A Paradigm Shift

The Evolution of a Nickel Exploration Model

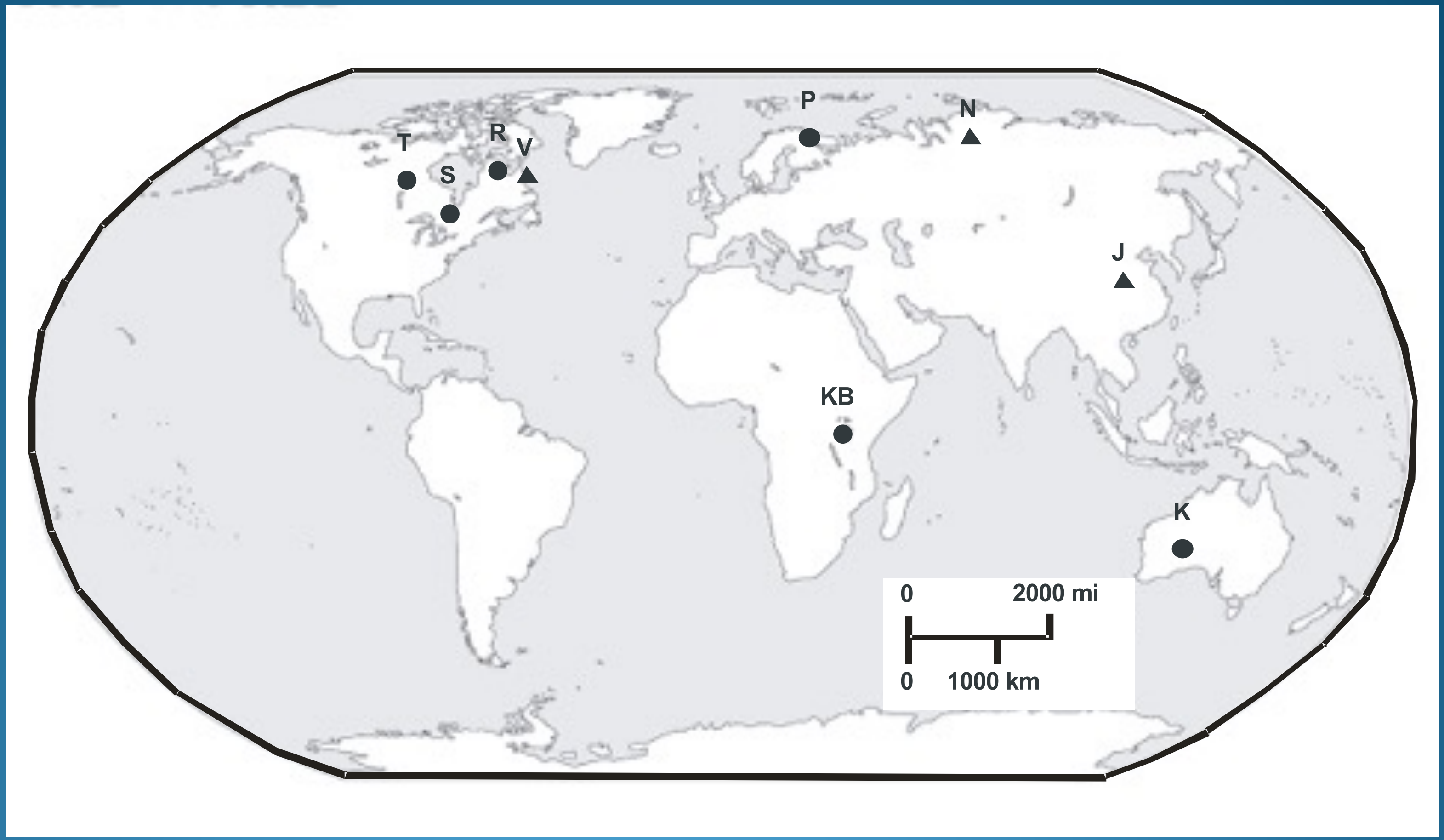
August 8 2024

1. Introduction
2. Review of Worldwide Nickel Deposits
3. Commonalities
4. Developing an Exploration Model
5. Exploration Guidelines
6. Conclusions

1. Introduction

- Historically Nickel deposits are rare but of high value
- Typically associated with Mafic to Ultramafic rocks
  - Nickel is Lithophile (typically occurs as an oxide) and Chalcophile (typically occurs as a sulphide)
    - Substitutes for Mg and Fe in Olivine [$(Fe,Mg)_2SiO_4$]
    - Will preferentially partition into sulphide if given the opportunity
- Most major sulphide nickel deposits worldwide show evidence of contamination and assimilation of sedimentary sulphur

2. Review of Worldwide Nickel Deposits



▲ Ni Deposits Within Magmatic Feeder Systems
● Komatiite Hosted Ni Deposits

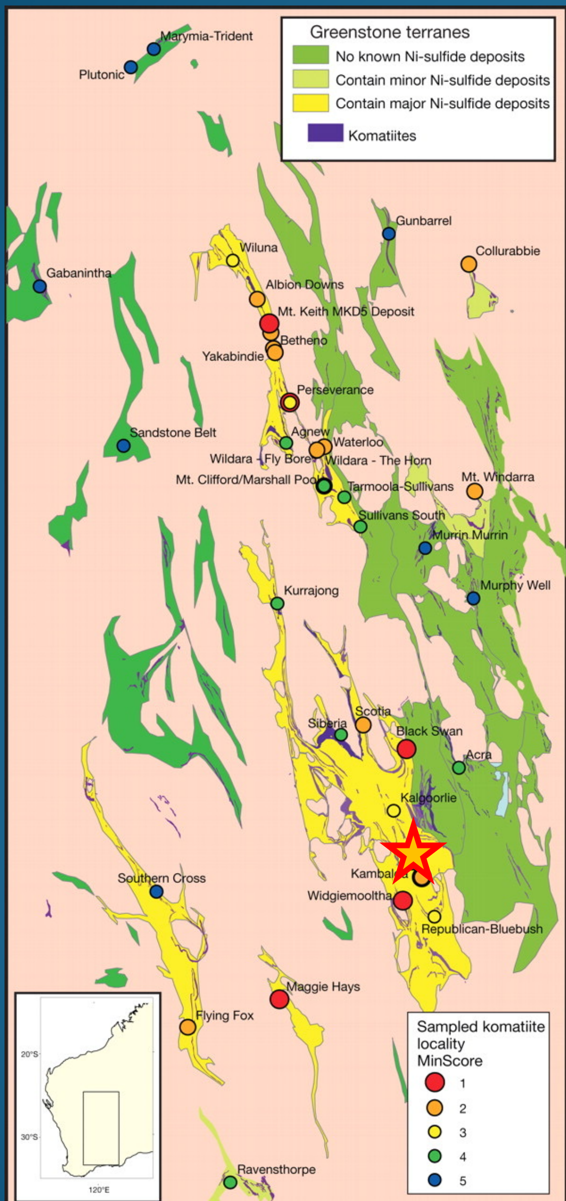
Location of major nickel deposits.

J – Jinchuan, **N** – Noril'sk, **V** – Voisey's Bay, **K** – Kambalda, **KB** – Kabanga, **P** – Pechenga, **R** – Raglan, **S** – Shaw Dome, **T** – Thompson.

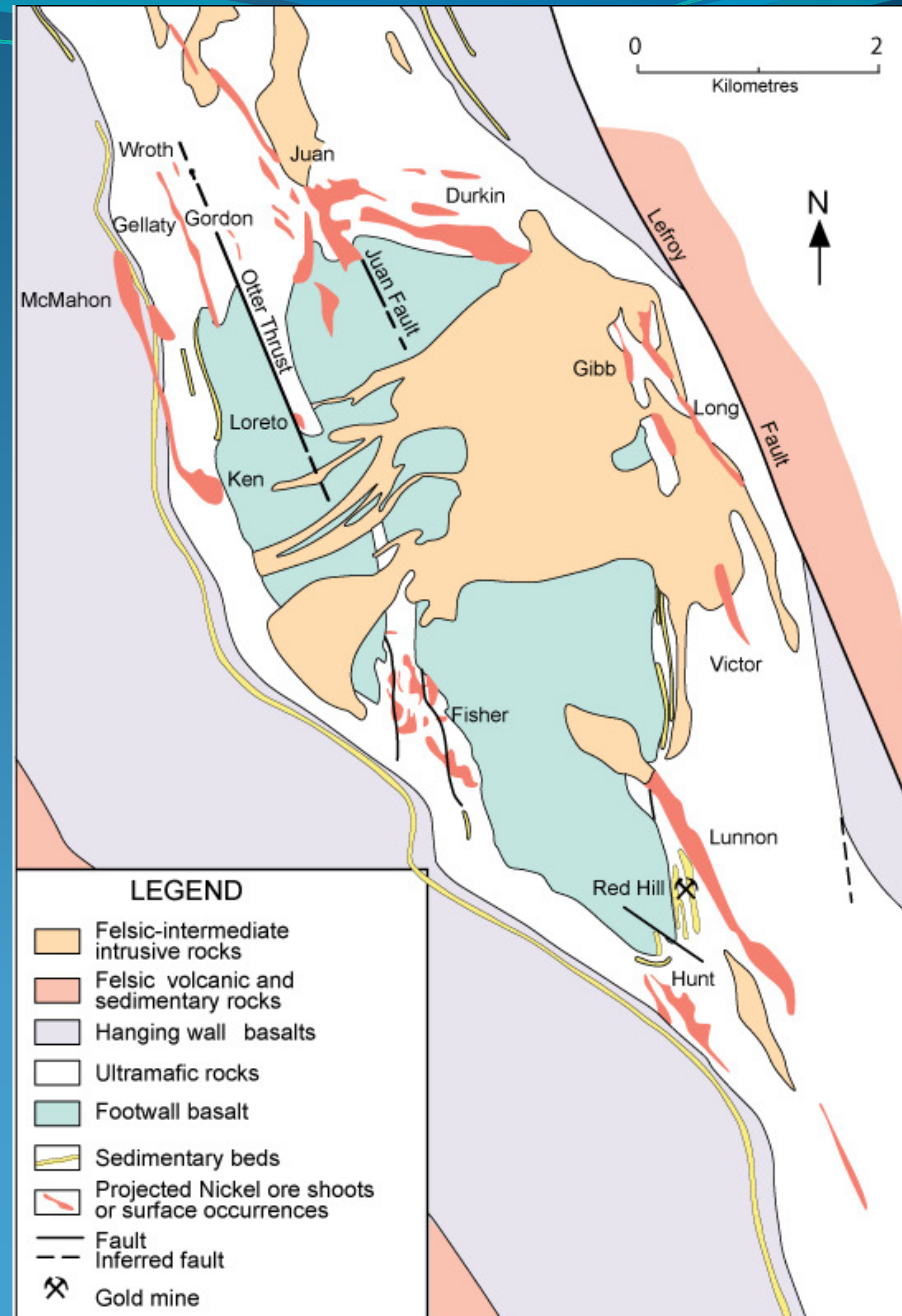
Major Nickel Deposit Examples

1. Kambalda
2. Pechenga
3. Raglan
4. Thompson

Kambalda

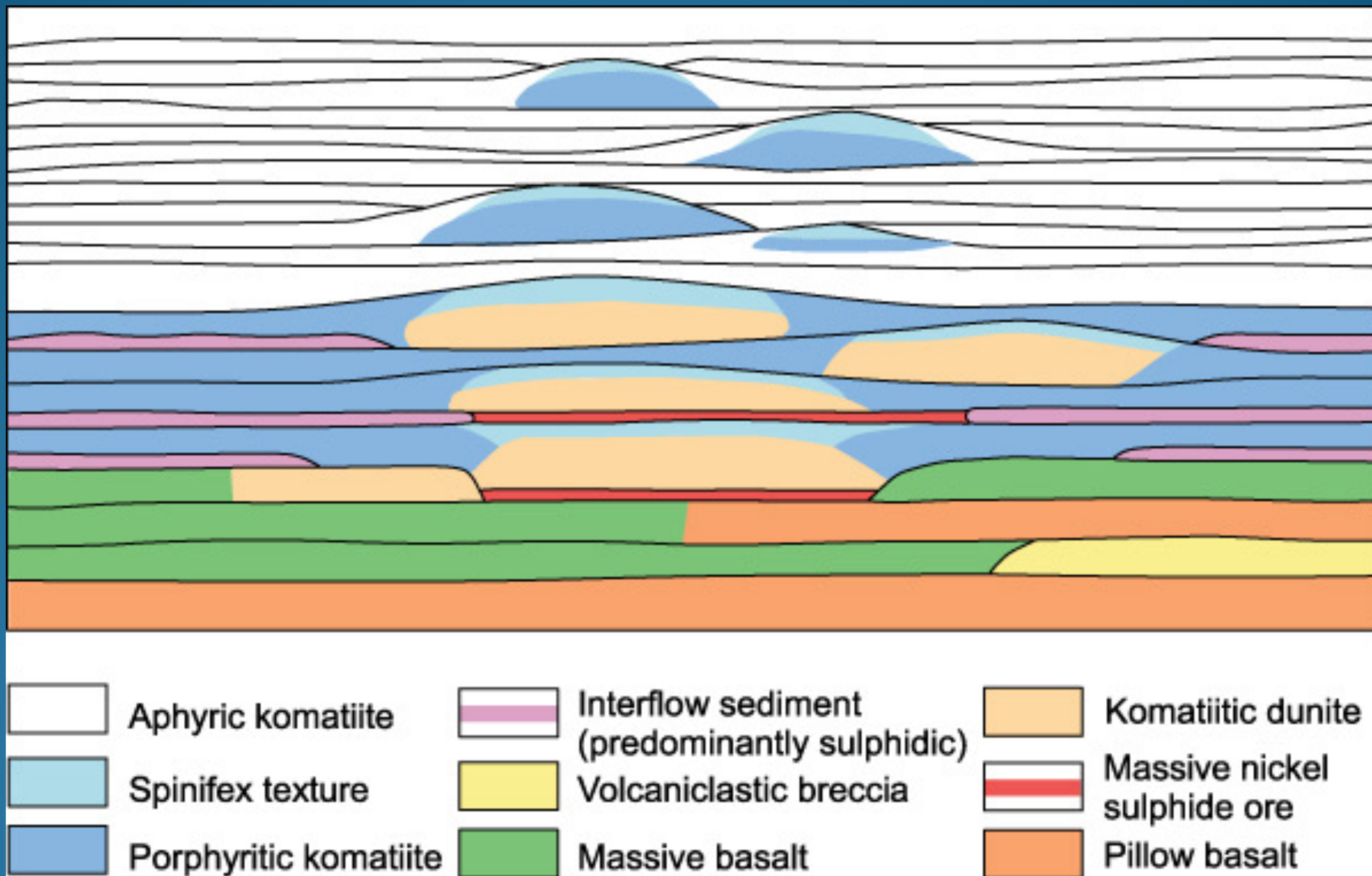


Yilgarn locality map (Fiorentini et al., 2010)



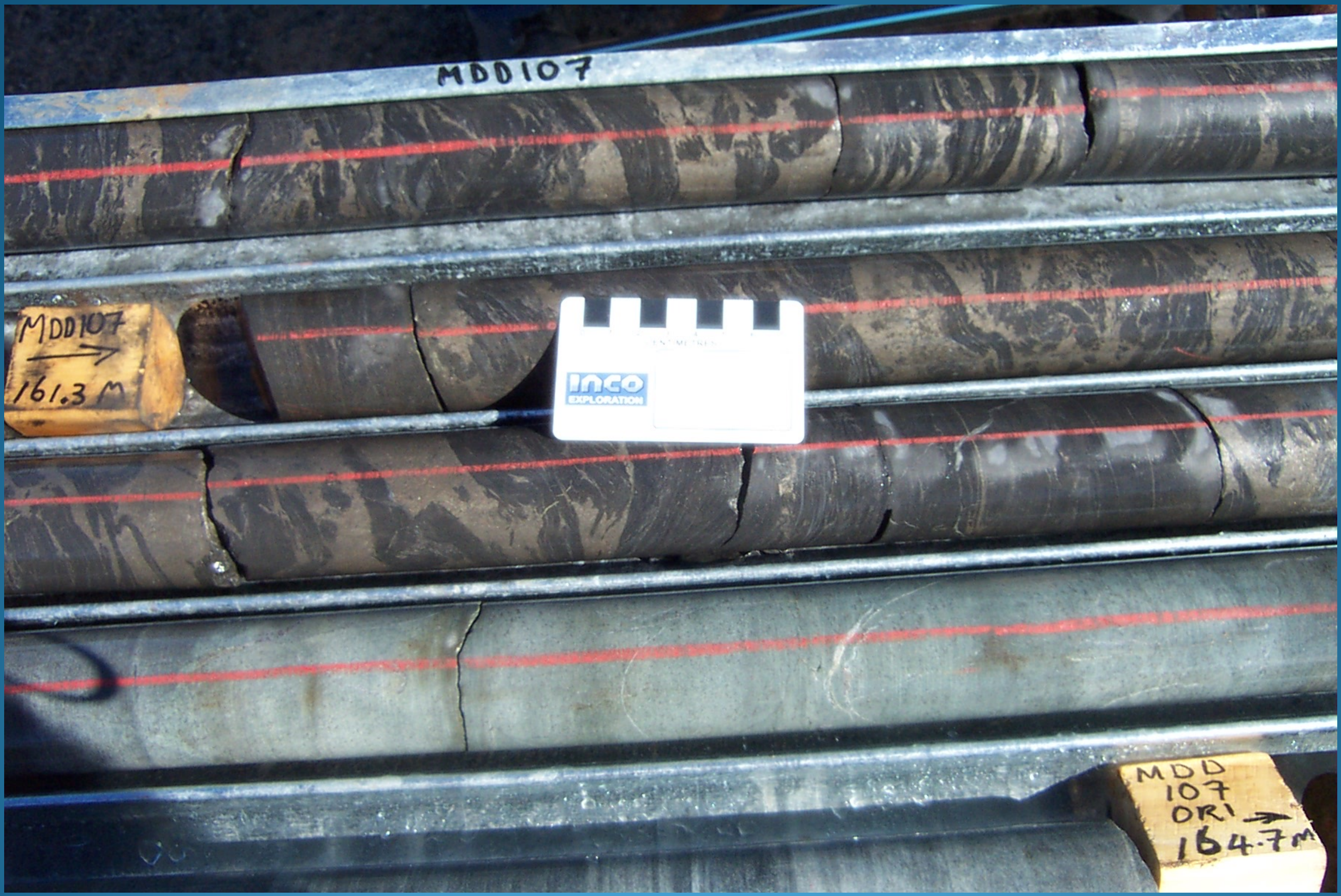
Kambalda district: geological map (after Gresham and Loftus-Hills, 1981)

Kambalda



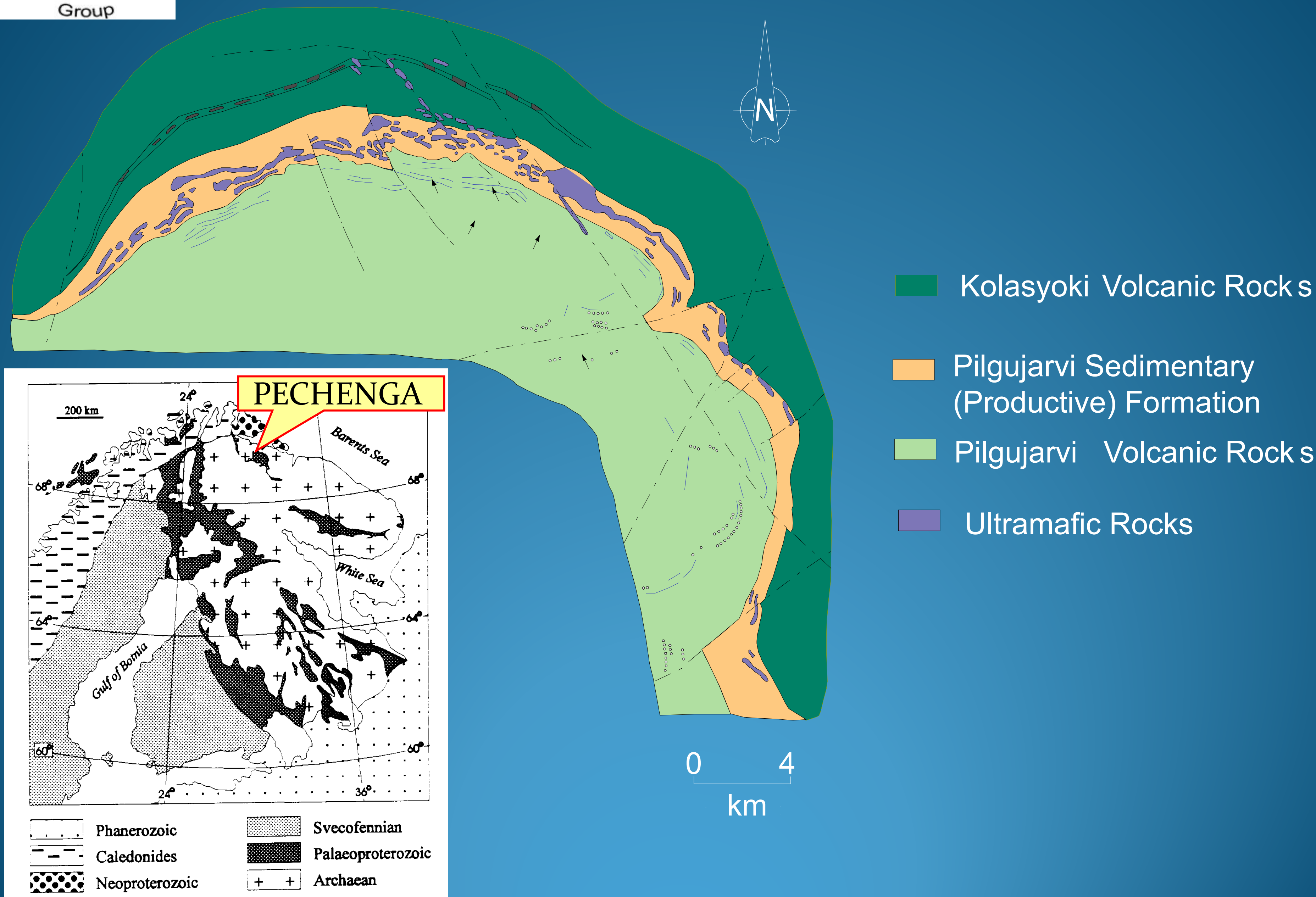
Generalized section of komatiitic flows and related nickel deposits (after Lesher, 1989).

Kambalda



Barren sulphidic argillite

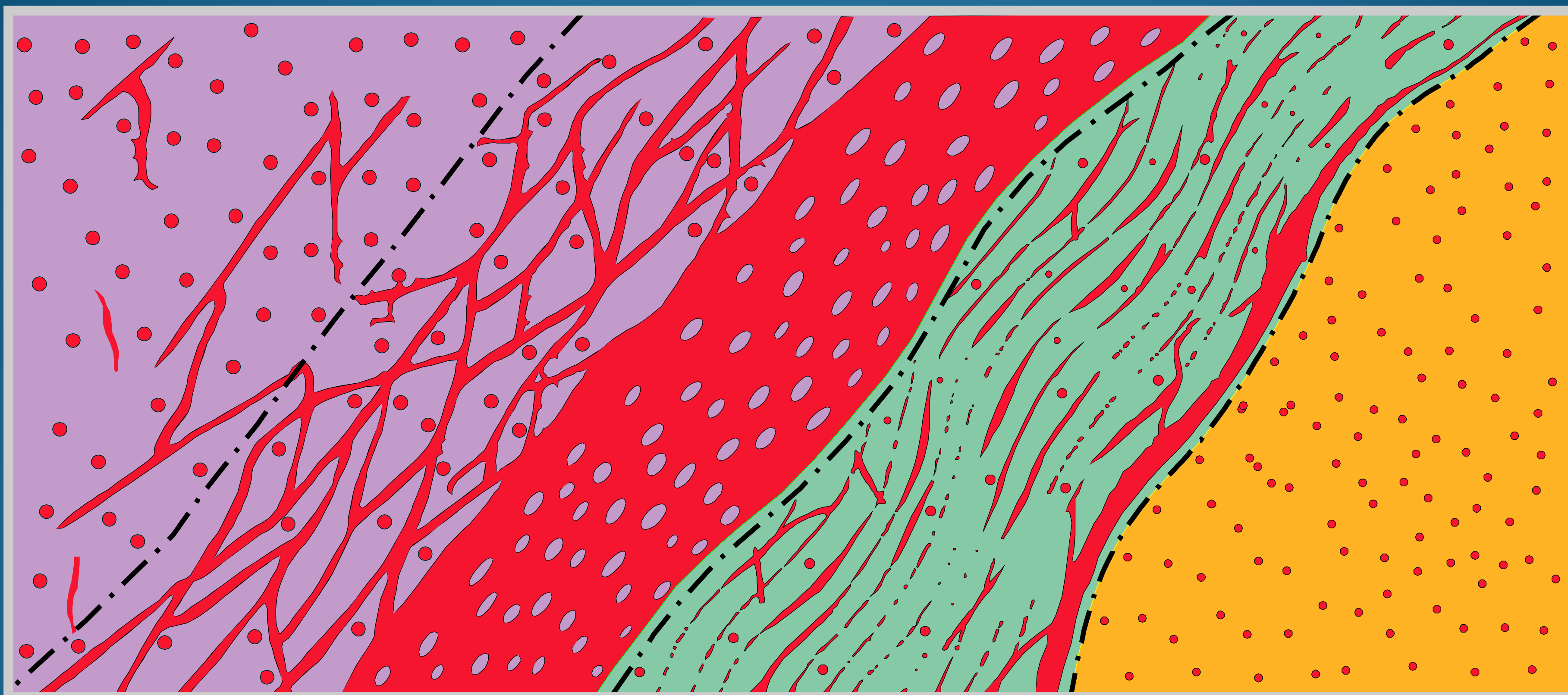
Pechenga



N
Kolasyoki Volcanic Rocks
Pilgujarvi Sedimentary (Productive) Formation
Pilgujarvi Volcanic Rocks
Ultramafic Rocks
0 4
km
PECHENGA
200 km
Barents Sea
White Sea
Gulf of Botnia
24°
36°
68°
64°
60°
Phanerozoic
Caledonides
Neoproterozoic
Svecofennian
Palaeoproterozoic
Archaean

Sibley Basin SBG Group

Pechenga



Massive Sulphide Ores

Breccia Sulphide Ores

Rich Disseminated Ores in Serpentinite

Weak Disseminated sulphide in Serpentinite

Mineralized Phyllite

Mineralized Tuffs

0 1 m

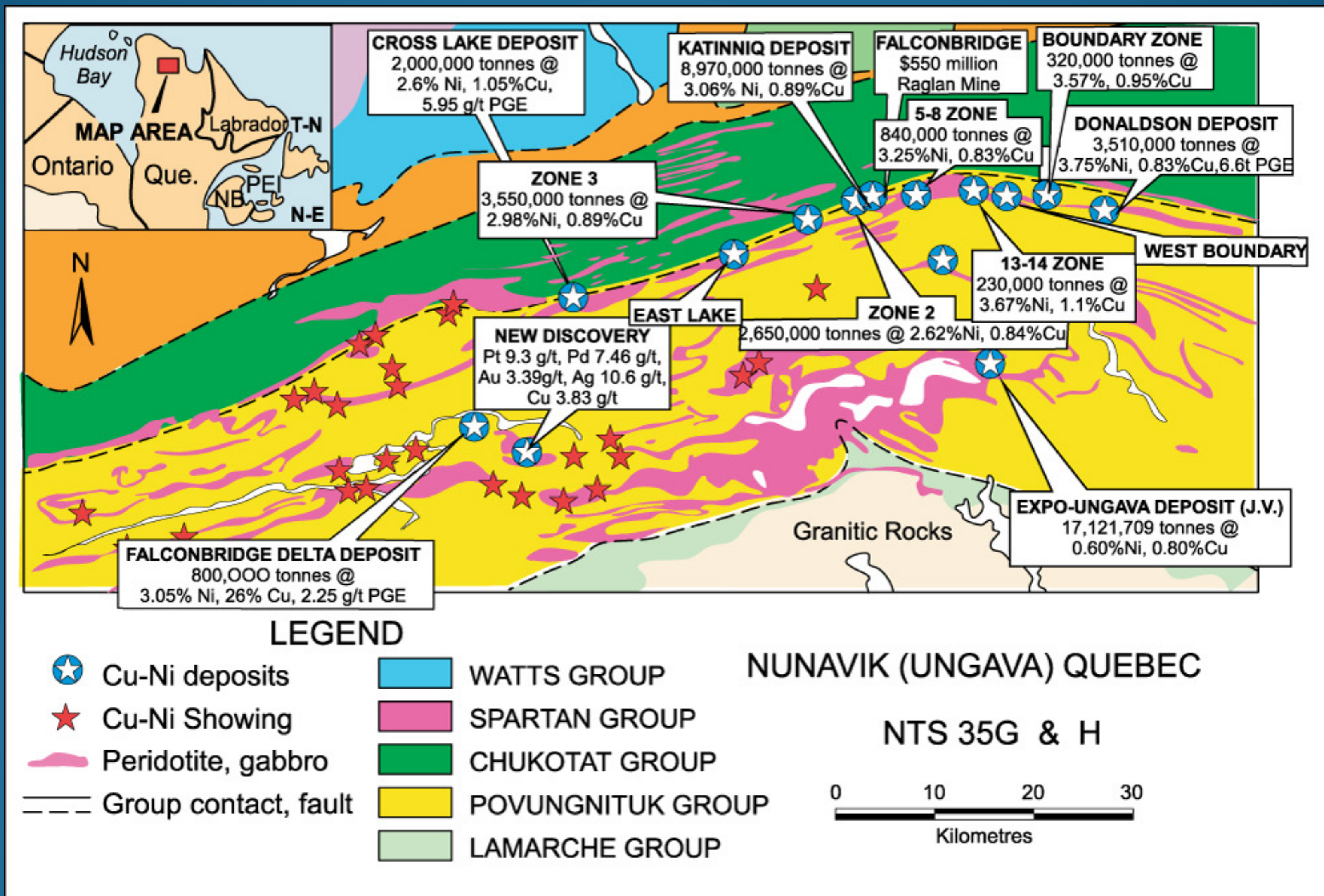
From: Smolkin (1999)

Pechenga

Barren Productive Formation phyllite

Sibley Basin SBG Group

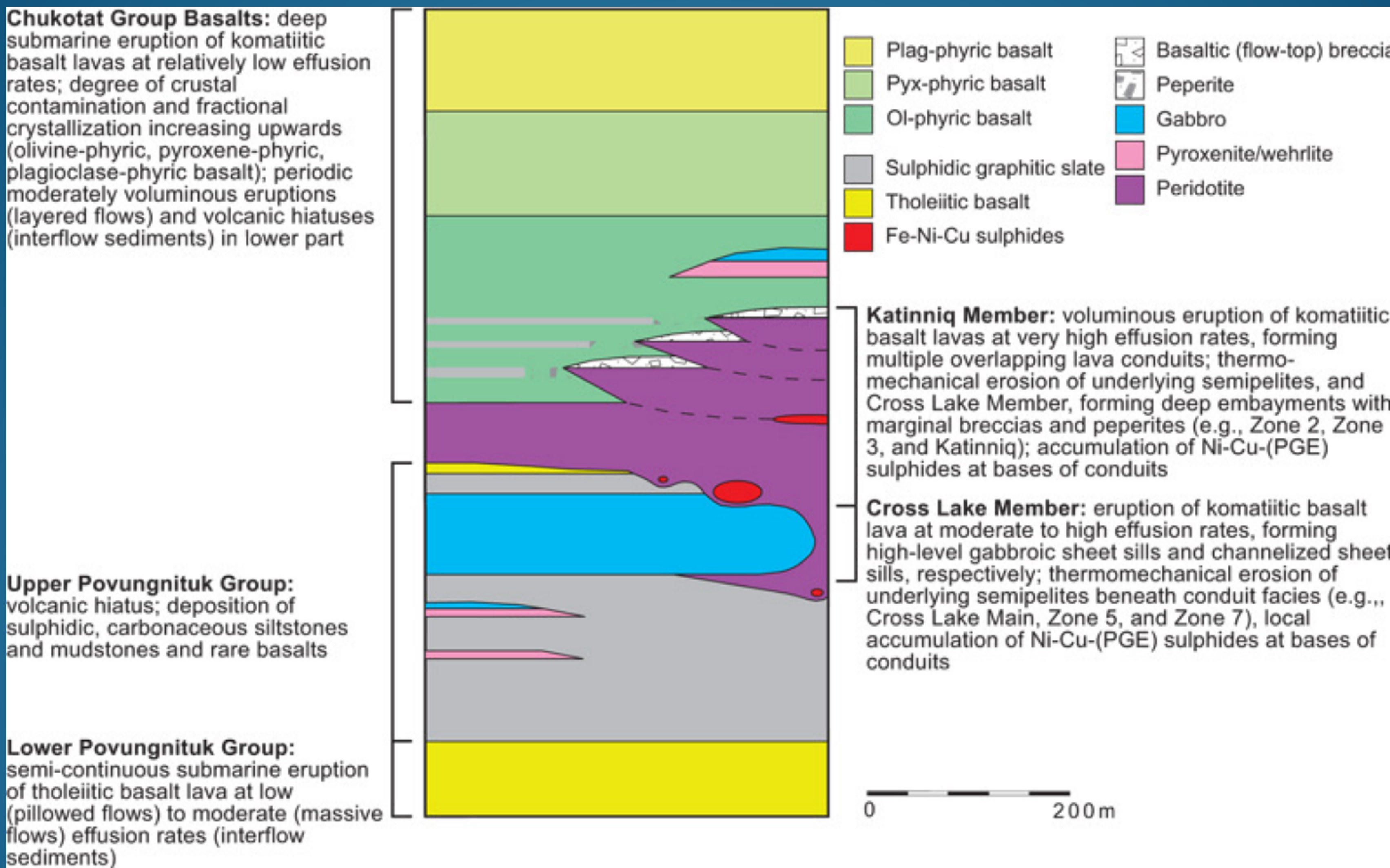
Raglan



Cape Smith Ungava district: geological map (from Canadian Royalties Inc. website)

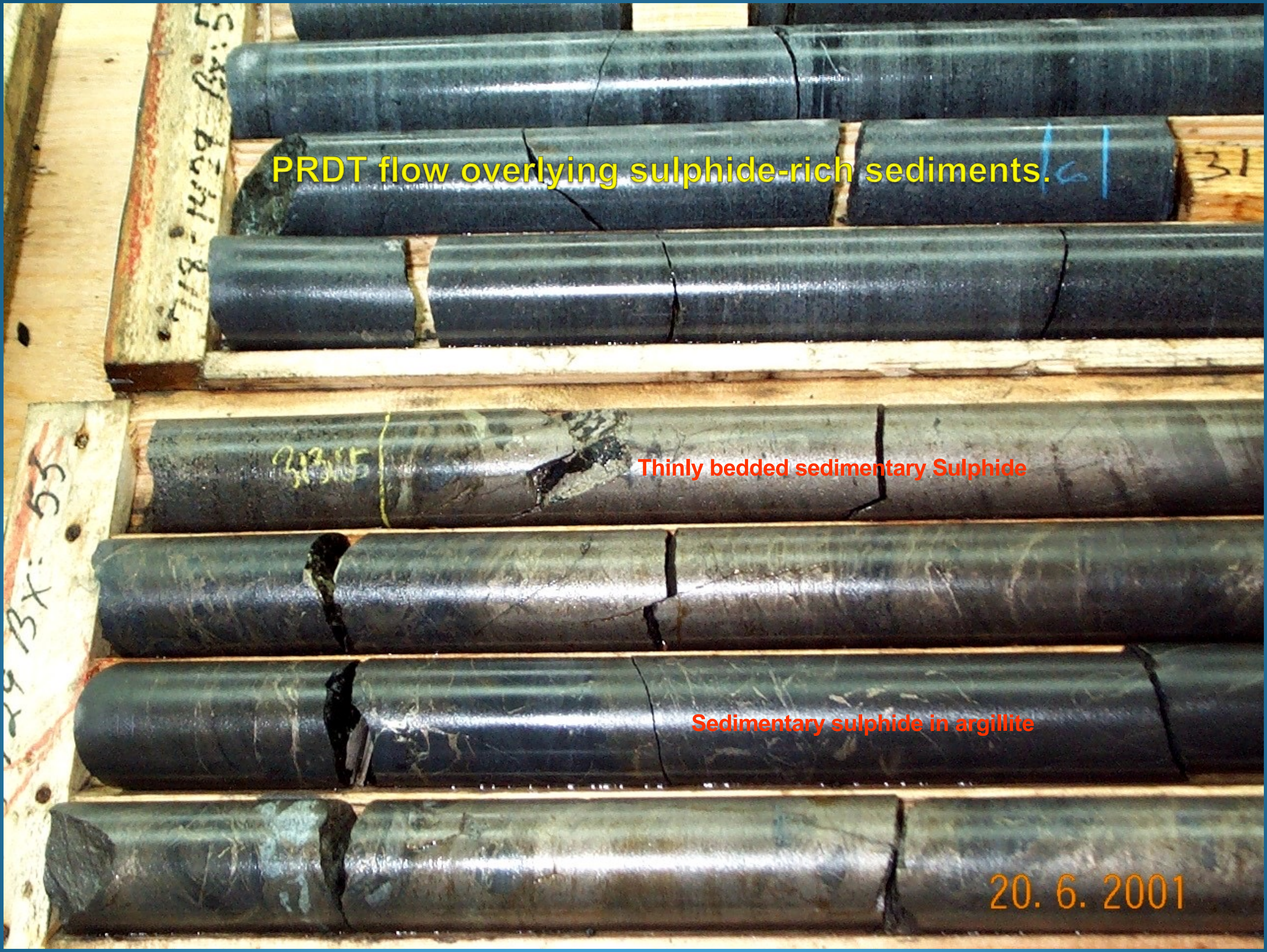
Sibley Basin SBG Group

Raglan



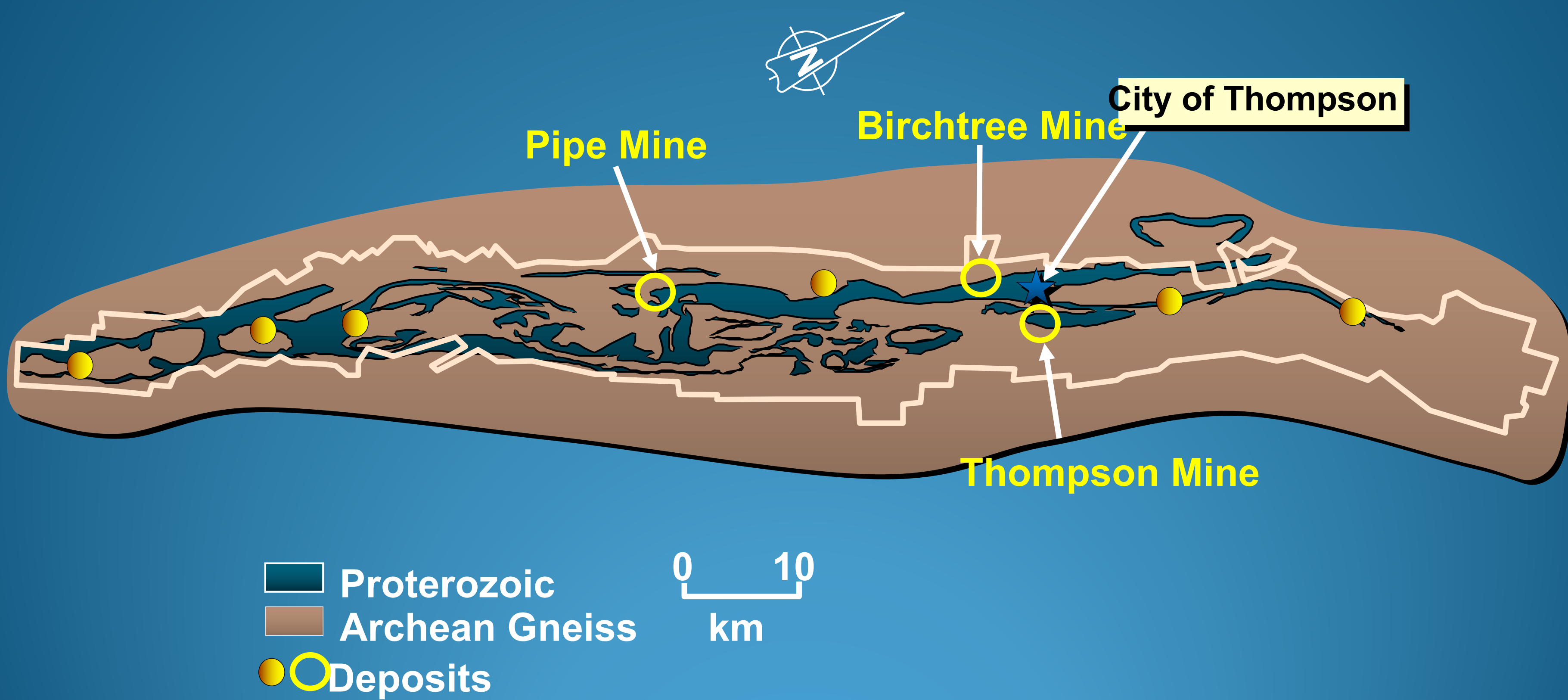
Interpretive stratigraphic column for the Raglan Formation (Lesher, 2008).

Raglan

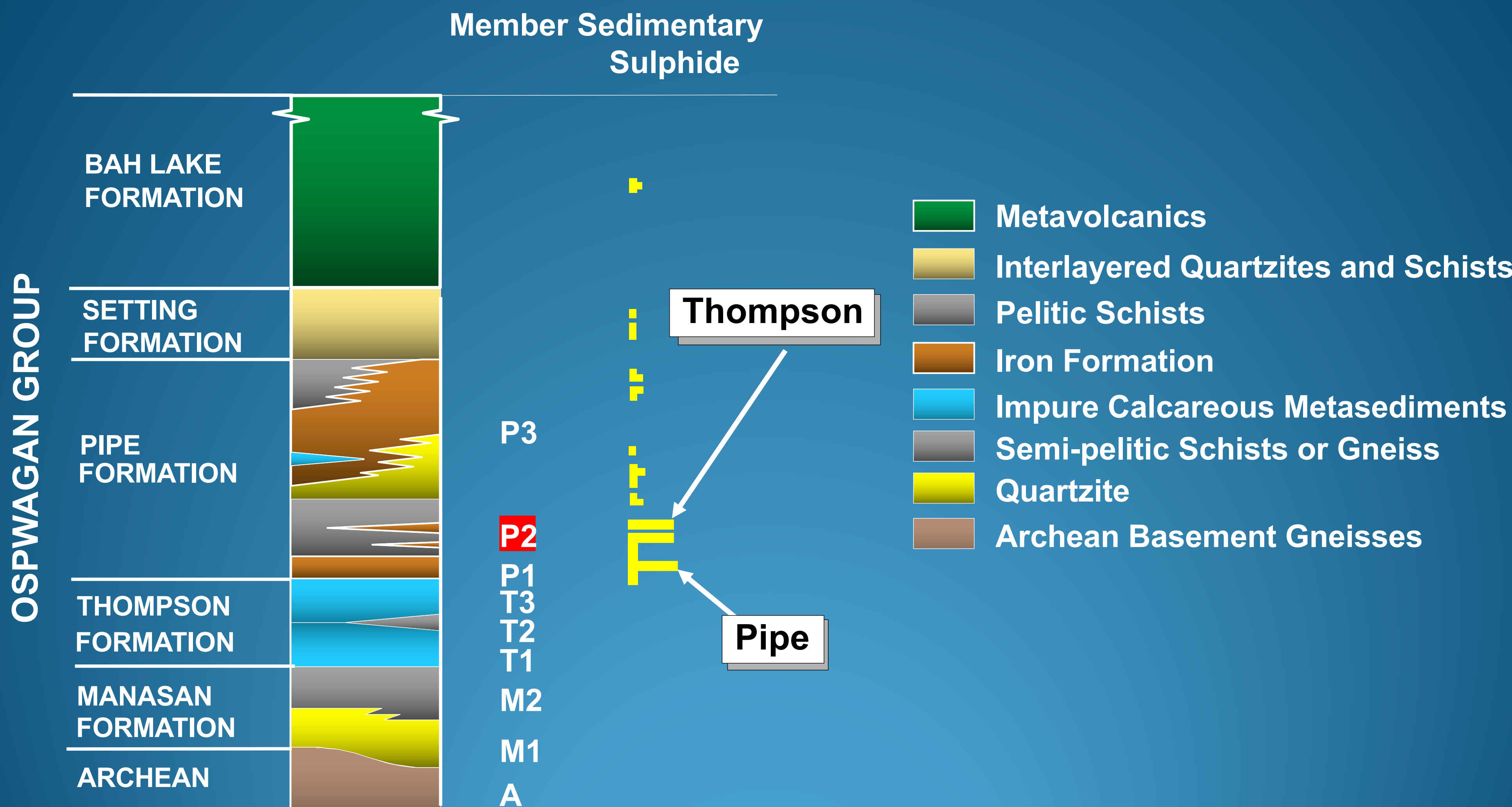


PRDT flow overlying sulphide-rich sediments.
Thinly bedded sedimentary Sulphide
Sedimentary sulphide in argillite
20. 6. 2001

Thompson


Pipe Mine
Birchtree Mine
City of Thompson
Thompson Mine
Proterozoic
Archean Gneiss
Deposits
0
10
km

Thompson



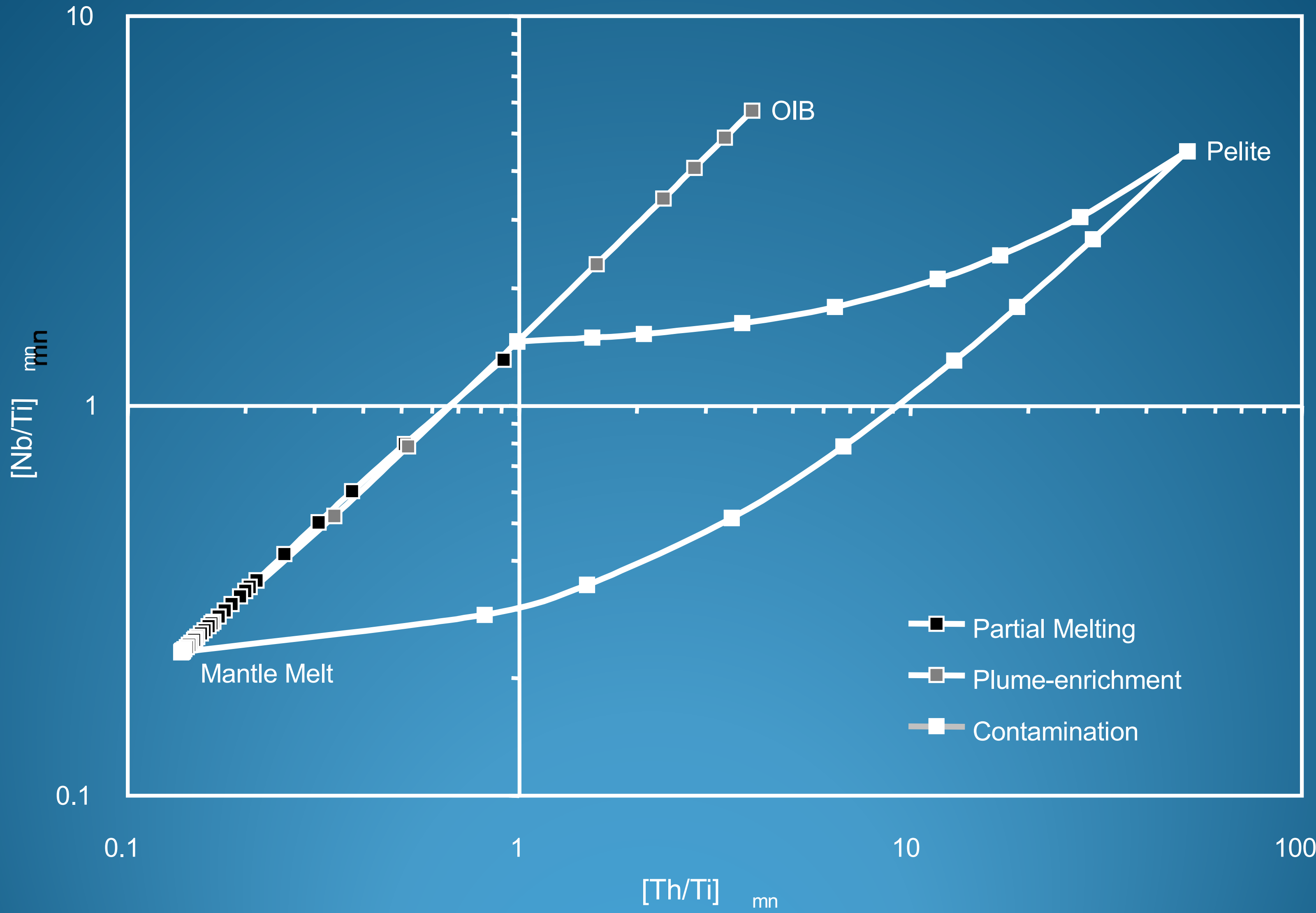
Member Sedimentary Sulphide
OSPWAGAN GROUP
BAH LAKE FORMATION
SETTING FORMATION
PIPE FORMATION
THOMPSON FORMATION
MANASAN FORMATION
ARCHEAN
P3
P2
P1
T3
T2
T1
M2
M1
A
Thompson
Pipe
Metavolcanics
Interlayered Quartzites and Schists
Pelitic Schists
Iron Formation
Impure Calcareous Metasediments
Semi-pelitic Schists or Gneiss
Quartzite
Archean Basement Gneisses

Sibley Basin
SBG
Group

Thompson

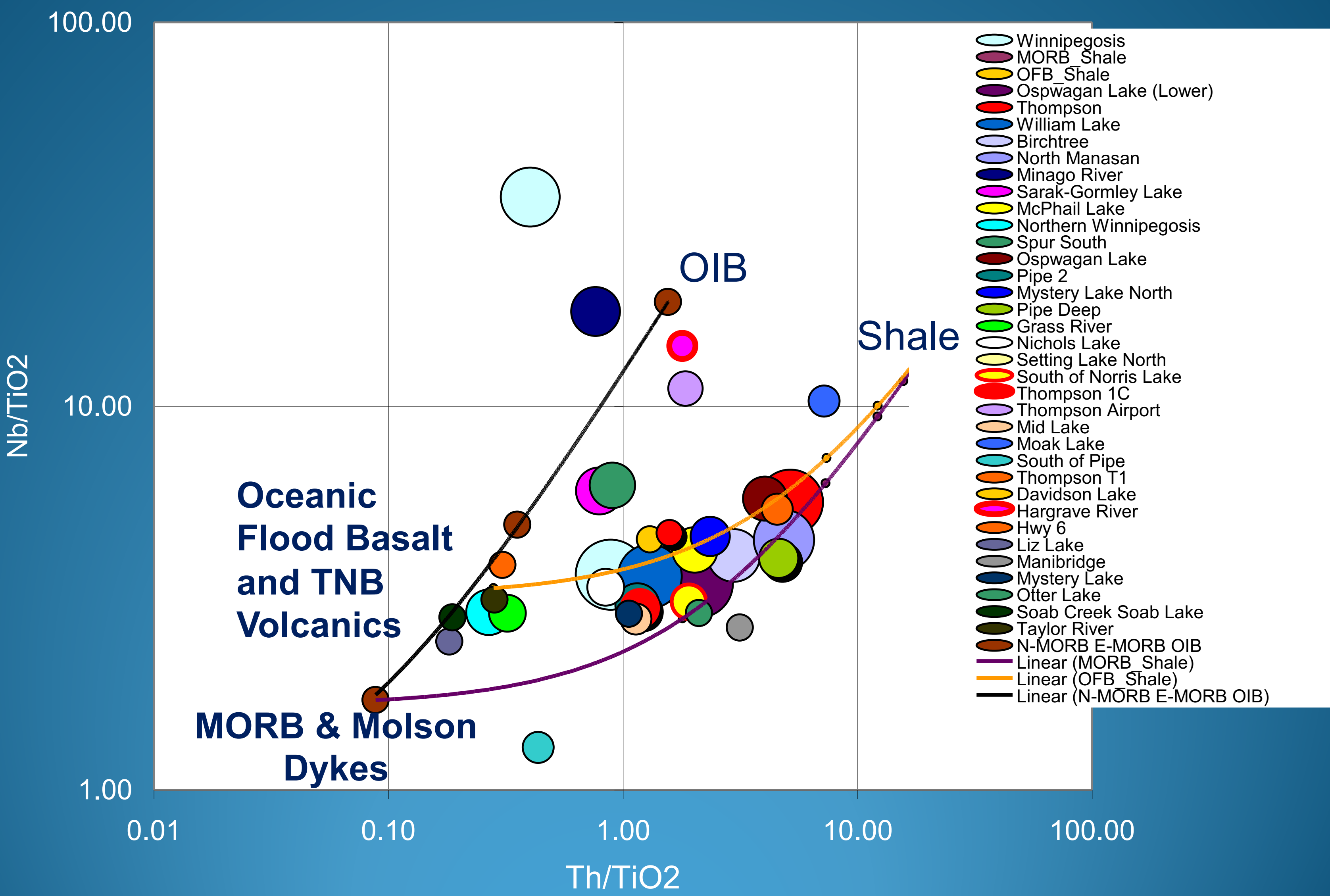
Sulphidic Phyllite with calc-silicate bed. Latter has been boudinaged (extension) and then folded (compression).

Evidence for Assimilation



Mantle-normalized Nb/Ti vs. Th/Ti

Evidence for Assimilation



Sibley Basin SBG Group

3. Commonalities

1. Nickel Sulphide Mineralization is hosted by ultramafics
2. Sulphides are at the stratigraphic base of the host ultramafic
3. Ultramafics are hosted by or in contact with sulphidic and carbonaceous argillaceous rocks.
4. Ultramafic bodies are stratabound and generally conformable to the host lithology
5. All are within an extensional basin

4. Developing an Exploration Model

Common Features:

1. Extensional environment
   1. Can be sediment dominated (i.e. Thompson).
      - Show development of a linear basin.
        - Shallow, near-shore beach sands
        - Moderate depth carbonate shelf
        - Deep basin sediments
   2. Can be volcanic dominated (i.e. Kambalda).
      - Nickel deposits associated directly with deep water sediments.
   3. Can be mixture of sediments and volcanics (i.e. Raglan and Pechenga)
2. Deposition of deep water sulphidic and carbonaceous sediments
3. Ultramafic bodies are stratabound by units having deep water sediments

Developing an Exploration Model

Other requirements to match observations:

1. Assimilation of sulphidic sediments
   - Need introduction of additional sulphide.
     - Magmatic sulphide not abundant enough to explain amount of nickeliferous sulphides present.
2. Required turbulent flow.
   - Need to have mixing of the immiscible sulphides with the magma to explain the high nickel tenors observed.

Both conditions are difficult, if not impossible to attain in any other environment other than as surface flows.

Developing an Exploration Model

Density "Problem"

- When rocks melt, they become about 10% less dense.
- Ultramafic rocks average about 3.1 g/cc density.
  - When melted that is about 2.8 g/cc density.
  - Average crust has a density of 2.7 or less.
- For ultramafic magma there must be a different mechanism other than density contrast.

- One proposed in the literature is "overpressure."
- This would explain why ultramafic bodies typically associated with extensional basins.

  - Extensional vertical fractures would tap the upper mantle and over-pressure would push the magma upward, even through less dense material.

Sibley Basin SBG Group

Developing an Exploration Model

Further notes on Density

- Forsterite (Mg_2SiO_4) has a density of about 3.27 g/cm3
- Fayalite (Fe_2Sio_4) has a density of about 4.39 g/cm3.
- Dunite (>90% olivine) has a density that will vary between 3.27 and 4.39 g/cm3 depending on the proportions of Forsterite and Fayalite .
- Peridotite (40-90% olivine) has a density usually between 3.1 and 3.4 g/cm3.

Further notes on Overpressure

- "When a fluid pressure is higher than estimated from the normal hydrostatic fluid gradient for a given depth, it is called overpressure. For this situation to occur, the fluid must first be trapped within a rock unit (pressure compartment)." (AAPG Wiki)

Developing an Exploration Model

Emplacement Mechanisms

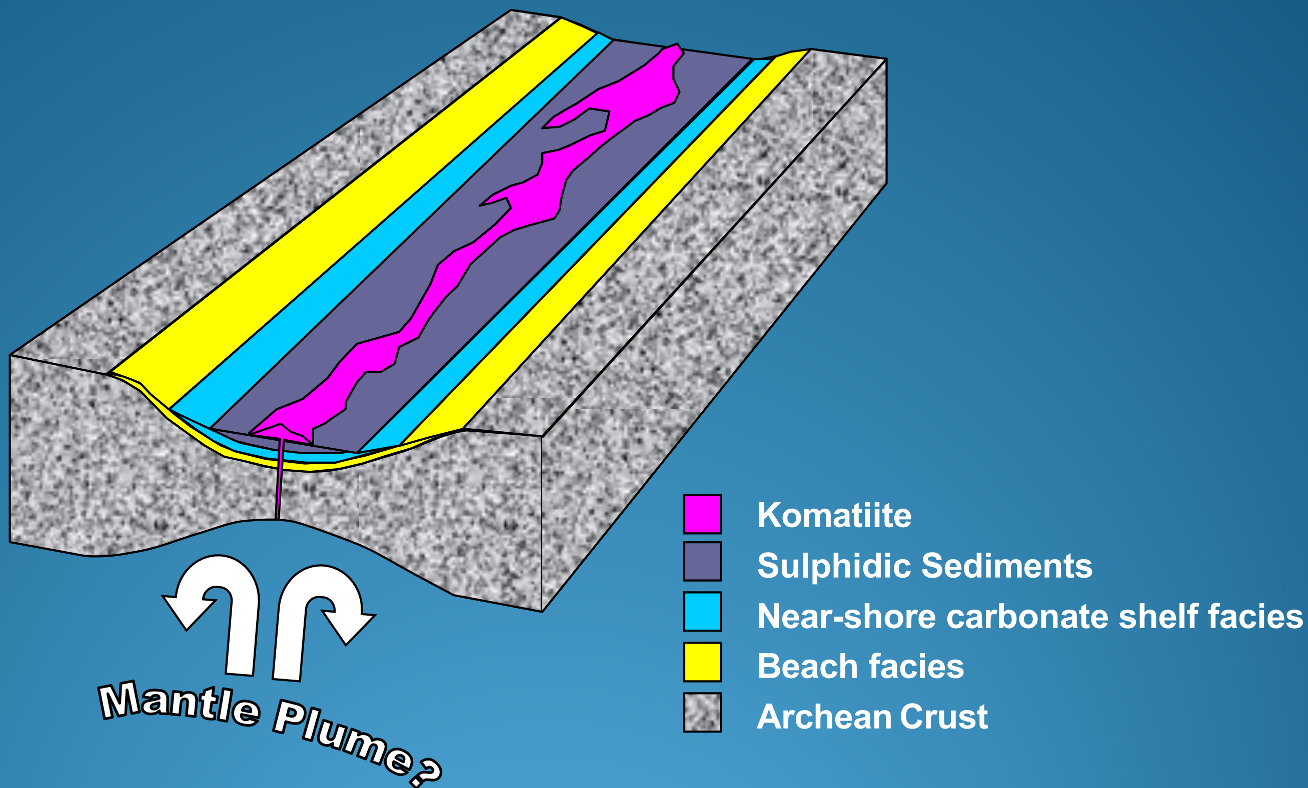
- In the case of facts, we need to consider what the possibilities are.

- With Ni-Cu Sulphide deposits
    - Many have considered chemistry.
    - Few have looked at Physical Properties.
        - i.e. If a melt is too dense for positive density contrast what alternatives can be applied?

            - Over Pressure
            - The introduction of volatiles (sea water?)
                - Decompressed gases expand in volume.
            - Other options?

Sibley Basin SBG Group

Exploration Model – sediment dominated end-member



Extension within an intracratonic area resulted in gentle down-warping of the crust. This linear basin became filled with continentally derived sediments. Once crustal thickness was thin enough that conduits could tap pooled primitive ultramafic magma, magma overpressure ensured emplacement along the rift axis and thus contact with sulphide rich sediments.

5. Exploration Guidelines

1. Look for evidence of an extensional basin
   - ➢ Long linear bands of sediments
   - ➢ Known ultramafic bodies within the sediments or nearby that are conformable to the stratigraphy.
   - ➢ Sediments could be, on a regional scale, absent.

2. Look for evidence of deep-water sediments (sulphidic and carbonaceous sediments).
   - ➢May have to consult drill logs for holes previously drilled in the area.

3. Are there belt-scale air-borne geophysical maps available?
   - ✓Look for "sidewalk conductors" – could be sulphidic and carbonaceous sediments.
   - ✓Look for linear conformable magnetic anomalies – could be serpentinized ultramafics
   - ✓Look for areas where the two come together! (Thermal erosion of ultramafic into sediments – Nickel Deposit!)

Sibley Basin SBG Group

6. Conclusions

- Many major nickel deposits worldwide share common features
  1. Ultramafic host is strata-bound
  2. Host stratigraphy documents development of an extensional basin
  3. Nickel deposits intimately associated with deep-water, sulphidic and graphitic sediments.
- There is typically evidence of assimilation of the sulphidic sediments within the ultramafic magma
  1. Turbulent flow allowed mixing of the sedimentary sulphide
  2. Nickel partitioned into the immiscible sulphide
  3. Gravity settling of the sulphide resulted in economic accumulations.

Exploration Model Summary

1. Look for environments that indicate formation of an extensional basin
   - Are deep water sediments present?
     - Typically, sulphidic black shales
2. Was the Mantle tapped?
   - Are there known ultramafic units concordant to local stratigraphy?
3. Focus exploration on those areas where both features are present.
   - Use Electomagnetic surveys to identify sulphidic sedimentary horizons
   - Use Magnetic surveys to identify possible serpentinised ultramafics
   - Pay particular attention where the two come together.