Innovations for gold exploration in greenstone belts:

Highlights from the Footprint and Metal Earth programs and potential applications to the Guiana Shield

Stéphane Perrouty *(sperrouty@laurentian.ca)*,
the NSERC-CMIC Footprint Team and the CFREF Metal Earth Team

LaurentianUniversity UniversitéLaurentienne

MERC Mineral Exploration Research Centre at the HARQUAIL SCHOOL OF EARTH SCIENCES

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Mineral Systems

- **Sources**

(fluids + metals)

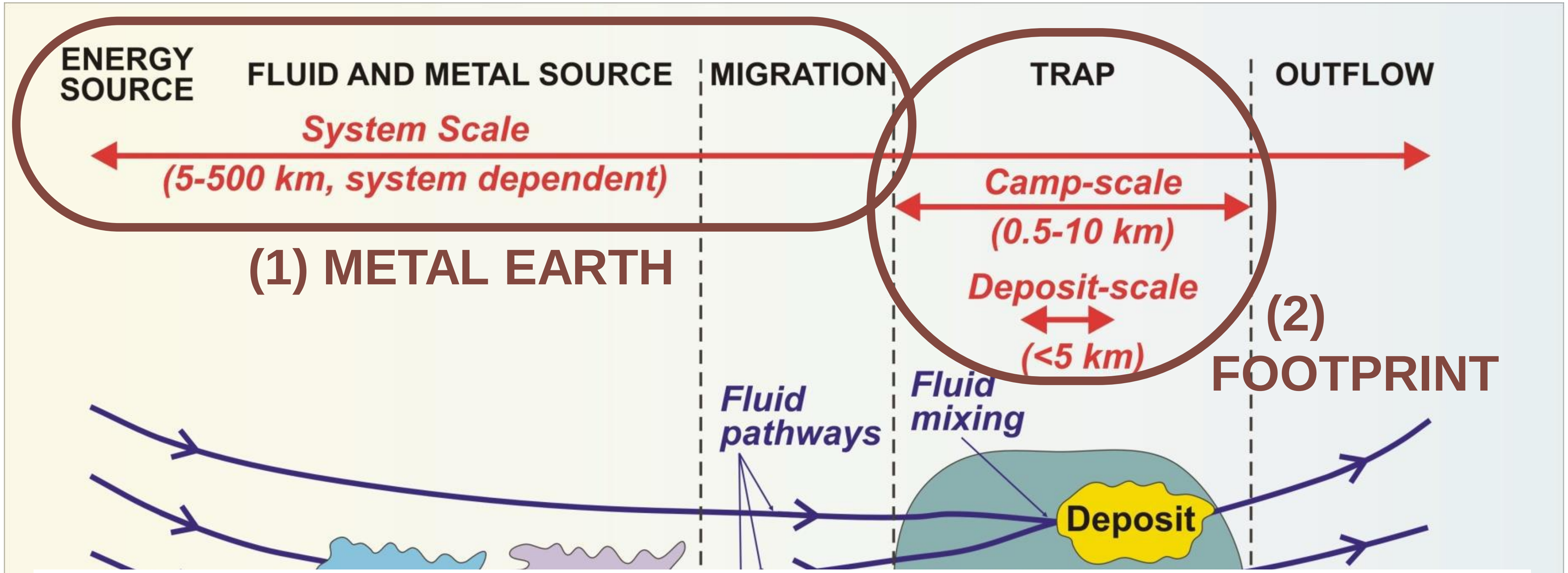
- **Pathways**

(structures)

- **Traps**

(chemical)

McCuaig *(2013, CET-UWA)*

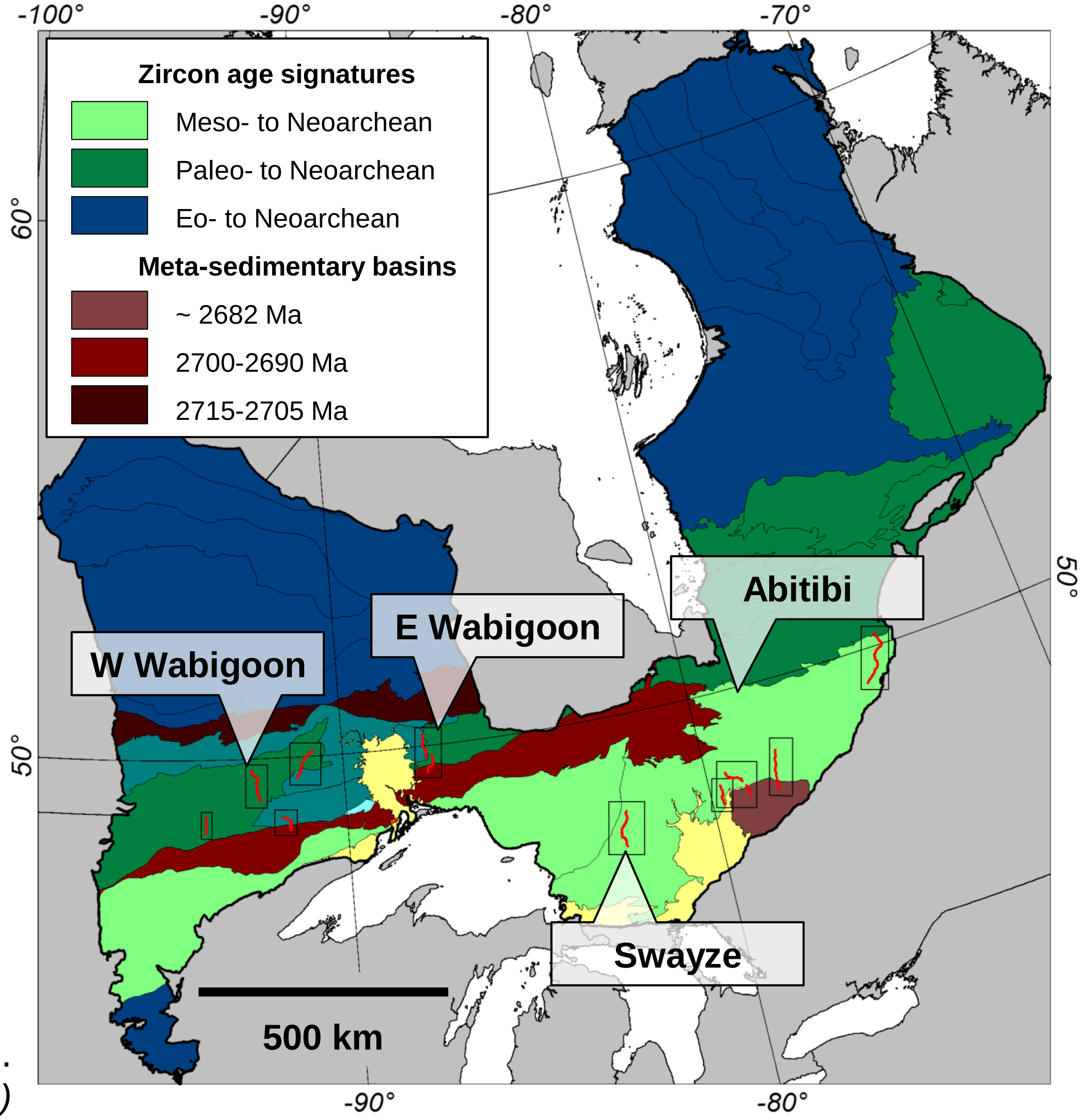


1) Need a better understanding of the metal and fluid sources and pathways to identify controls on metal endowment.

2) Need bigger targets to facilitate exploration of deeply buried systems.

Metal Earth Objectives

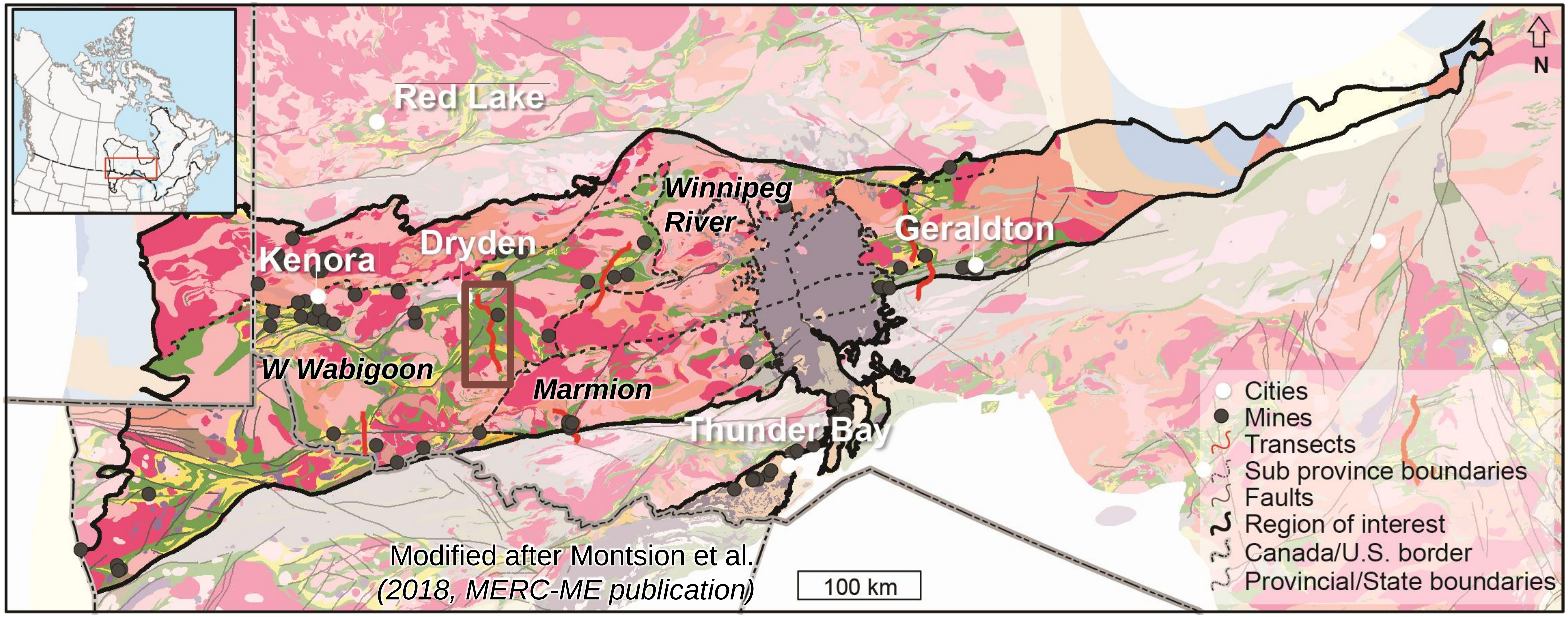
- **Define the key geological characteristics of well endowed versus less endowed crust**, to understand the processes responsible for Earth's differential base and precious metal endowment
- **Recognize differences in the mantle, the subcontinental lithospheric mantle, and in the deep crustal structures between well endowed and less endowed areas**, which may explain metal endowment localization



Modified after Frieman et al. *(2017, Precambrian Research)*

Abitibi (>150 Moz) – W Wabigoon (~20,000 oz)

- **The Abitibi and the western Wabigoon subprovinces have similar scale, age, igneous and sedimentary stratigraphy, structural evolution and geodynamic setting … but very different historical gold production.**



Field Studies

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Crustal-Scale Investigations
3D Implicit Modelling

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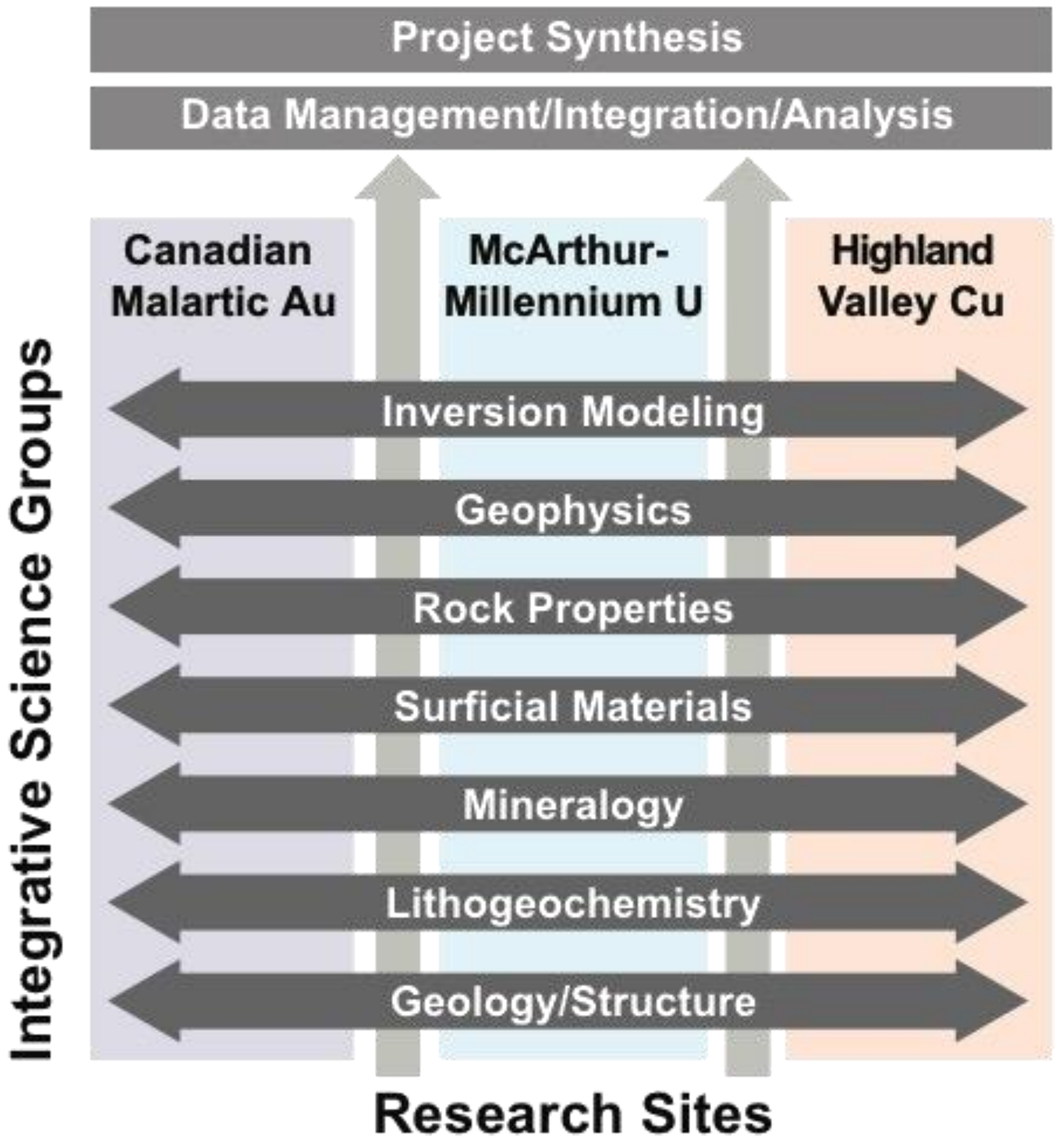
Footprint (2013-2018) Objectives

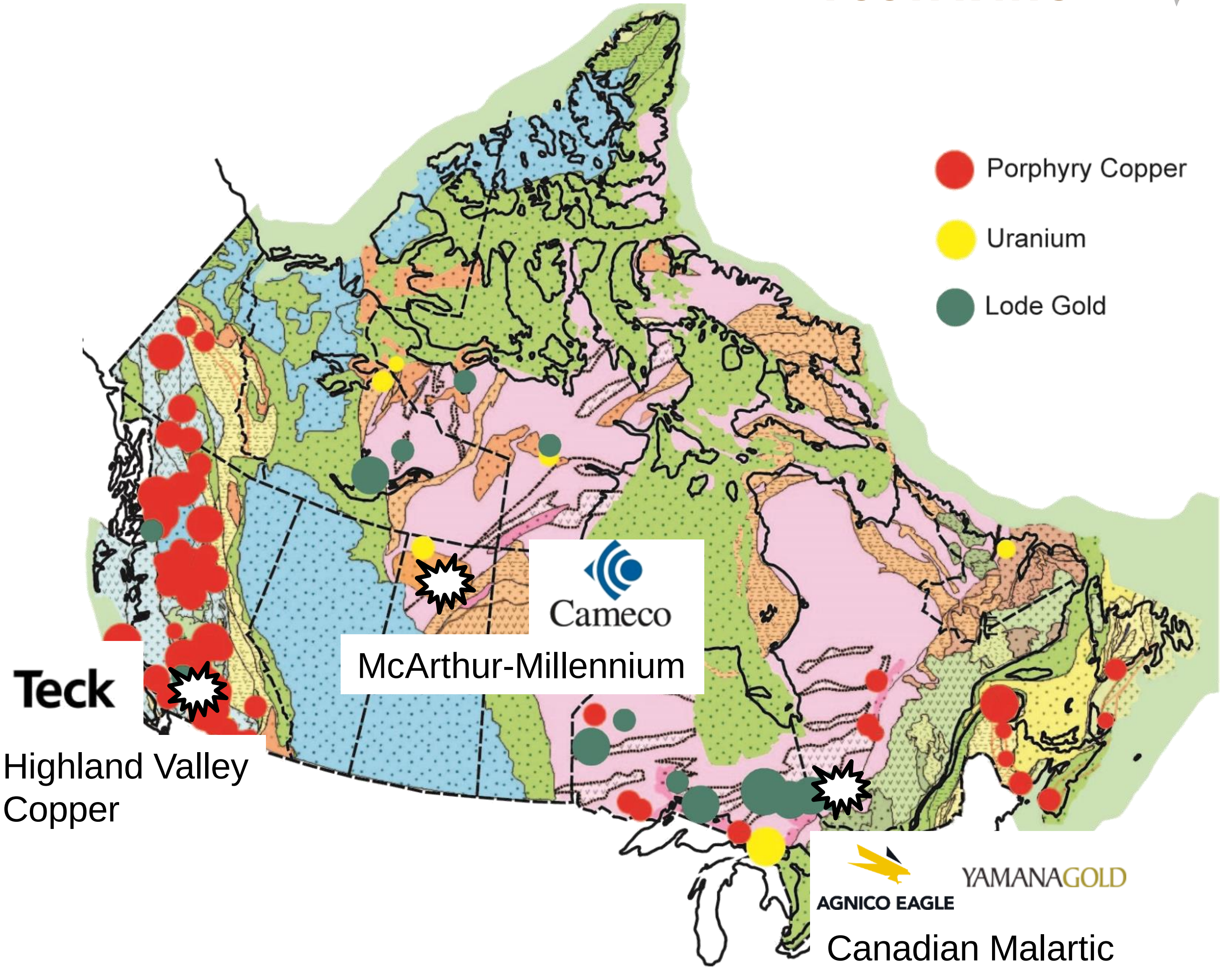
NSERC-CMIC FOOTPRINTS

- **Develop comprehensive and robust models of the footprints of large-scale ore-forming systems at three integrated study sites**, combining geological, mineralogical, geochemical, geophysical and physical rock properties from the local to the camp scale
- **Develop novel methods for integrating and interrogating multiple data sets that** will enhance the exploration process and, at the same time, answer fundamental questions about the origins of large-scale ore-forming systems



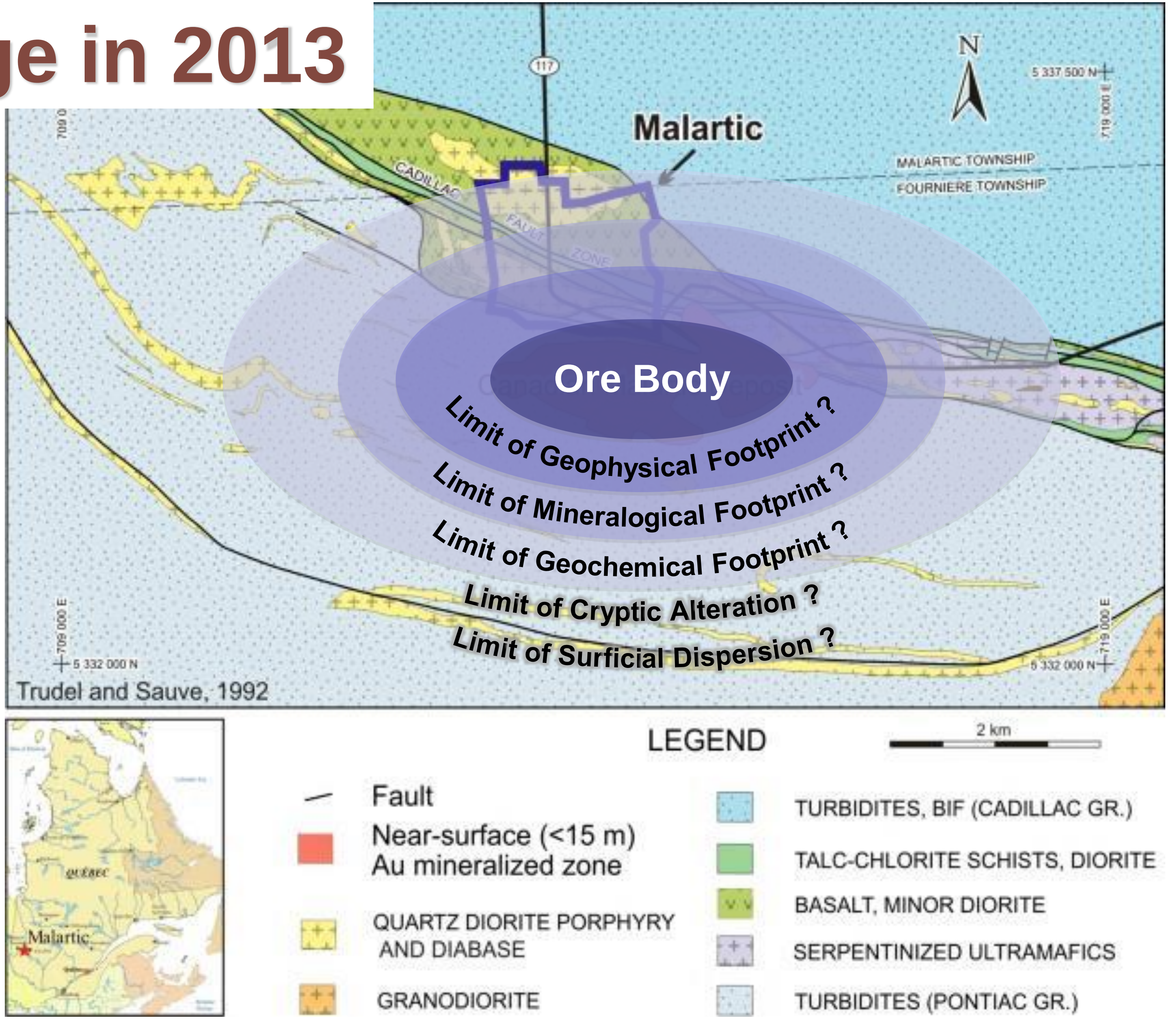
Location of Footprint Sites

- **Canadian Malartic:**
  - **>18.6 Moz Au**
  - **South of the Cadillac - Larder Lake Deformation Zone, Québec**
  - **Oxidized intrusion-related deposit**
    (Helt et al., 2012, *Economic Geology*)
  - **Stockwork-disseminated system**
    (De Souza et al., 2016, *Economic Geology*)



State of Knowledge in 2013

- **Structurally-controlled biotite, calcite and pyrite alteration** (Derry, 1939, *Econ. Geol.*)
- **This deposit should have a large footprint but its expression is unknown**
- **Geophysics does not work for direct ore targeting**
- **Long mining history makes current surficial exploration techniques (e.g., soil geochemistry) inefficient**



Our Understanding in 2018

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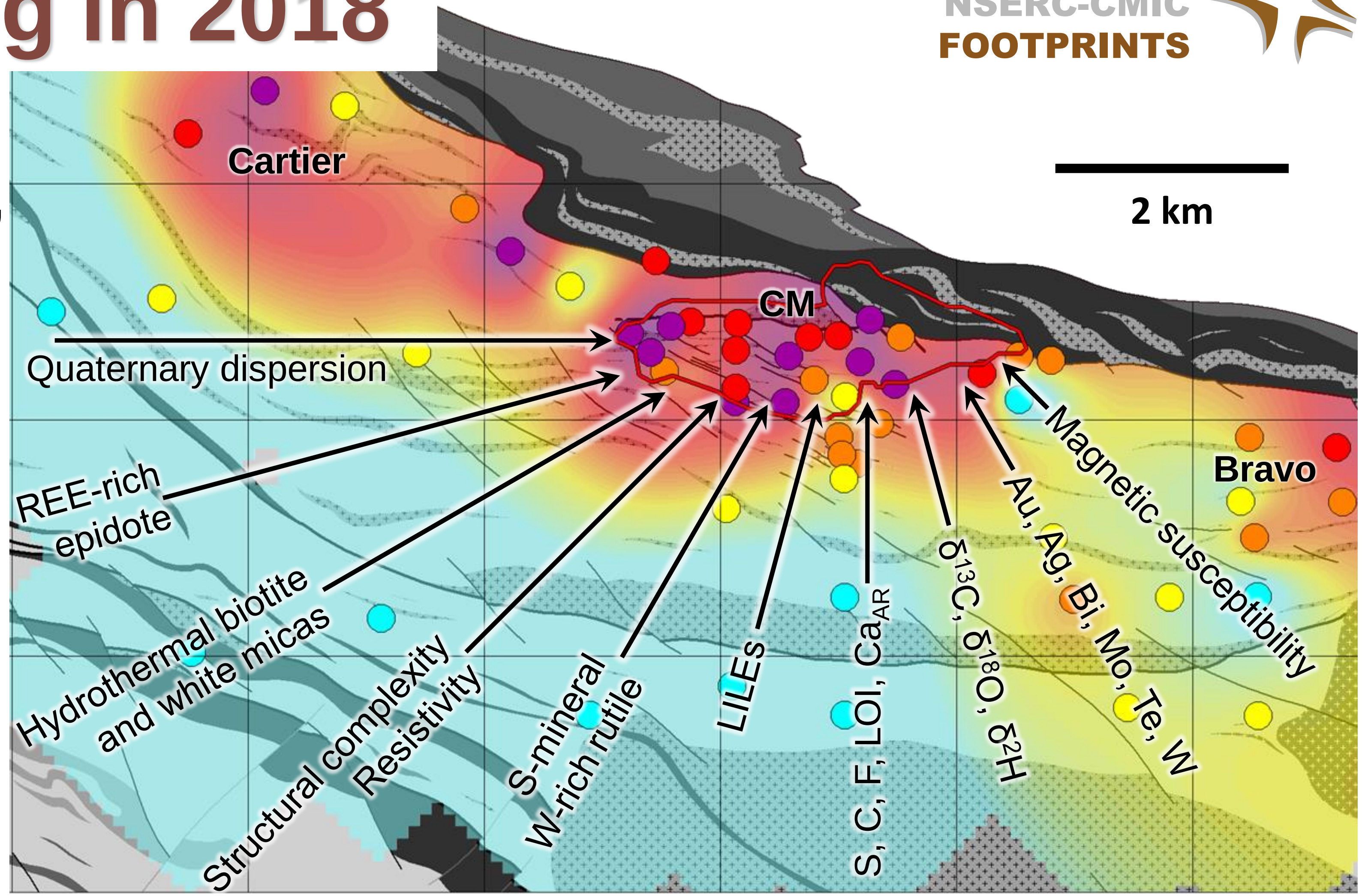
- **118 structural, geophysical, geochemical, mineralogical, and petrophysical halos**
- **Sizes range from 500 m to 6 km from the core of the system**
- **Multiple alteration centers** (CM, Cartier, Bravo/Odyssey)
- **New models: structural/ metamorphic/hydrothermal**
- **New techniques applicable to gold exploration**



Main vectoring tools in the Canadian Malartic footprint

Geological Setting

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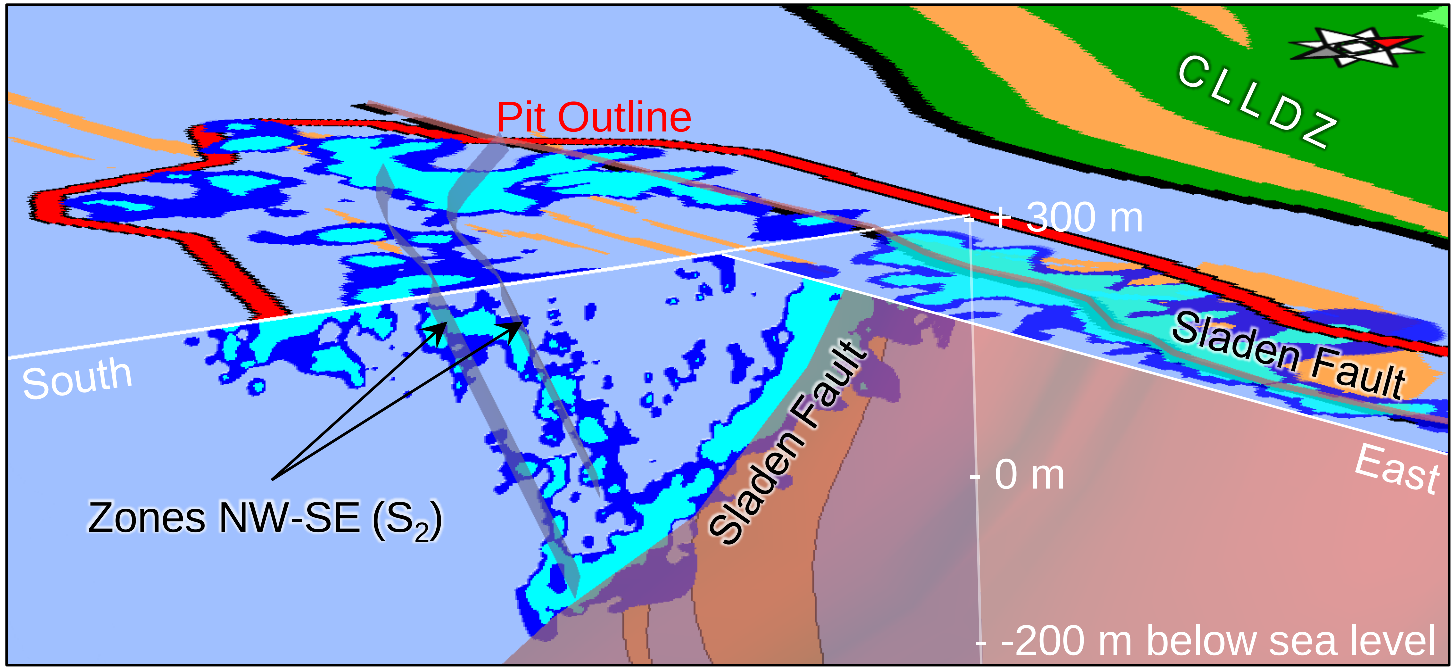
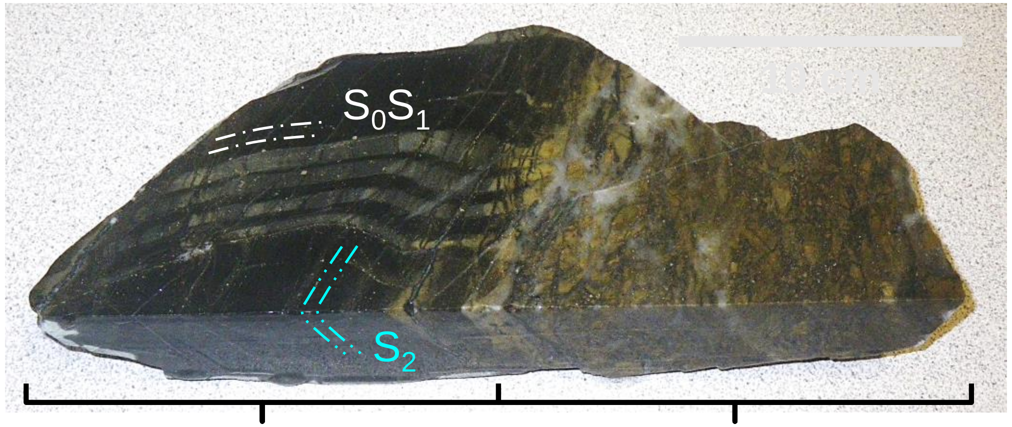
- **3 deformation events: D_1** - isoclinal F_1 folds, pressure-solution cleavage (S_1)
  D_2 - close s-shaped F_2 folds, NW-SE biotite cleavage (S_2)
  D_3 - subtle crenulation cleavage (S_3)

- **2 structural controls: E-W fault and NW-SE high-strain zones in F_2 fold hinges**





- **Main ore mineral association:**
  Biotite, microcline, albite, calcite, ferroan-dolomite, pyrite, quartz

Perrouty et al. *(2017, Ore Geology Reviews)*

Structural Footprint

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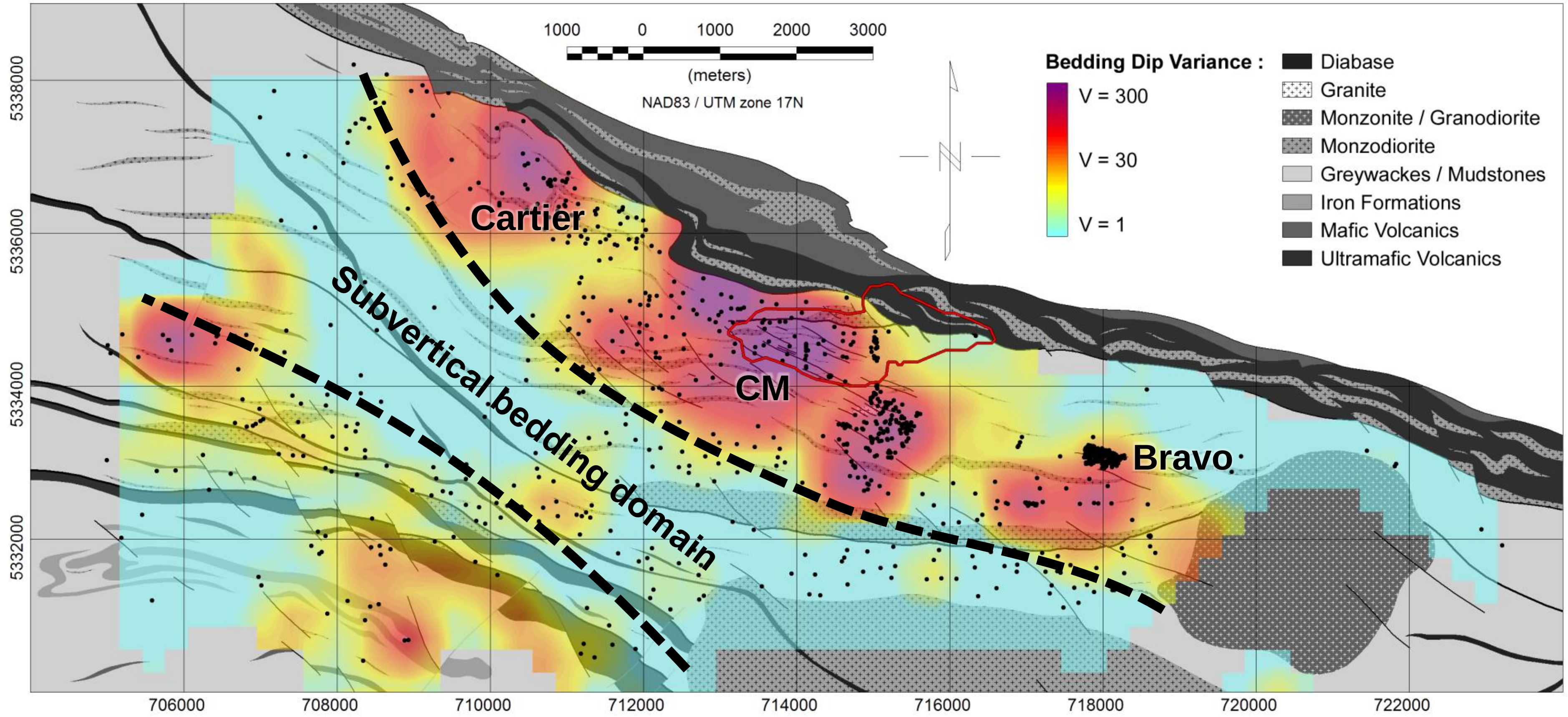
- Field mapping suggests that alteration zones are spatially associated with structurally complex zones (F_1 and F_2 fold hinges)
- The variance of the bedding dip highlights these fold interference zones



Perrouty et al. *(2017, Ore Geology Reviews)*

Mineralogy (*mafic dykes*)

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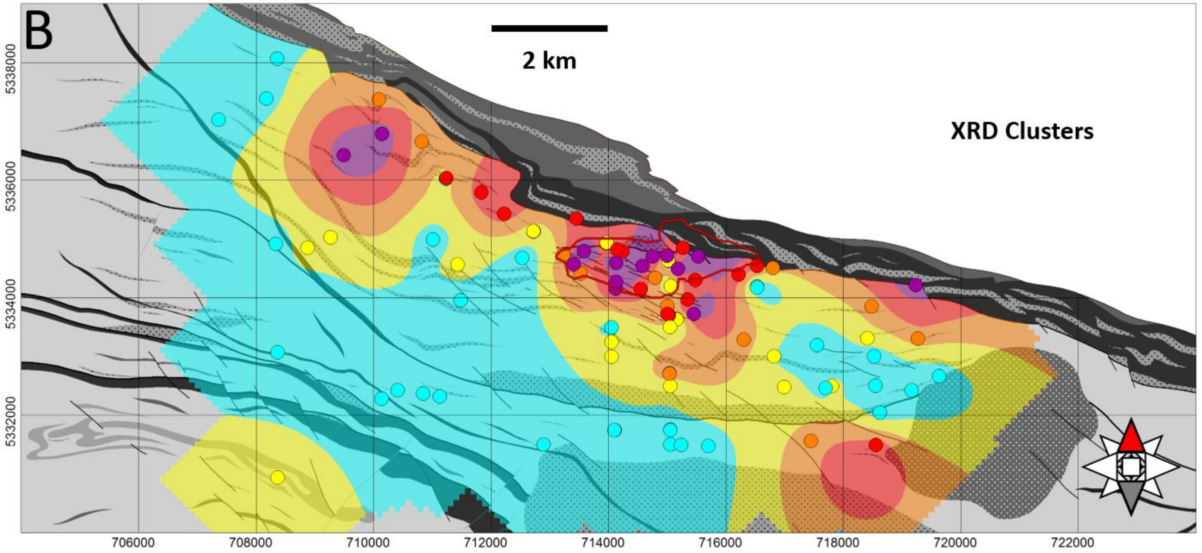
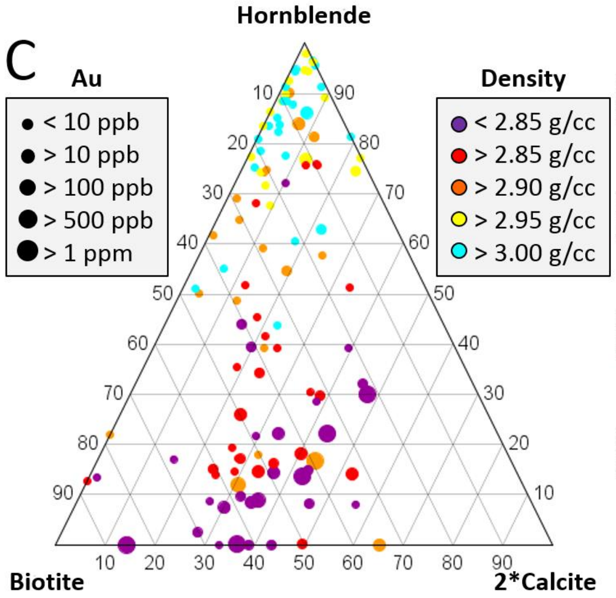
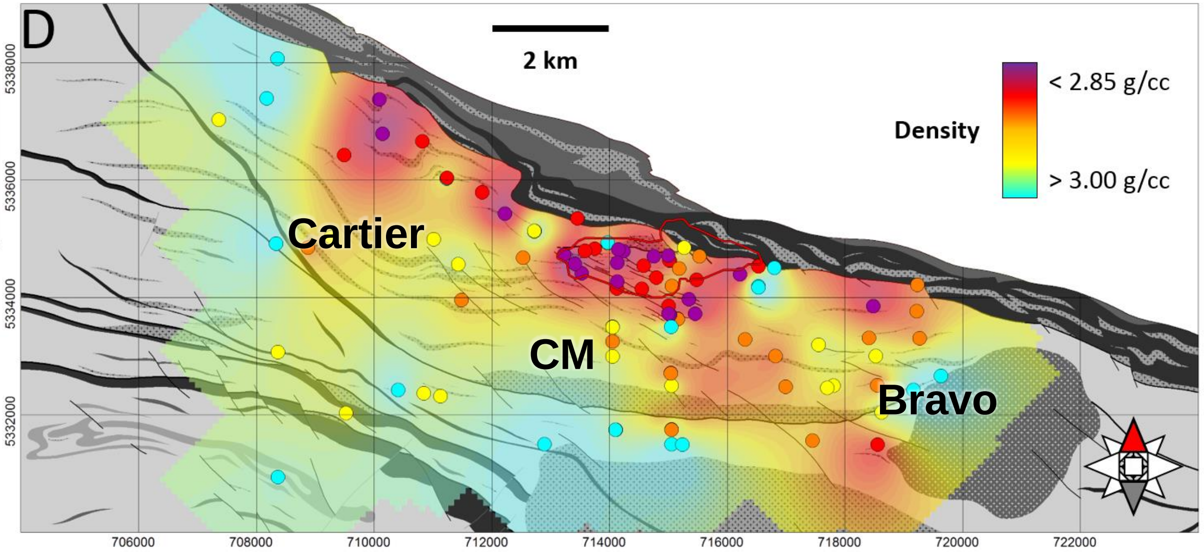
A

Cluster	#	Amp (%)	Bt (%)	Chl (%)	Pl (%)	Qz (%)	Cal (%)
A	6	84	1	2	13	2	< 1
B	21	78	1	4	13	4	< 1
C	9	77	< 1	4	4	15	< 1
D	11	53	3	5	28	11	1
E	12	39	16	2	31	12	< 1
F	13	13	36	< 1	24	24	3
G	18	< 1	67	1	4	13	14
H	3	< 1	48	3	4	31	14
I	17	< 1	45	1	30	11	13



- **XRD cluster analysis was performed to quantify and outline mineralogical changes**
- **Mineralogical changes are integrated with WR lithogeochemistry and rock density.**

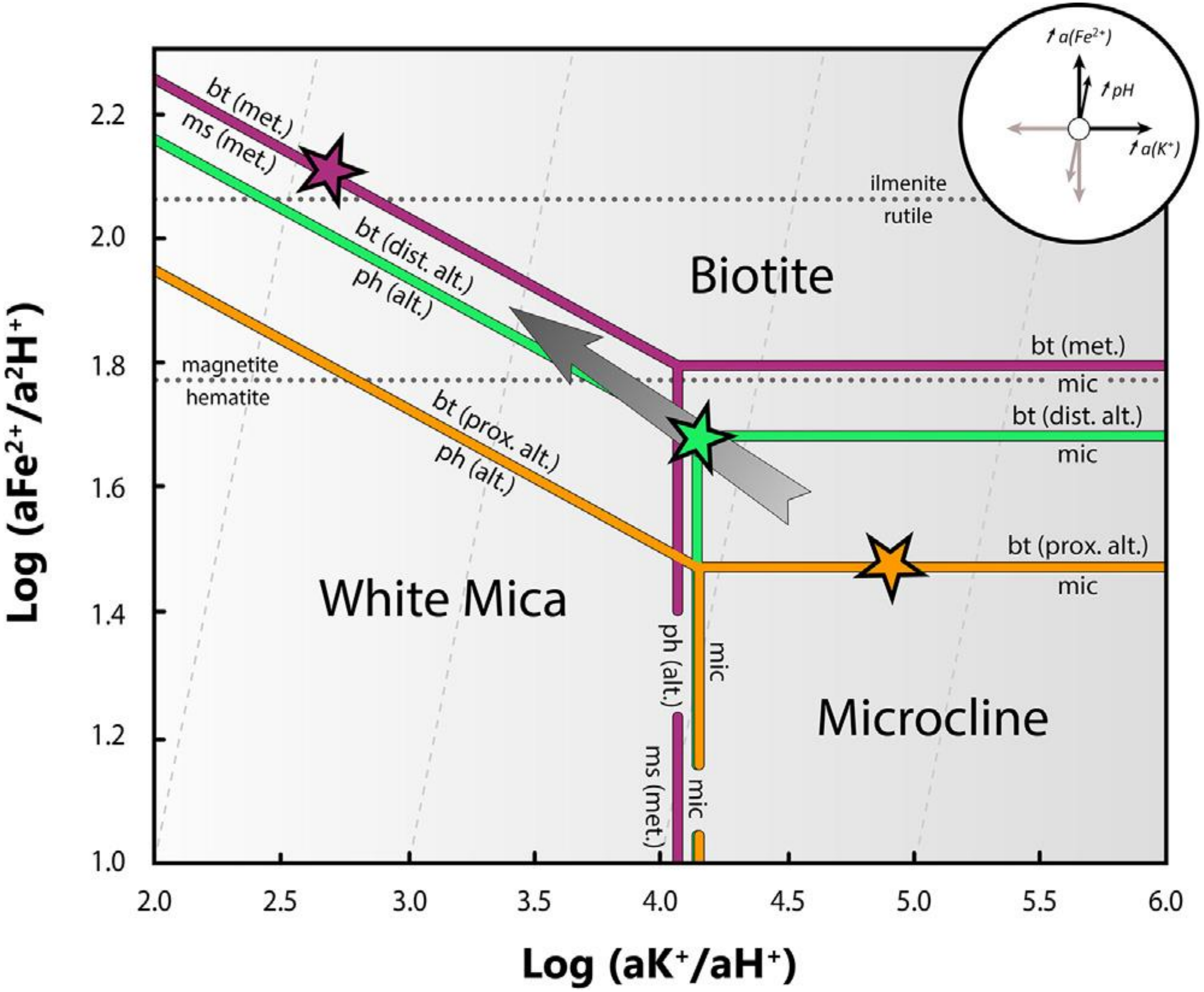




Perrouty et al. *(2018, Mineralium Deposita)*

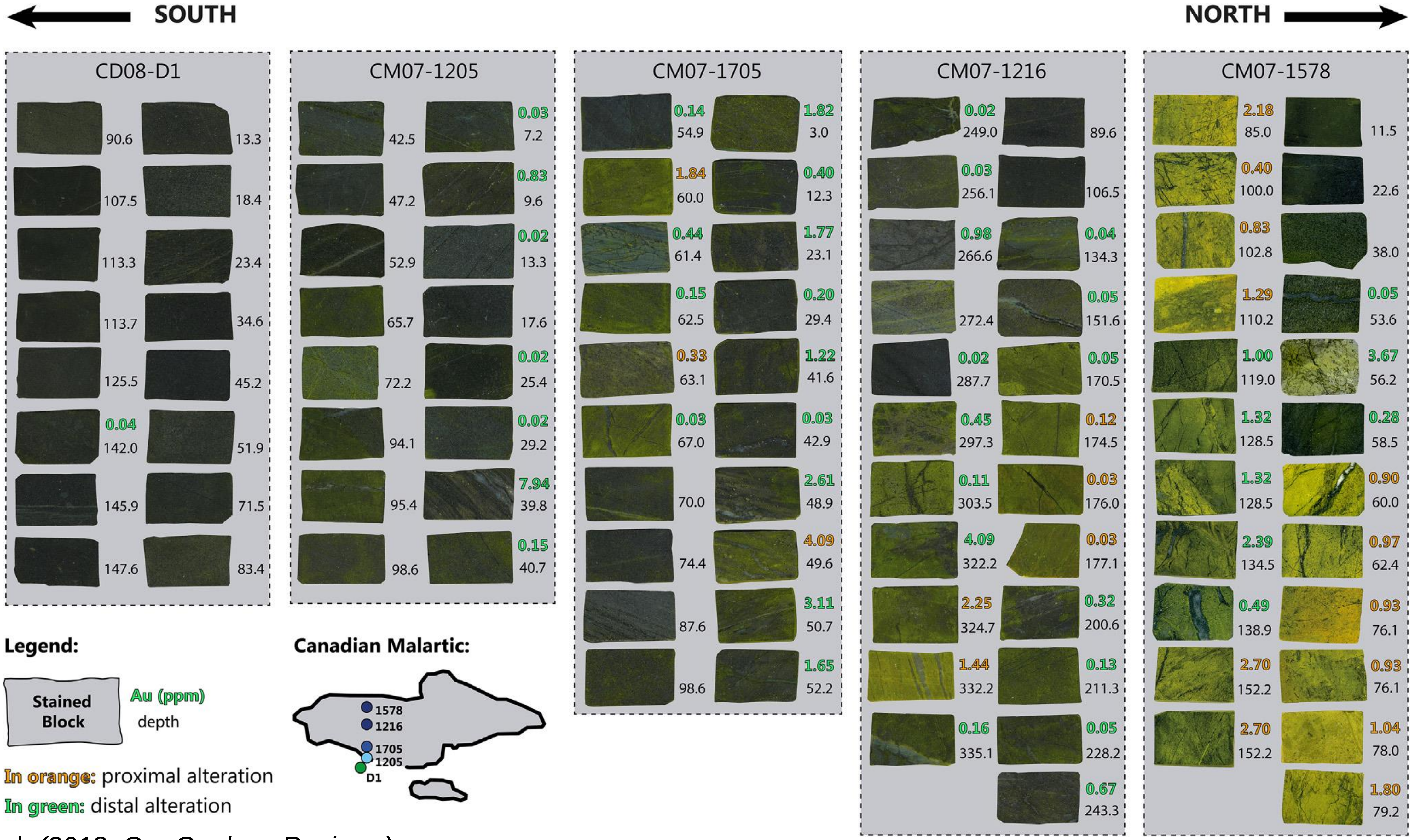
Mineral Chemistry (*metasedimentary rocks*)

- **Diagram showing stability relationships among hydrothermal alteration K-silicates** (biotite, white mica and microcline) **in greywacke at the estimated conditions of ore formation** (475 °C and 3 kbar; Helt et al., *2014, Economic Geology*)
- The inferred physico-chemical conditions are represented by stars for the non-altered metamorphic assemblage (purple), and for the distal (green) and proximal (orange) alteration zones
- **The apparent increase in the aFe^{2+}/a^2H^+ ratio is interpreted to reflect decreasing sulfur content (less pyritization) with distance from the hydrothermal center**



Gaillard et al. *(2018, Ore Geology Reviews)*

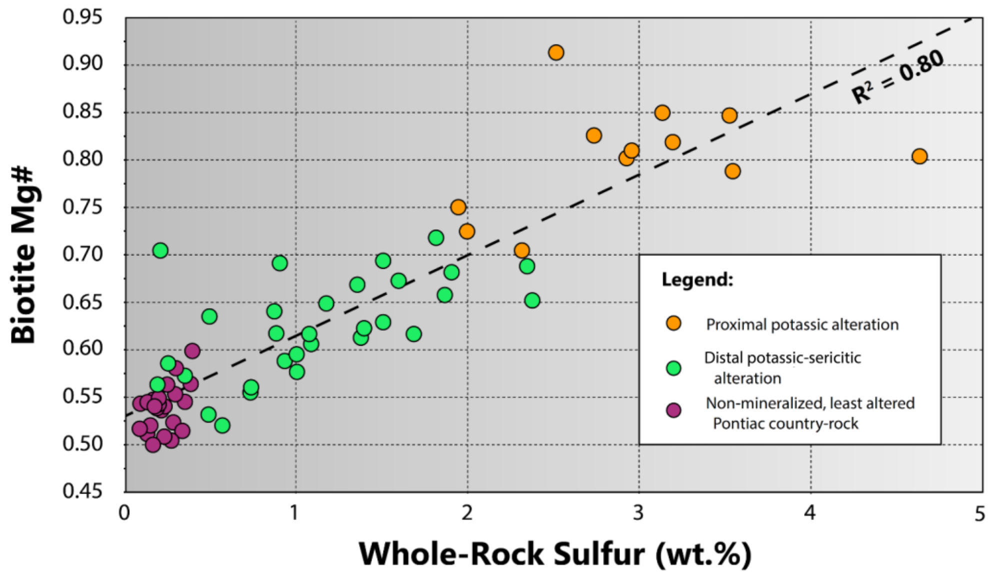
Feldspar Staining



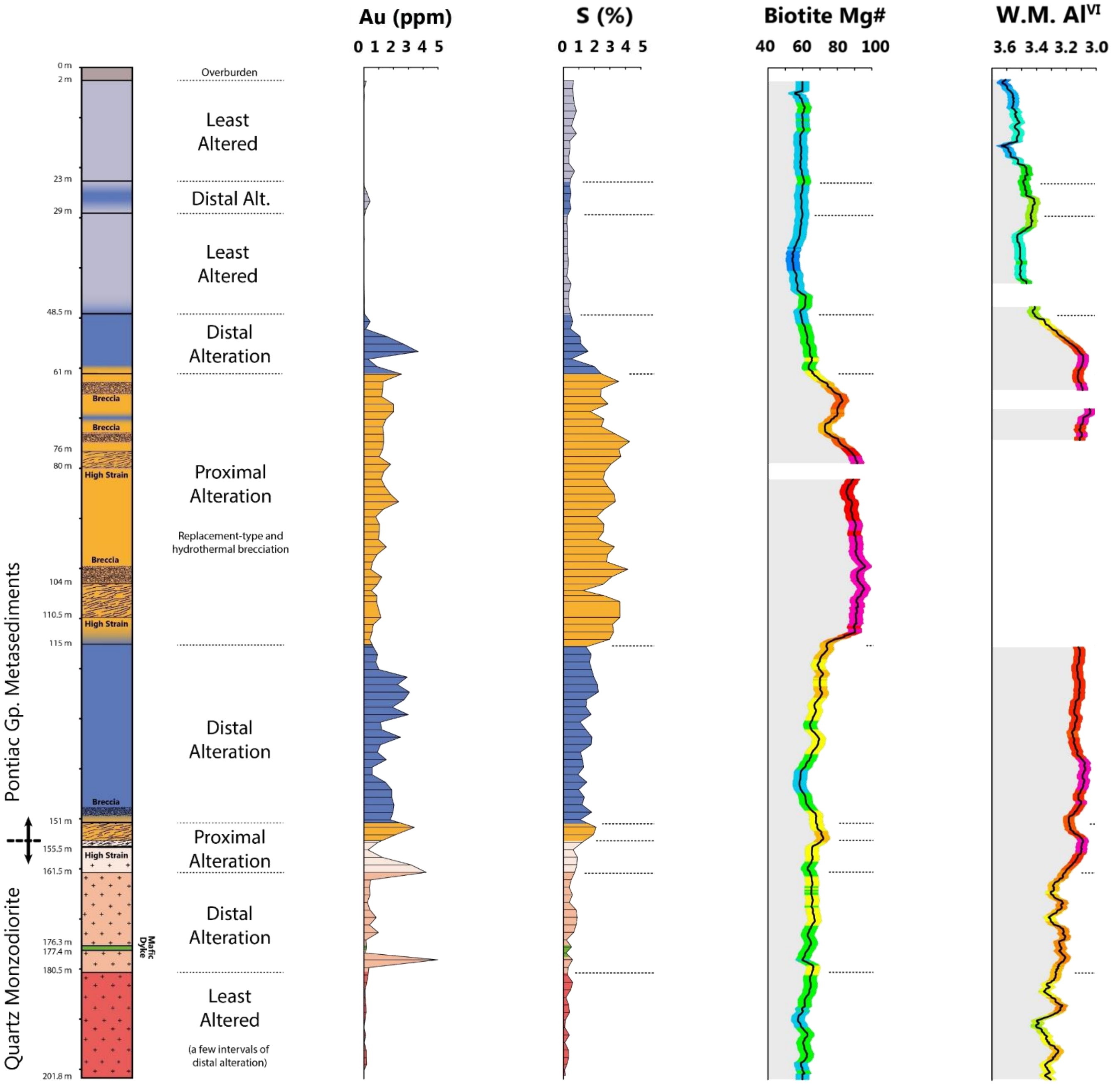
Gaillard et al. *(2018, Ore Geology Reviews)*

Mica Chemistry

- **Biotite Mg# correlates positively with whole-rock sulfur content** *(i.e., a proxy for pyrite)*



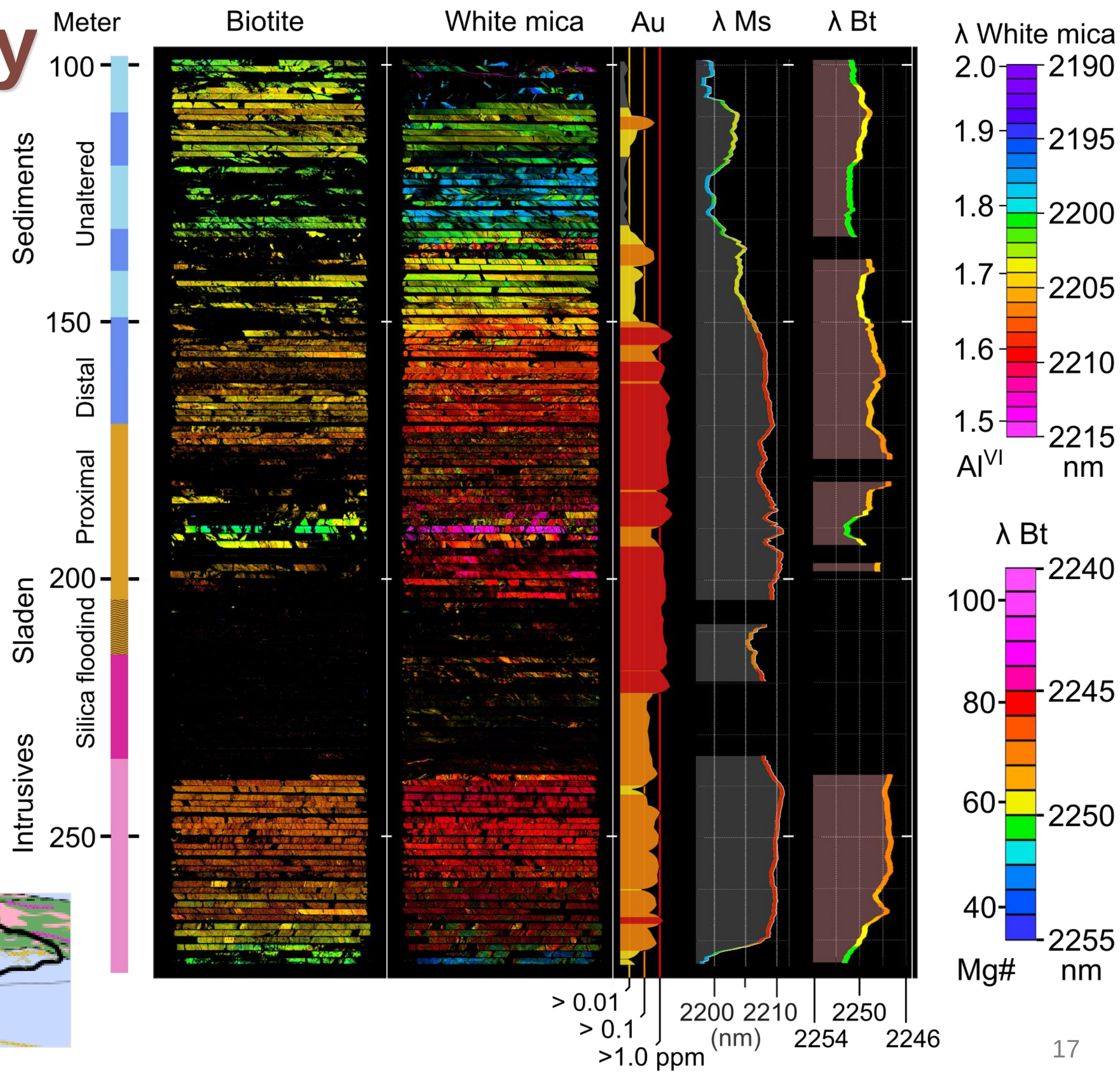
- Mg-enrichment of ore-zone biotite was caused by Fe-buffering by pyrite under increasing ∑aS-fO_2 conditions. Tschermak exchange in mica from proximal and distal alteration zones was controlled by variations in $a(K^+)$ and/or pH.



Gaillard et al. *(2018, Ore Geology Reviews)*

Hyperspectral Imagery

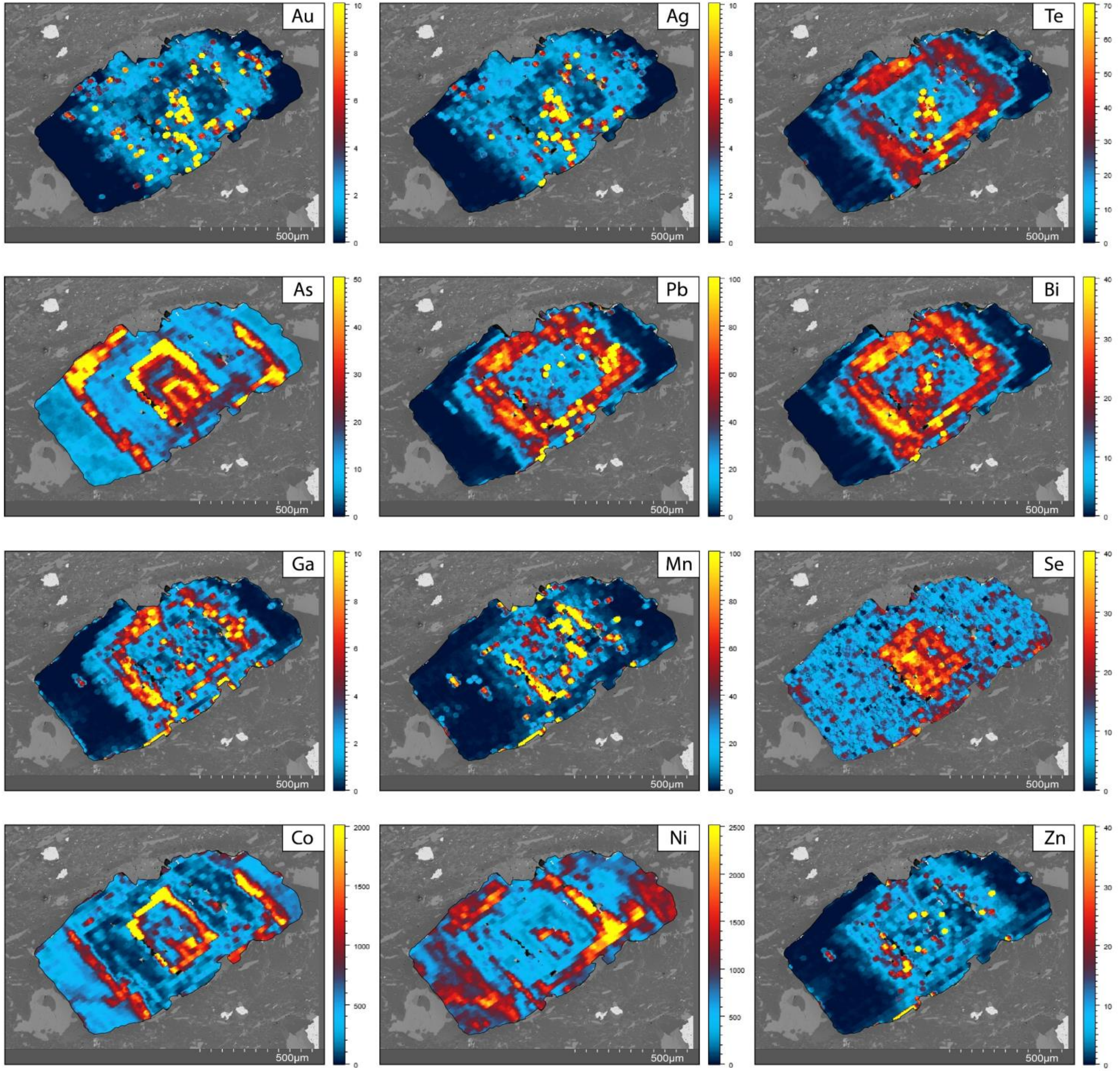
- Chemical analysis of biotite and white mica using hyperspectral imagery:
  - **Can be used as a proxy for alteration in metasedimentary and intrusive rocks.**
  - **Enables the rapid delineation of altered intervals.**
  - **Minimizes assaying barren intervals.**

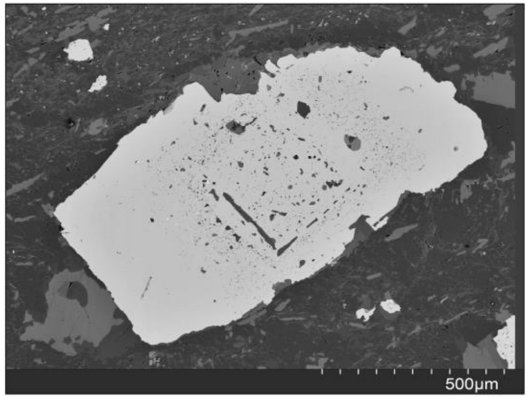


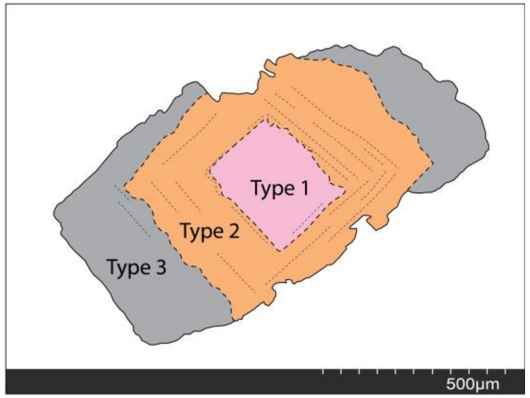
Lypaczewski et al. *(Submitted)*

Pyrite Maps

- **Three hydrothermal pyrite types:** pyrite 1 and 2 contain numerous inclusions (gold, tellurides) and is overgrown by inclusion-free pyrite 3
- **ICP-MS trace element mapping shows that pyrite 2 is associated with the main ore-forming event and is enriched in Au-Ag-Te-Bi-Pb**



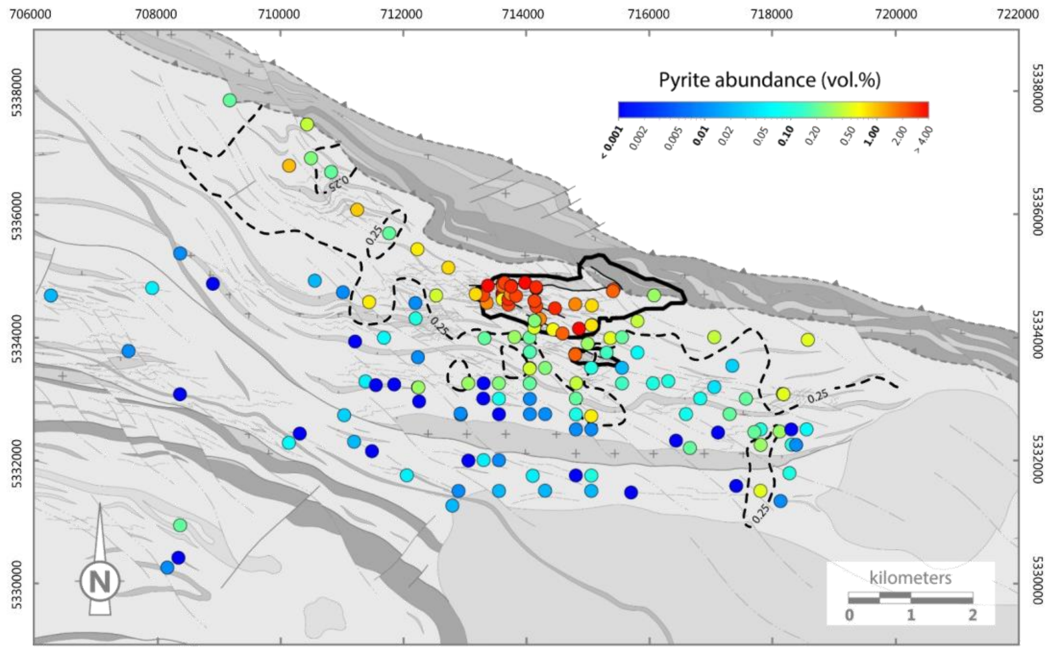


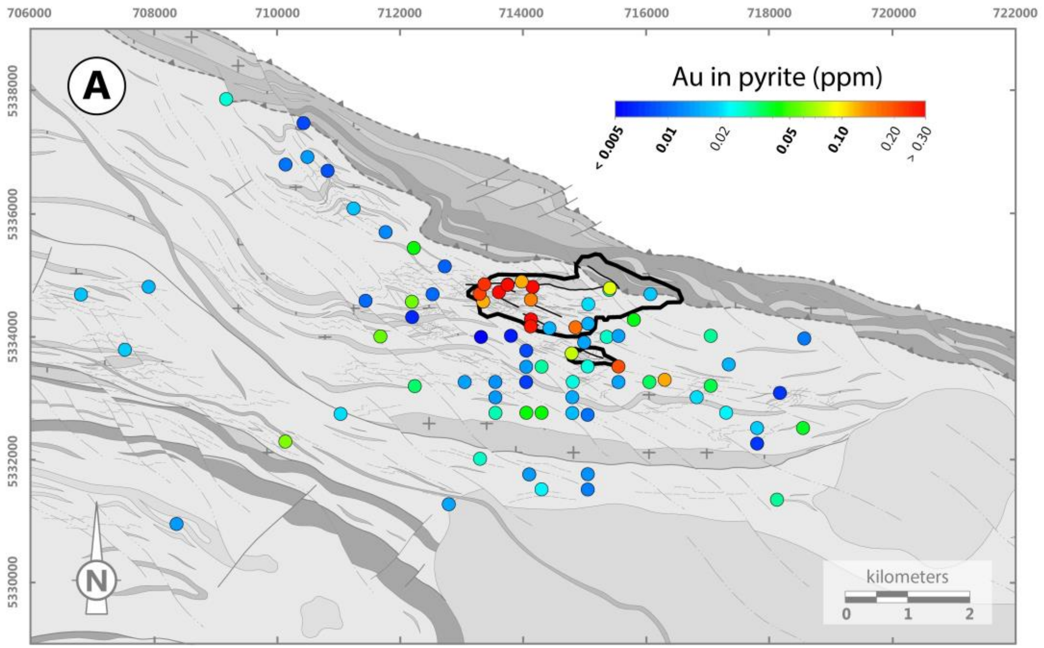


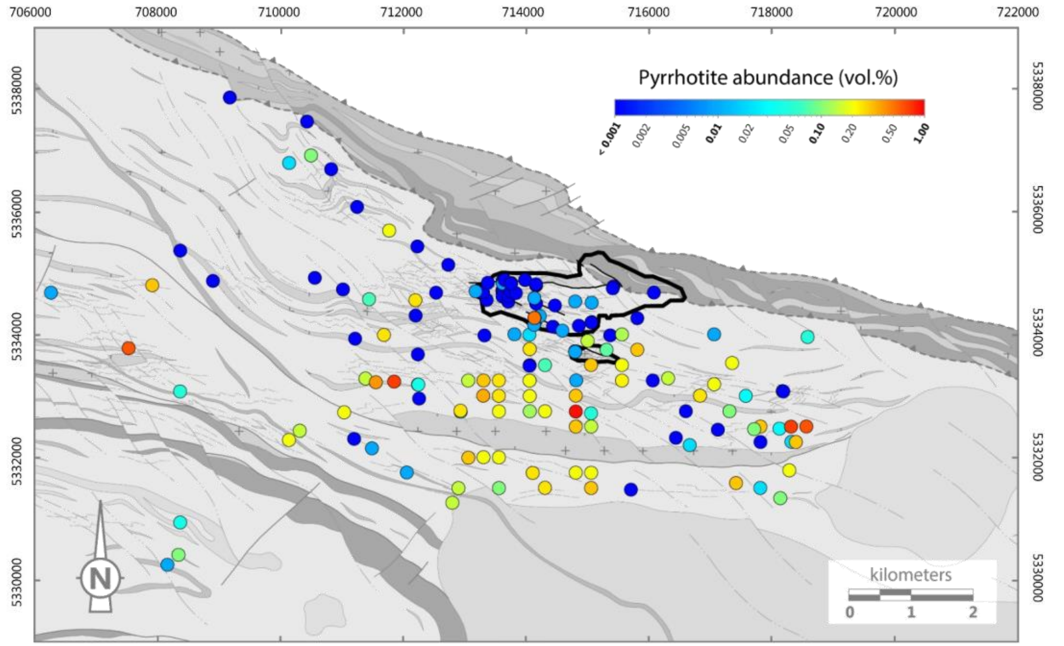
Gaillard et al.
(submitted)

Sulfide Minerals

- Samples with elevated pyrite abundance (>0.25 vol%) delineate an hydrothermal halo parallel to the CLLDZ and to the E-W Sladen Fault.
- Pyrrhotite formed by gradual replacement of pyrite during prograde metamorphism.
- Hydrothermal pyrite in the deposit is enriched in Au (and Te) relative to pyrite beyond the ore-shell.







Gaillard et al. *(submitted)*

Geophysical Implications

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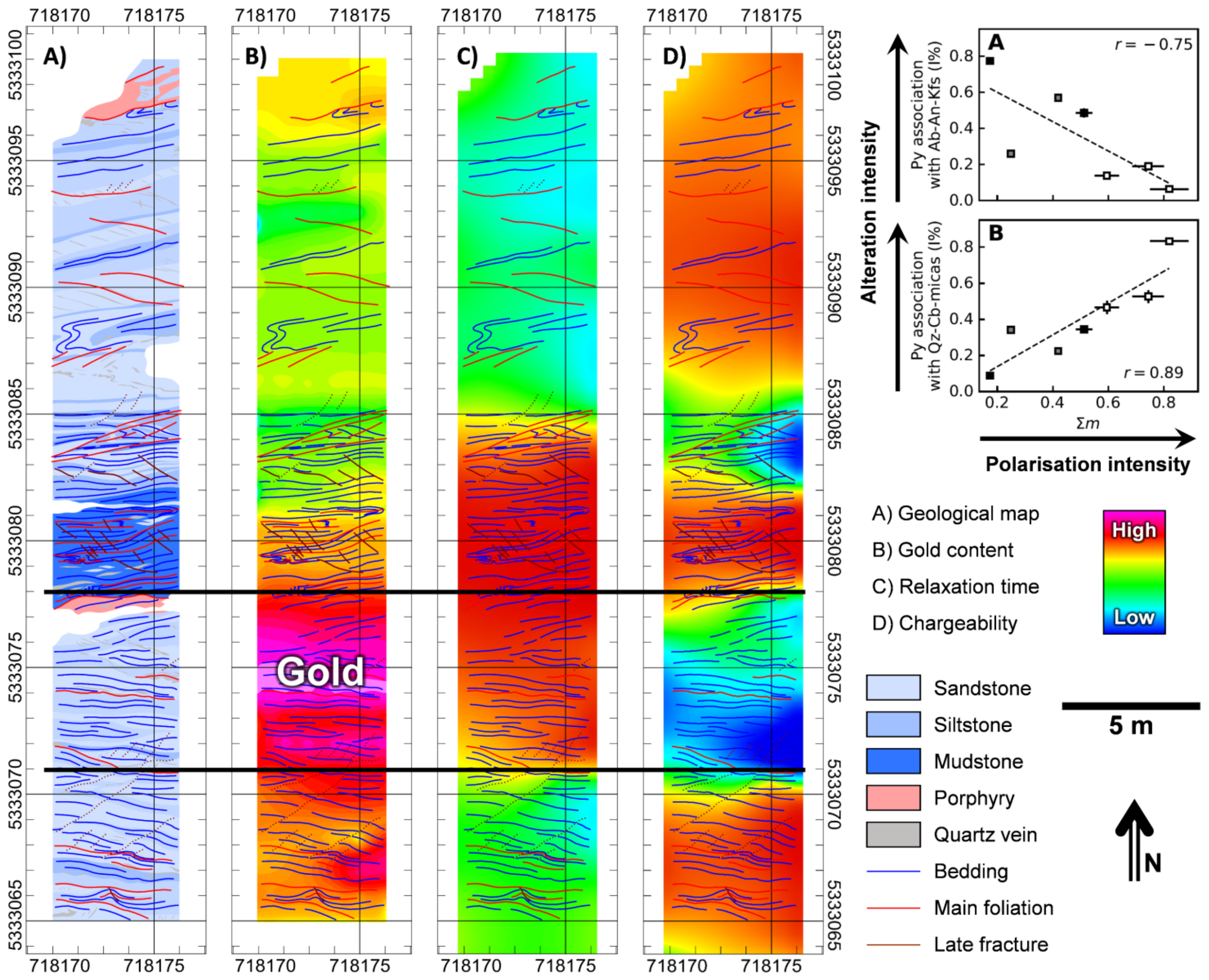
- ~~More pyrite => more chargeability?~~
- **Chargeability increases with increasing surface of contact between sulfide minerals and porosity:**
- Medial/distal alteration is marked by pyrite (or pyrrhotite) in contact with biotite and white mica.
- Proximal alteration is marked by pyrite encapsulated in microcline and/or albite.
- **At Canadian Malartic, zones of pervasive hydrothermal alteration are characterized by low chargeability.**



Bérubé et al. *(in preparation)*

Summary

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- **There are several structural, mineralogical, lithogeochemical and geophysical expressions of the footprint of the Canadian Malartic deposit:**
  - **Mineralogy analysis of mafic dykes** is a simple and field-based solution (just need a hand-lens) to detect hydrothermal alteration and gold mineralization.
  - **Carbonates or K-feldspar staining, hyperspectral imagery of mica and spectral IP survey** in metasedimentary rocks are simple tools to outline alteration and vector high-grade horizons.
  - **Pyrite abundance, texture and compositions** help to understand hydrothermal systems and can provide vectors toward mineralization.
  - **Zones of pervasive alteration are characterized by low chargeability** due to encapsulation of pyrite within feldspars.
  - **W-rich rutile and REE-bearing fluorocarbonates** are markers of the alteration.
  - **Whole-rock lithogeochemical analysis (total and partial digestion)** provides several vectoring information that can be easily integrated using PCA. Alternative field tools are pXRF.

Footprint Sponsors/Collaborators

NSERC-CMIC FOOTPRINTS

Collaborators: GSC TGI4 Program
MRN Québec
Saskatchewan Geological Survey
BC Geological Survey

Supporters: Fullagar Geophysics
Rekasa Rocks
UBC Geophysical Inversion Facility

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