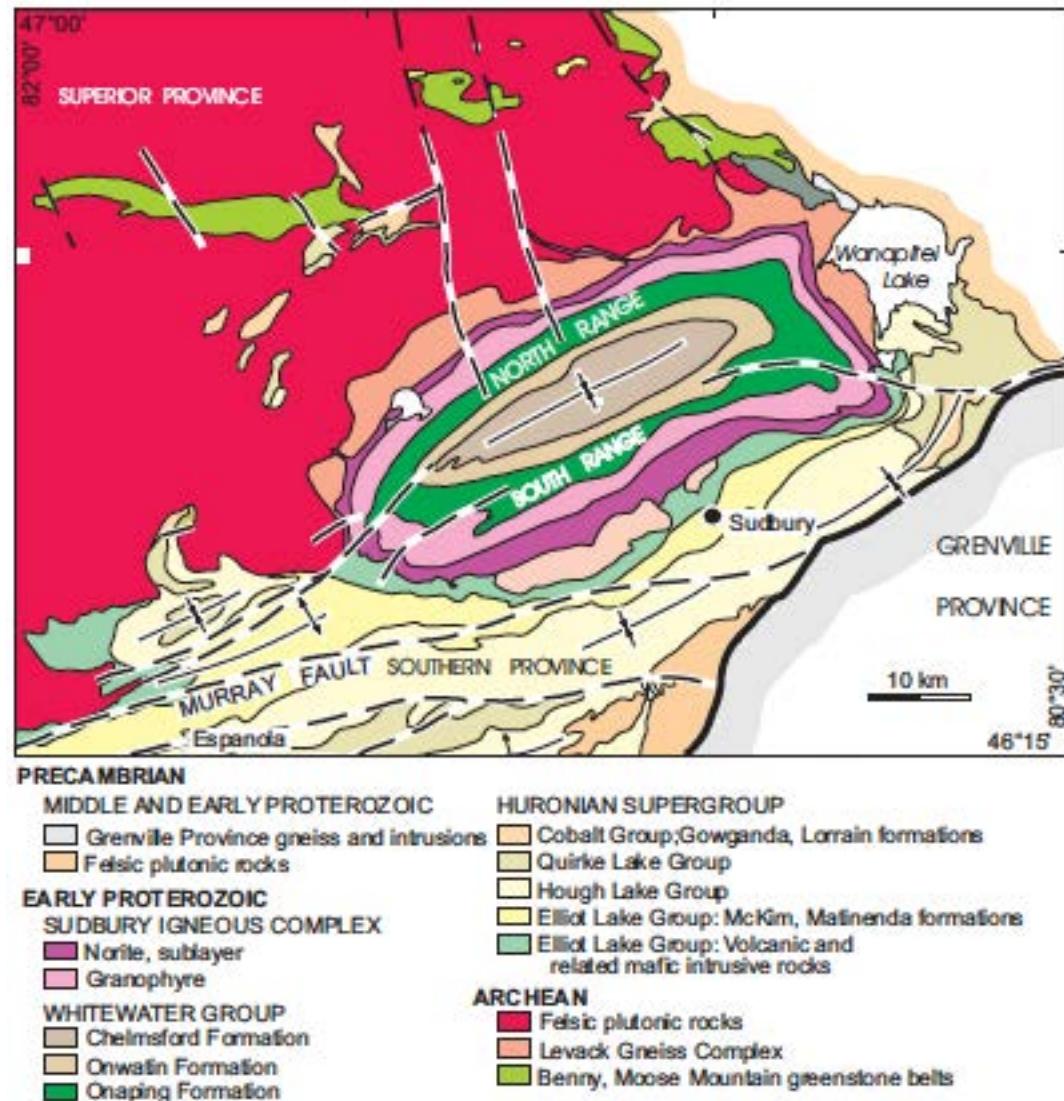
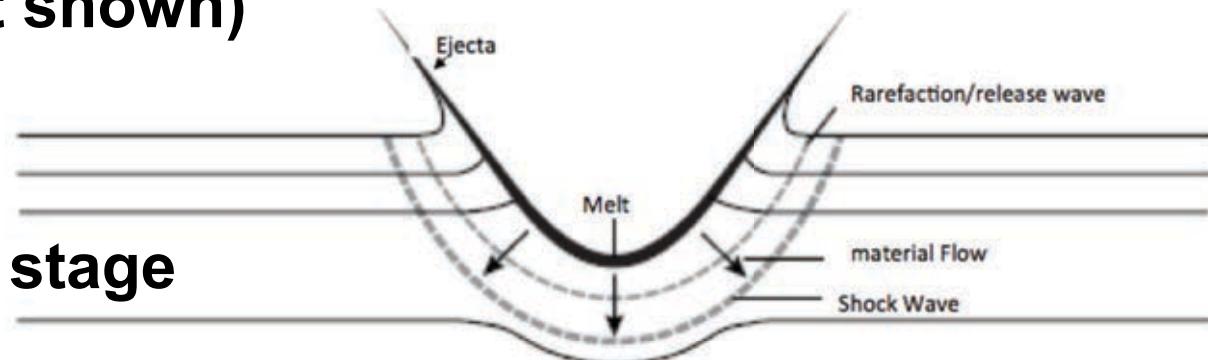


FIGURE 2. Regional geological setting of the Sudbury Structure. The Sudbury Igneous Complex (SIC) straddles the boundary between the Neoproterozoic Superior Province and the Paleoproterozoic Southern Province.

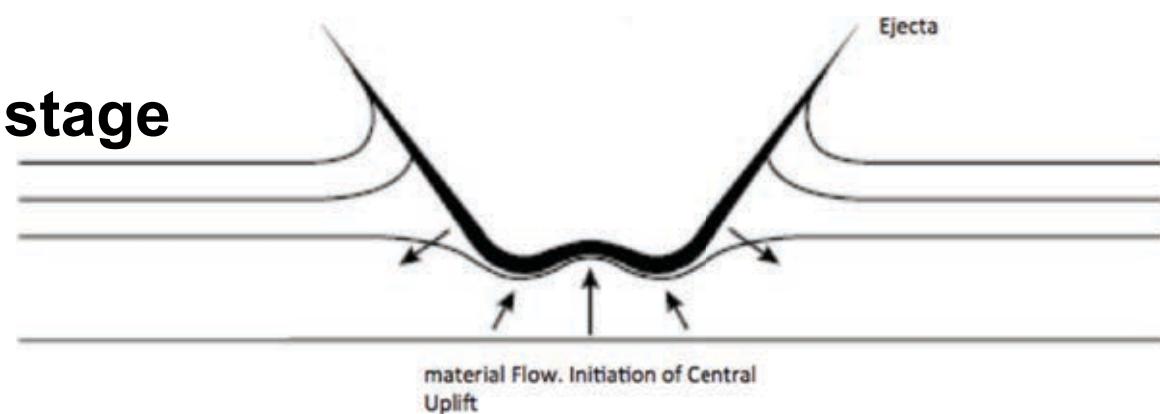
1850 Ma: BOOM!!! – Sudbury impact



## Stage 1: Boom! (not shown)

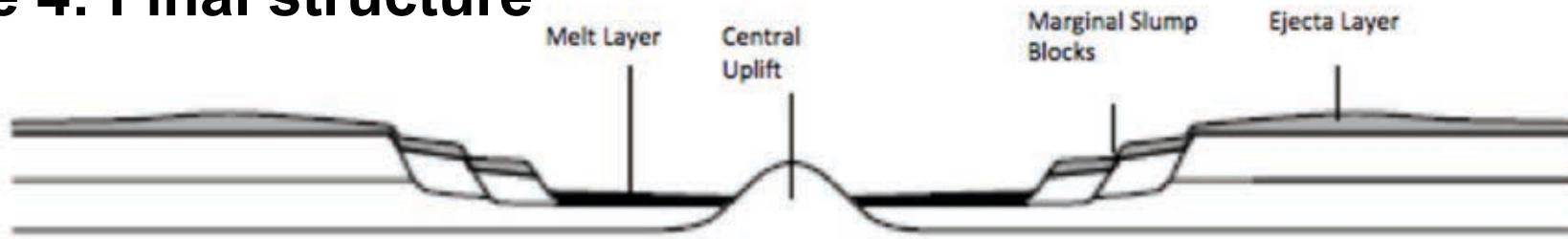


## Stage 2: Excavation stage

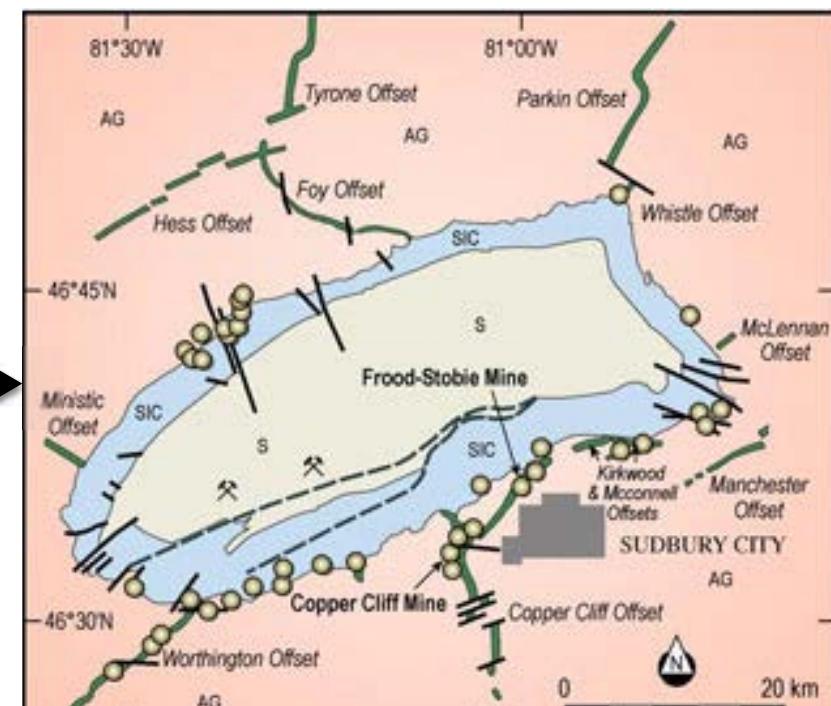
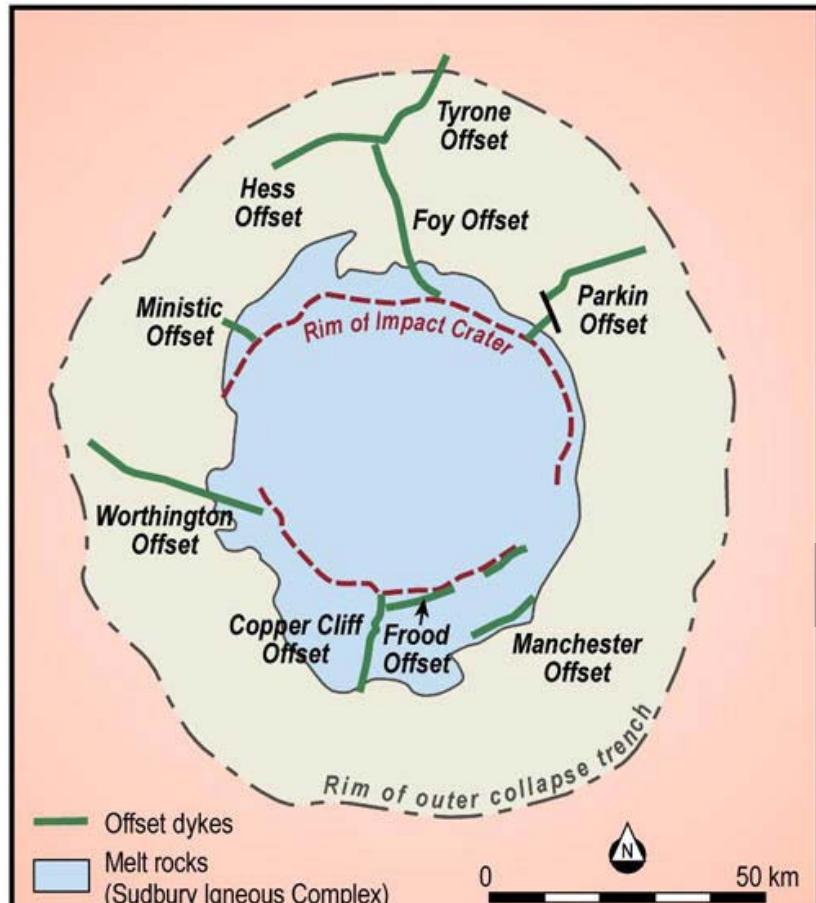


## Stage 3: Modification stage (Centre rebounds)

## Stage 4: Final structure



# 1850 Ma: BOOM – Sudbury impact



# Evidence of impact

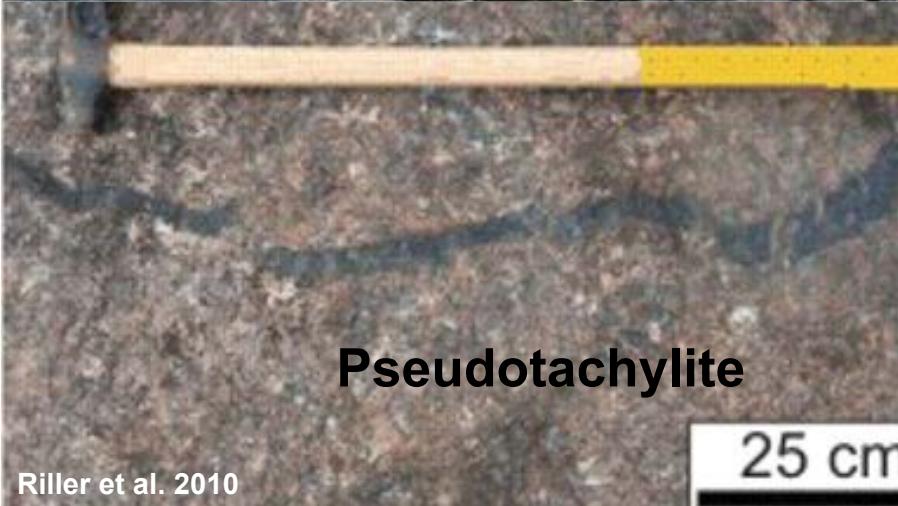
Shatter Cones



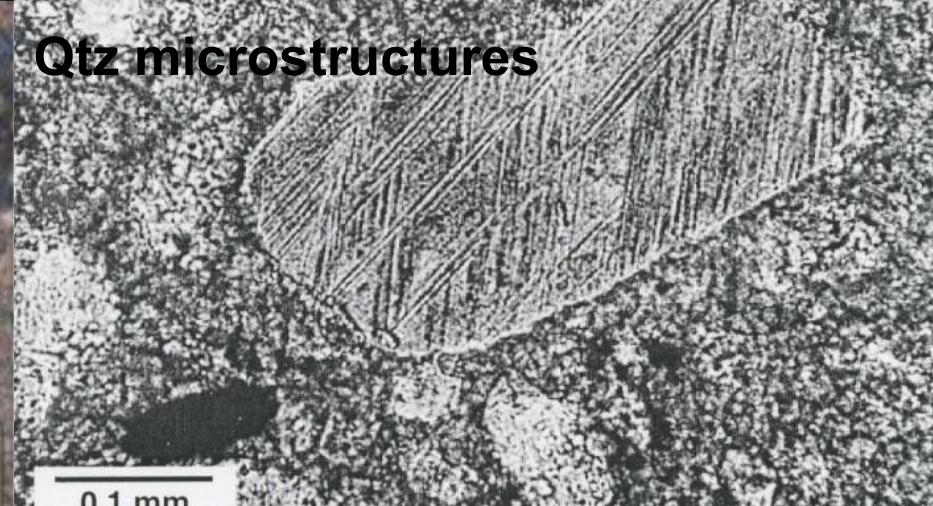
Ejecta



Pseudotachylite

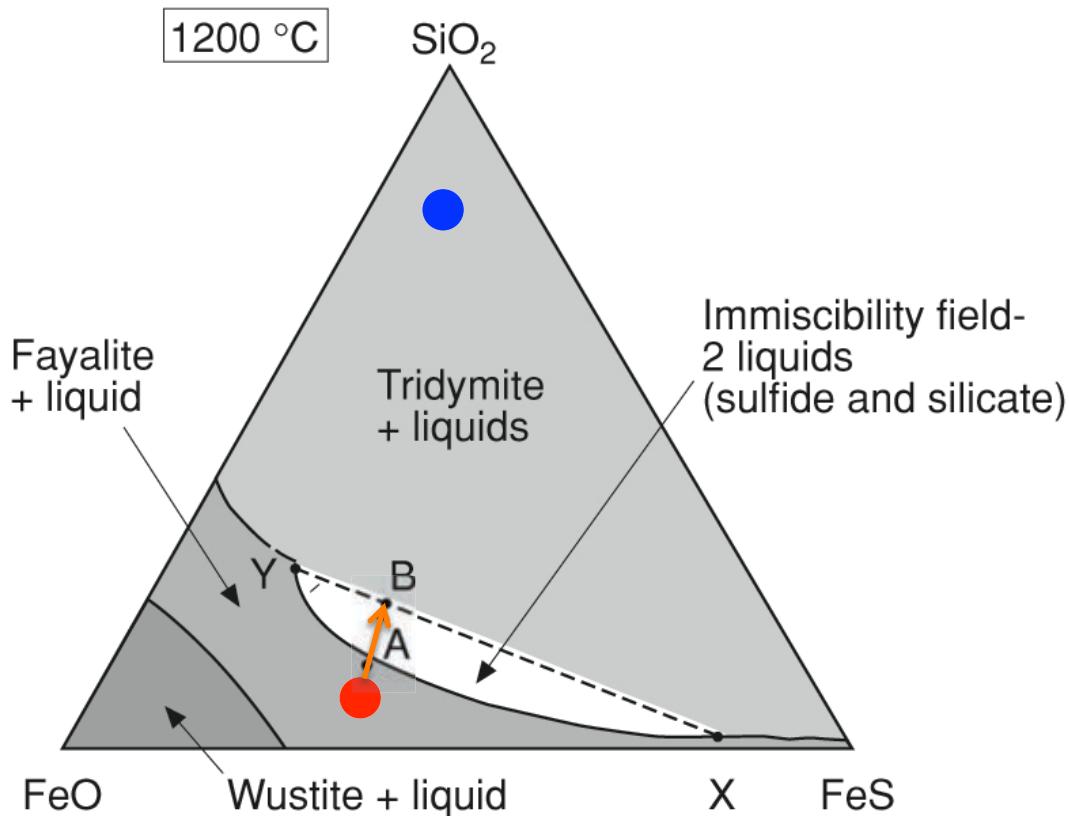


Qtz microstructures



## Genetic model (one of them...)

1. Impact melting of granite–gneiss and volcano-sedimentary greenstone sequence producing a ~1 km thick well-homogenized melt sheet (roughly a Qtz-diorite bulk composition)
2. Melt differentiated into a suite:
  - **Norite** (Opx–Pl gabbro; crystallized first)
  - Qtz gabbro
  - Granophyre (Qtz–Kfs)
  - [Note the absence of ultramafic rocks]
3. Contamination of norite with **crustal material** drove system towards two immiscible liquids (sulfide and silicate)



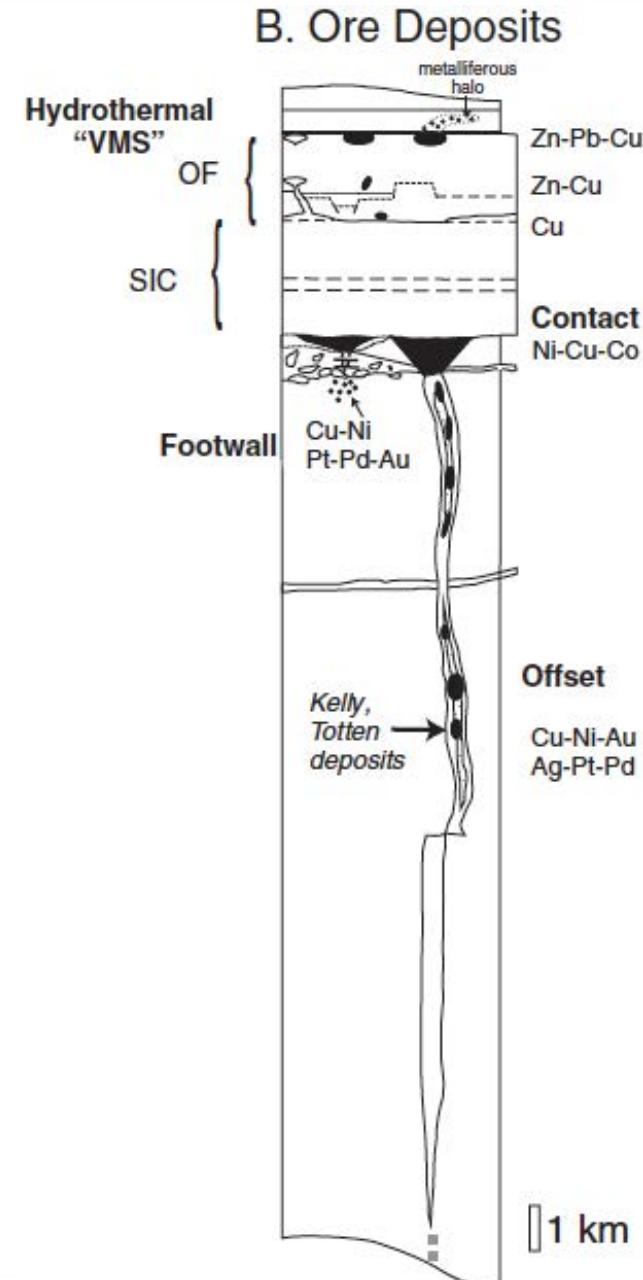
## Sudbury genetic model

**Source:** melting of pre-existing rocks

- Sulfur isotopes suggest crustal origin for S in the norite and sublayer
- Sr–Nd isotopes suggest SIC plots between Levack Gneiss and Upper Crust

**Transport:** melt injected into impact breccia and basement

**Trap:** dykes and magma chambers through cooling, fractional crystallization and sulfur immiscibility



## Take Home Messages

### **Five magmatic processes:**

1. Very low degrees of partial melting (e.g. U in Namibia)
2. Fractional crystallization (Bushveld chromitites)
3. Crystallization of the last increments of melt (pegmatites)
4. Separation of two immiscible liquids (Komatiites and Sudbury)
5. Physical incorporation of a minerals (diamondiferous kimberlites)

**Sulfide and oxide saturation** in magma is modified by many factors, which contributes to ore deposit genesis through fractional crystallization or liquid–liquid immiscibility.