Exploration 2007, Toronto
Workshop 3: Indicator Mineral Methods
in Mineral Exploration

Viable indicators in surficial sediments for two major base metal deposit types: Ni-Cu-PGE and porphyry Cu

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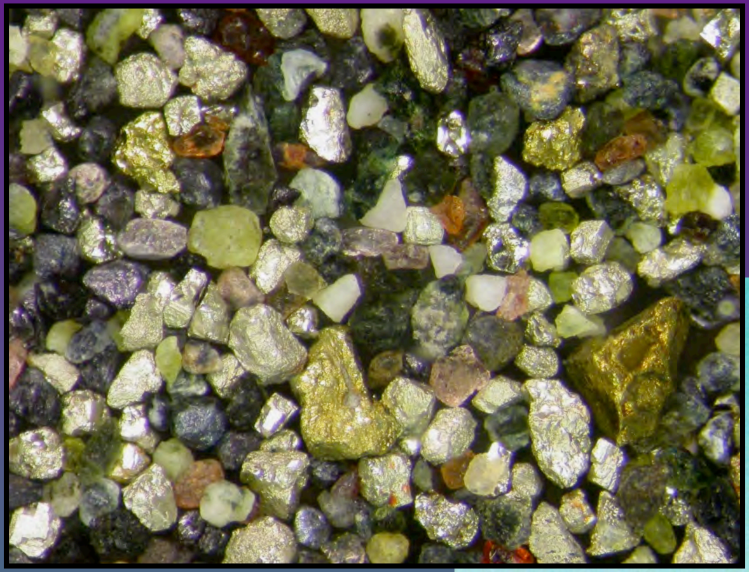
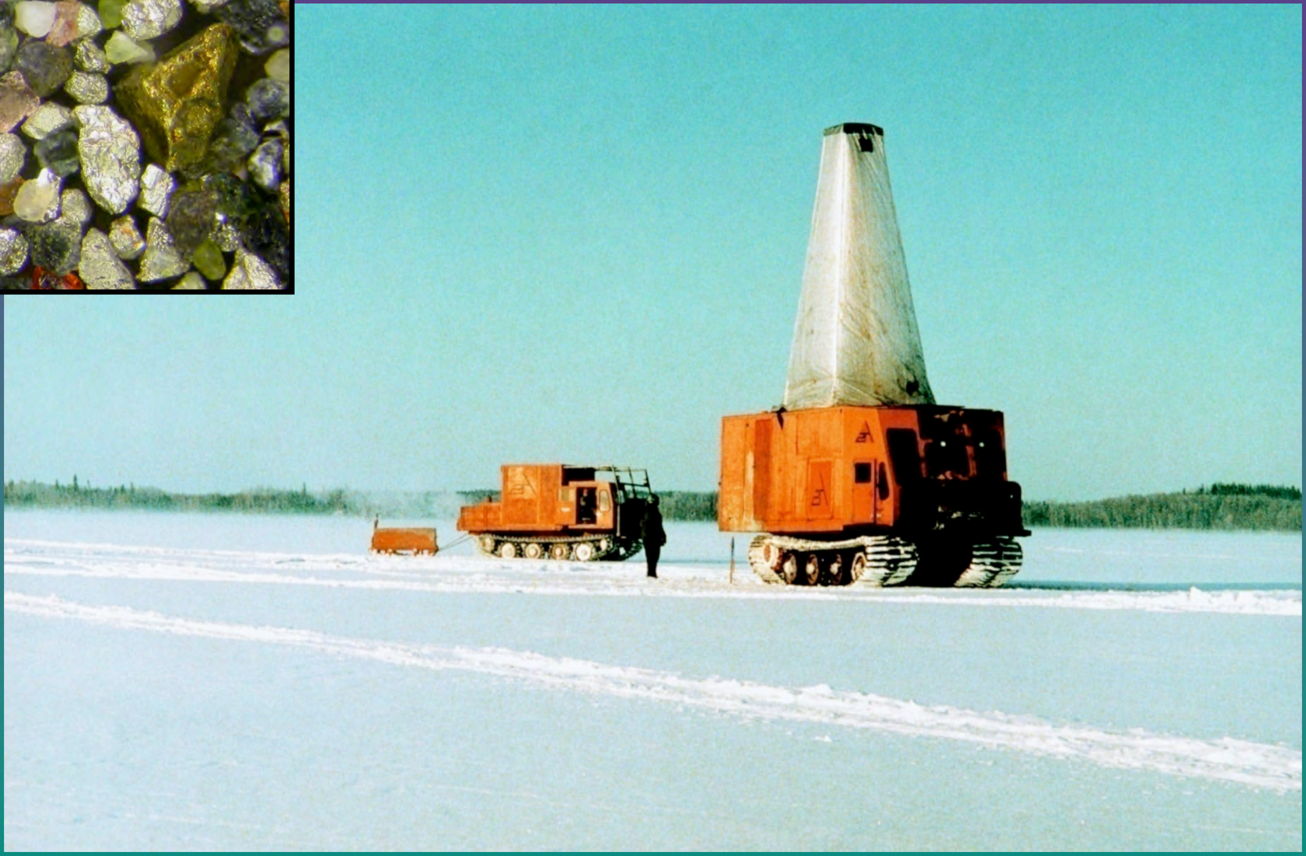
September 09, 2007

Properties of an Indicator Mineral

- source-specific
- heavy
- reasonably stable in weathered sediments
- coarse-grained (>0.25 mm; unless ultra-heavy –
  e.g. gold and PGMs)





Fresh heavy minerals recovered by reverse circulation drilling

Indicator Minerals for Magmatic Base Metal Sulphide Deposits

Separate mineral suites exist for:

- each type of deposit
- each stage of mineralization
- each alteration zone

Outline 1 – Ni-Cu-PGE Indicator Minerals

Four mineral subsuites indicating:

- a fertile melt
- rapid, localized fractionation of cumulus minerals from the melt (promotes sulphide saturation)
- assimilation of felsic rocks by the melt (also promotes sulphide saturation)
- actual mineralization

Outline 2 – Porphyry Cu Indicator Minerals (PCIMs®)

1. Indicator subsuites for each alteration zone:
   - potassic
   - propylitic
   - phyllic (sericitic)
   - Advanced argillic/epithermal Au

2. Arid weathering is beneficial; it converts unstable hypogene sulphides into stable, useful supergene indicators


10 cm
Garnet Peridotite
Premier mine, Pretoria, South Africa
F. R. Boyd
Courtesy: Smithsonian Institution

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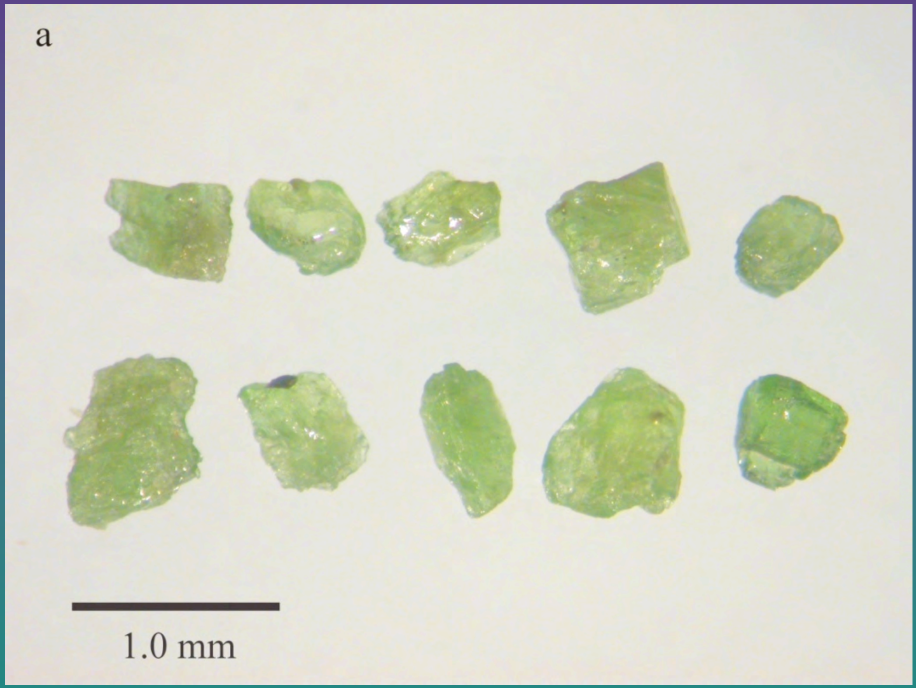
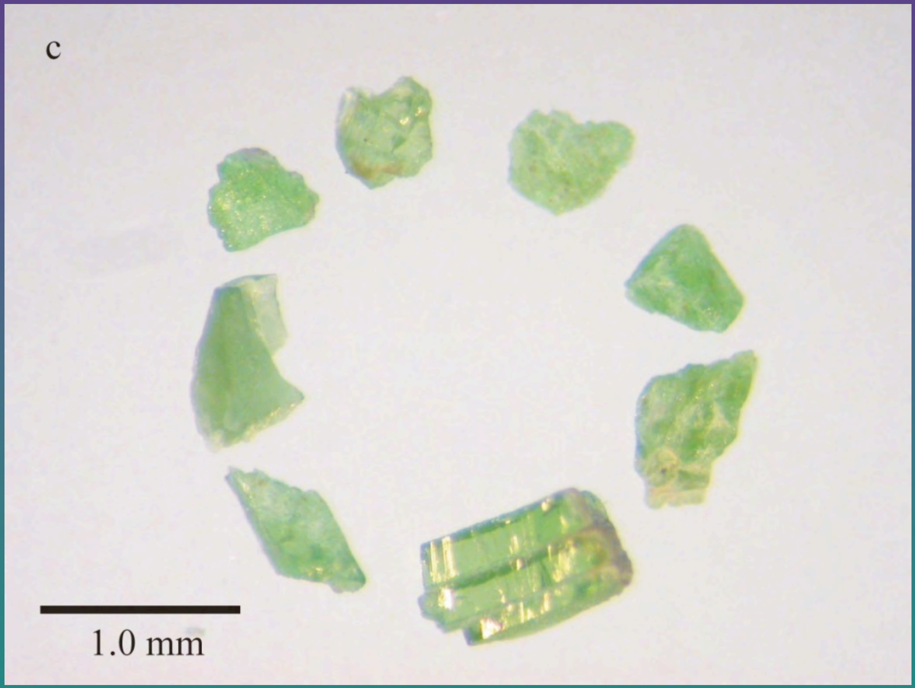
Indicators of a Fertile Melt

- orthopyroxene (enstatite – $Mg_2Si_2O_6$)
- olivine (forsterite – $MgSiO_4$)
- Cr-diopside – $Ca(Mg,Cr)Si_2O_6$
- chromite – $(Fe,Mg)(Cr,Al)O_4$

Cr-diopside

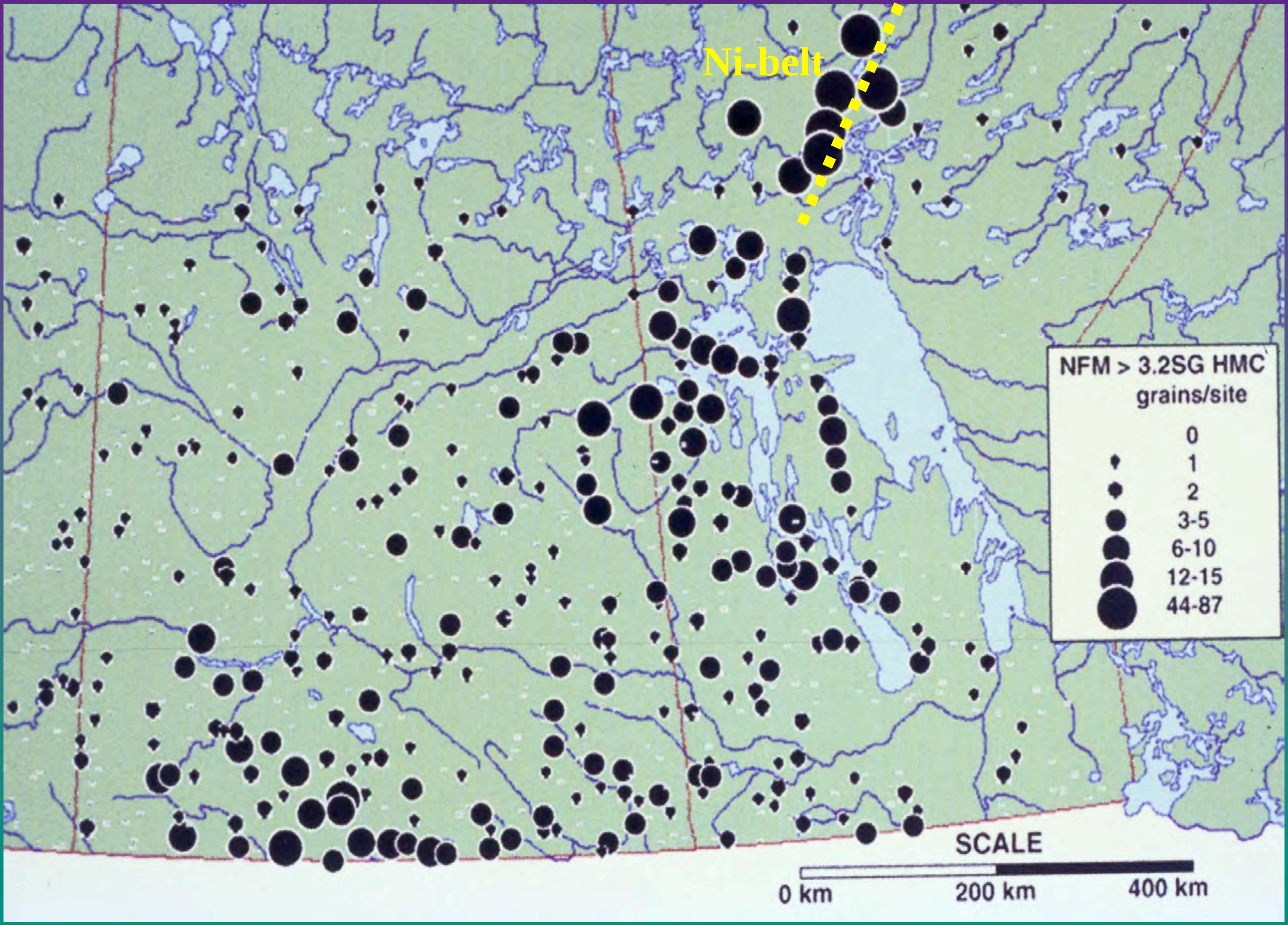




Non-kimberlitic
<1.25% Cr_2O_3

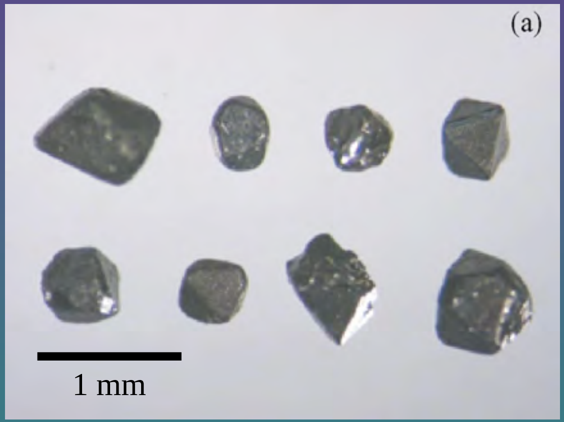
Kimberlitic
>1.25% Cr_2O_3

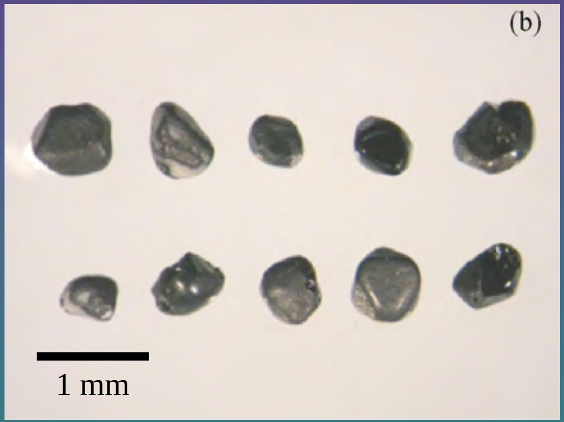
Dispersal of Cr-diopside from Thompson Ni-Belt

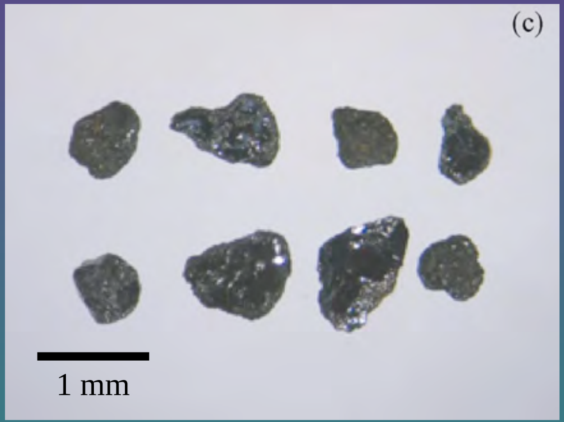


Courtesy: Harvey Thorliefson

Chromite







Non-kimberlitic

Kimberlitic

Lateriti
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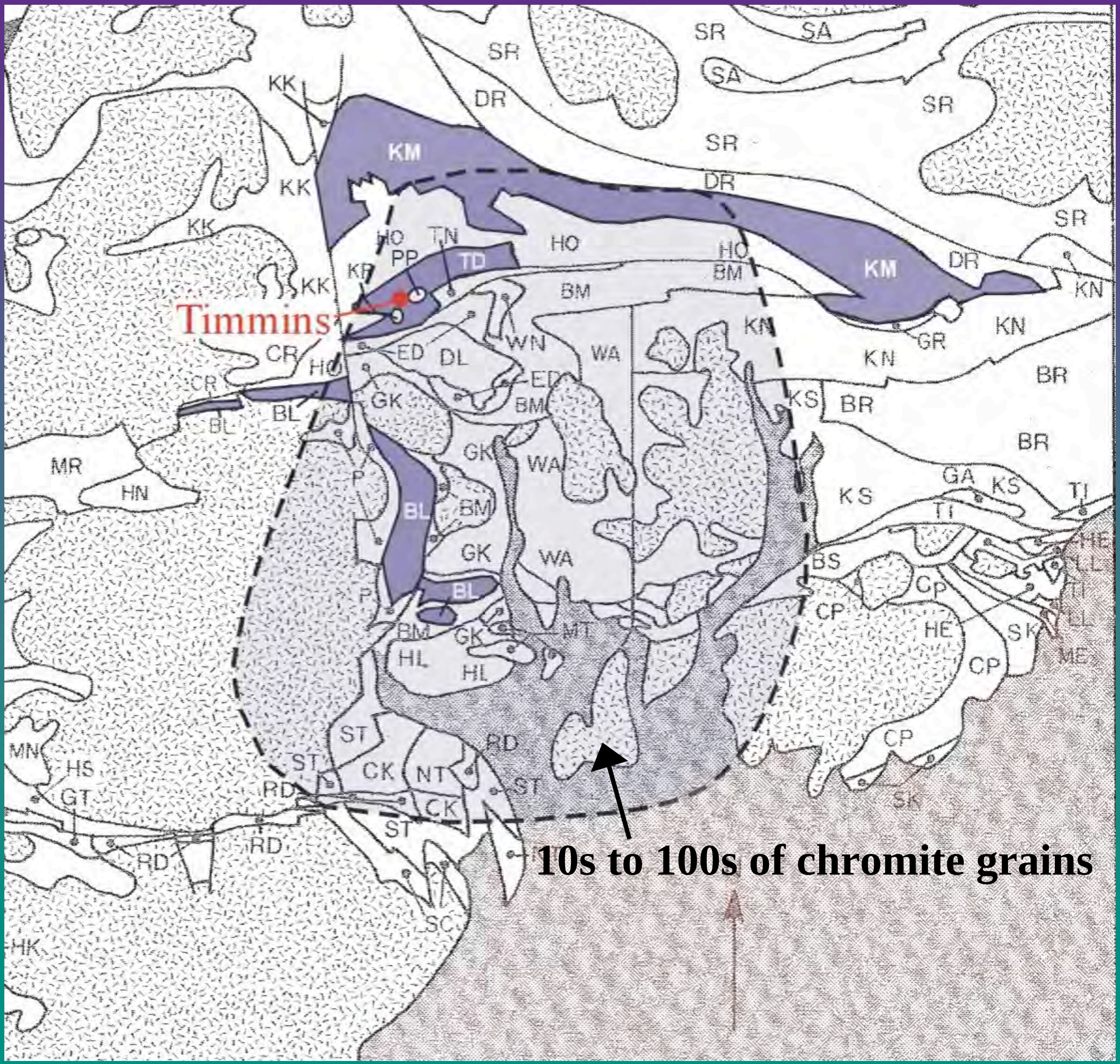
Dispersal of chromite from fertile Timmins komatiites



Role of Sulphide Saturation

- Causes sulphide liquid to separate from silicate melt
- Sulphide liquid collects Ni-Cu-PGE from silicate melt
- Heavy sulphide liquid settles in pools or layers, further concentrating metals

Outline 1 – Ni-Cu-PGE Indicator Minerals

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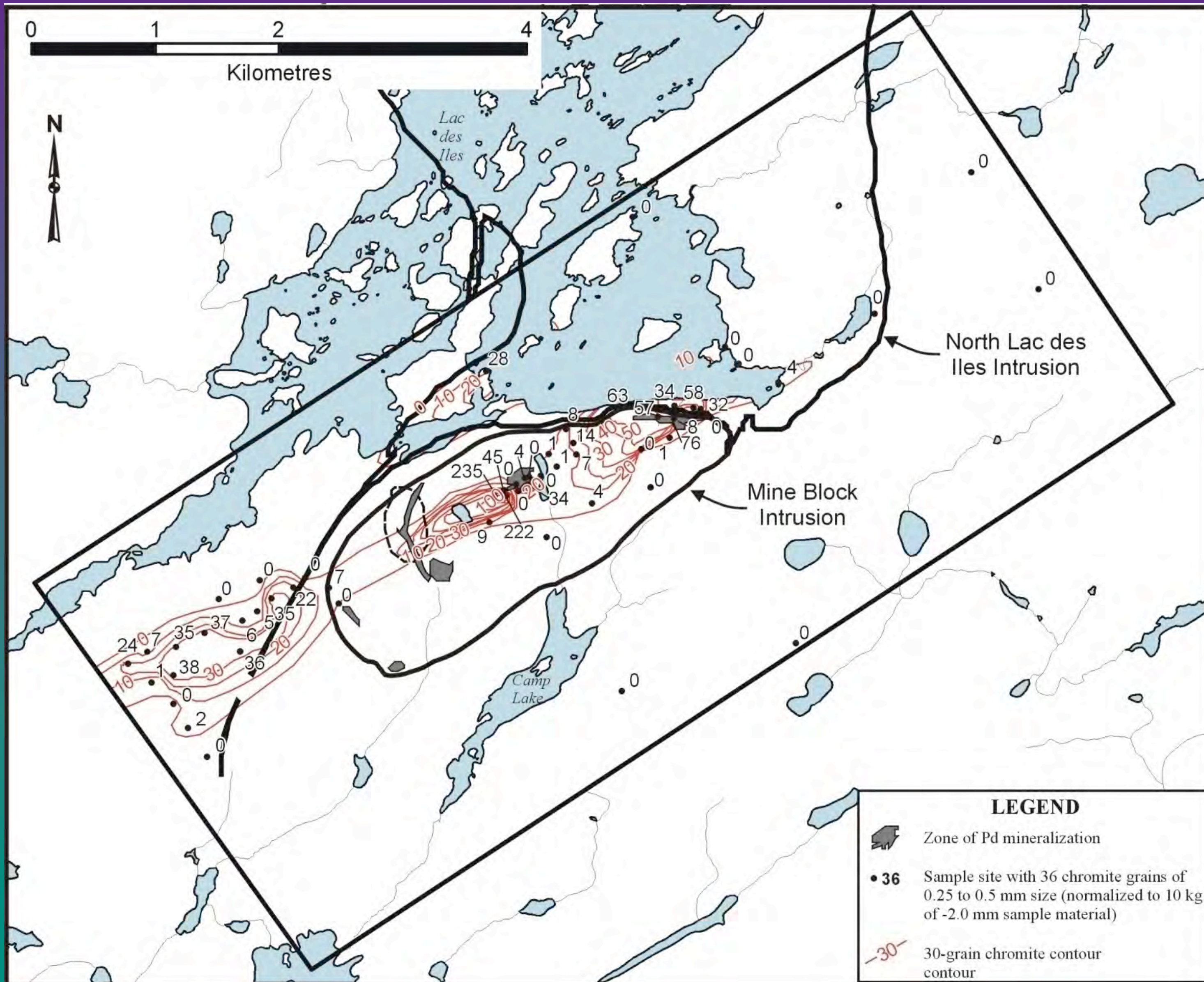
- actual mineralization

Indicators of Concentrated Cumulus Segregation

- orthopyroxene (enstatite – $Mg_2Si_2O_6$)
- olivine (forsterite – $MgSiO_4$)
- Cr-diopside – $Ca(Mg,Cr)Si_2O_6$
- chromite – $(Fe,Mg)(Cr,Al)O_4$

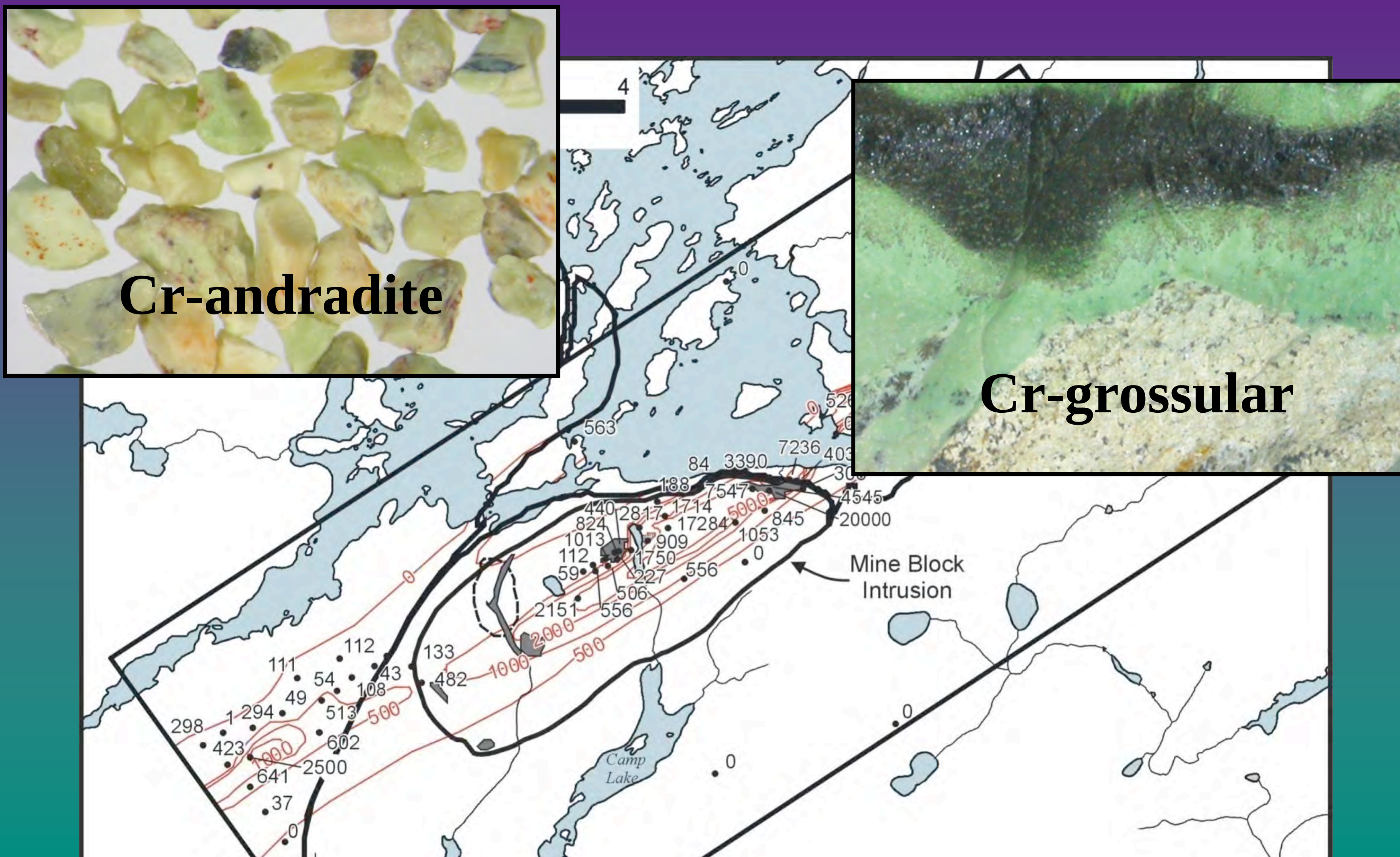
Dispersal of chromite from Lac des Iles Intrusive Complex



Courtesy: Peter Barnett

Ruby Corundum $(Al,Cr)_2O_3$

Dispersal of Cr-andradite from Lac des Iles Intrusive Complex



Courtesy: Peter Barnett

Outline 1 – Ni-Cu-PGE Indicator Minerals

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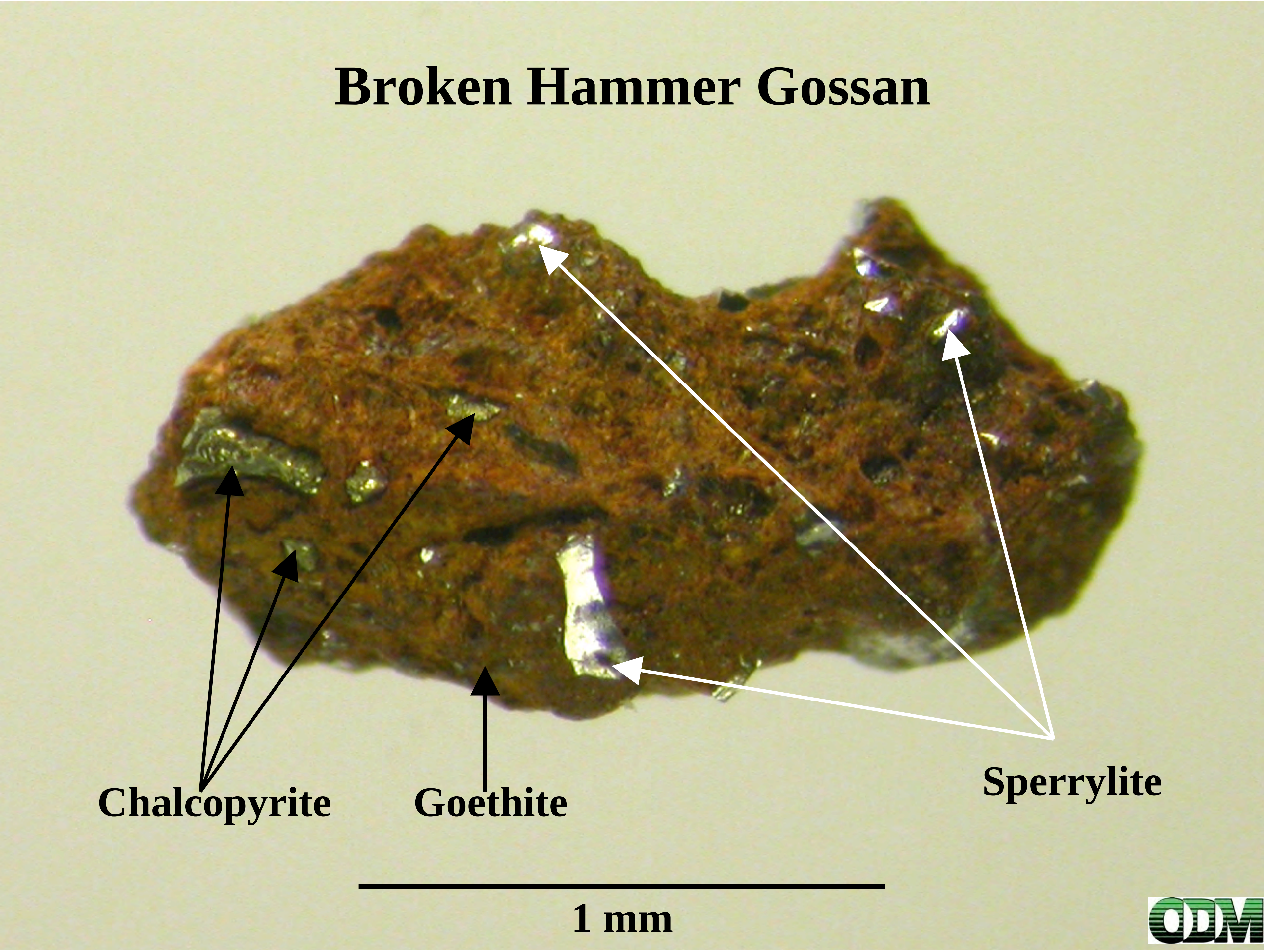
Relative stabilities of Fe-sulphides and Ni-Cu-PGE ore minerals

Mineral	Stability
Ni-sulphides	unstable
PGE-sulphides	unstable
PGE-tellurides	unstable
pyrrhotite	unstable
pyrite	unstable
chalcopyrite	marginally stable
FeNi and PGE-arsenides	stable (but silt-sized)
PGE-antimonides	stable (but silt-sized)
native Au and PGE	very stable (but silt-sized)


Broken Hammer Gossan
Chalcopyrite
Goethite
Sperrylite
1 mm

How to Use Ni-Cu-PGE Indicators: The Step-by-Step Path to Discovery

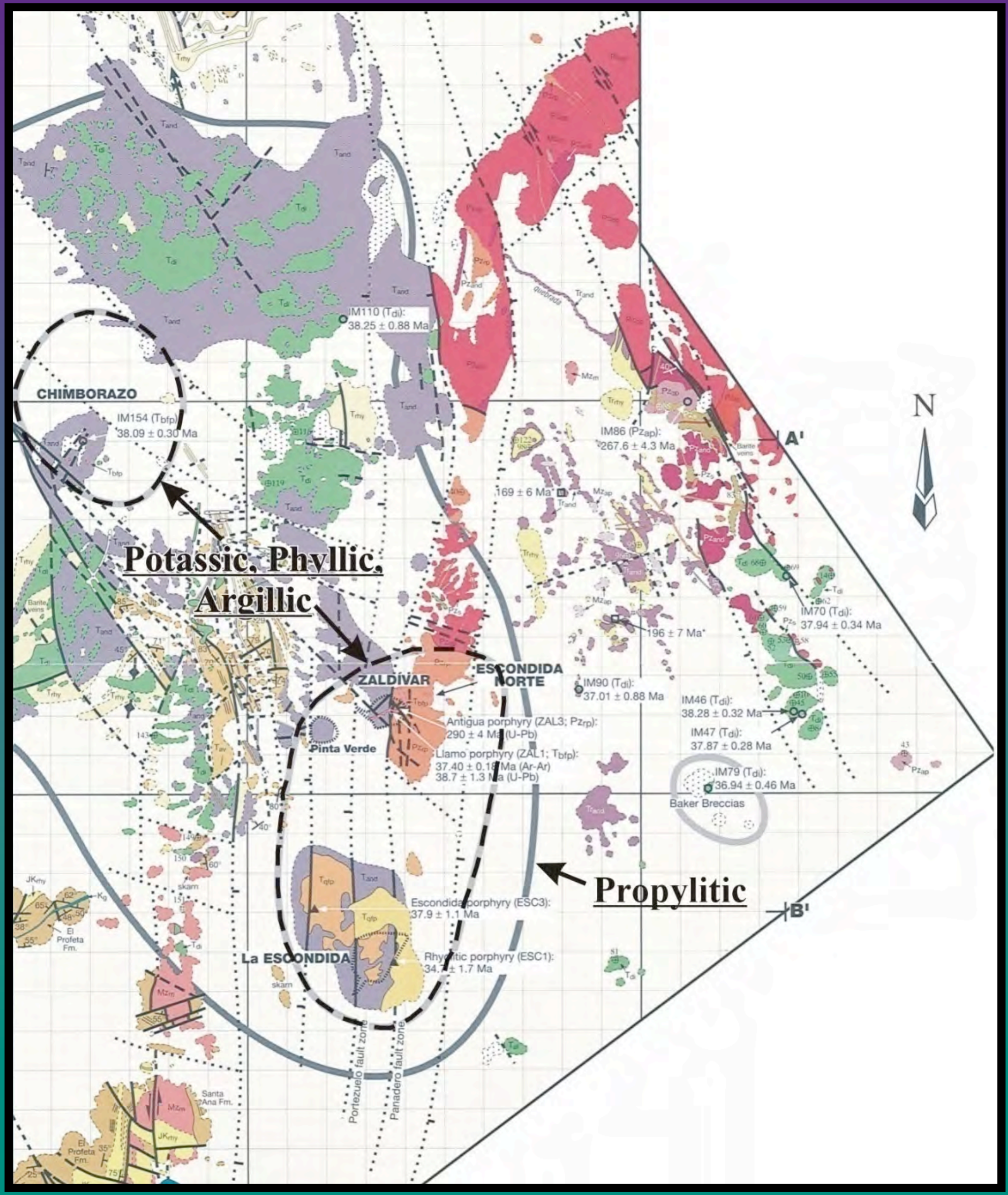
1. Recover and identify all four subsuites of indicator minerals
2. Differentiate the crossover Mg and Cr-rich indicators from kimberlite indicators
3. Use any large anomalies in these minerals to locate a fertile intrusion or flow belt
4. Tighten sample spacing; locate areas of potential sulphide saturation using cumulus and hybrid indicators
5. Further tighten spacing and search for anomalous levels of chalcopyrite and other ore indicator minerals

Outline 2 – Porphyry Cu Indicator Minerals (PCIMs®)

1. Indicator subsuites for each alteration zone:
- potassic
- propylitic
- phyllic (sericitic)
- Advanced argillic/epithermal Au

2. Arid weathering is beneficial; it converts unstable hypogene sulphides into stable, useful supergene indicators

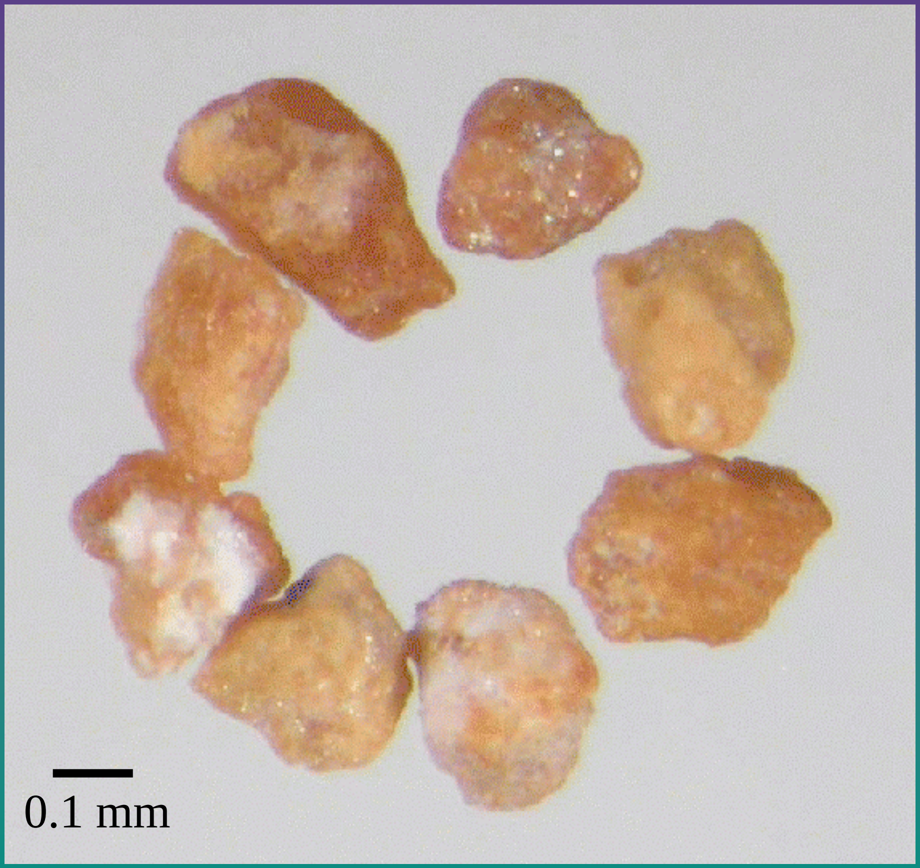
Alteration zones, Escondida, Chile



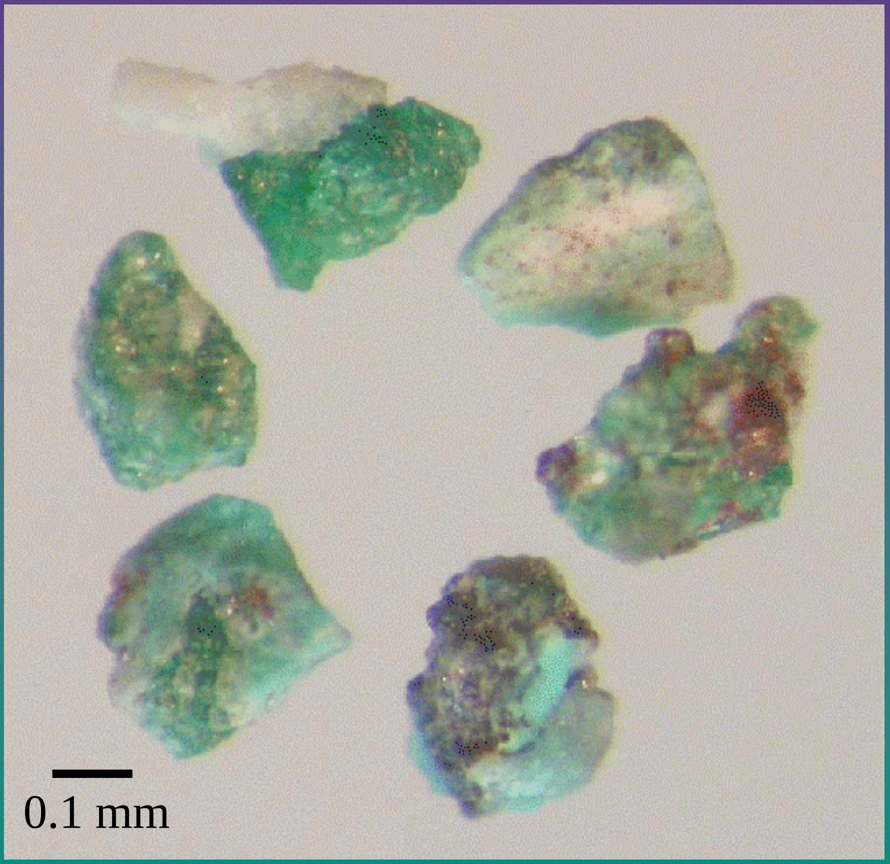
ODM

Arid landscape, Atacama Desert, Chile

Jarosite



Atacamite



Mineral	Density	Composition	Potassic	Argillic	Phyllic	Propylitic	Epithermal Au
			Principal provenance (alteration zone)				

Hypogene suite:

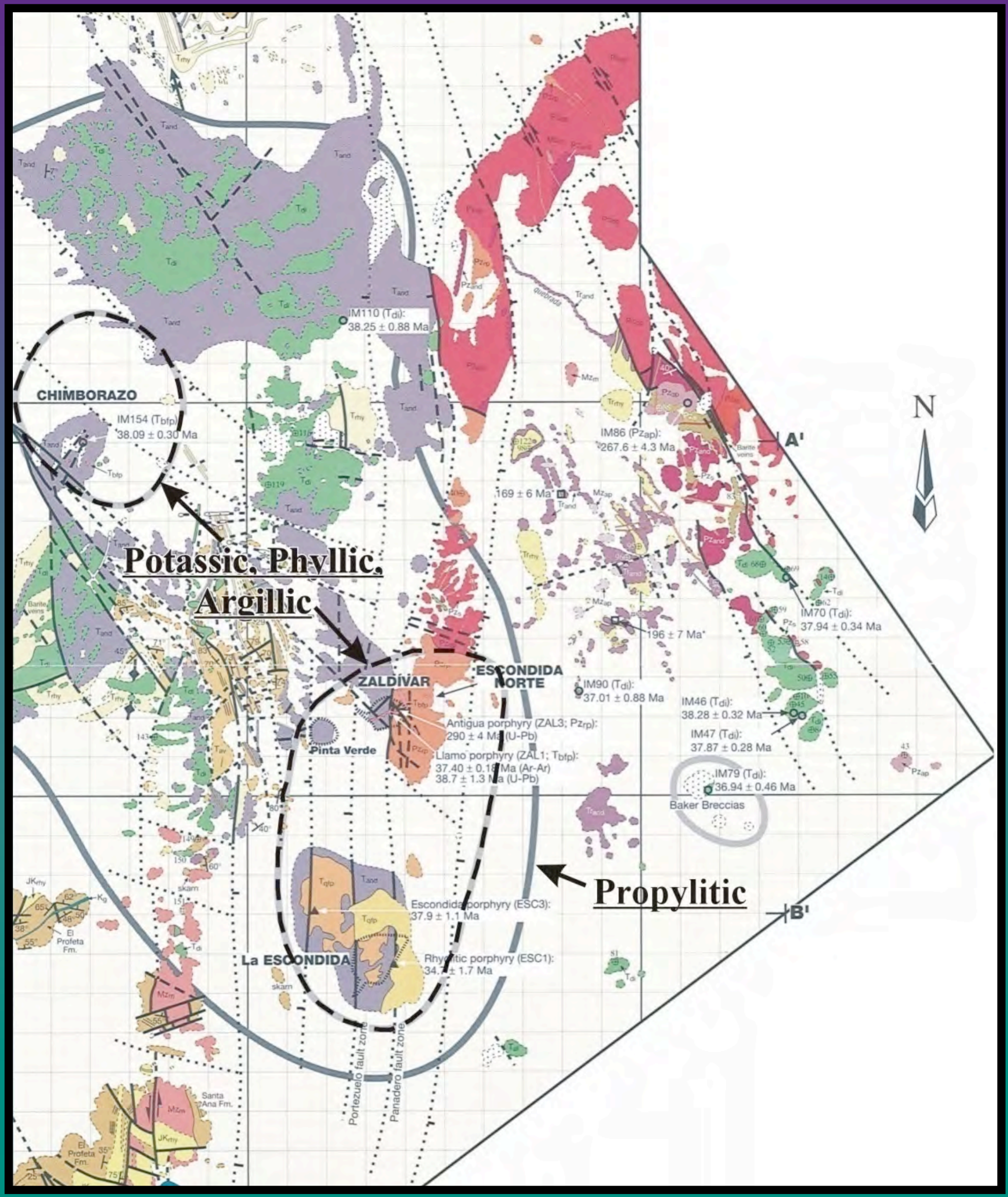
Mineral	Density	Composition	Potassic	Argillic	Phyllic	Propylitic	Epithermal Au
Diaspore	3.4	$AlO(OH)$		X			
Alunite	2.9	$(K,Na)Al_3(SO_4)_2(OH)_6$	X	X			
Dravite	3.0	$NaMg_3Al_6(BO_3)_3(Si_6O_{18})(OH)_4$		X			
Andradite	3.9	$Ca_3Fe_2(SiO_4)_3$				X	
Barite	4.5	$BaSO_4$					X

Supergene suite:

Mineral	Density	Composition	Potassic	Argillic	Phyllic	Propylitic	Epithermal Au
Alunite	2.8	$(K,Na)Al_3(SO_4)_2(OH)_6$	X	X			
Jarosite	3.1	$(K,Na)Fe_3(SO_4)_2(OH)_6$	X	X			
Atacamite	3.8	$Cu_2Cl(OH)_3$	X	X	X		
Turquoise	2.8	$CuAl_6(PO_4)_4(OH)_{8.5}H_2O$		X			
Malachite	4.0	$Cu_2CO_3(OH)_2$			X	X	

Proven porphyry Cu indicator minerals (PCIMs®)

Alteration zones, Escondida, Chile



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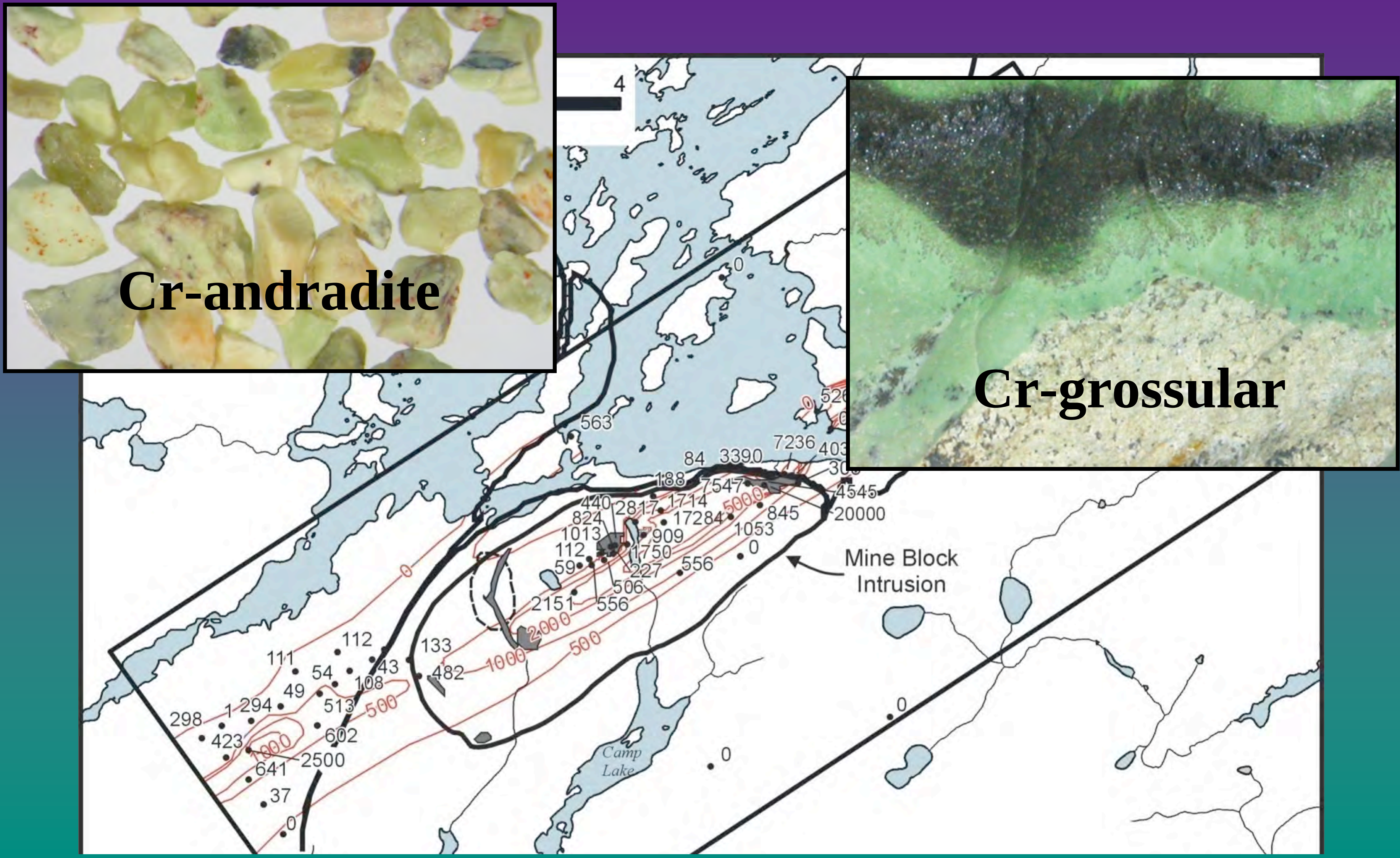
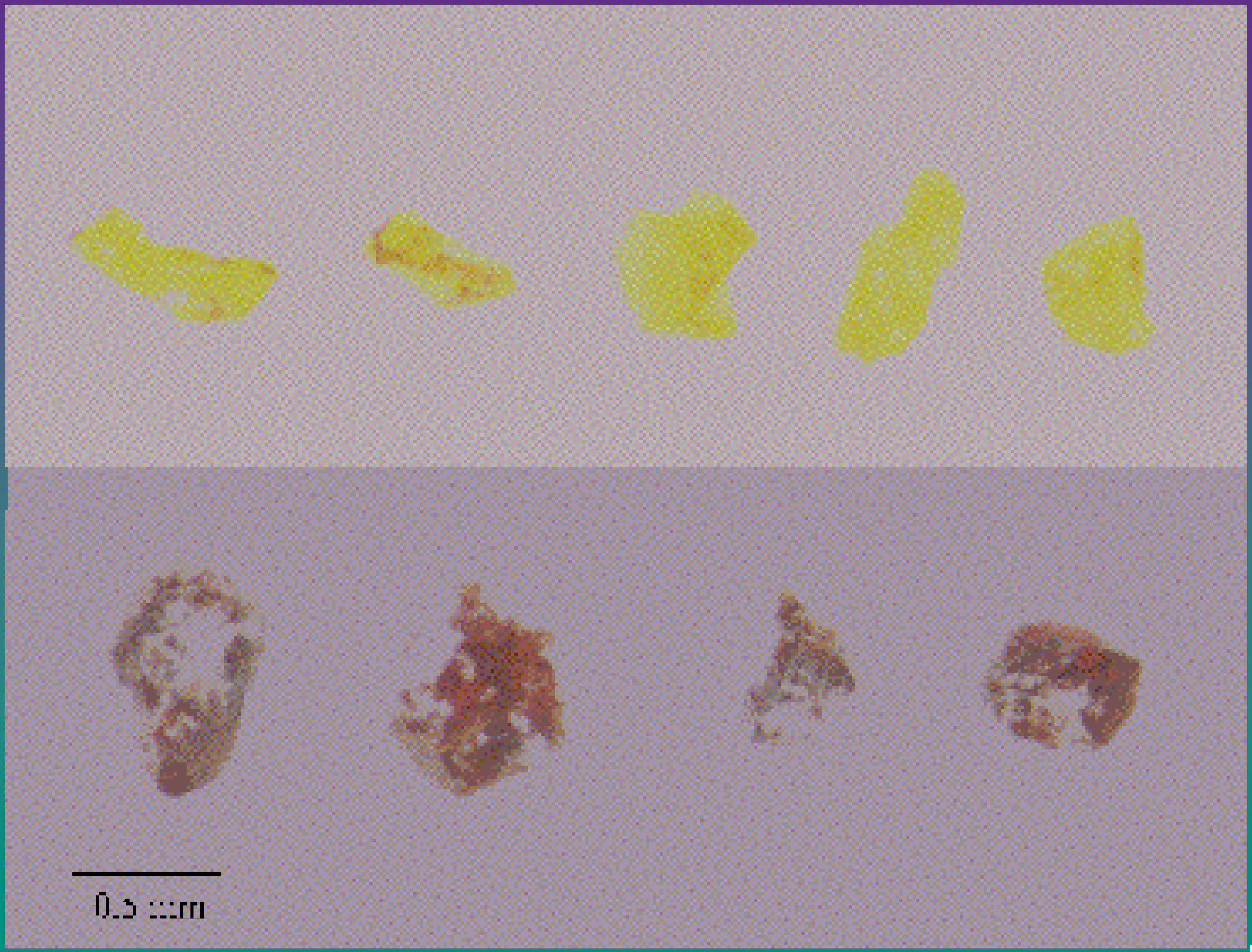
Proven porphyry Cu indicator minerals (PCIMs®)

Dispersal of Cr-andradite from Lac des Iles Intrusive Complex

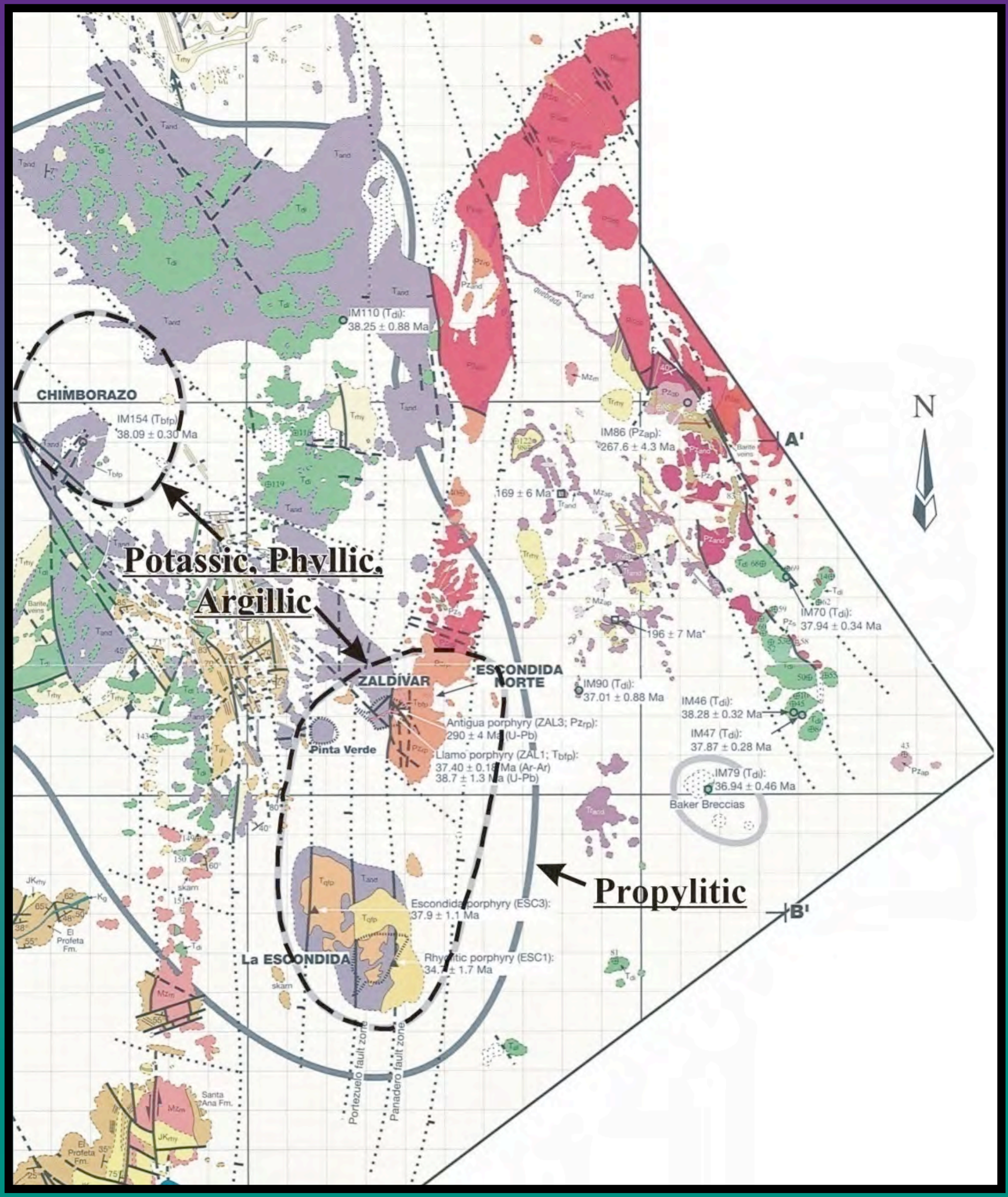


Courtesy: Peter Barnett

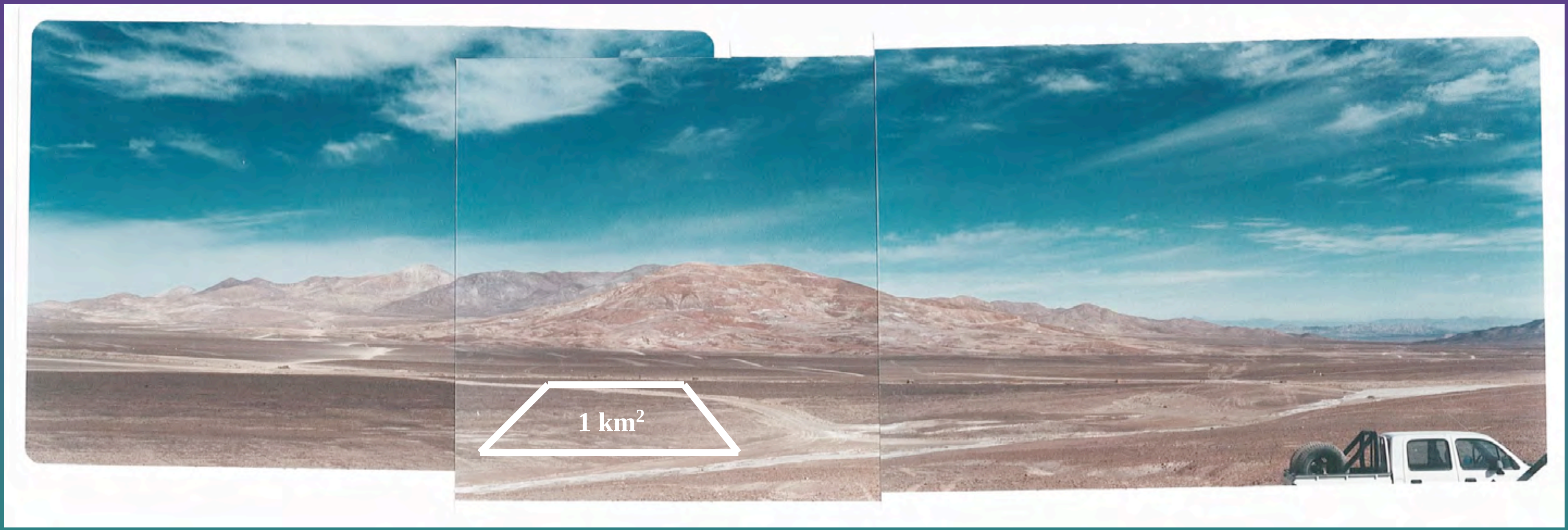
Andradite garnet – $Ca_3Fe_2(SiO_4)_3$



Alteration zones, Escondida, Chile

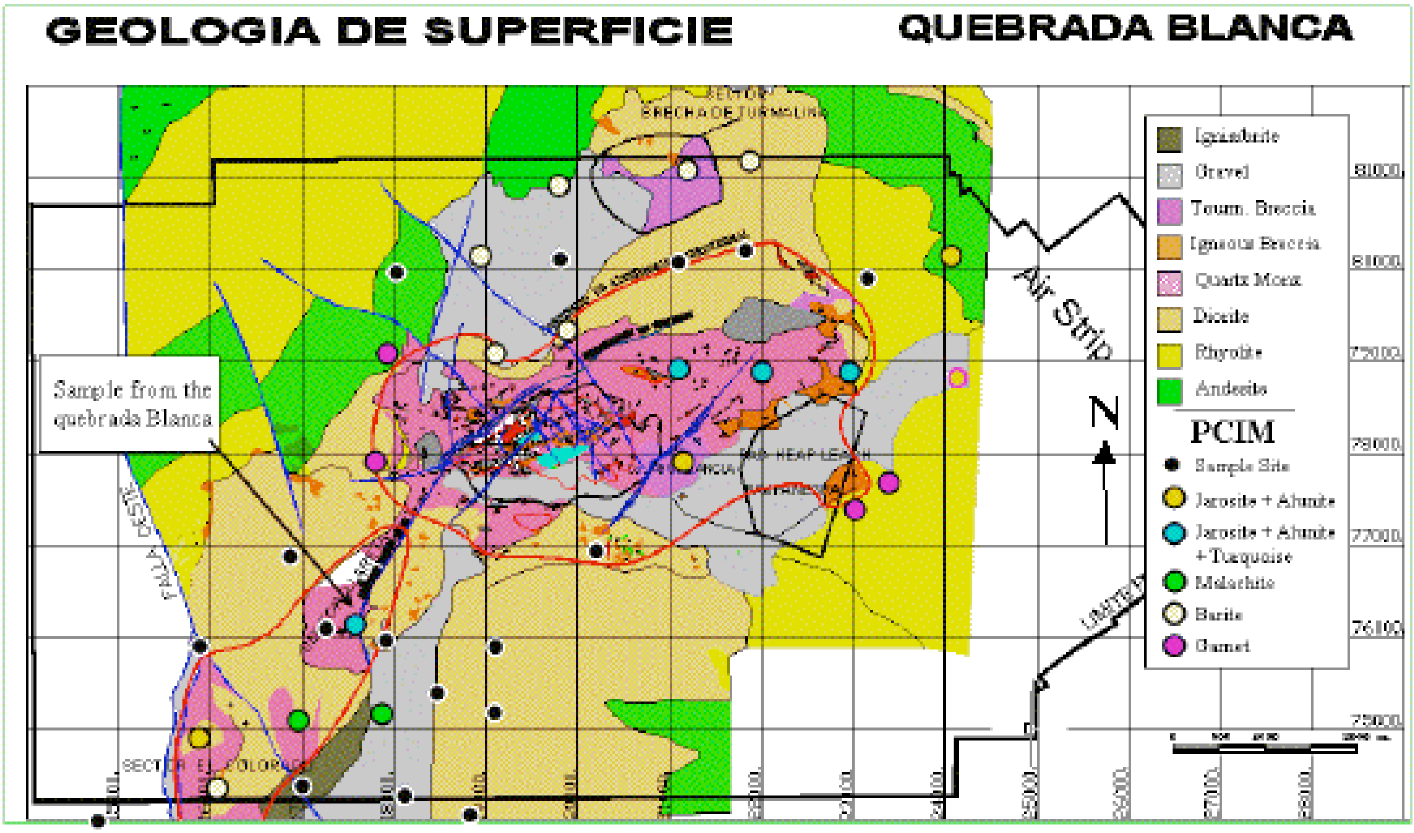


Arid landscape, Atacama Desert, Chile



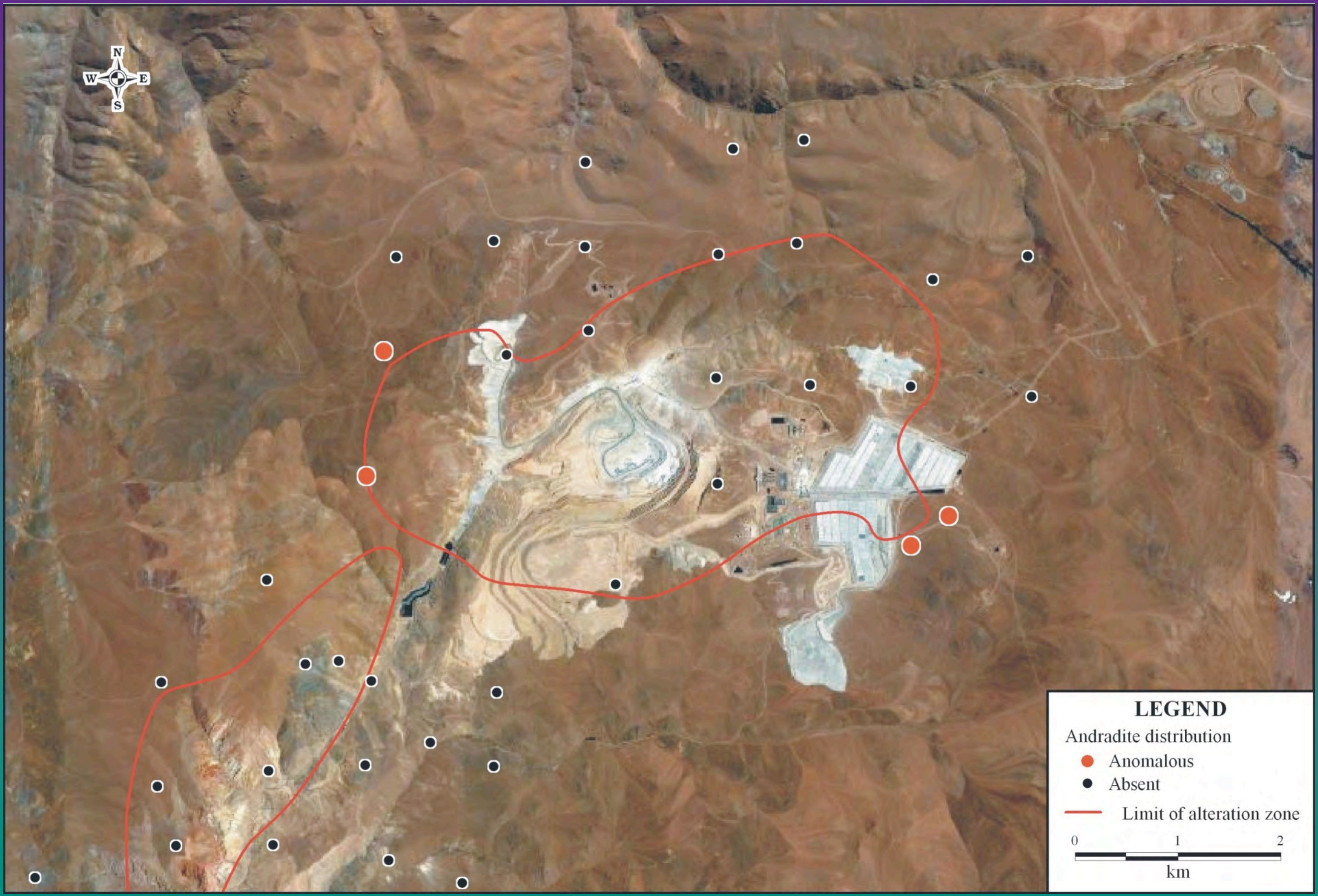
Sample sites, Quebrada Blanca

Courtesy: Aur Resources



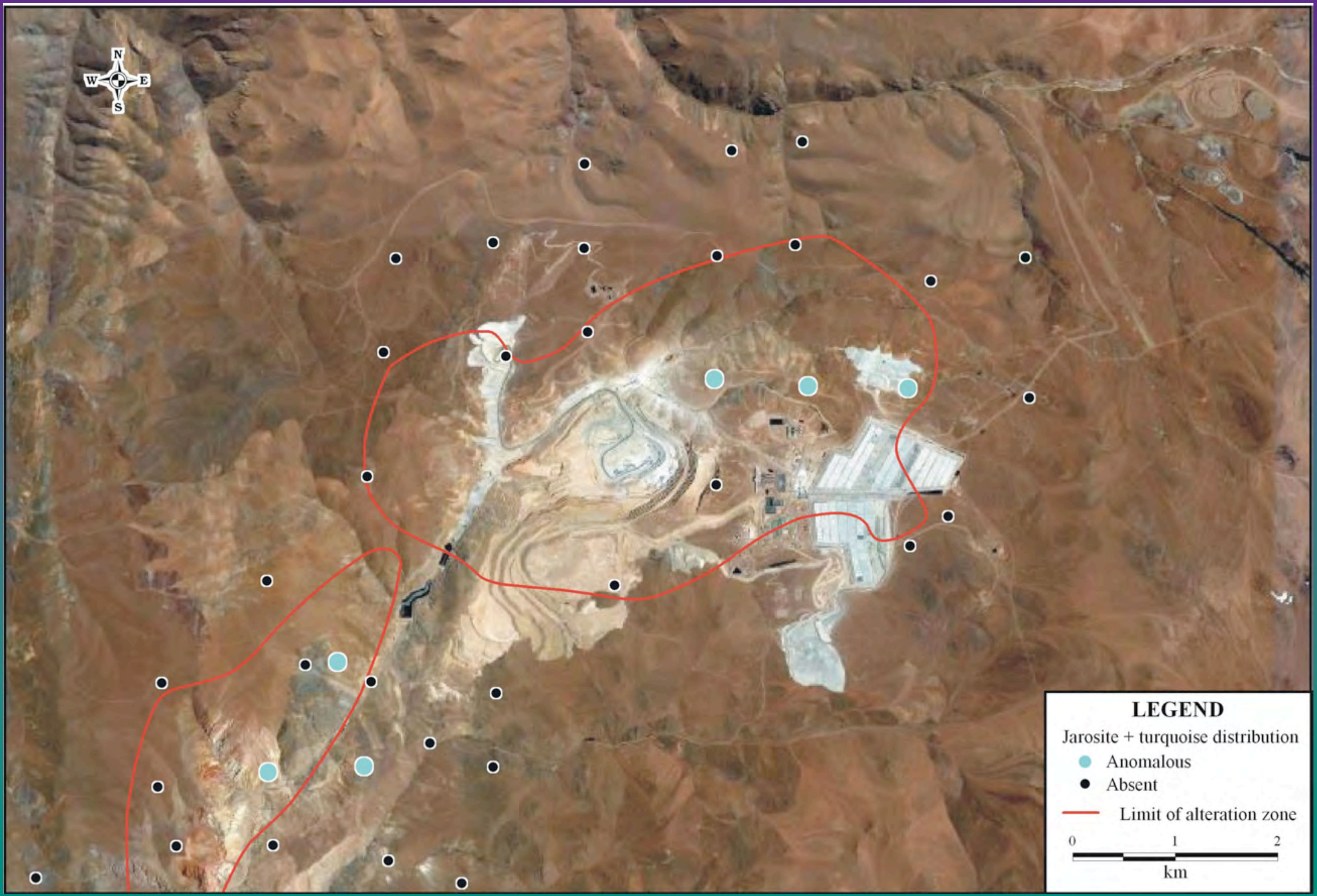
Courtesy: Aur Resources

Andradite in alluvium, Quebrada Blanca



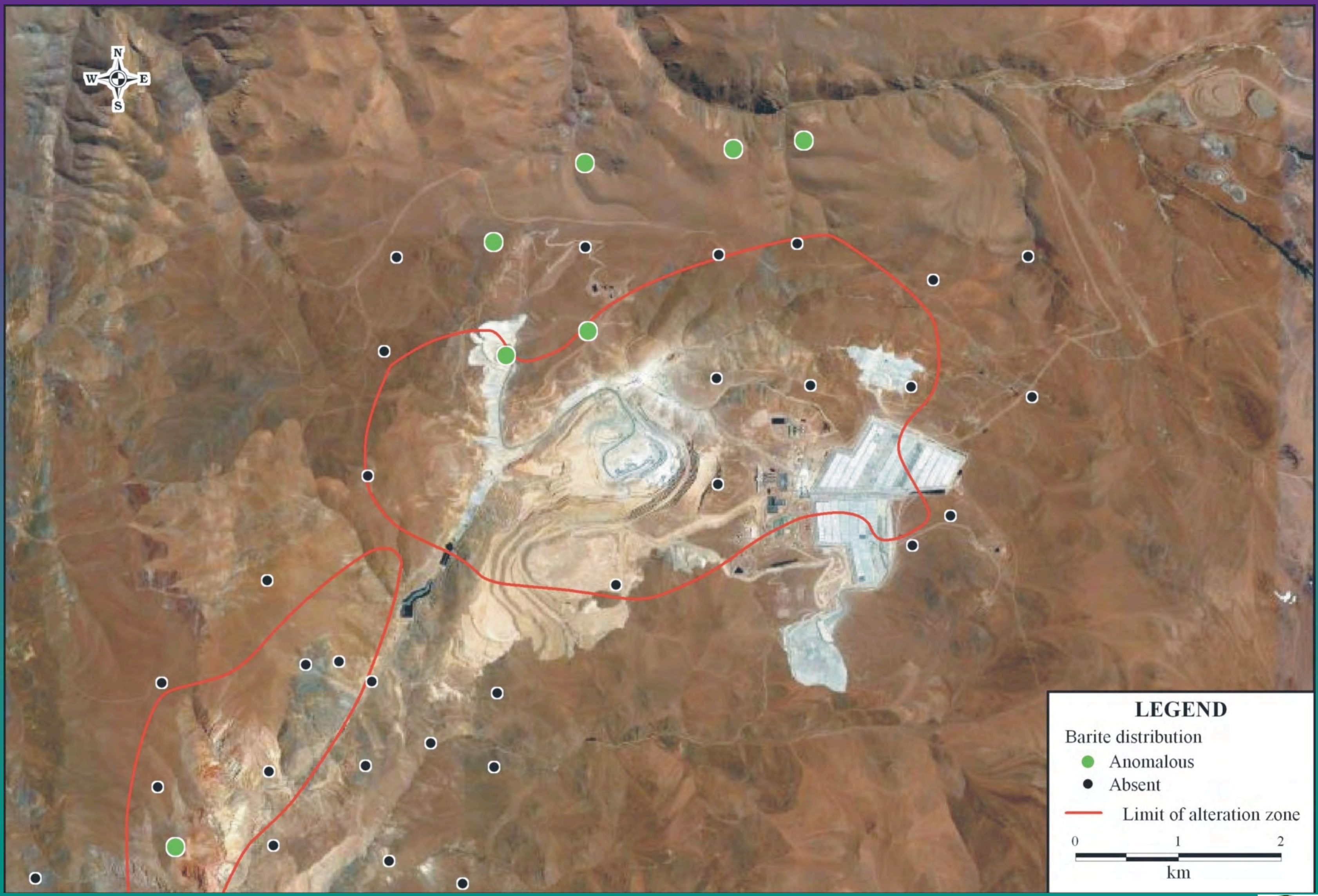
Courtesy: Aur Resources

Jarosite + turquoise in alluvium, Quebrada Blanca



Courtesy: Aur Resources

Barite in alluvium, Quebrada Blanca



Courtesy: Aur Resources

PCIM® Summary - What We Know in 2007

- Ten minerals are proven as PCIMs®
- PCIM® anomalies are strong and large, therefore detectable with small (0.5 kg), widely spaced samples (1 per km^2)
- Arid weathering increases the number and importance of indicator mineral species
- If cover <20 m, anomalies are very specific; individual alteration zones are readily outlined
- If cover >20 m, RC drilling will improve anomaly definition
- Andradite garnet is the “holy grail” of PCIMs

What We Hope to Learn by 2017!

- Is the trace element chemistry of andradite or other nine proven PCIMs® useful?
- The following five minerals also appear promising. Can we upgrade them to PCIM® status?
  - red rutile
  - rose zircon
  - blond titanite
  - apatite
  - sapphire corundum
- PCIMs® prove that *physical, variably soluble particles* of both mineralization and alteration are *plentiful* in surface alluvium. QUESTION: Are any *geochemical* anomalies actually caused by upward migration of *ions* through thick, dry alluvium?????