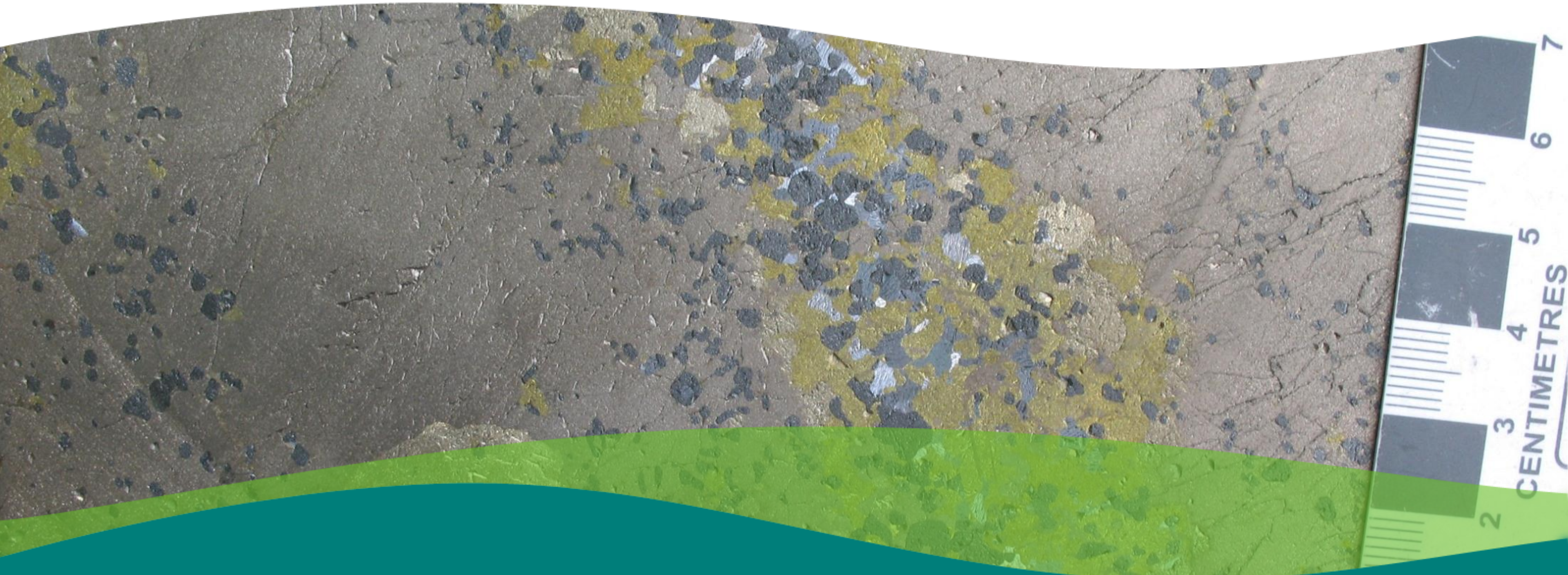
Simexmin

VI Simpósio Brasileiro de Exploração Mineral

VI Brazilian Symposium on Mineral Exploration

May 14th 2014

VALE



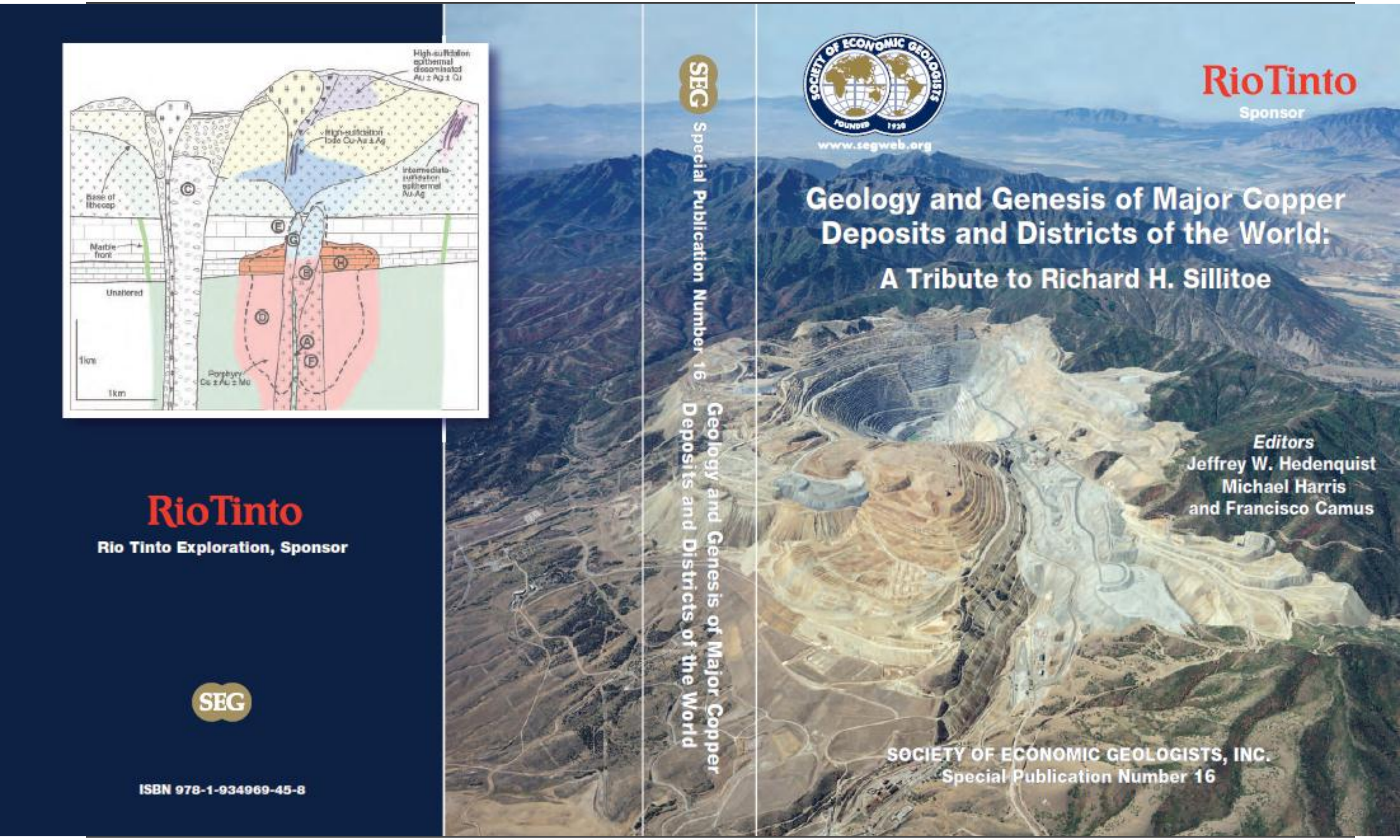
Copper-Rich Magmatic Ni-Cu-PGE deposits

David R. Burrows

Copper-Rich Magmatic Ni-Cu-PGE deposits
Outline of Talk

- Introduction and characteristics
- Examine key examples of Cu-rich magmatic systems to highlight Cu-enrichment processes
  - **Sudbury**: FC processes-maximized as slow cooling
  - **Noril'sk**: High R factor and sulphide FC
  - **Voisey's Bay**: High Cu, rel. low PGEs ores; limited FC
  - Mid Continental Rift in USA and Canada
    - **Duluth Complex**: Very Cu-rich mineralization
    - **Eagle deposit**: Small high grade deposit
- Summary of exploration criteria for Cu-rich magmatic mineralization
- Potential in Brazil for Cu-rich magmatic Cu-Ni-PGE deposits

Copper-Rich Magmatic Ni-Cu-PGE deposits



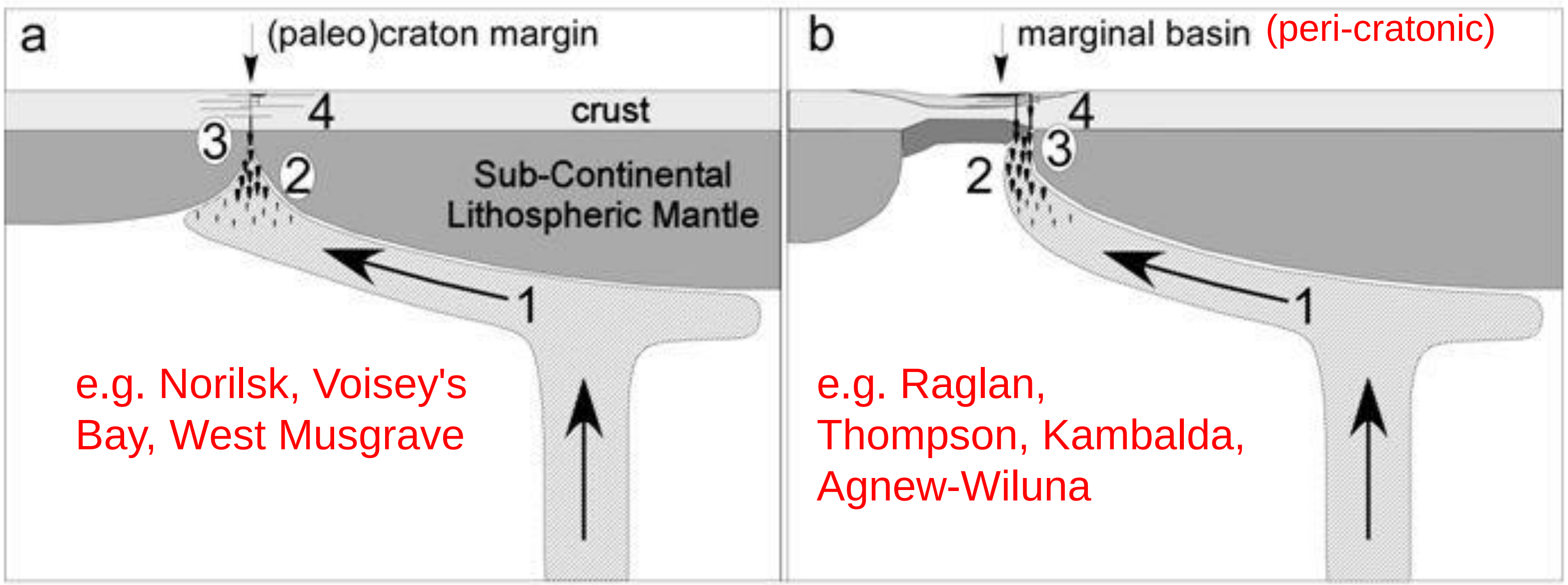
VALE

Magmatic Ni-Cu-PGE deposits

General Model

From Begg et al., 2010, Econ. Geol., 105, 1057-1070

Low-MgO (Mafic) style | High-MgO (Ultramafic) style



1. Mantle plume impact and flow towards areas of thinner lithosphere
2. Decompression melting of plume at shallower levels (sulfur undersaturated magmas)
3. Transfer of melts into the (upper) crustal environment via active trans-lithospheric faults and an interconnected intrusion (sills) network
4. Variable interaction of melts with crust (sulfur saturation)
5. Nickel sulphide precipitation and accumulation

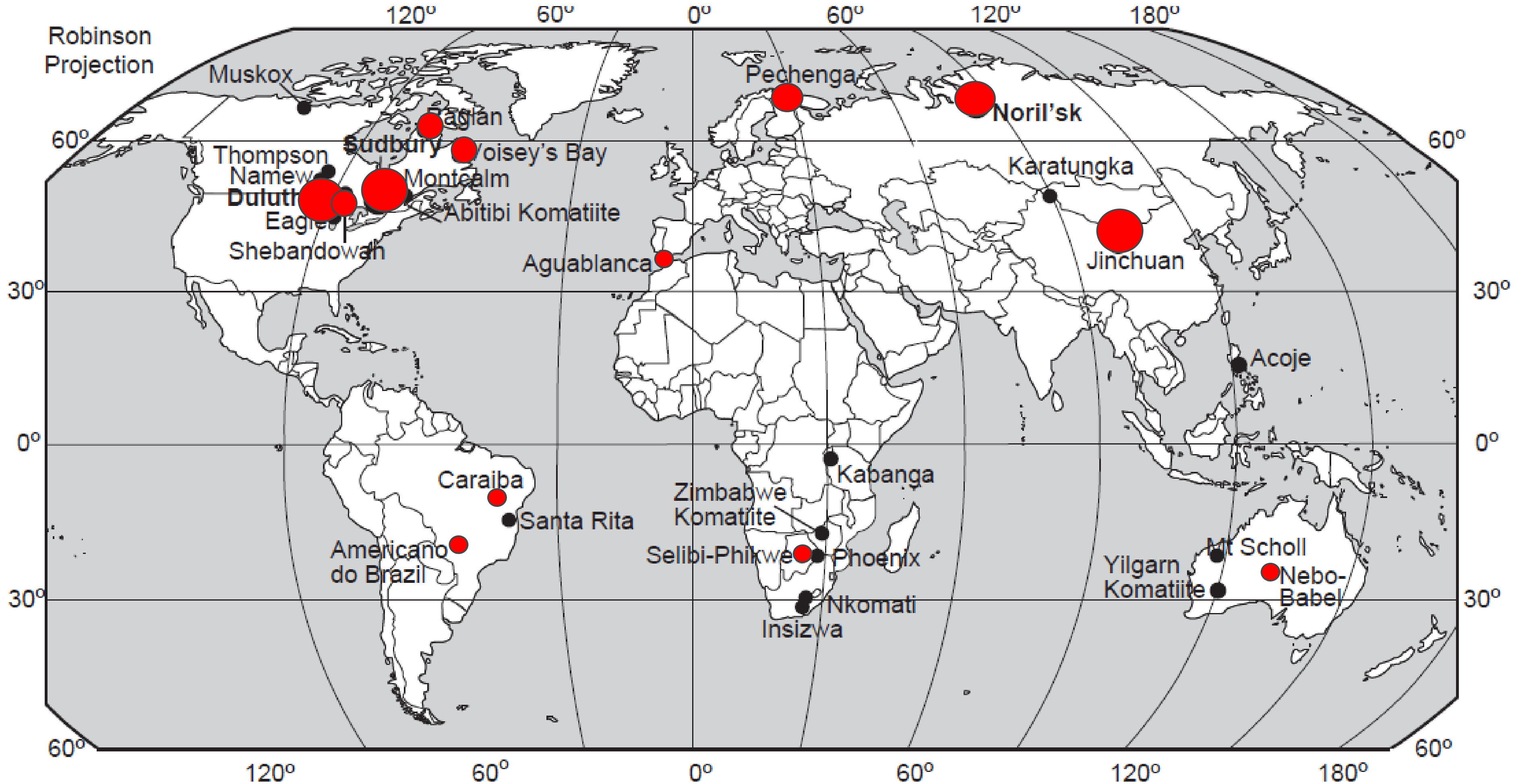
Why are some magmatic deposits richer in copper than others?

1. Composition of source, and conditions during melting and degree of partial melting
2. Degree of fractional crystallization (FC) ± crustal contamination <u>prior</u> to sulphide segregation
3. The amount of silicate magma that reacts with the sulphide melt (R factor)
4. Degree of FC of sulphides <u>after</u> it has segregated from magma

VALE

Cu-rich magmatic Ni-Cu-PGE deposits

Distribution of Cu-rich variety



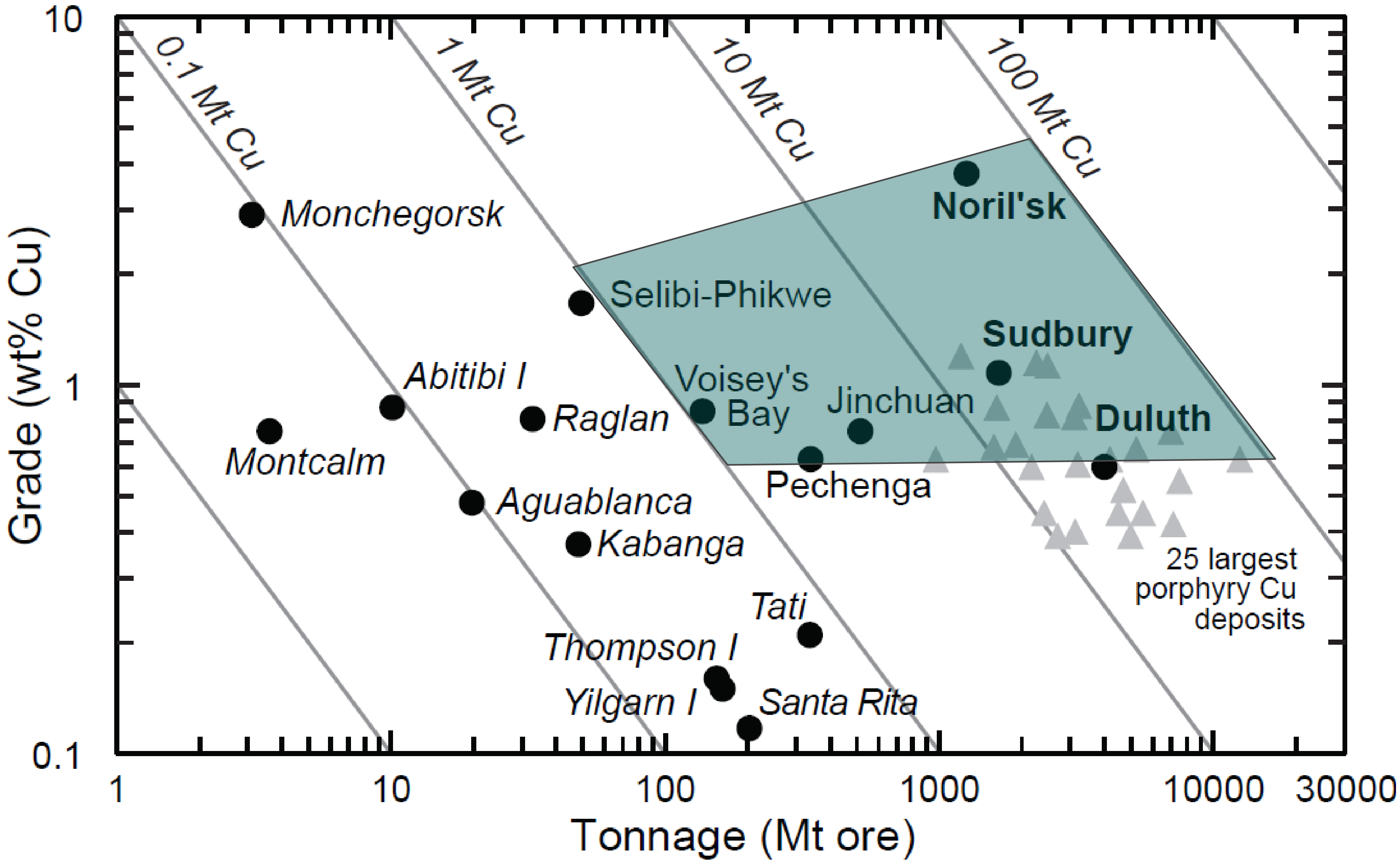
VALE

Cu-rich magmatic Ni-Cu-PGE deposits

Top magmatic deposit producers (2007-2008)

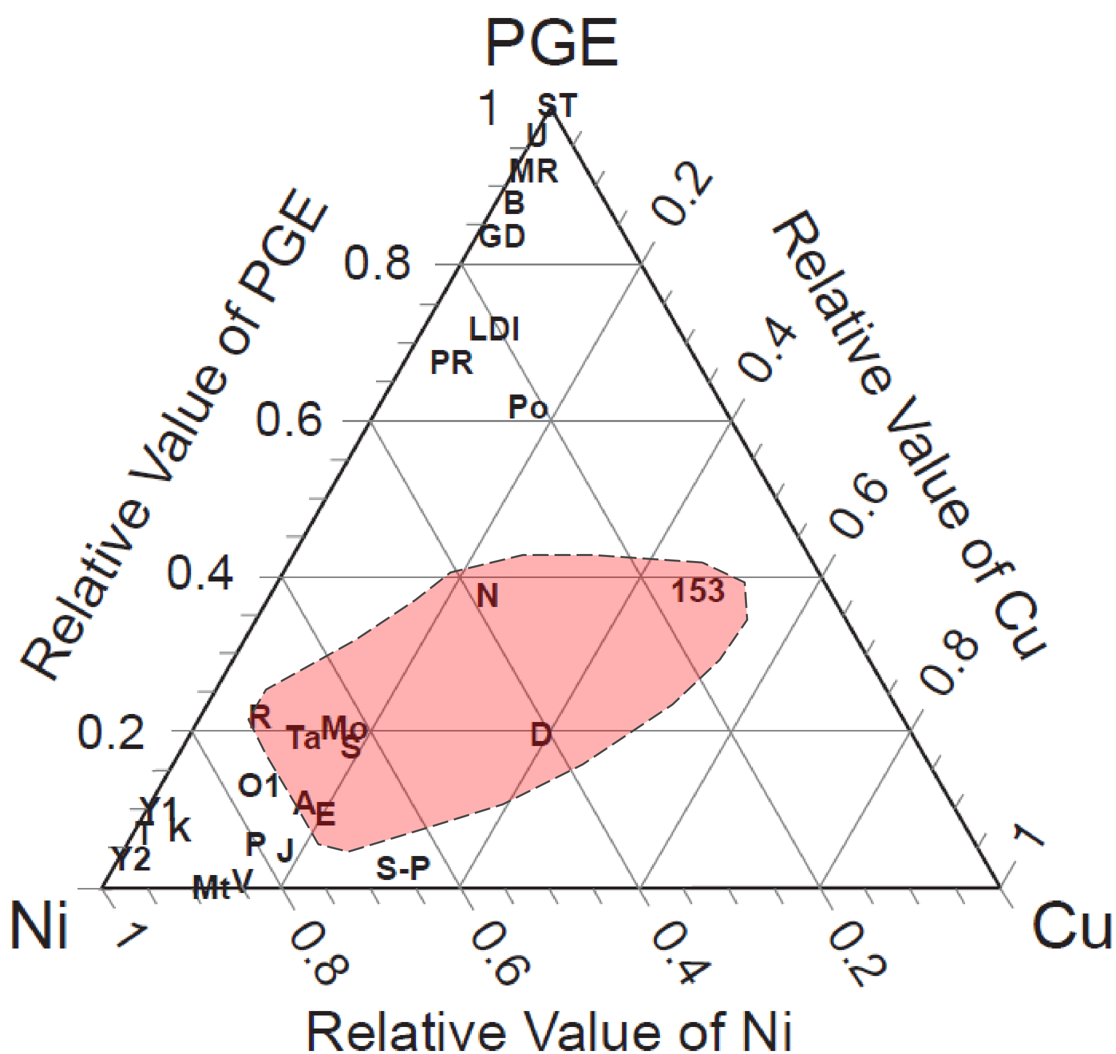
Deposit	Location	Operator(s)	Cu pa (tonnes)	Cu Grade
Noril'sk	Taimyr Peninsula, Russia	Nori'sk Nickel	364,400	2.60%
Sudbury	Ontario, Canada	Vale Glencore	134,000	1.27%
Voisey's Bay	Labrador, Canada	Vale	55,400	1.53%
Jinchuan	Gansu Province, PRC	Jinchuan Non-Ferrous Metal Corp.	52,000	0.66%
Selibi-Phikwe	Botswana		24,289	0.55%
Caraiba	Curaca Valley, Bahia, Brazil		22,720	1.00%
Pechenga	Kola Peninsula, Russia	Noril'sk Nickel	18,000	0.35%
Phoenix	Botswana		13,400	0.18%
Raglan	Nunavik, Canada	Glencore	7,134	0.68%
Aguablanca	Extremadura, Spain		5,484	0.40%
Santa Rita (Mirabela)	Bahia State, Brazil		3,239	0.13%
Nkomati	RSA		2,300	0.13%
Montcalm	Ontario, Canada	Glencore	1,179	0.61%
Karatungk (Kalatongke)	Xinjiang, China			1.30%
Total			703,545	0.81%

Cu-rich magmatic Ni-Cu-PGE deposits
Significant Producers



Cu-rich magmatic Ni-Cu-PGE deposits

Value from different metals



Ni-Cu Rich

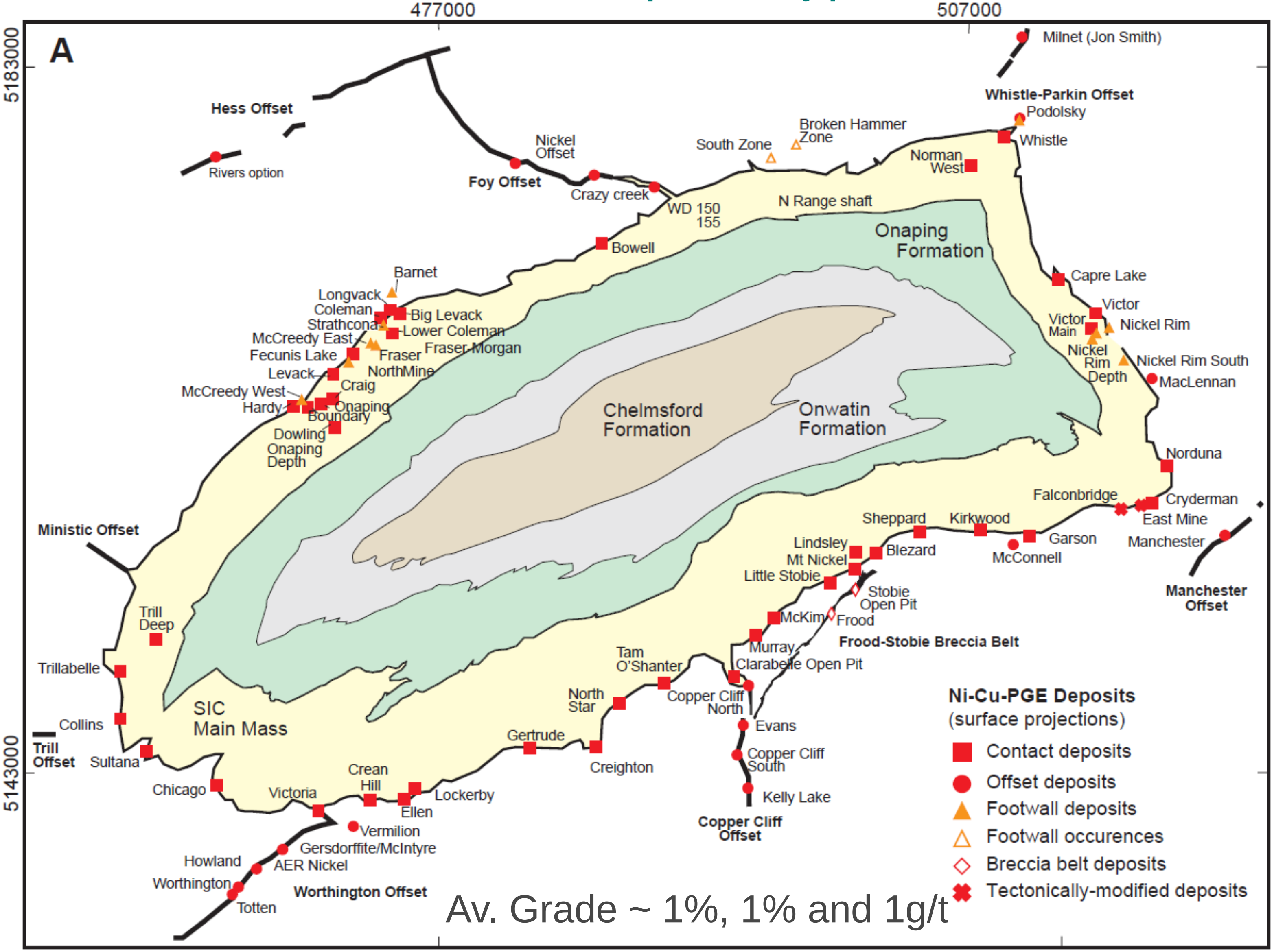
- **Y1** Yilgarn Komatiite Type I (W Australia)
- **Y2** Yilgarn Komatiite Type II (W Australia)
- **Z** Zimbabwe High-Grade
- **O1** Ontario Komatiite Type I
- **T** Thompson High-Grade (Manitoba)
- **R** Raglan (Nunavut)
- **N** Noril'sk (Russia)
- **D** Duluth (Minnesota)
- **J** Jinchuan (China)
- **S-P** Selibe-Phikwe (Botswana)
- **Ta** Tati (Botswana)
- **K** Kabanga (Tanzania)
- **Mo** Monchegorsk (Russia)
- **P** Pechenga (Russia)
- **V** Voisey's Bay (Labrador)
- **Mt** Montcalm (Ontario)
- **A** Aguablanca (Spain)
- **S** Sudbury (Ontario)
- **153** McCreedy East 153 Zone (Sudbury)
- **E** Eagle (Michigan)

PGE Rich

- **B** Total Bushveld (South Africa)
- **MR** MR - Merensky Reef (Bushveld)
- **U** UG-2 (Bushveld)
- **PR** Platreef (Bushveld)
- **GD** Great Dyke (Zimbabwe)
- **ST** Stillwater (Montana)
- **Po** Portimo Complex (Finland)
- **L** Lac des Iles (Ontario)

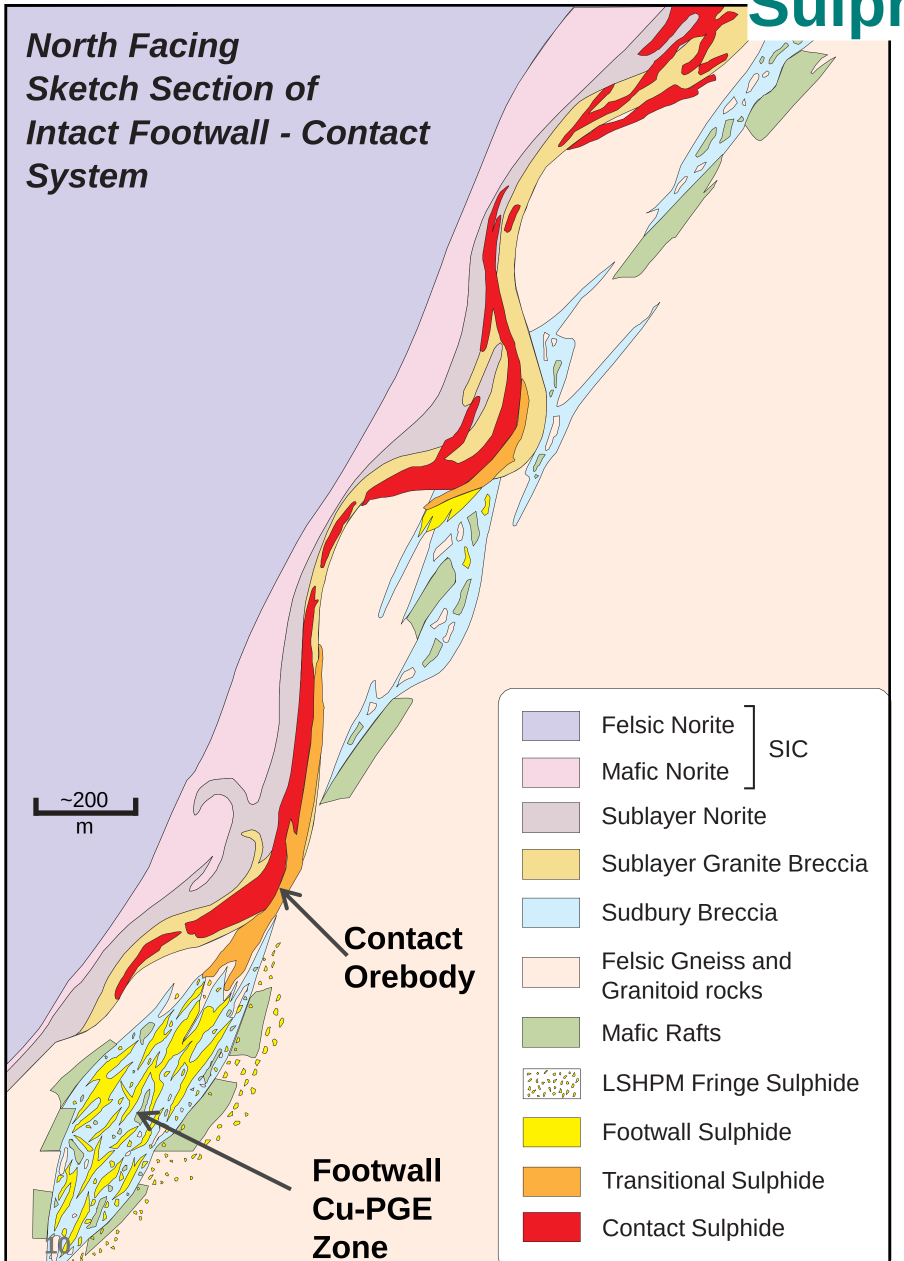
Sudbury Igneous Complex

Location of different Deposit Types



Av. Grade ~ 1%, 1% and 1g/t

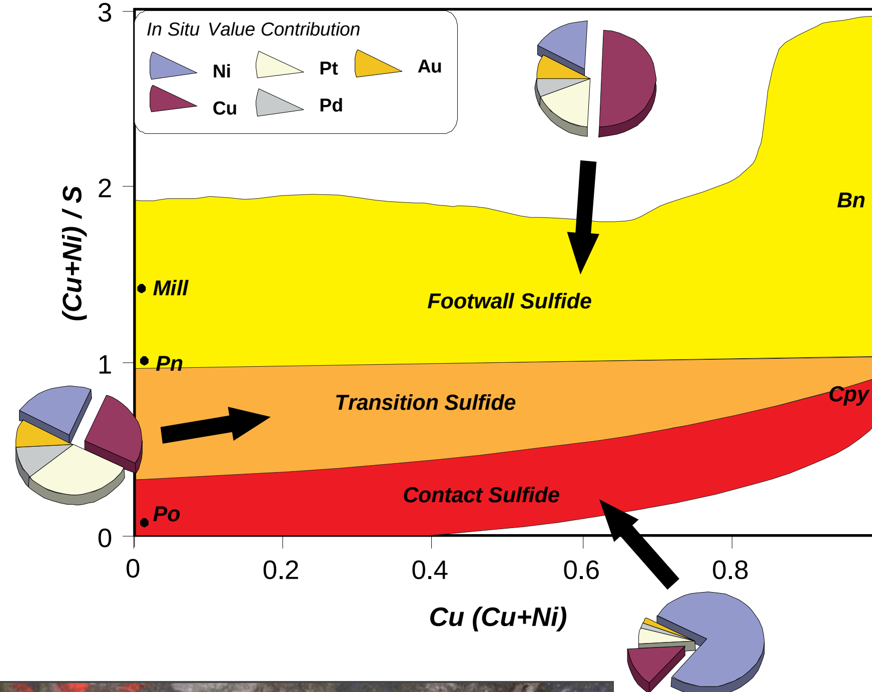
Sudbury Footwall Copper deposits Sulphide Fractional Crystallization

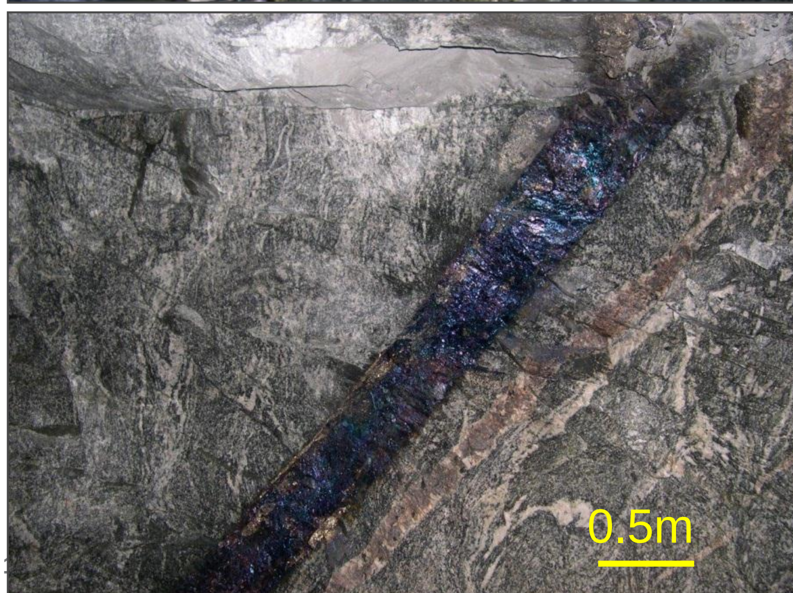


- Segregation of sulfide melt (1100°C) and Early crystallization of MSS
- Fractional crystallization of MSS
  → pyrrhotite rich cumulate (Ni)
  → Cu-rich residual (liquid) melt
  (Pd, Pt, Ag, Au, Bi etc. partition to late melt)
- Crystallization of ISS (→ cp ± pn)
- Late Cl-rich brines from the late-stage melt or from an exsolved magmatic fluid that remobilizes metals (Pt, Pd, Ag, Au, As, Bi, Te)

Sudbury Footwall Mineralization

Ore types in 153 ore body, Coleman mine





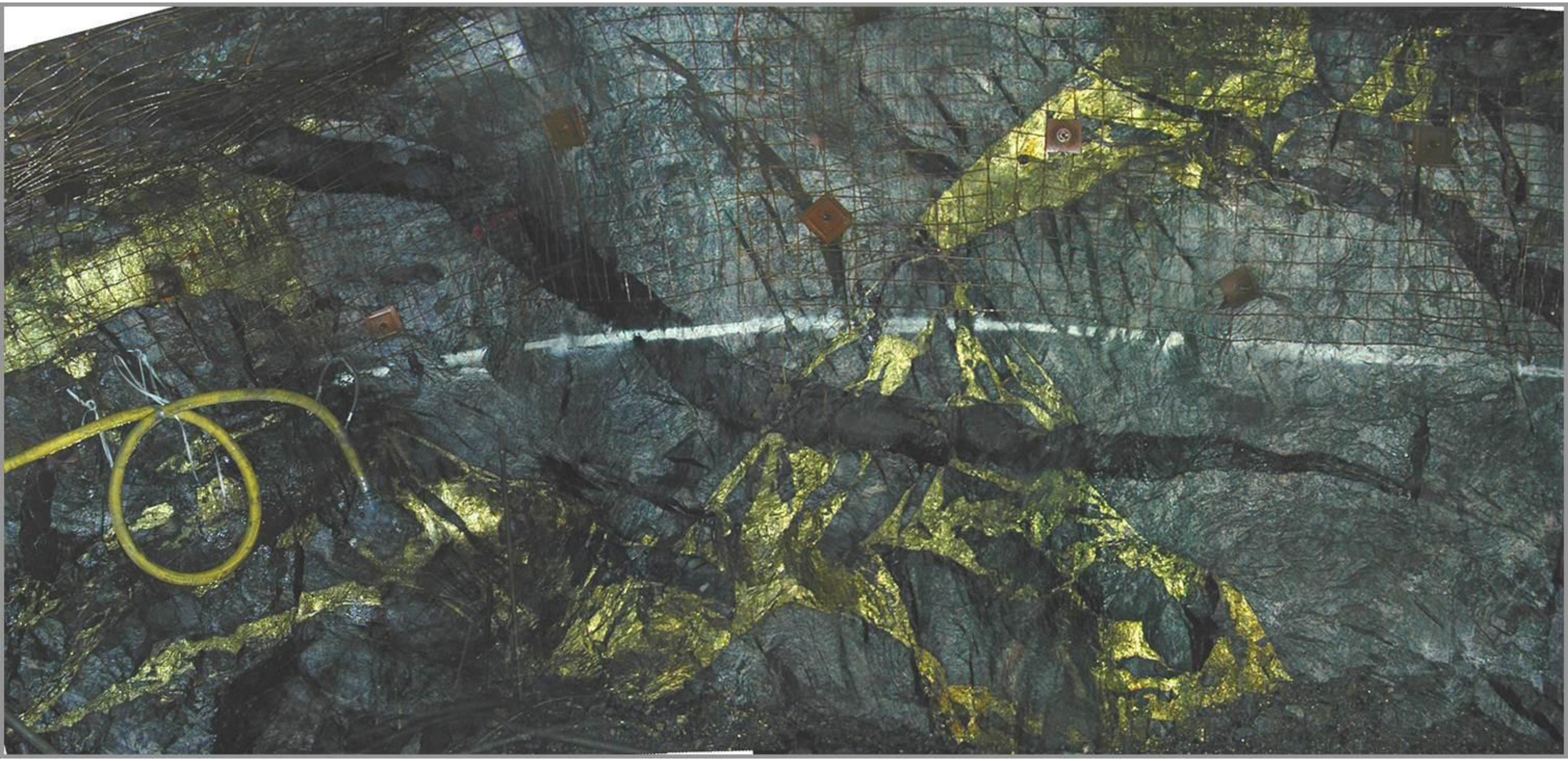
Sudbury Footwall Cooper mineralization

Chalcopyrite Vein, North zone, Norman property (KGHM)

Channel	Length Feet	Cu %	Ni %	TPM %	In Situ CDN$ / tonne
A	8.8	28.7	0.2	16.3	1,042.00
B	13.1	17.6	0.5	11.3	707.00
C	18.4	15.8	0.5	10.3	653.00

Sudbury Footwall Cooper mineralization

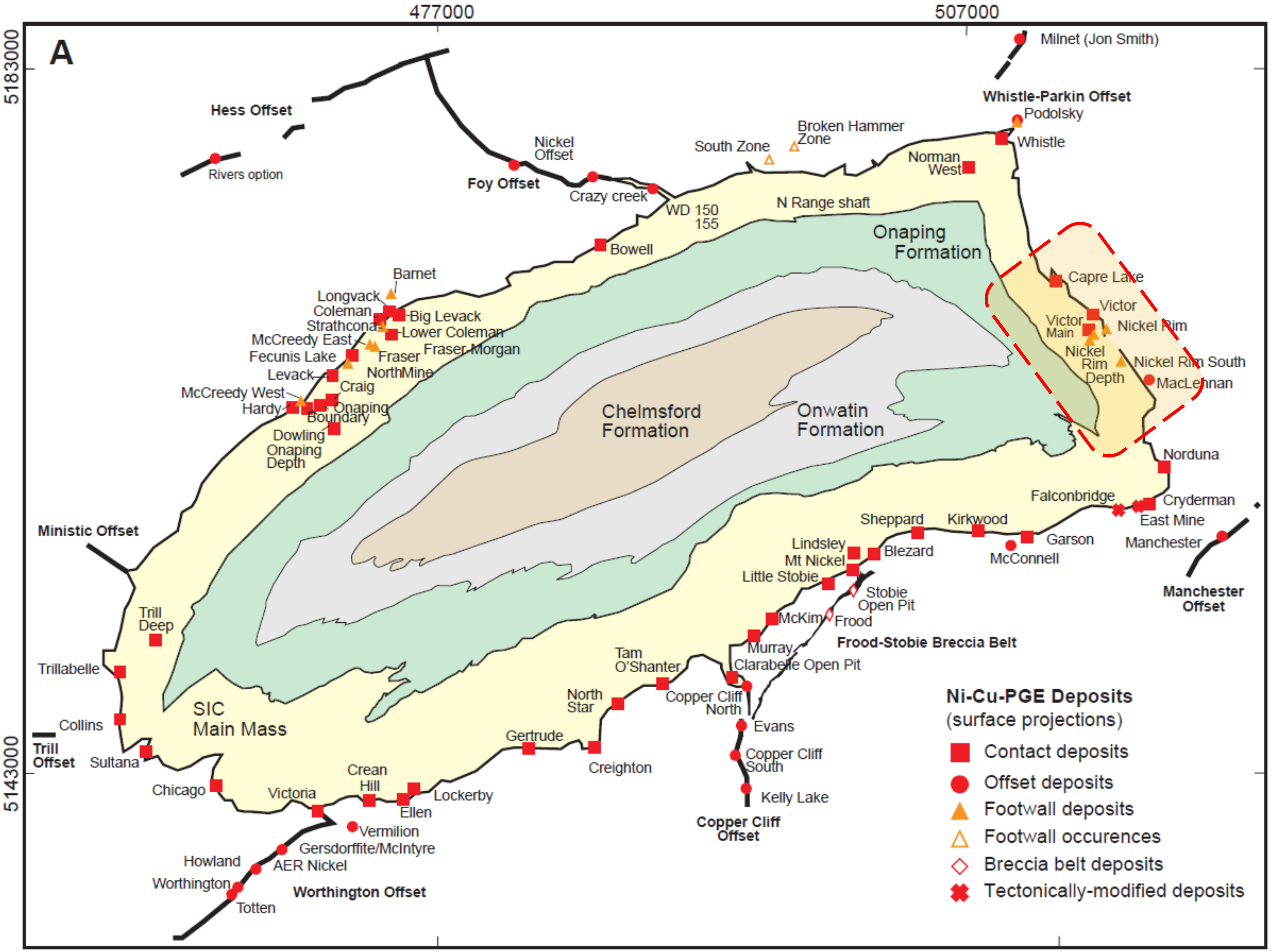
Irregular chalcopyrite-PGE veins in 153 Coleman ore body



VALE

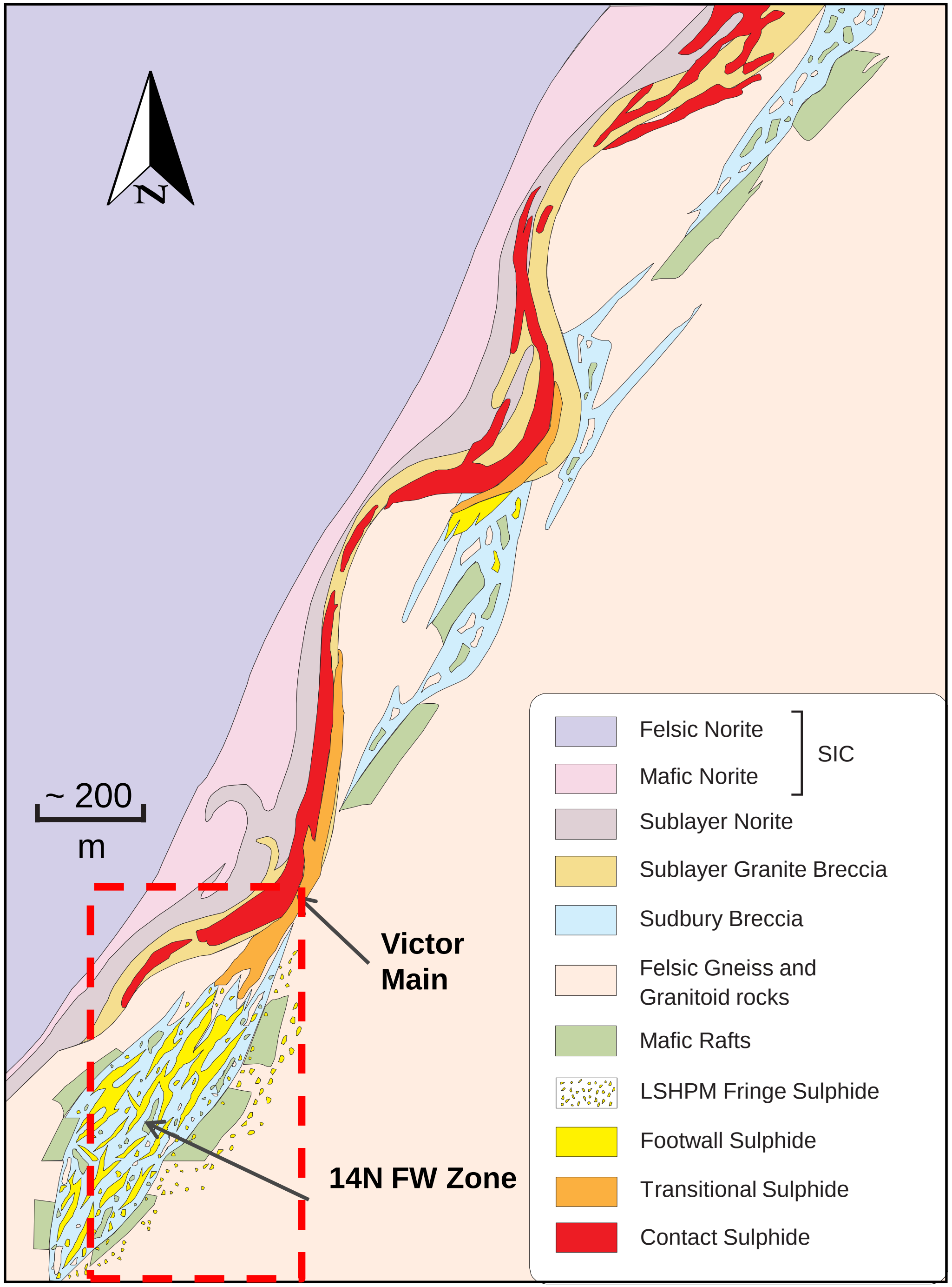
Sudbury Basin

Vale Exploration Results from Victor / Capre area



Victor Footwall and Contact Ore bodies

North facing sketch section



Old Victor BH1294240

Mineralization from 268.4 to 288 m

2.74% Ni, 1.68% Cu, 0.89 g/t TPM over 19.6m (core length)

Victor property

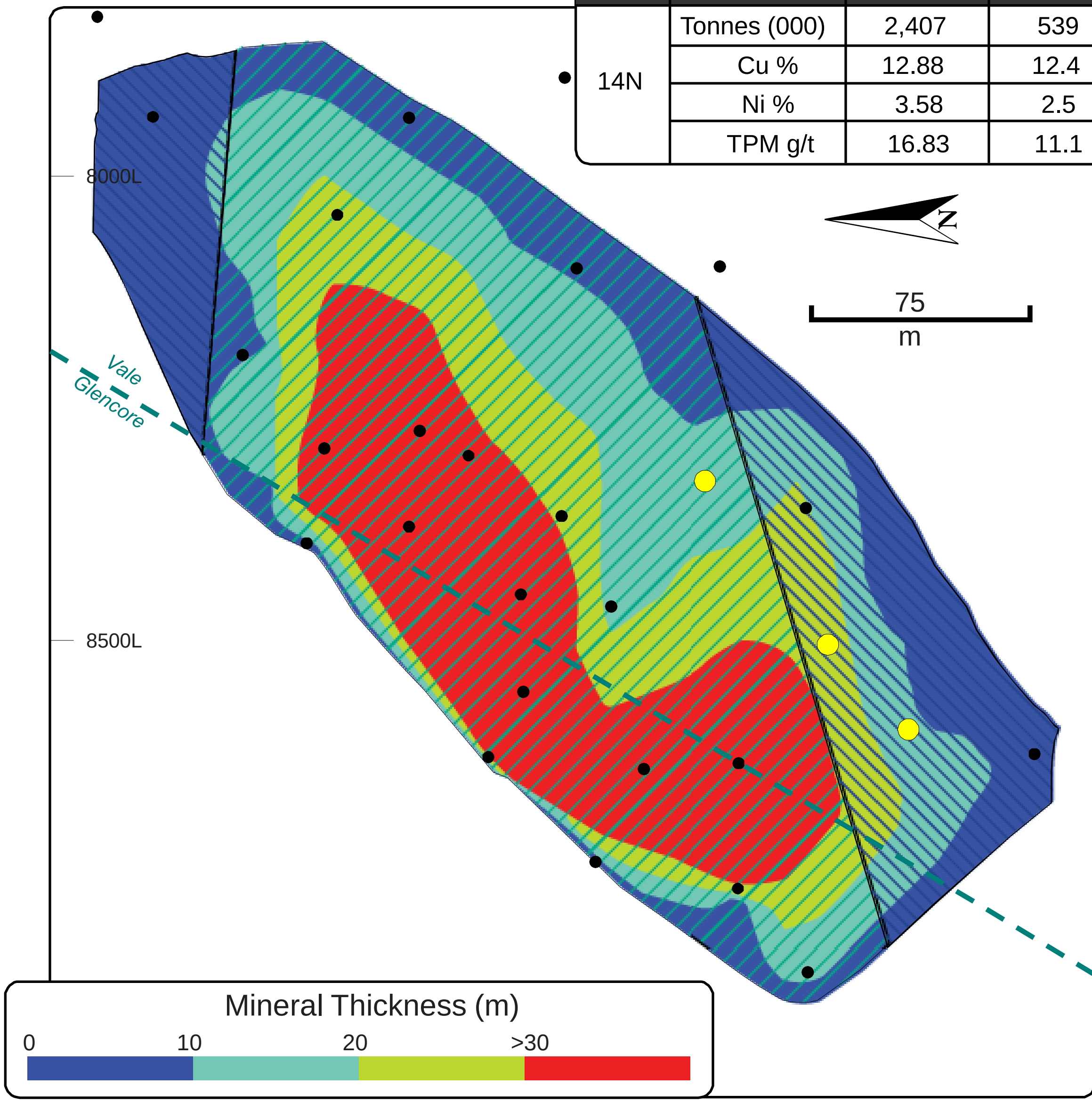
14N FW Zone Drill hole MAC091Q

Estimated 10 % Cu, 2 % Ni over 30.4 m starting at 840m

Victor Footwall 14N – Longitudinal (Looking East)

Contoured Ore Thickness

OB	Class	Indicated	Inferred
14N	Tonnes (000)	2,407	539
	Cu %	12.88	12.4
	Ni %	3.58	2.5
	TPM g/t	16.83	11.1



Victor Footwall Cu zone

BH MAC078F

VALE

Massive sulphide between 2533.9 - 2545.6m

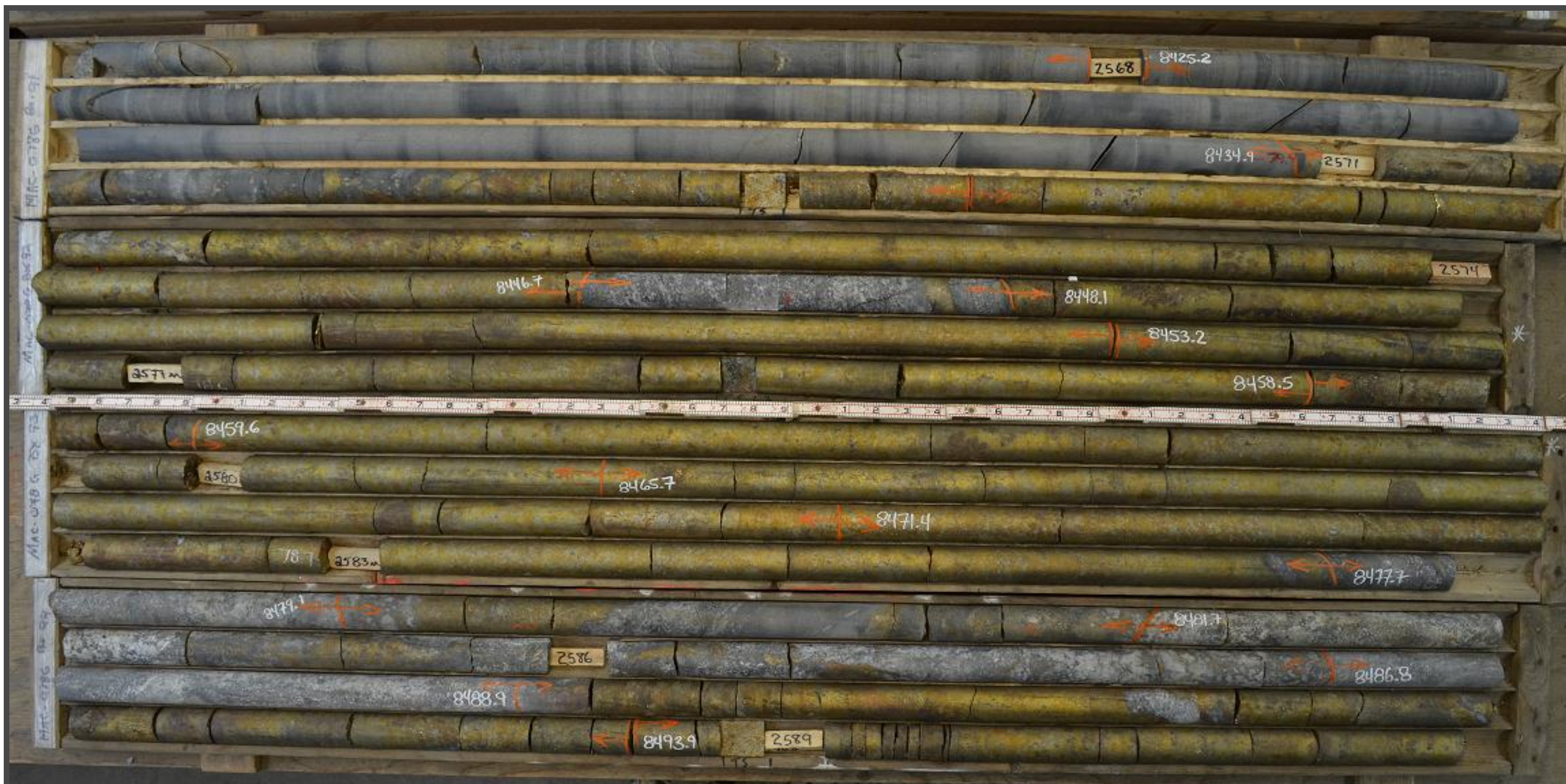
1.9 % Ni, 9.1% Cu, 7.8 g/t TPM over 46.4m
Including 4.9% Ni, 24.3% Cu, 20.8 g/t TPM over 11.7m (core length)

VALE

Victor Footwall Cu zone
BH MAC078G

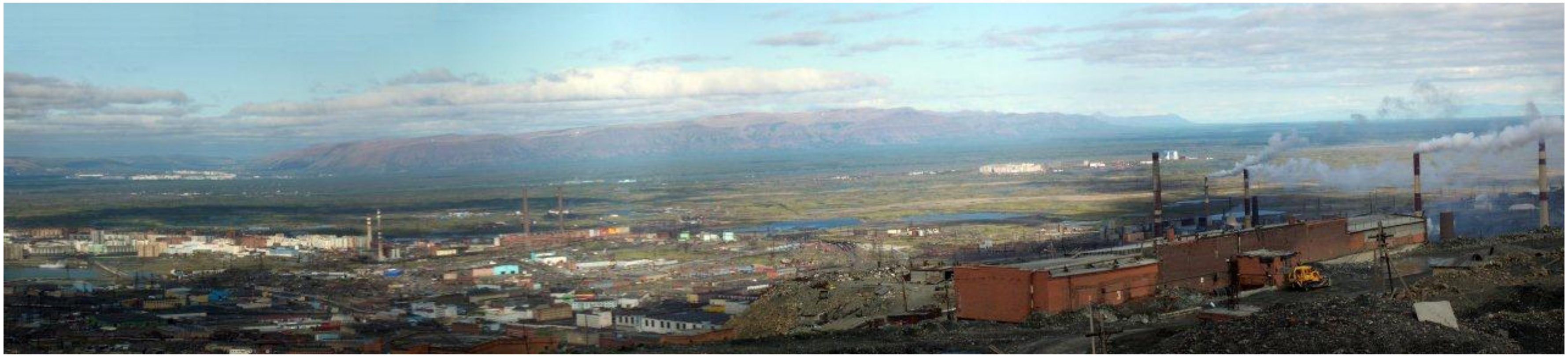
VALE

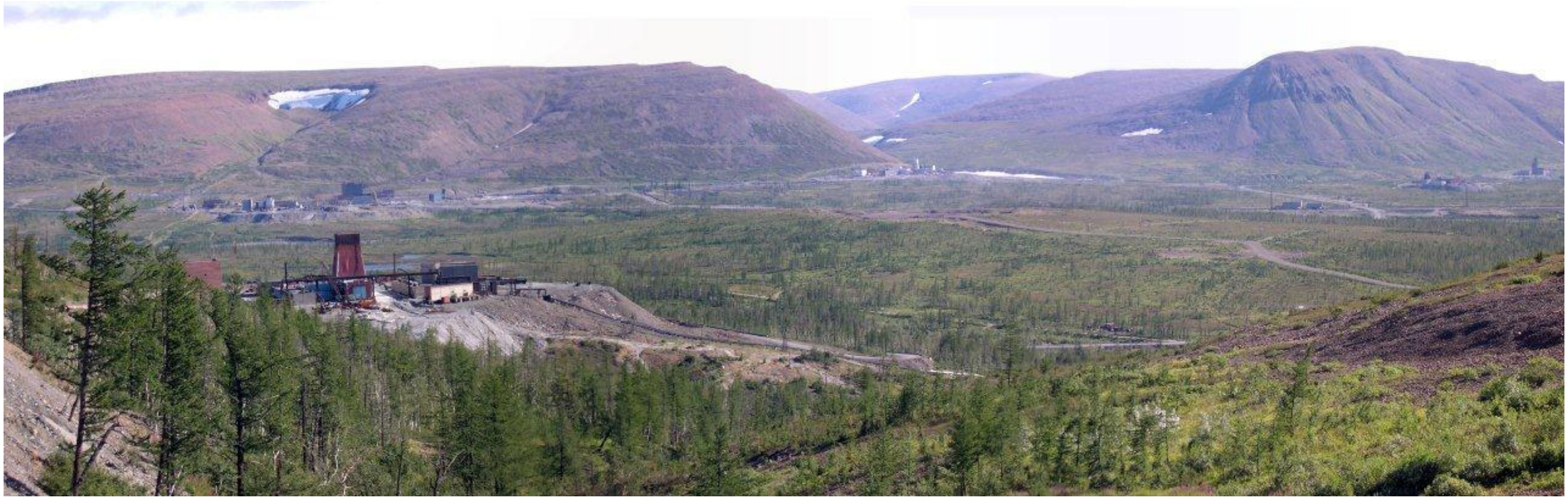
Mineralization between 2548.4 – 2631.7m
1.9 % Ni, 11.9 % Cu, 8 g/t TPM over 83.3m
Including 2.8% Ni, 26.1 % Cu, 15 g/t TPM over 13.1m (core length)



VALE

Noril'sk-Talnakh Area
Views towards Talnakh and Kharaelakh area

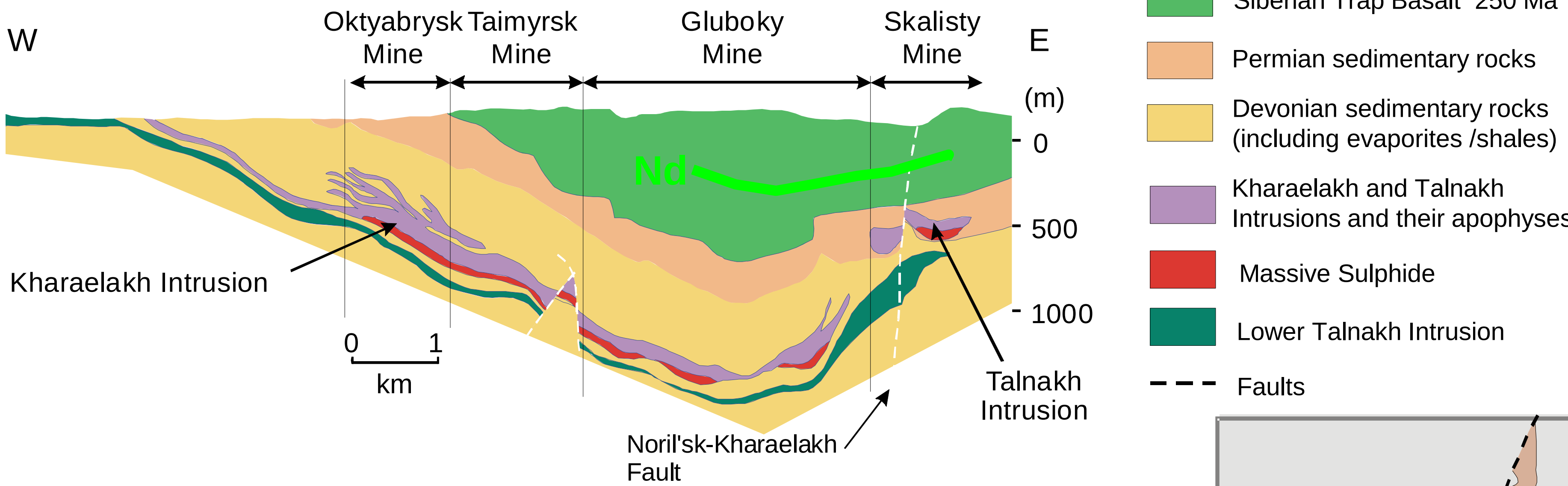


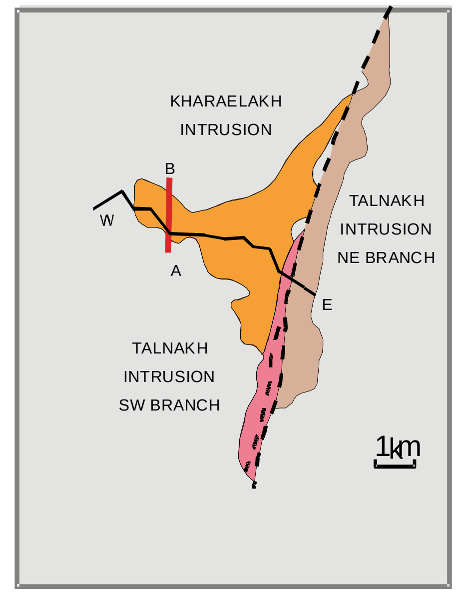


VALE

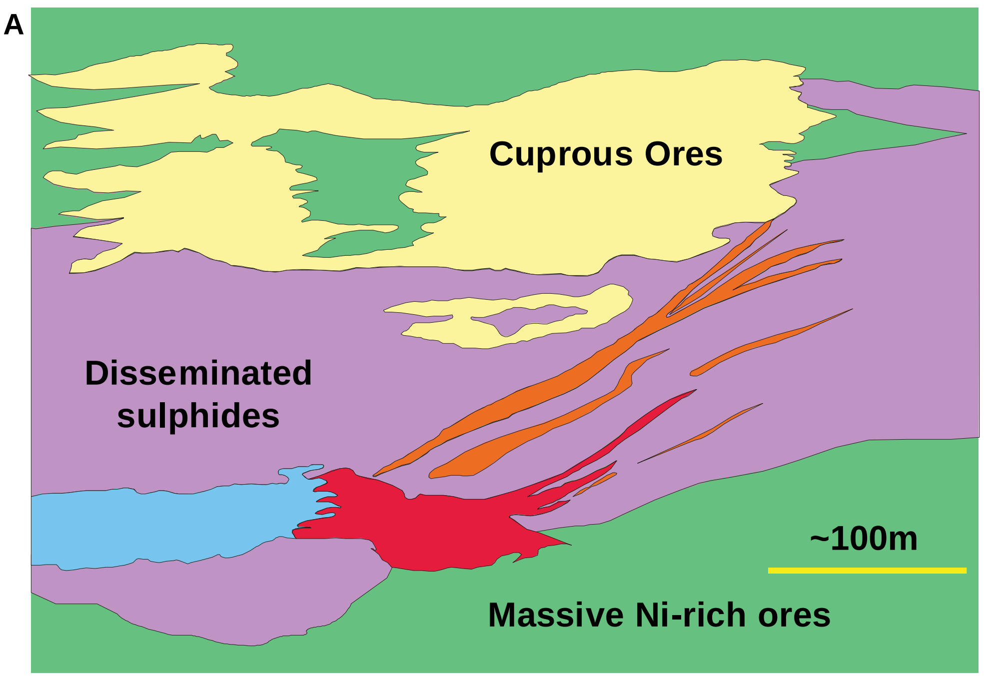
Kharaelakh and Talnakh Intrusions

After Naldrett et al. (1992)





West-facing Section through the Oktyabrsk Deposit



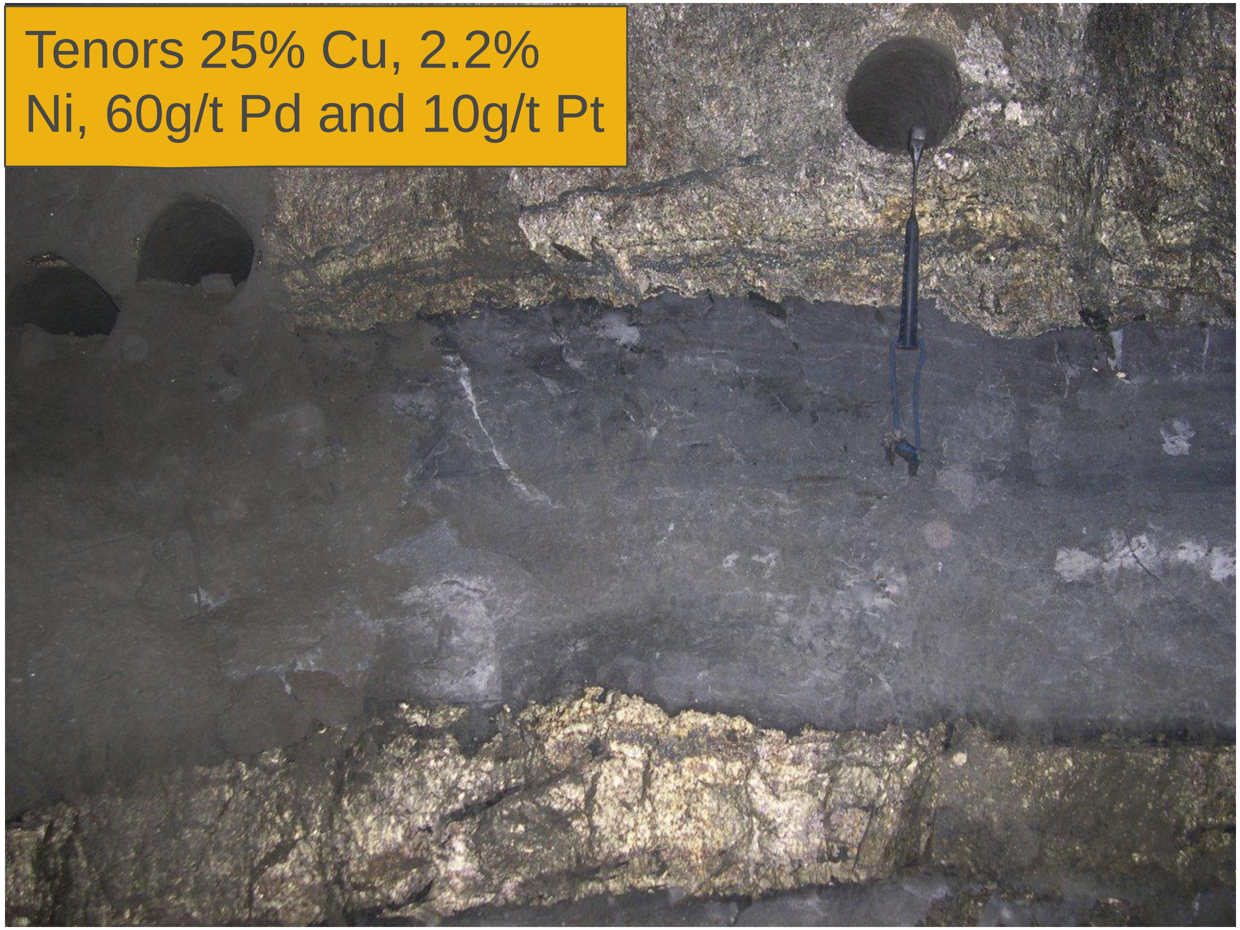
From Lightfoot & Zotov, 2006

Oktyabrsky deposit, 600L, Talnakh
Cubanite-mooihoekite-pentlandite basal ores

- Two different processes operating at Noril’sk

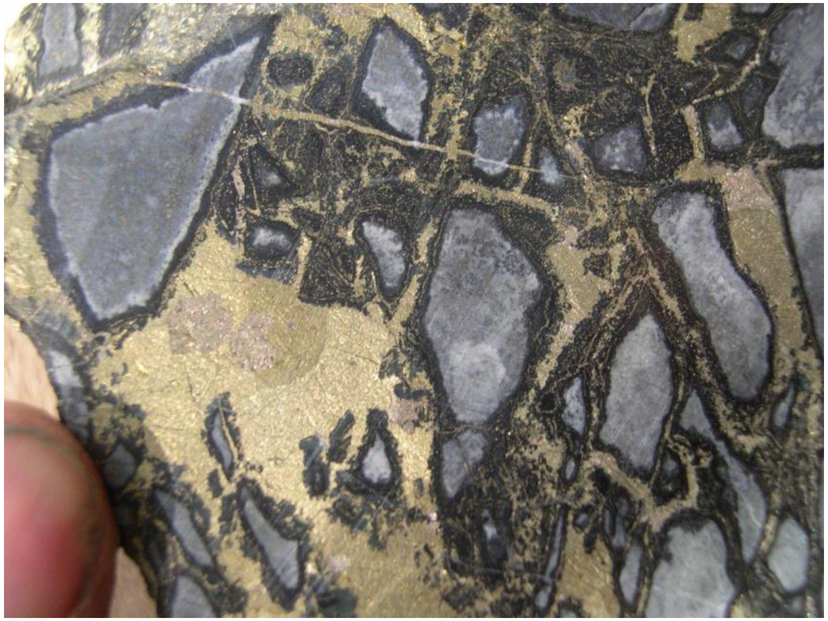
1. Very high R factors (early sulphides enriched in PGEs, Cu and Ni)

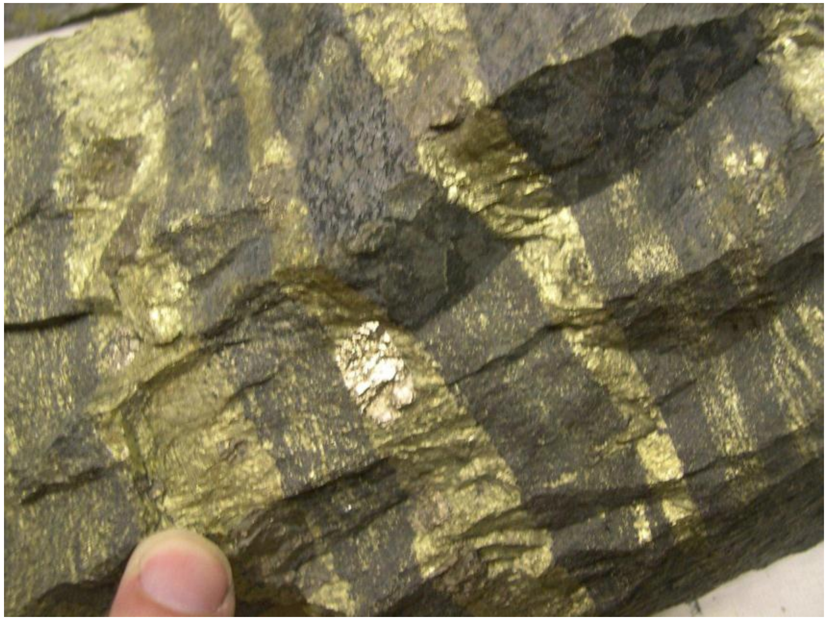
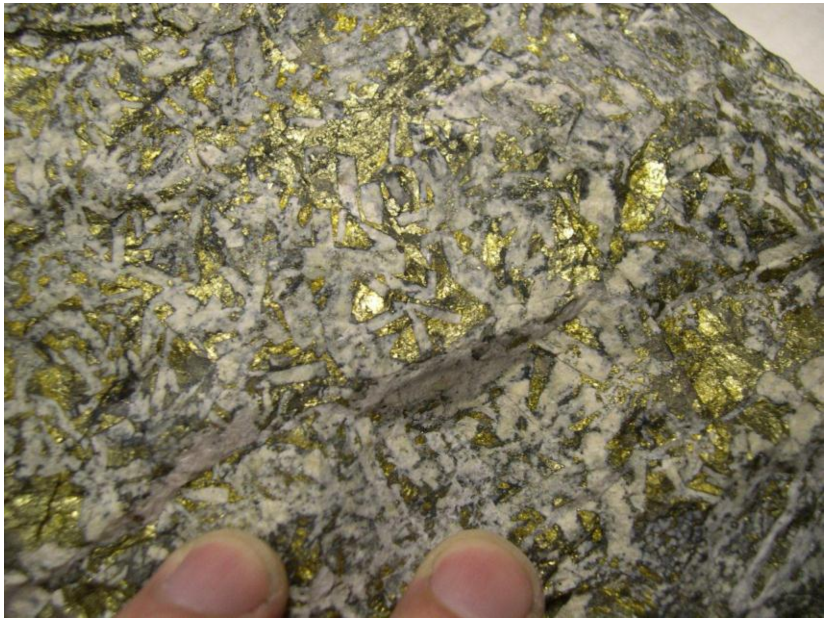
2. Late stage FC and fluid-assisted separation of Cu-PGEs (esp. Pd) into higher “Cuprous” zones



VALE

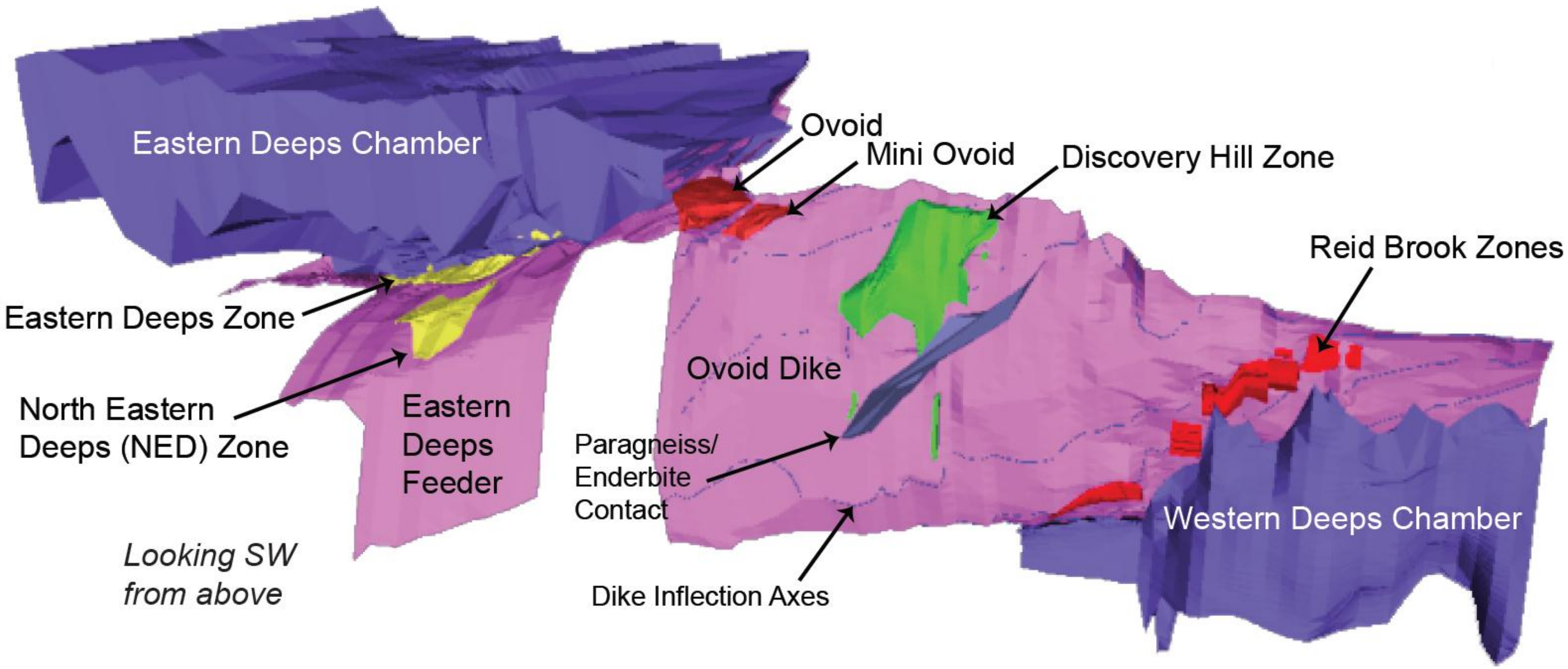
Cuprous replacement ores from Komsomolsky deposit



Vale's Voisey's Bay Deposit, Labrador

3D representation of VB conduit system (5km) looking SW

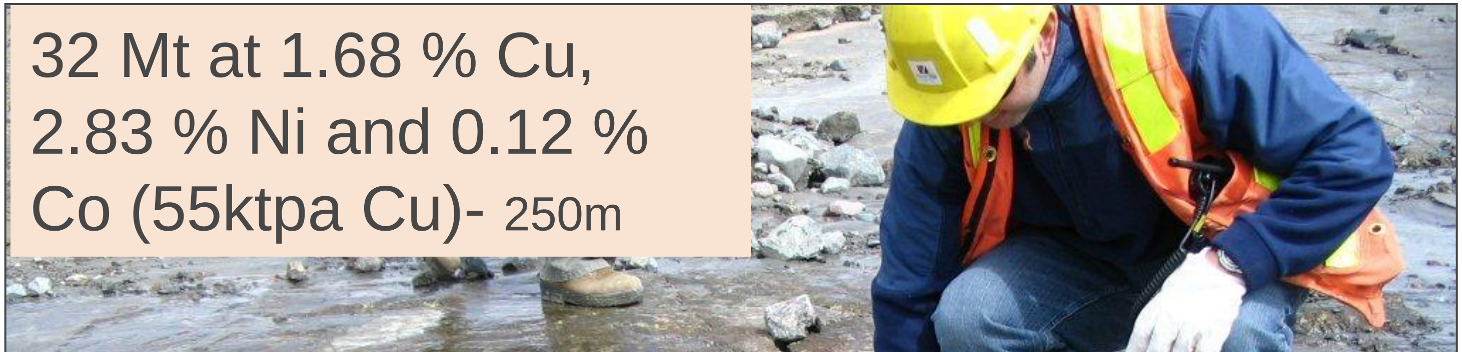


- Associated with troctolites (olivine gabbro) part of 1.34 Ga anorthositic Nain Plutonic Suite straddling a 1.8 Ga suture
- Sulphides moved up series of conduit dikes from a series of "staging chambers"- Cu enriched, PGE-depleted

Voisey's Bay Deposit, Labrador

Glacially-polished massive sulphides prior to mining

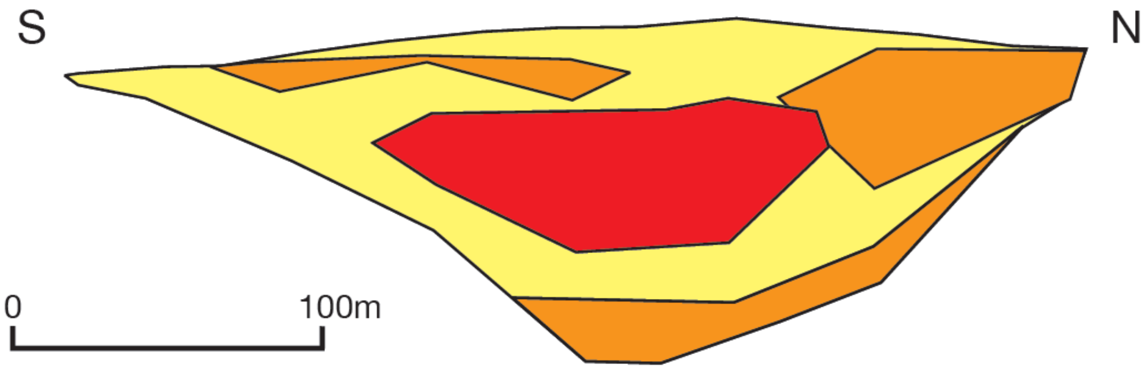
32 Mt at 1.68 % Cu, 2.83 % Ni and 0.12 % Co (55ktpa Cu)- 250m



VALE

Voisey's Bay Ovoid zone

Mineralogical and chemical zonation

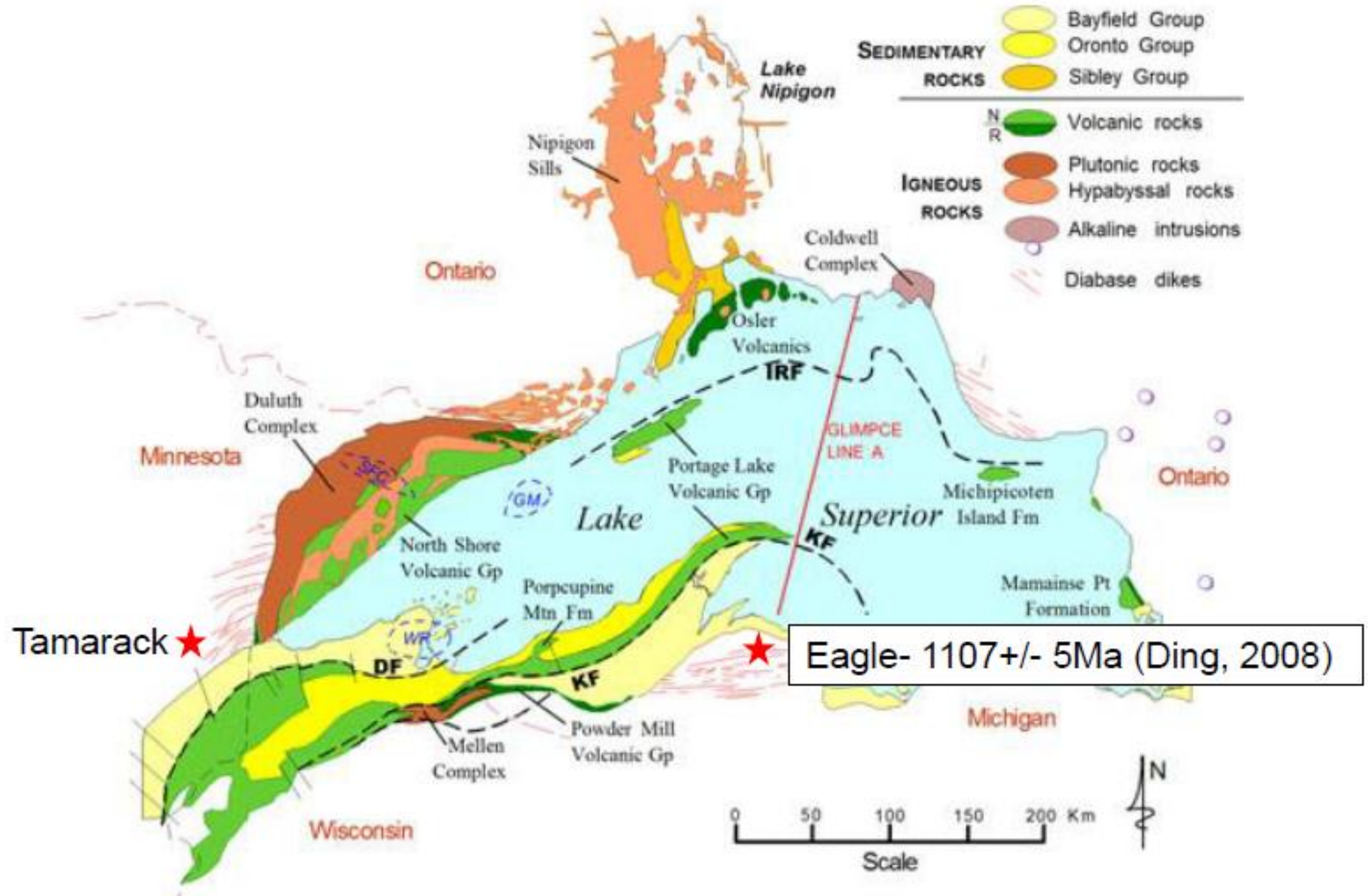


	Type	%Po	%Ccp-Cb	%Pn	%Mag	Pt	Pd	Zn	Pb
(orange)	III	70-90	1-6	10.5-11.5	0-15	lowest	moderate	low	low
(yellow)	II	60-75	>9	11.5-13.5	5-15	gradational	highest	highest	low
(red)	I	50-65	5-9	10.5-11.5	15-35	highest	moderate	low*	highest**

**except in centre of this zone where it increases* ***except in centre of this zone where it is low*

- Ovoid broadly zones towards a upper central core with elevated Cu (with cubanite), Pt-Pd, Pb and Ag
- No major segregation of Cu-rich residual sulphide melts

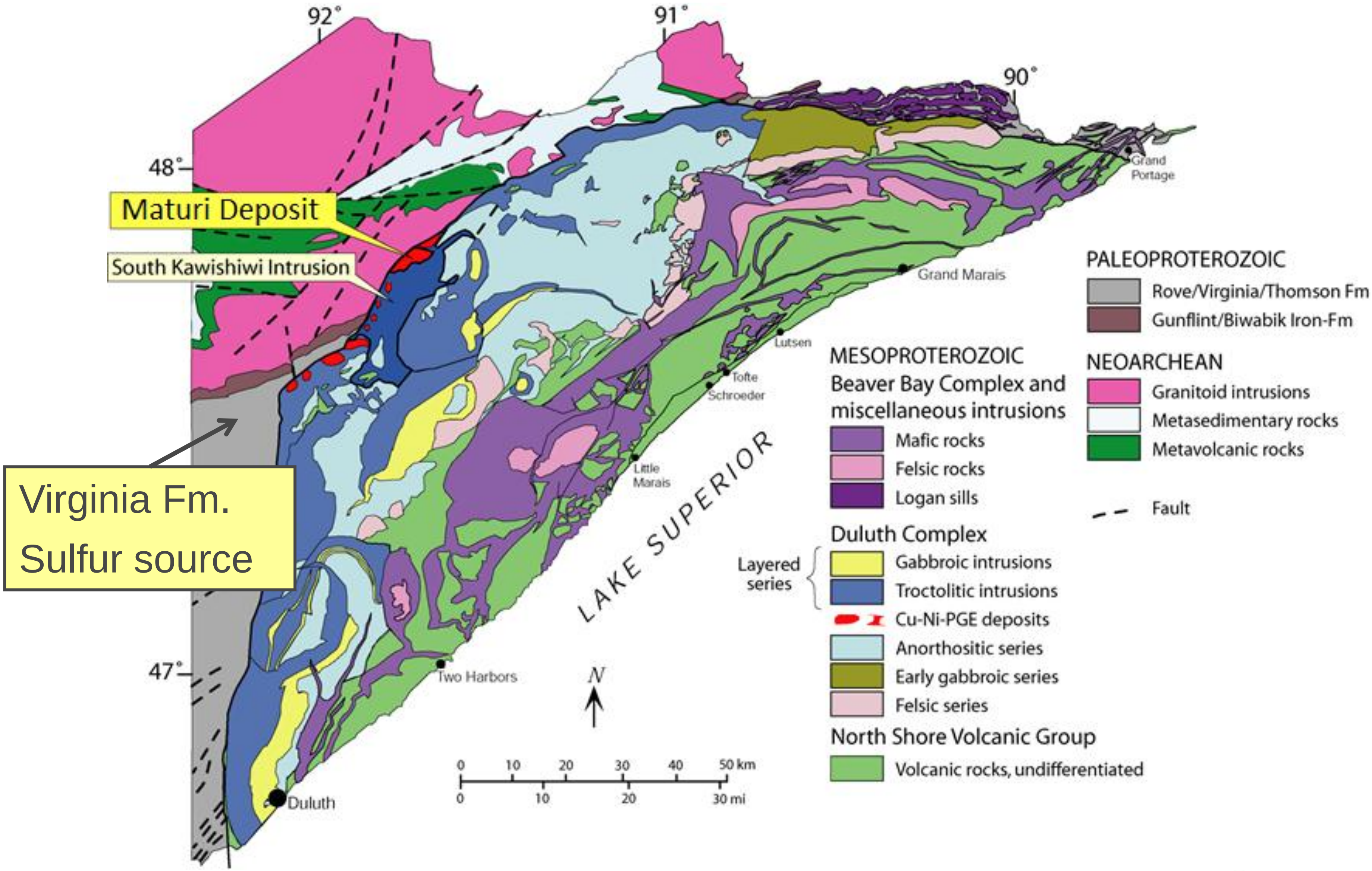
Mid Continental Rift (MCR)- Keeweenawan
Location and Geological setting



Modified from: Goldner (2011)

VALE

Duluth Complex, Minnesota
Geology Map



Duluth Complex Mineralization

- Over **4.4 Billion tonnes** of diss. Ni-Cu-PGE mineralization at ~0.6% Cu and 0.2% Ni
- 12 major deposits close to the basal contacts over 55 km in basal troctolites
- Nokomis, Maturi, Birch Lake, and Dunka Pit deposits in the South Kawishiwi intrusion
- Mesaba and NorthMet deposits in the Partridge River intrusion

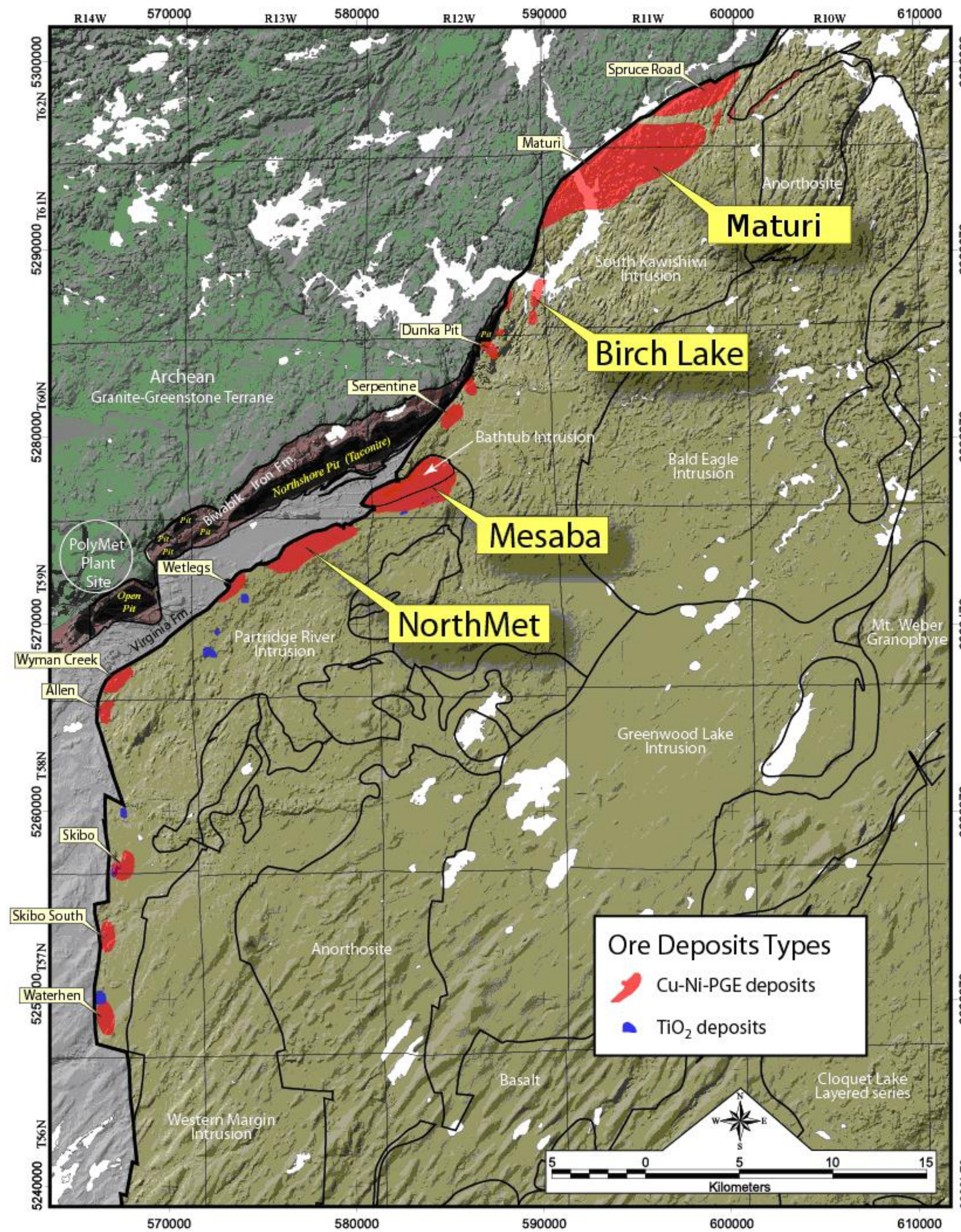


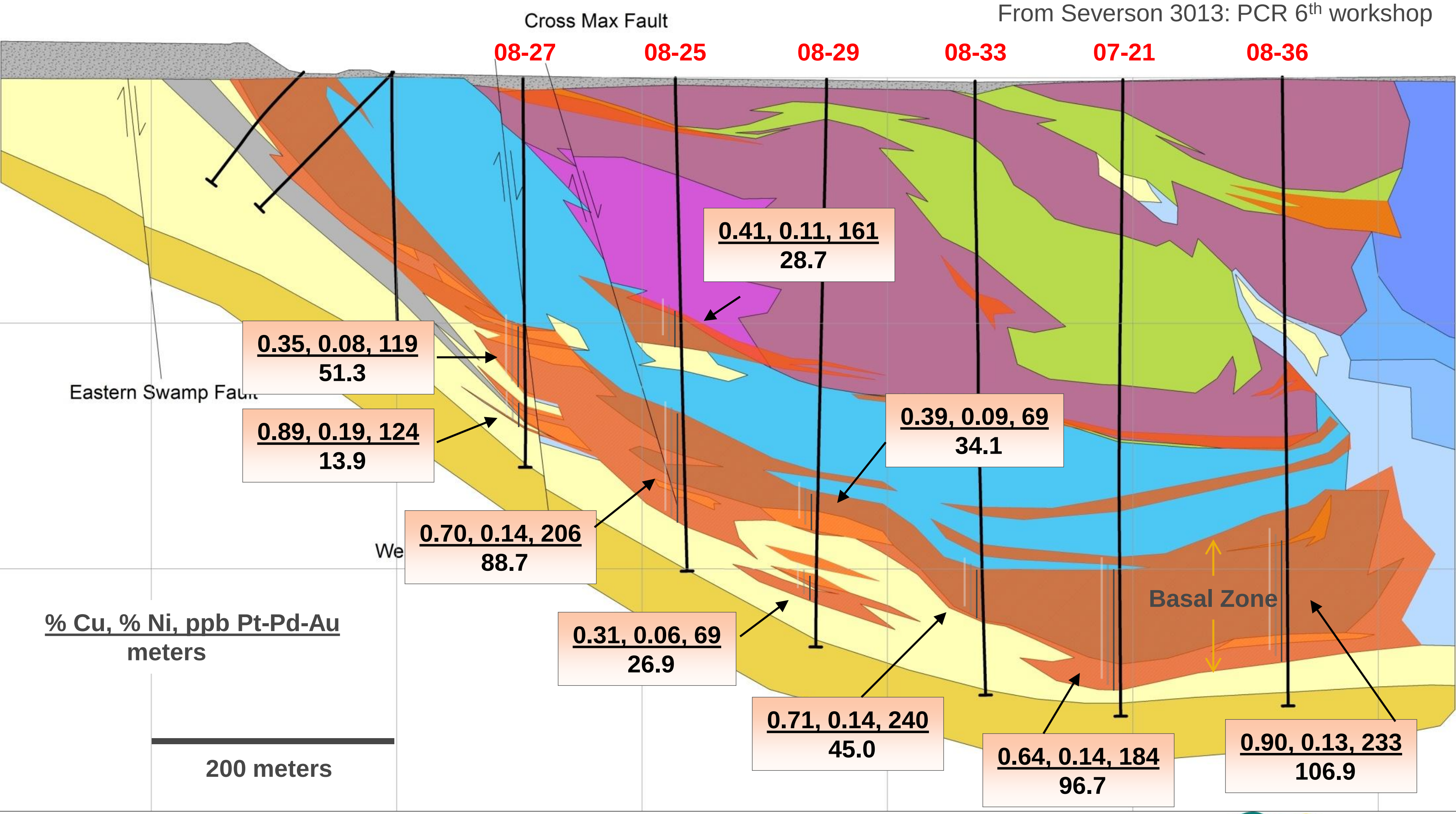
Image from Jim Miller presentation at PCR 6th workshop, 2013

VALE

Mesaba Deposit (Teck)

Section L 3600 West looking ENE showing mineralization

From Severson 3013: PCR 6th workshop

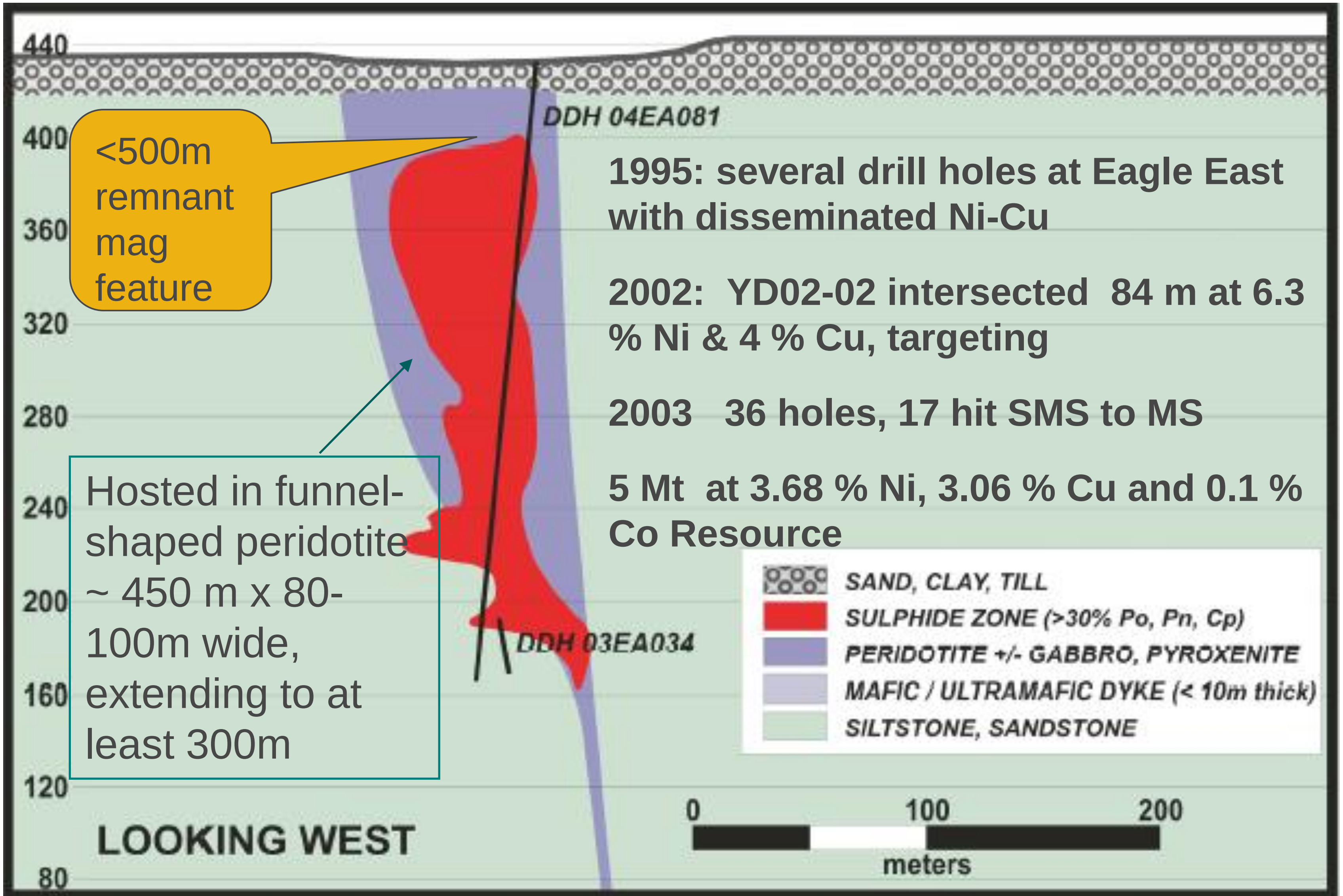


Mesaba Deposit (Teck)

Typical coarse disseminated mineralization

- Immense Resource; processing issues; potential hydromet. options
- Teck, Antofagasta, Glencore all involved trying to optimize recovery

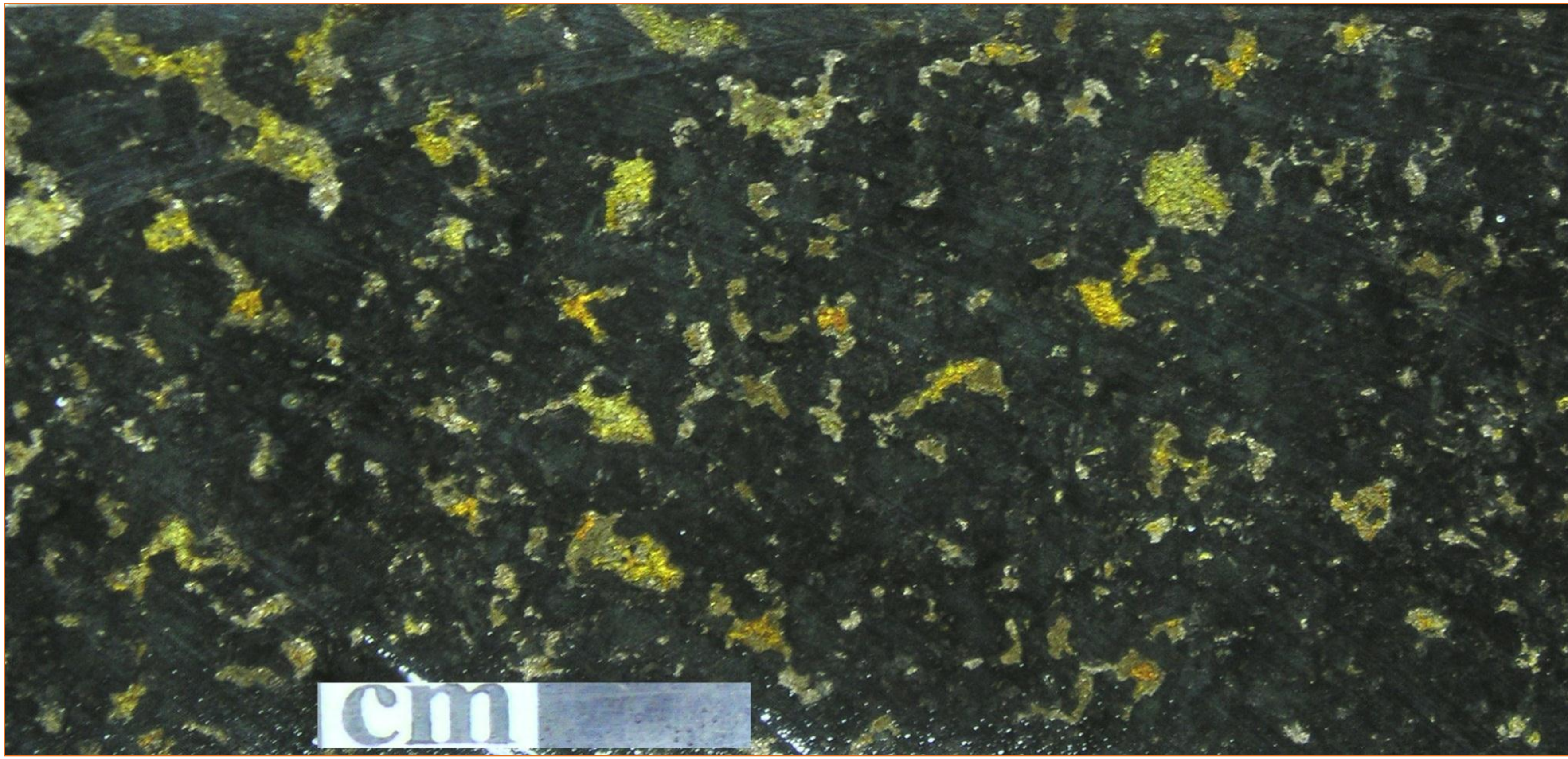
Eagle deposit, Michigan
Western section through deposit



From Rossell, PRC Cu-Ni workshop, Duluth, Oct. 2013; Ding et al., 2011

VALE

Eagle deposit, Michigan
Cu-rich net-textured sulphides



DDH 03EA-034, 220.7m: 0.41% Cu, 0.75 % Ni, 3.16% S

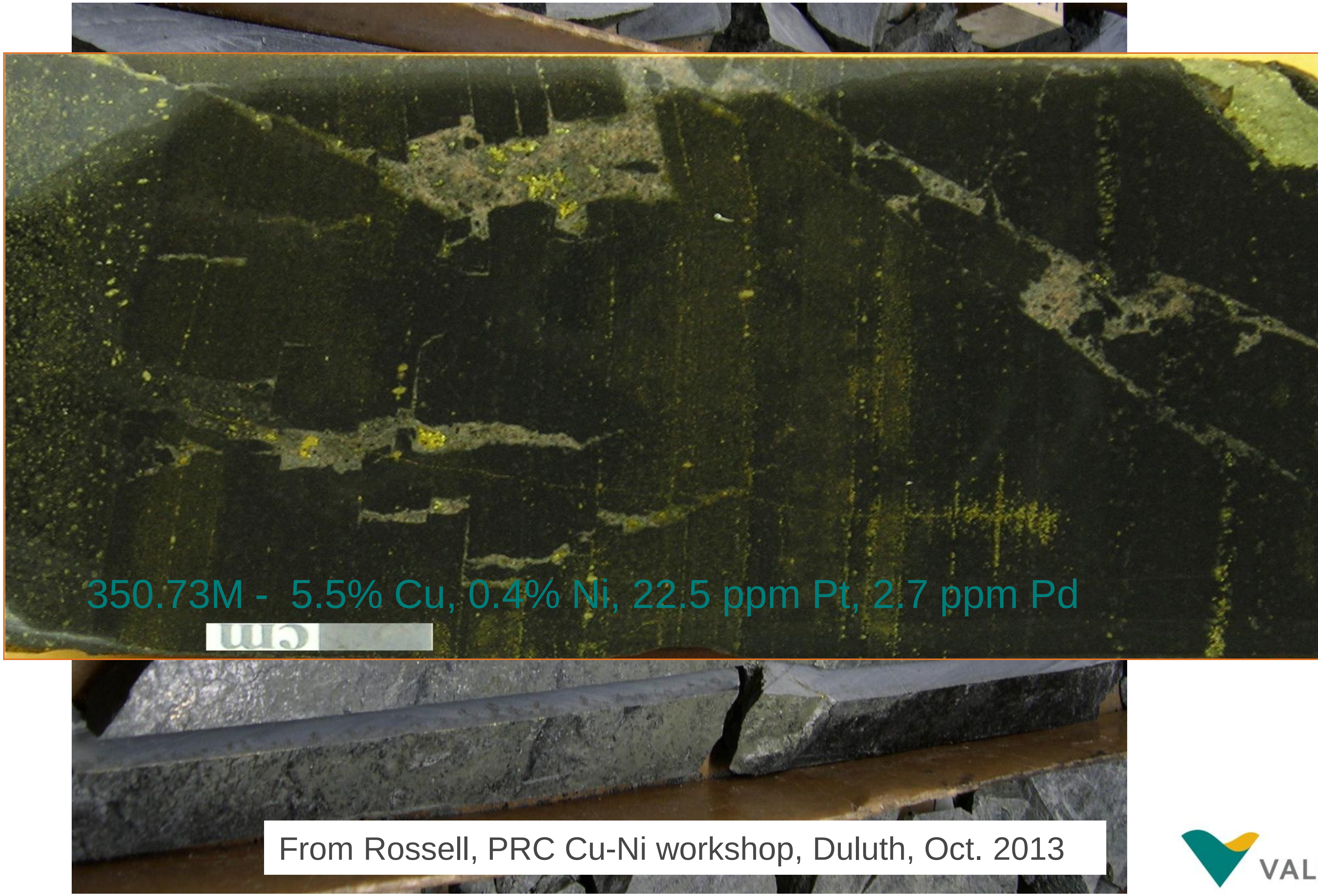
From Rossell, PRC Cu-Ni workshop, Duluth, Oct. 2013

Eagle deposit, Michigan

Cu-poor (lower) and Cu-rich massive sulphides

Eagle deposit, Michigan

Chalcopyrite veinlets in footwall sediments in 03EA-030,



From Rossell, PRC Cu-Ni workshop, Duluth, Oct. 2013

VALE

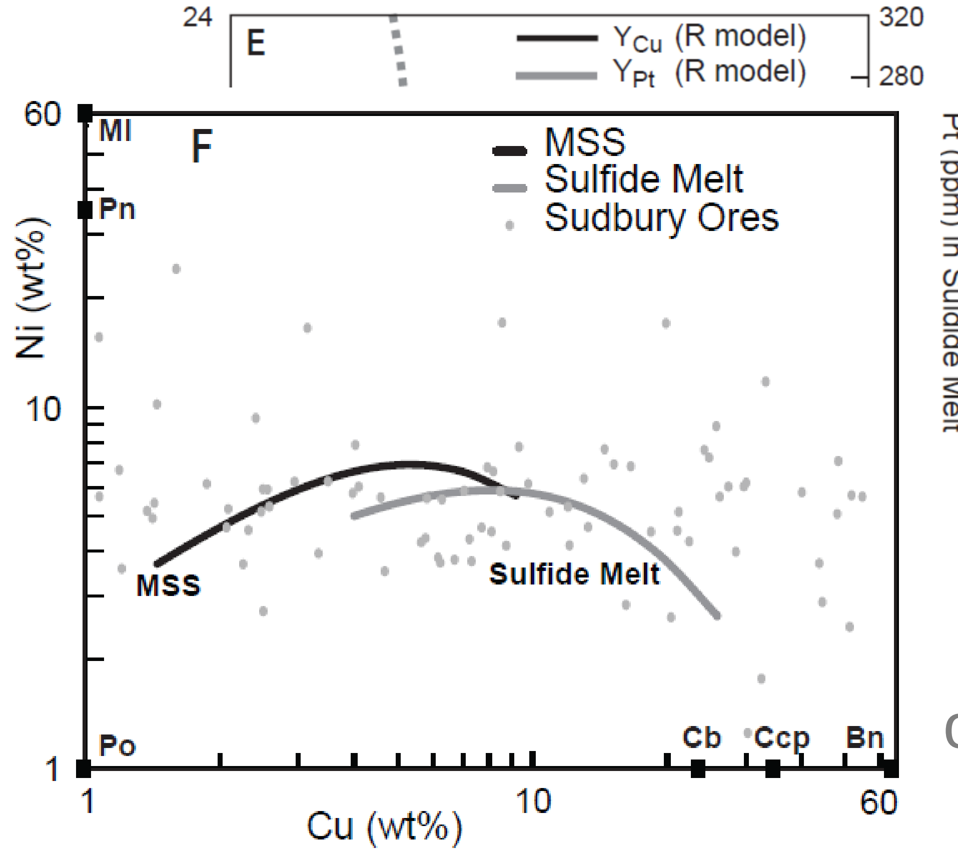
Why are some magmatic deposits richer in copper than others?

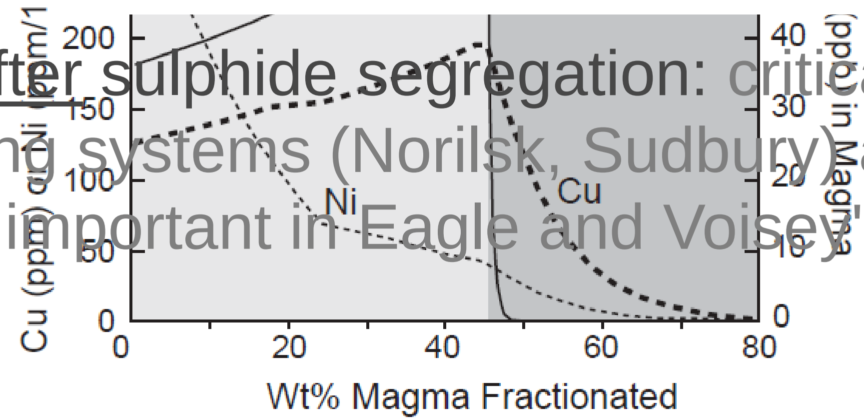
1. Partial Melting P
   of pyroxenitc sou
   component from

2. FC <u>prior</u> to sulphi
   magmas (gabrro)
   sulphide saturati

3. Silicate-sulphide
   volumes of magm
   sulphides result i ... of

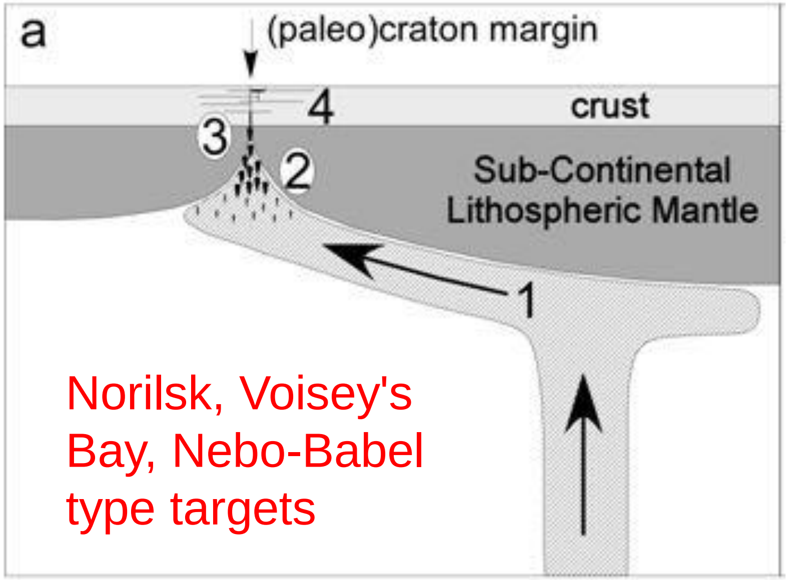
4. FC of MSS <u>after</u> sulphide segregation: critical in hot, slowing cooling systems (Norilsk, Sudbury) and to lesser extent important in Eagle and Voisey's Bay





VALE

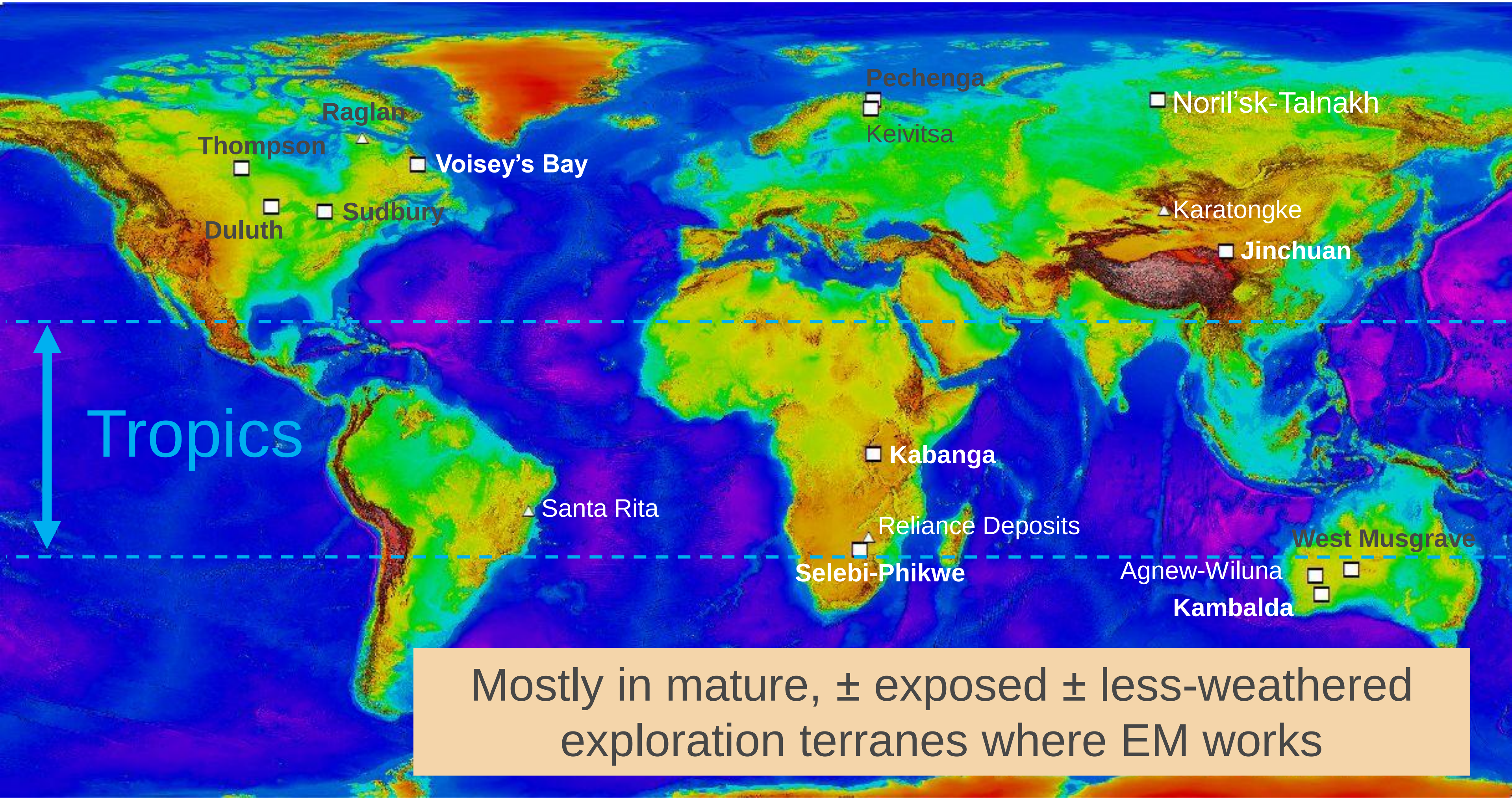
Magmatic Ni-Cu-PGE deposits
Cu-rich varieties related to Low MgO (Mafic) intrusions



1. Mantle **plume** impact and flow towards areas of thinner lithosphere
2. Decompression melting of plume at shallower levels- **LIP**
3. Transfer of melts into the (upper) crustal environment via **trans-lithospheric faults at terrane boundaries** and an interconnected **intrusion-sills networks**
4. Variable interaction of melts with crust
5. Nickel sulphide segregation and accumulation

- **Small** intrusions (chonoliths) with ferropicritic and/or gabbroic compositions-often not magnetic
- Must be at right erosional level, or use **EM** to look beneath volcanic cover and/or look for metal depletion/contamination in coeval volcanics
- **Surficial geochemistry** effective but small footprint- pay attention to Cu + PGE anomalies (rather than Ni that reflects MUM intrusion)

Distribution of larger Ni-Cu-PGE deposits and camps
Paucity in Brazil

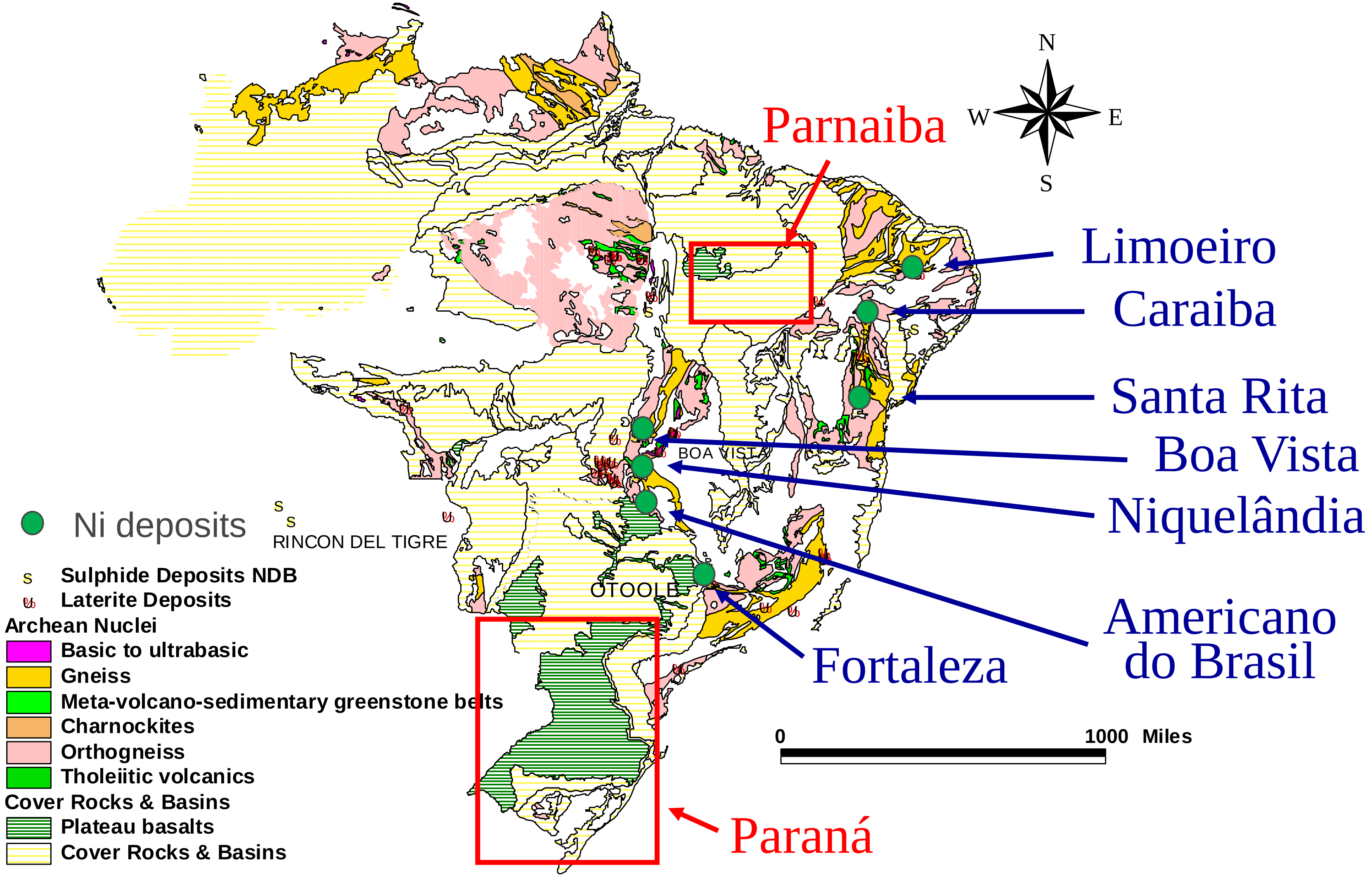


- Santa Rita only large Ni-Cu deposits currently known in Brazil

VALE

Magmatic Ni-Cu-PGE deposits in Brasil

A few potential exploration areas



Paraná (and Parnaiba) Basins

- 120 Ma CAMP LIP related to formation of central Atlantic ocean
- Flood basalts cover ~ 1.4 million km^2 in southern Brasil; average thickness 500 m in series of sub-basins (high R factor, dynamic conduits)
- Flood basalts overlying sediments with potential sulphur sources (S-sat.)
- MgO-rich sills known (e.g. Lomba Grande), lots of available regional data

VALE

Thank you

David Burrows
Chief Geologist Copper and Nickel

Global Exploration DIPM

Email: david.burrows@vale.com

VALE

For a world with new values.