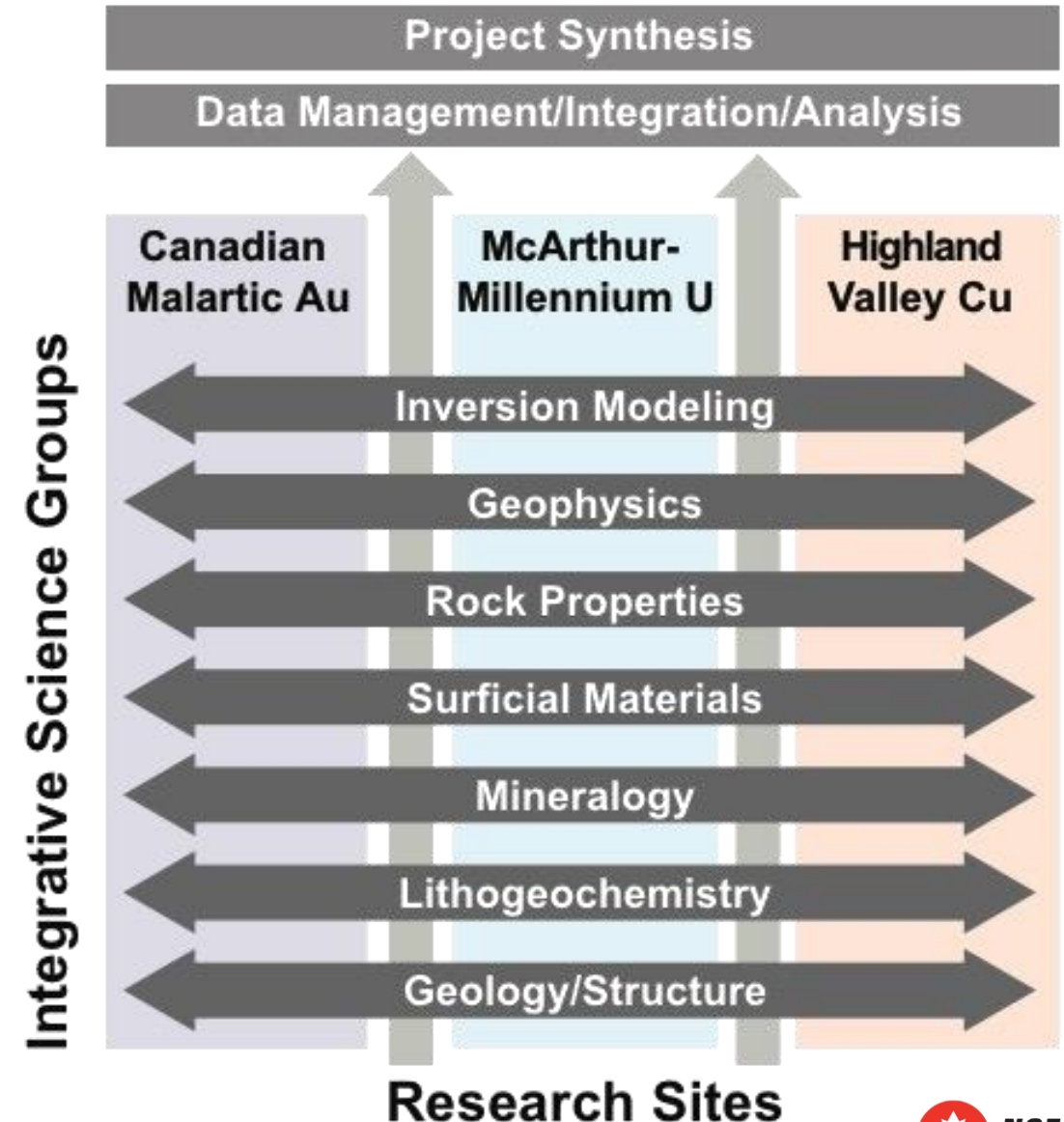


Integrated Multi-Parameter Footprint of the Canadian Malartic Gold Deposit

Stéphane Perrouty, Laurentian University
Robert L. Linnen, Western University
Gema R. Olivo, Queen's University
and the **NSERC-CMIC Mineral Exploration Research Network**

Footprint Project Objectives

- **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



Au Site Team

◉ **Research associates**

- ◉ Stéphane Perrouy, *Western*
- ◉ James R. Clark, *McGill*

◉ **PhD students**

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- ◉ Kun Guo, *Toronto*
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- ◉ Thomas Raskevicius, *Laval*
- ◉ Caroline E. Taylor, *Waterloo*

◉ **BSc students**

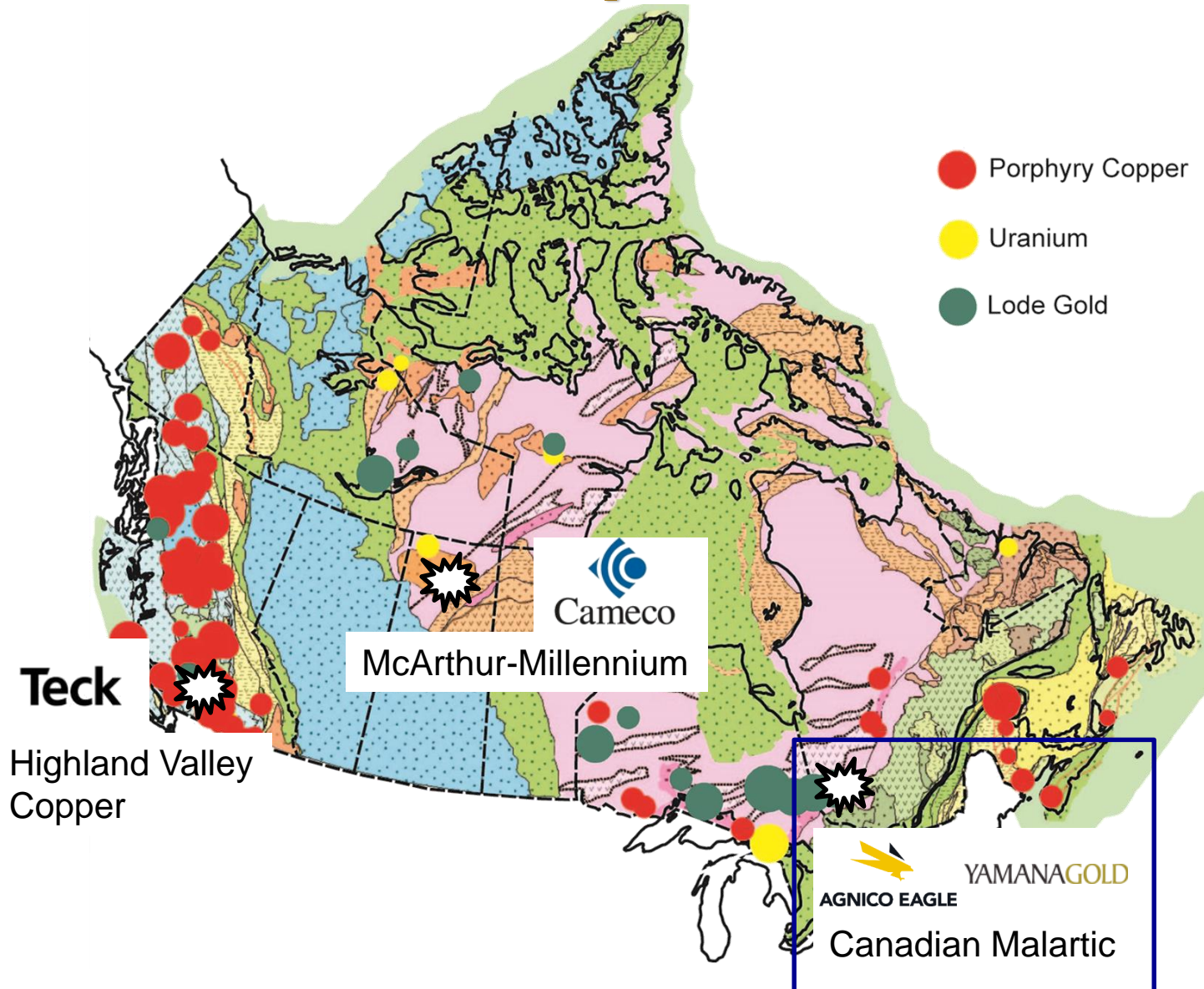
- ◉ Natalie Blacklock, *Queen's*
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- ◉ Robin K. Taves, *Waterloo*

◉ **Researchers and collaborators**

- ◉ Georges Beaudoin, *Laval*
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- ◉ Christian Dupuis, *Laval*
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- ◉ Jilu Feng, *Alberta*
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- ◉ Robert L. Linnen, *Western*
- ◉ Bernd M. Milkereit, *Toronto*
- ◉ Reza Mir, *Laurentian*
- ◉ William A. Morris, *McMaster*
- ◉ Gema R. Olivo, *Queen's*
- ◉ Steve J. Piercey, *Memorial*
- ◉ Benoit Rivard, *Alberta*
- ◉ Martin Ross, *Waterloo*
- ◉ Stefano Salvi, *Toulouse*
- ◉ Iain M. Samson, *Windsor*
- ◉ Pejman Shamsipour, *Poly. Mtl.*
- ◉ Richard S. Smith, *Laurentian*
- ◉ Clifford R. Stanley, *Acadia*
- ◉ Marc Vallée, *Memorial*
- ◉ Anthony E. Williams-Jones, *McGill*

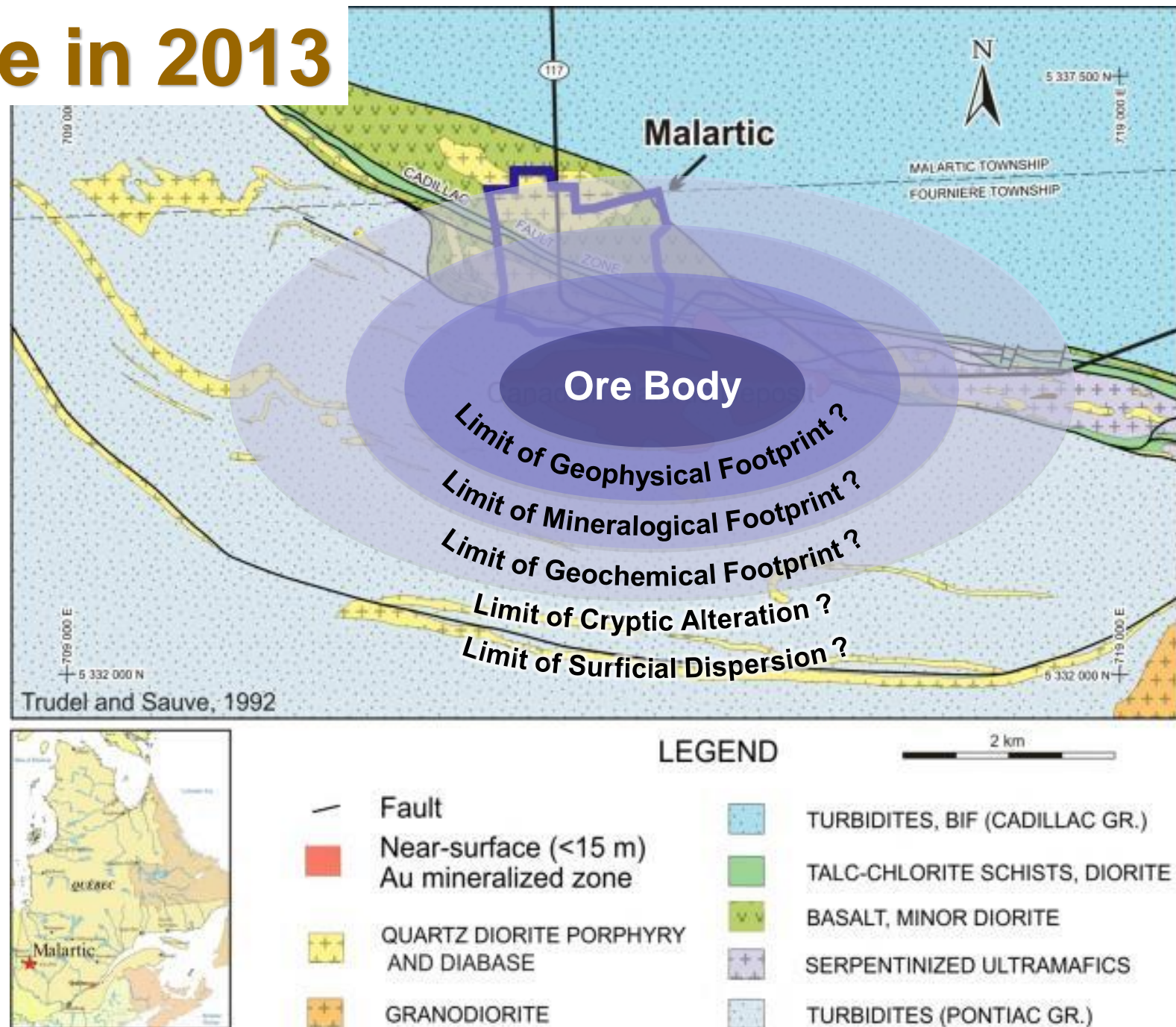
Location of Footprint Sites



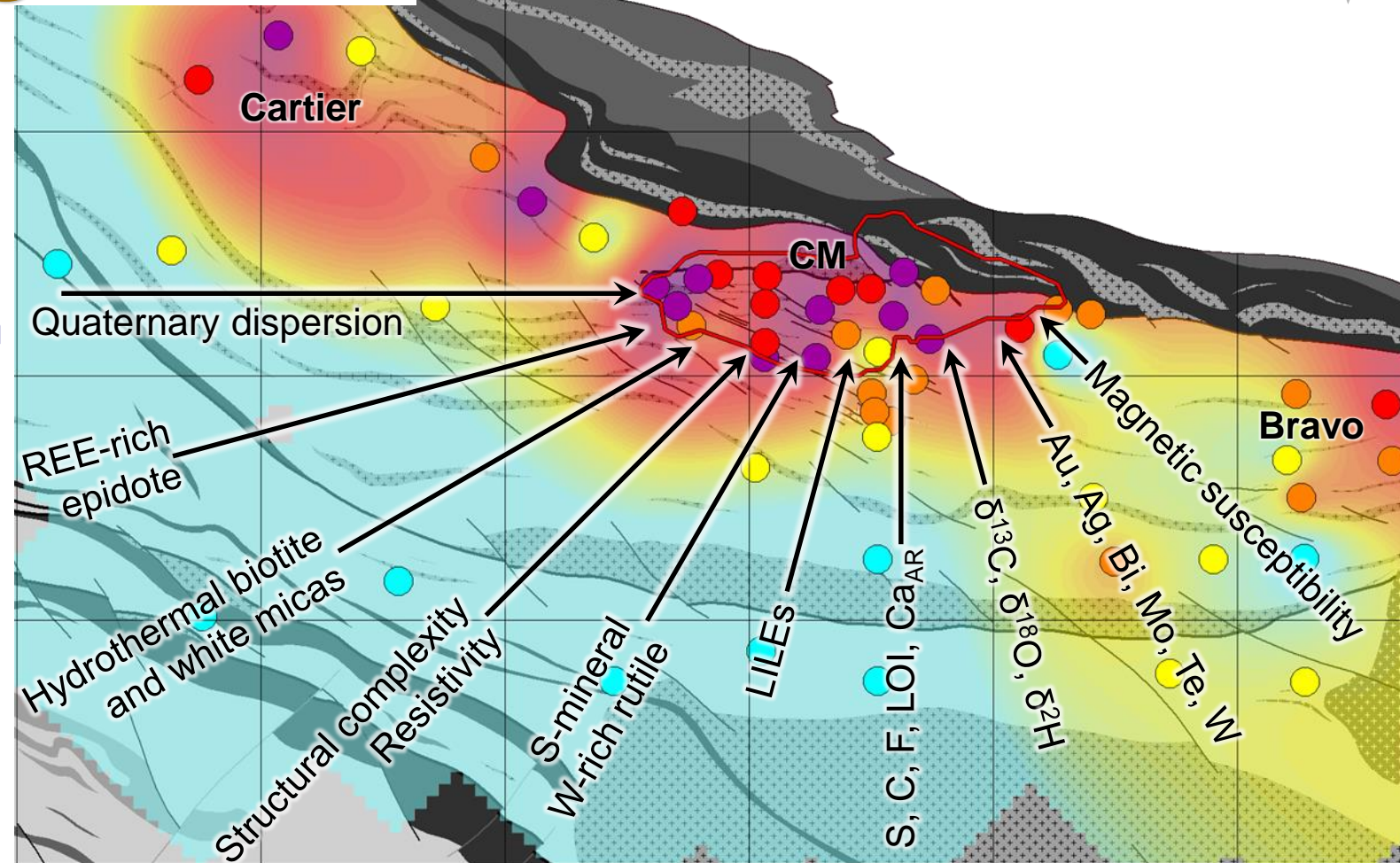
- **Canadian Malartic:**
 - **>18.6 Moz Au**
 - **South of the Cadillac - Larder Lake Deformation Zone, Québec**
 - **Oxidized intrusion-related deposit**
(Helt et al., 2012, *Economic Geology*)
 - **Stockwork-disseminated system** (De Souza et al., 2016, *Economic Geology*)

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



- 118 structural, geophysical, geochemical, mineralogical, and petrophysical halos
- Sizes range from 0.5 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

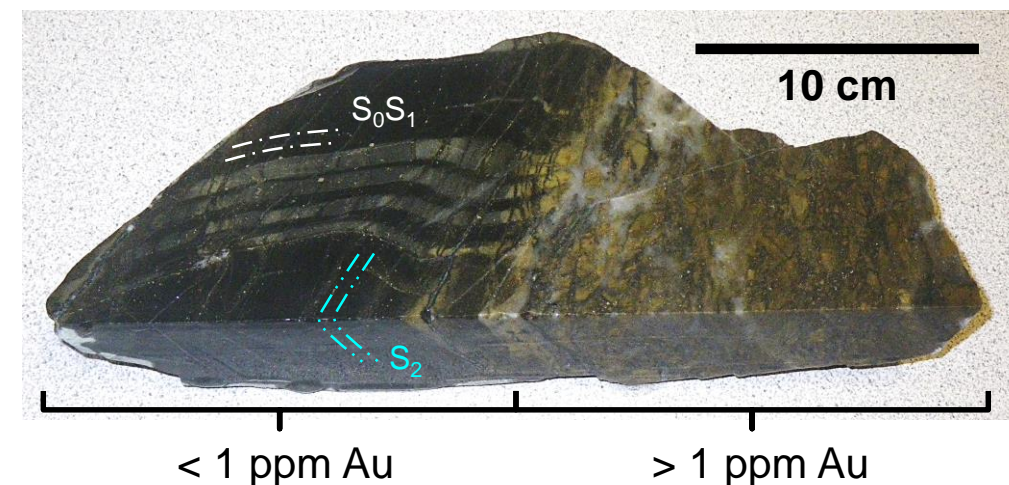
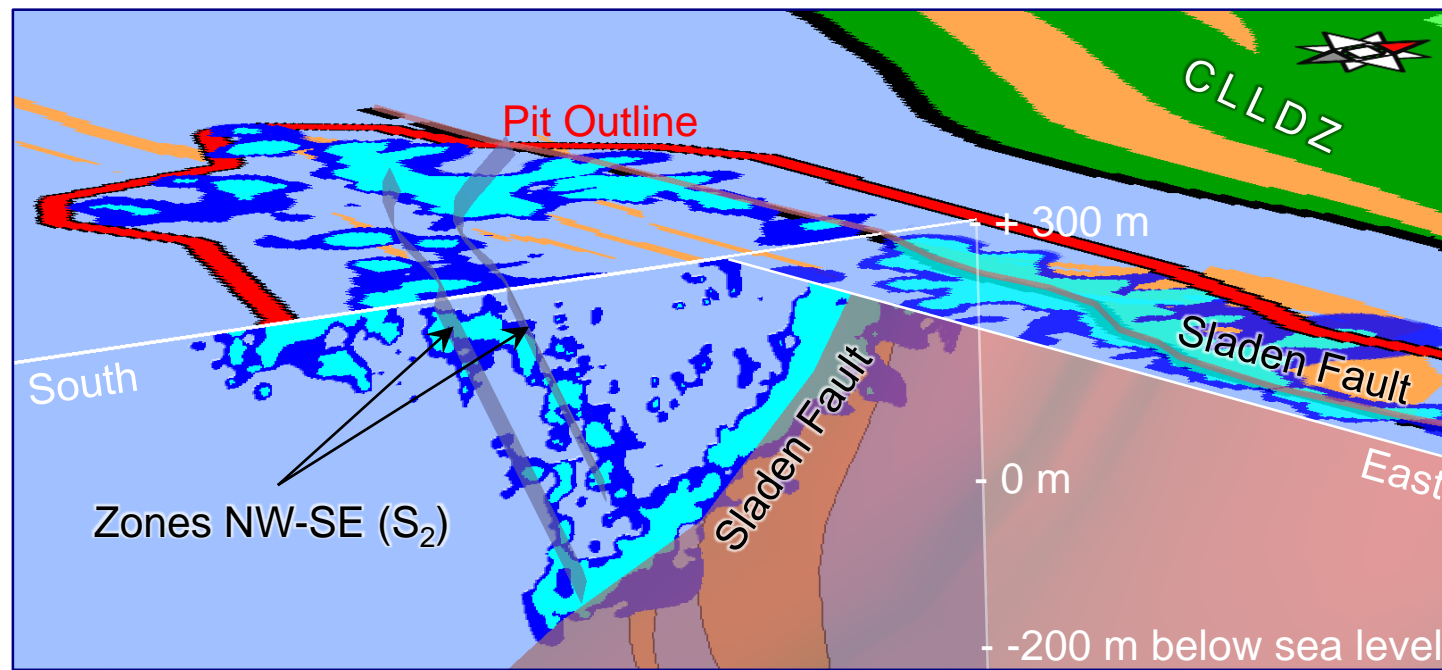
Main vectoring tools in the Canadian Malartic footprint

Major Results

- ◉ **Geological setting** and new metamorphic evolution model of the footprint
- ◉ **Structural footprint (zones of structural complexity, biotite foliation)**
- ◉ **Lithogeochemical, mineralogical and petrophysical halos in mafic dykes, metasedimentary and felsic-intermediate intrusive rocks**
- ◉ Isotopic ($\delta^2\text{H}$, $\delta^{18}\text{O}$, $\delta^{13}\text{C}$, $\delta^{34}\text{S}$) halos in mafic dykes and metasedimentary rocks
- ◉ **Mineral chemistry halos in metasedimentary rocks**
- ◉ **New geophysical approaches: spectral IP, anisotropy of resistivity, variance**
- ◉ Multi-parameter integration through PCA and machine learning approaches
- ◉ **New surficial exploration approach using mica compositions**

Geological Setting

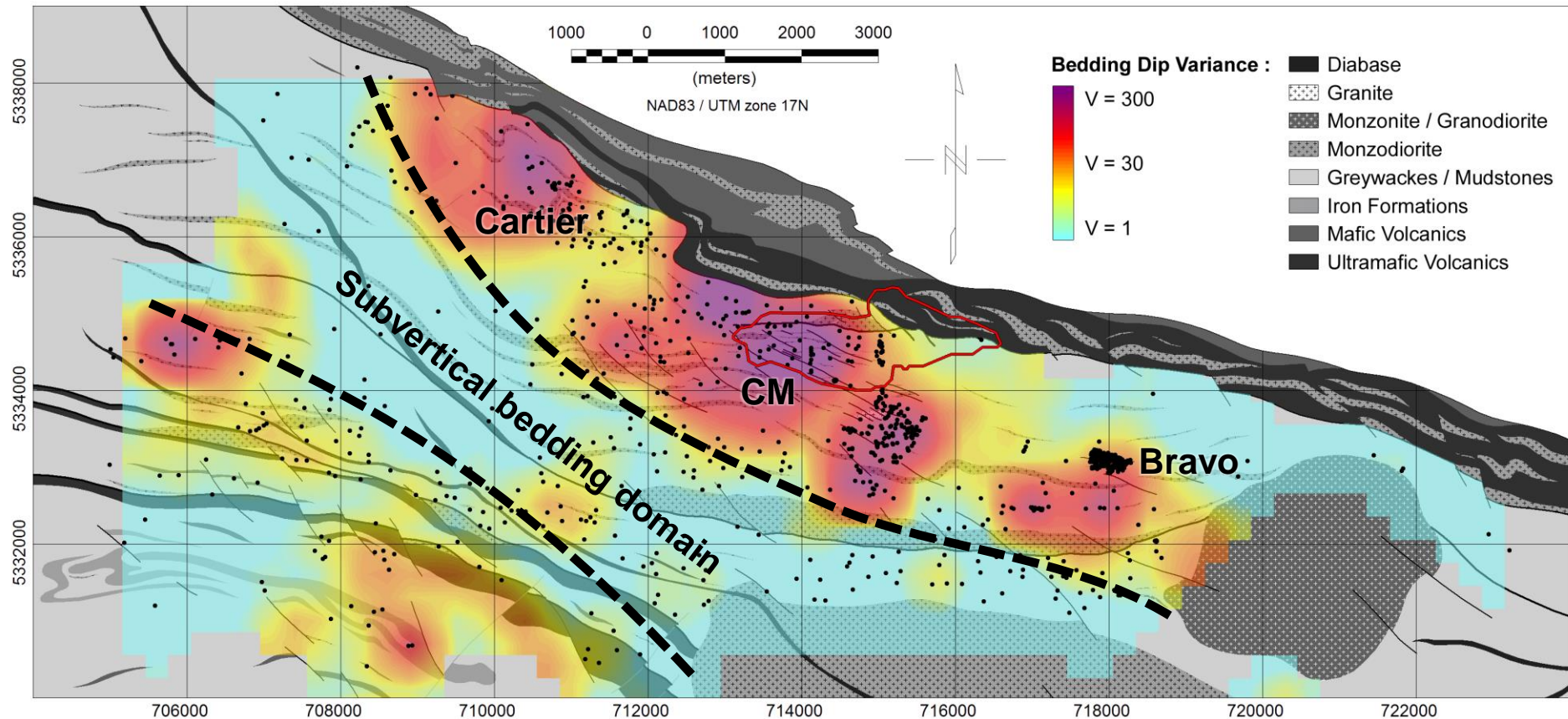
- 3 deformation events: D_1 - isoclinal F_1 folds, pressure-solution cleavage (S_1)
 D_2 - close s-shaped F_2 folds, NW-SE biotite cleavage (S_2)
 D_3 - subtle crenulation cleavage (S_3)
- 2 structural controls: E-W Sladen fault and NW-SE high-strain zones (in F_2 fold hinges)



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

Structural Footprint

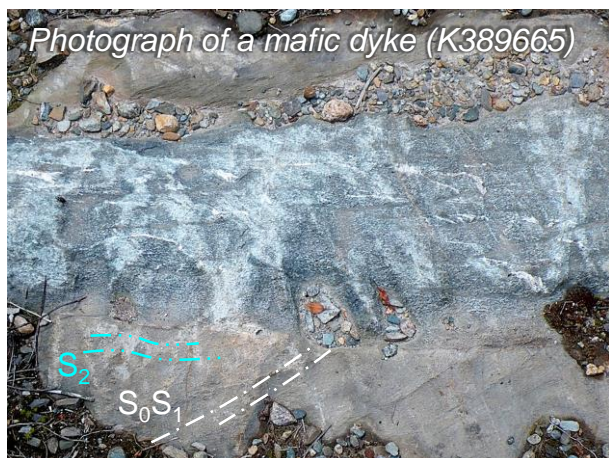
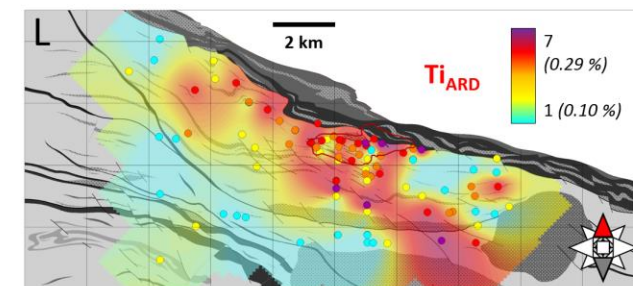
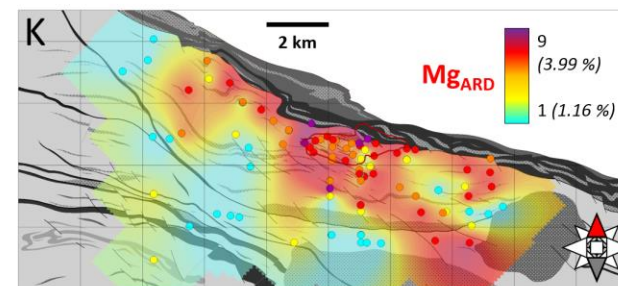
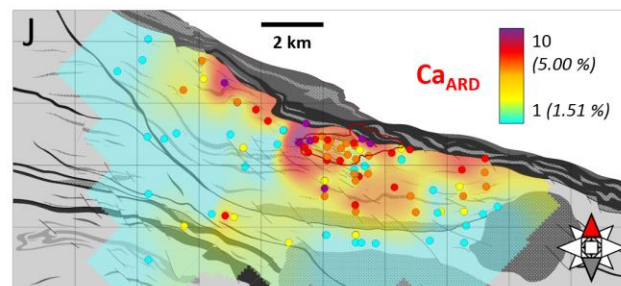
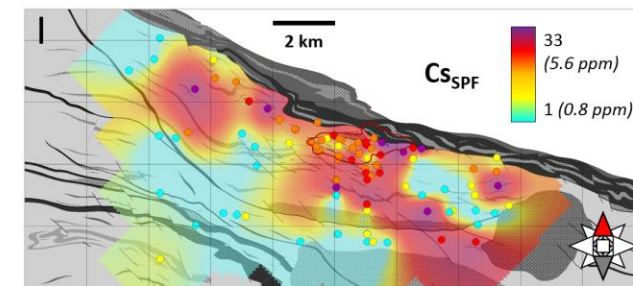
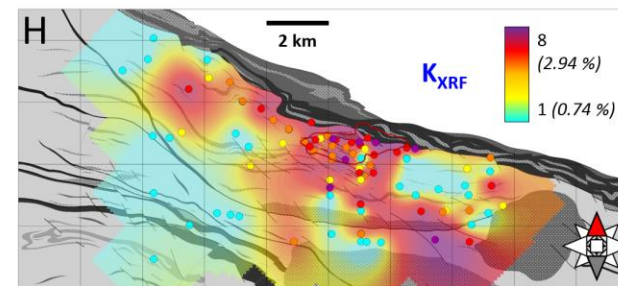
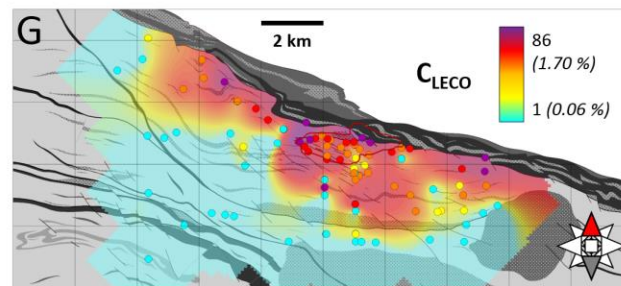
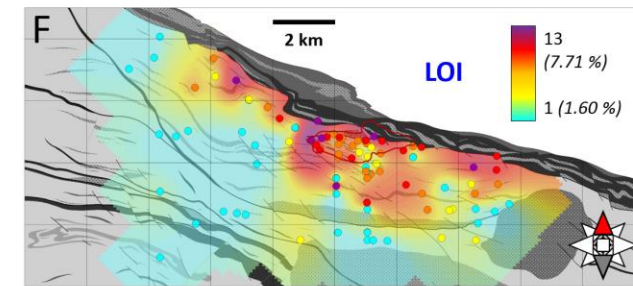
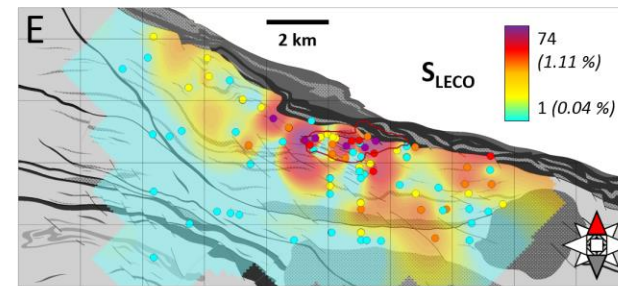
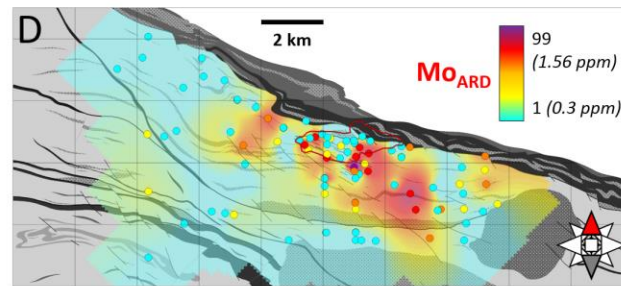
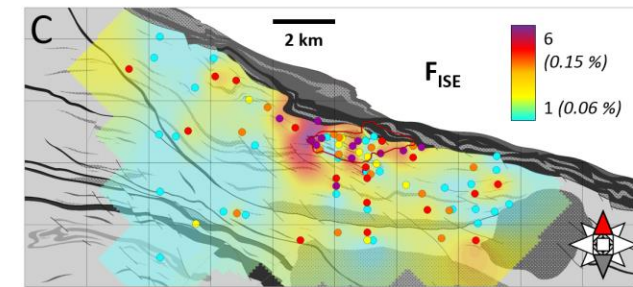
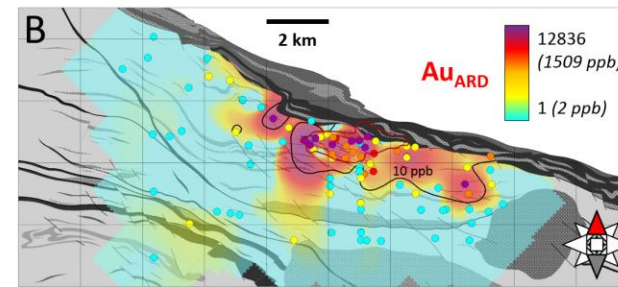
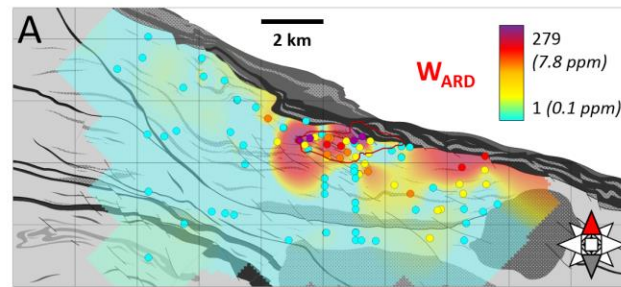
- Field mapping suggests that alteration zones are spatially associated with structurally complex zones (F_1 and F_2 fold hinges).
- The variance of the bedding dip highlights these fold interference zones.



Perrouy et al. (2017,
Ore Geology Reviews)

Geochemical Halos (*in mafic dykes*)

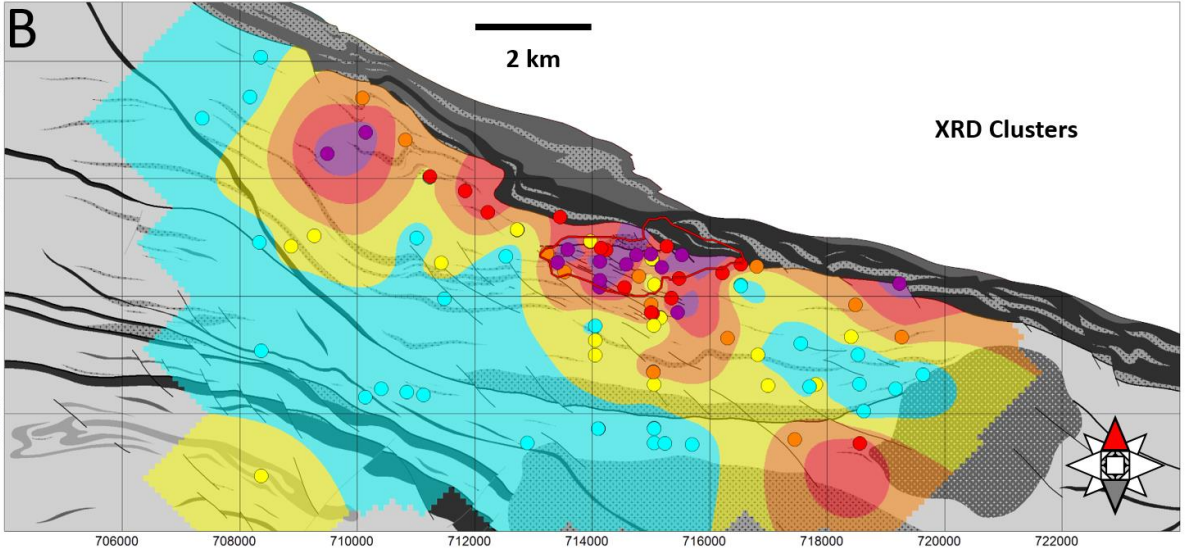
- Whole-rock (partial and total digestion) lithogeochemical halos are controlled by structures.
- Concentration gain factors are calculated using the method of Gresens (1967) and MacLean (1990).



Mineralogical Halos (in mafic dykes)

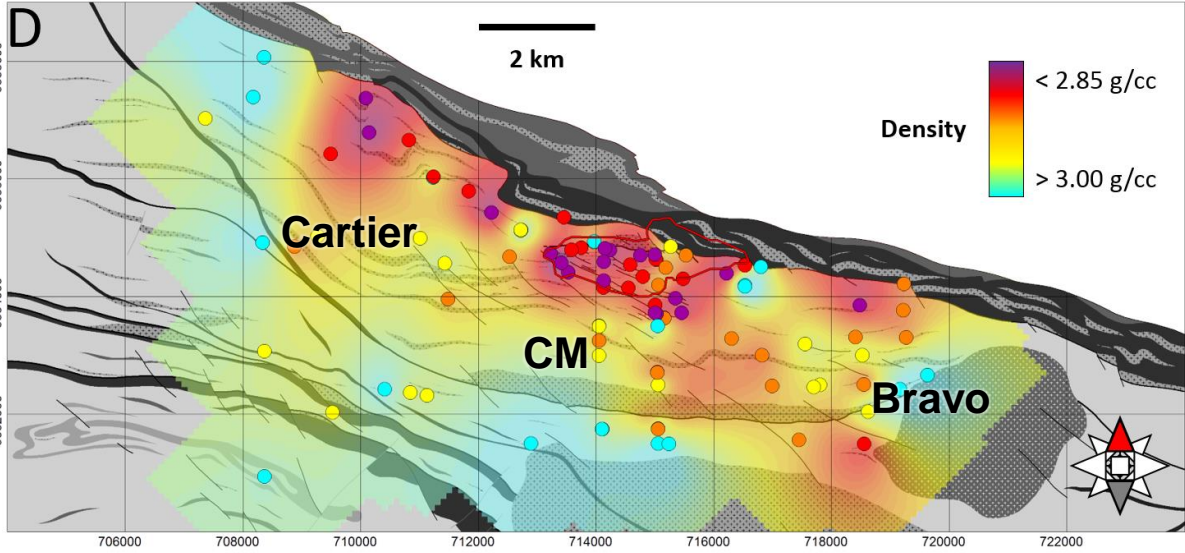
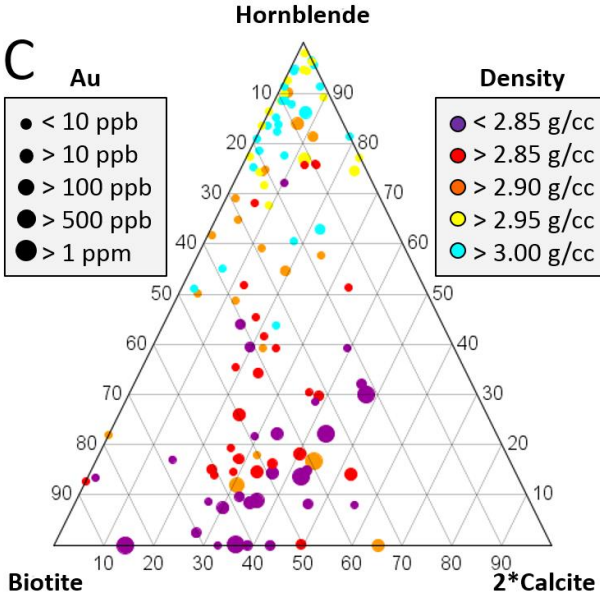
A

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



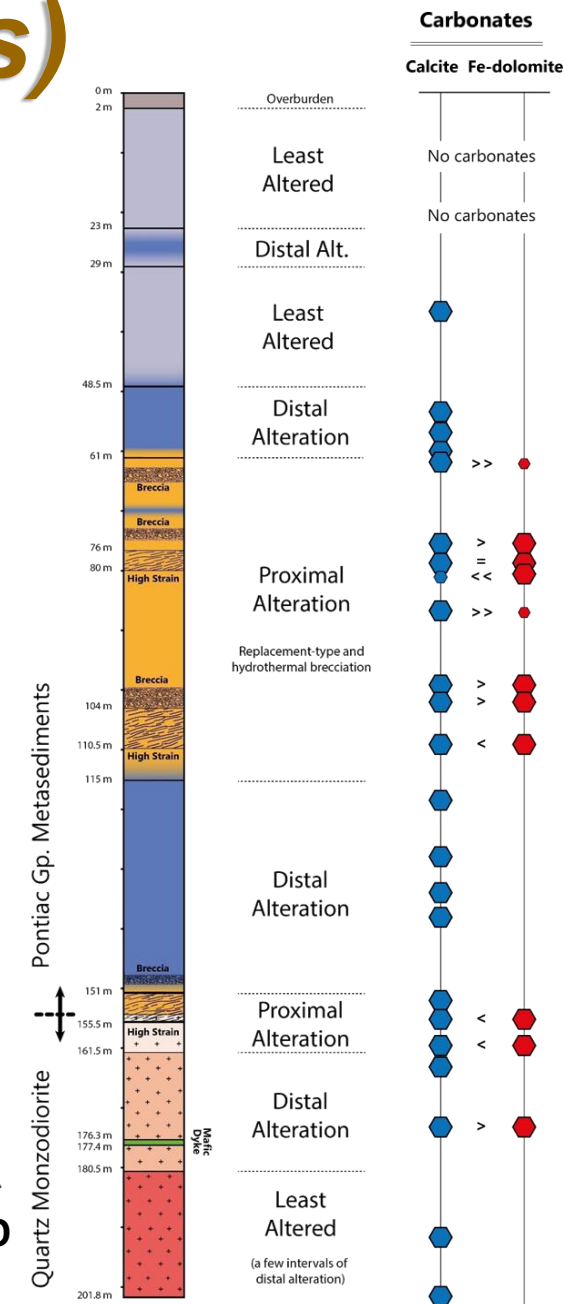
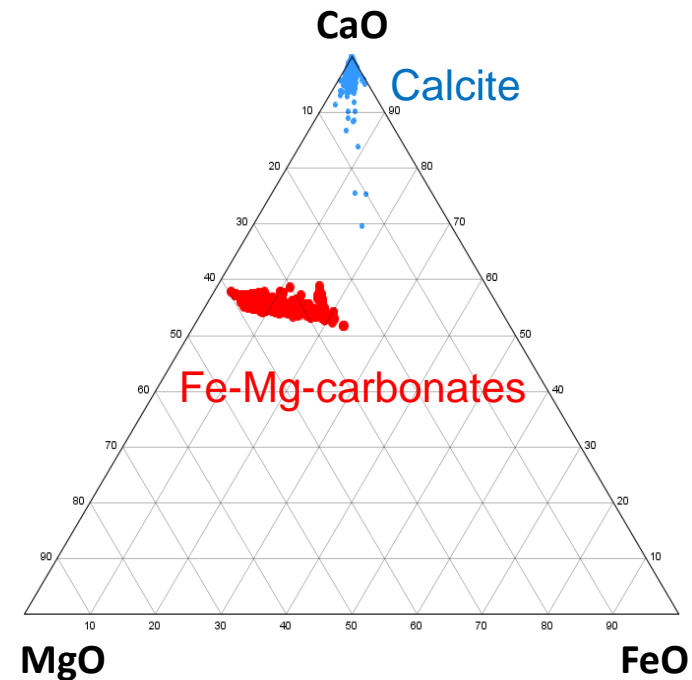
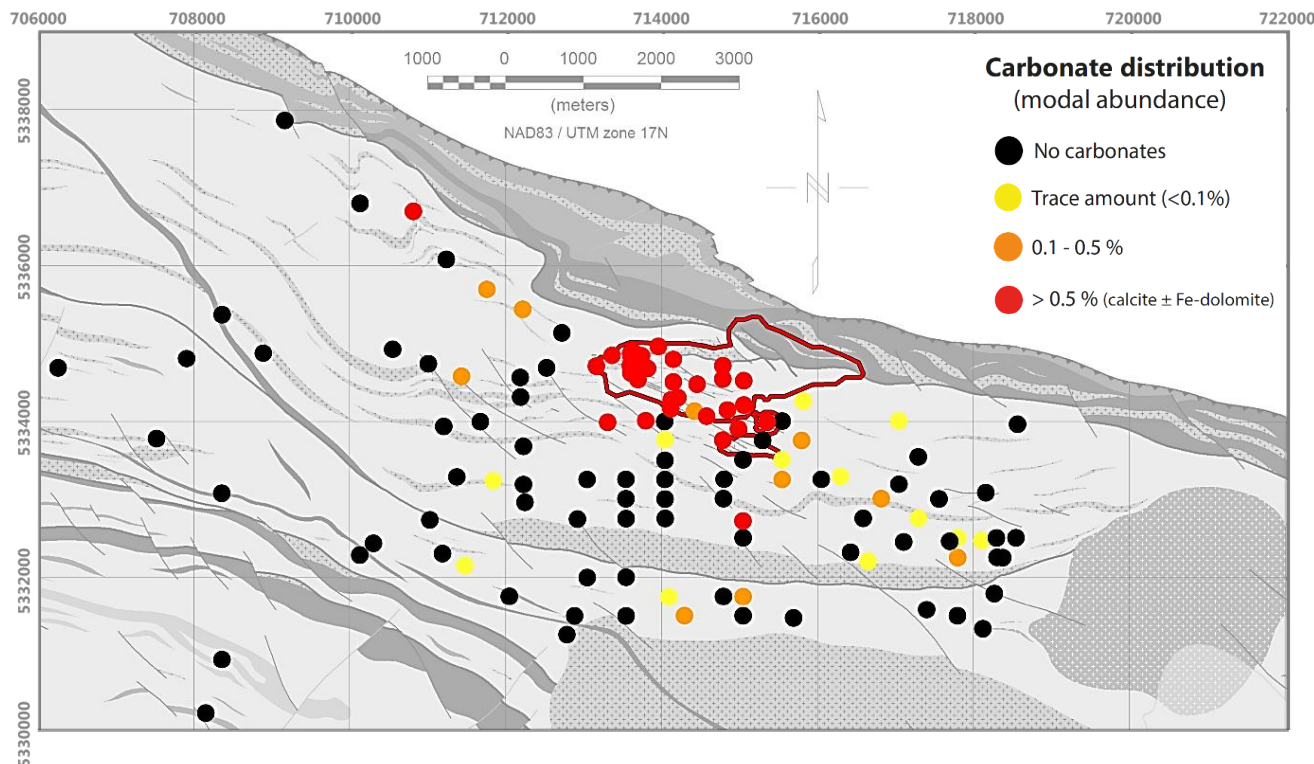
- Lithogeochemical changes are reflected in the mineralogy and rock density.

- XRD cluster analysis was performed to quantify and outline mineralogical changes.



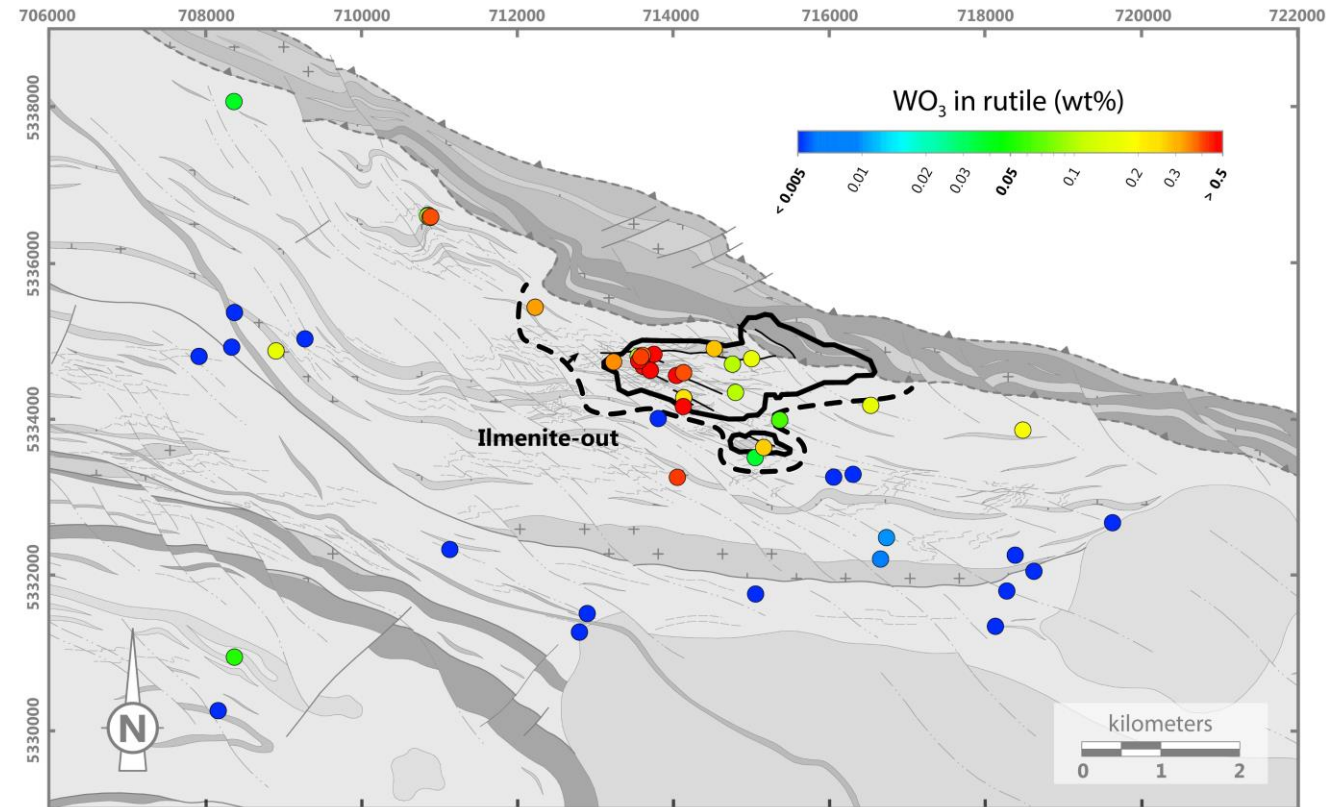
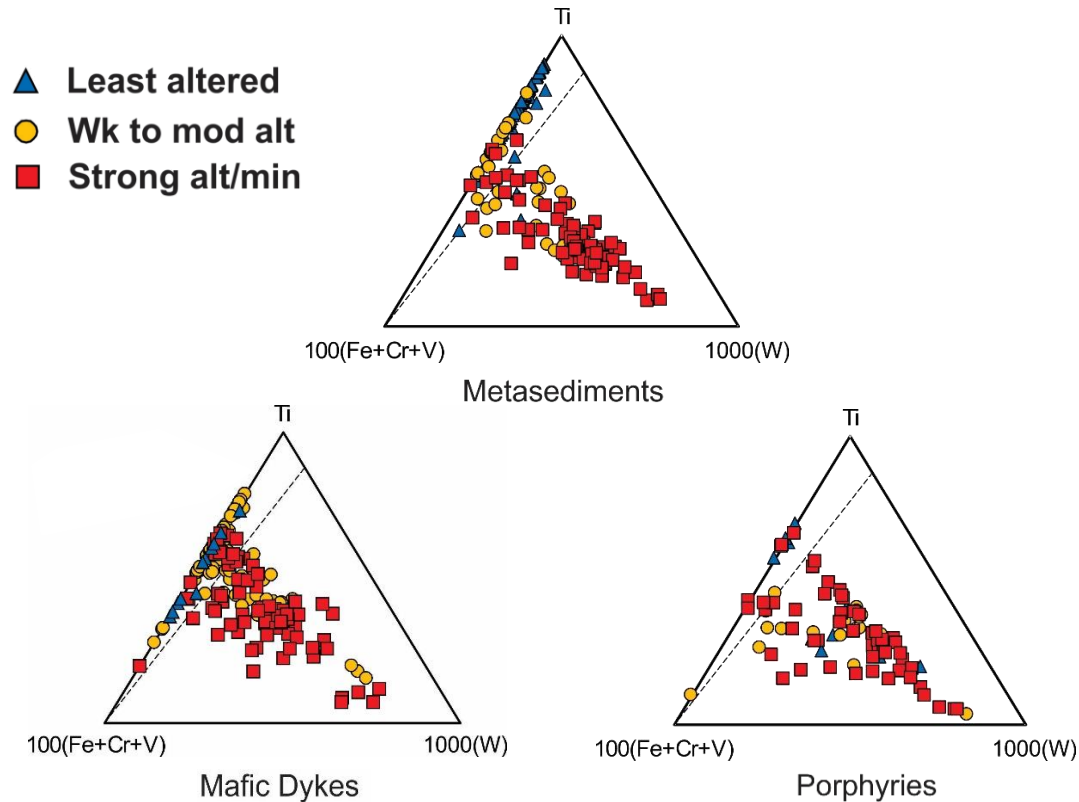
Carbonates (*in metasedimentary rocks*)

- Decreasing X_{CO_2} conditions away from the hydrothermal pathways
=> zonation of carbonate abundance and compositions:
- Fe-Mg-carbonates are restricted to the proximal alteration zones.
- Calcite is present in proximal and medial/distal alteration zones.



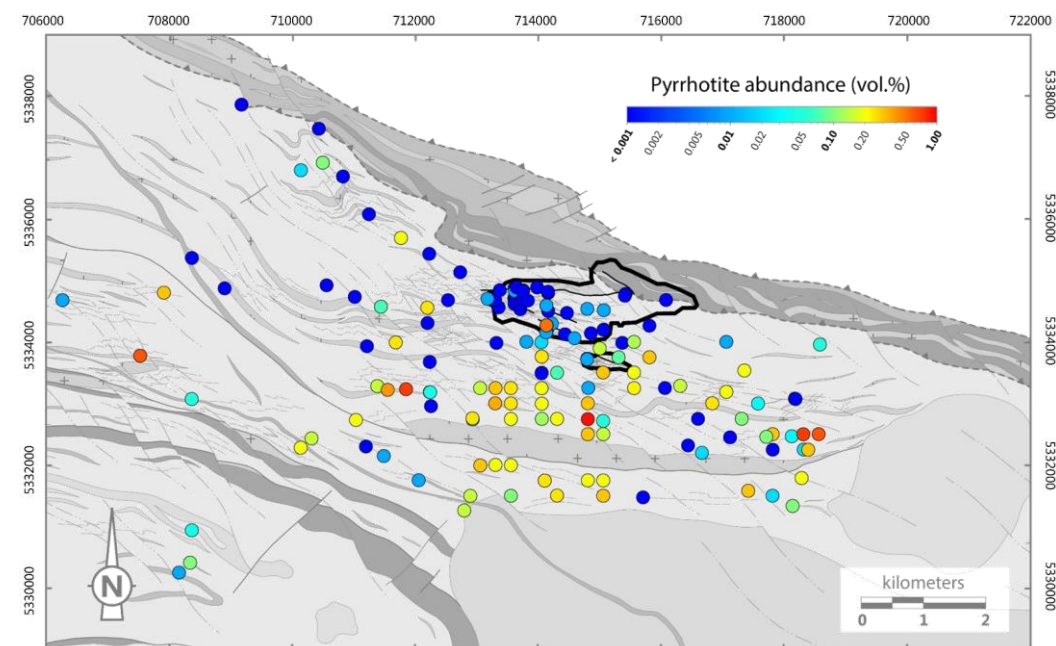
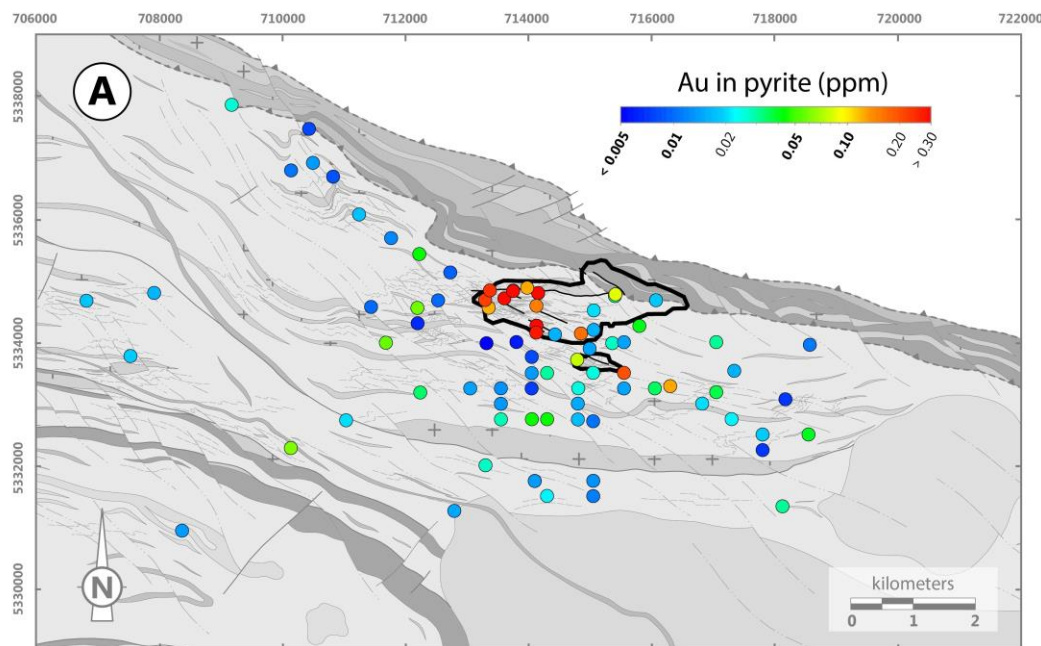
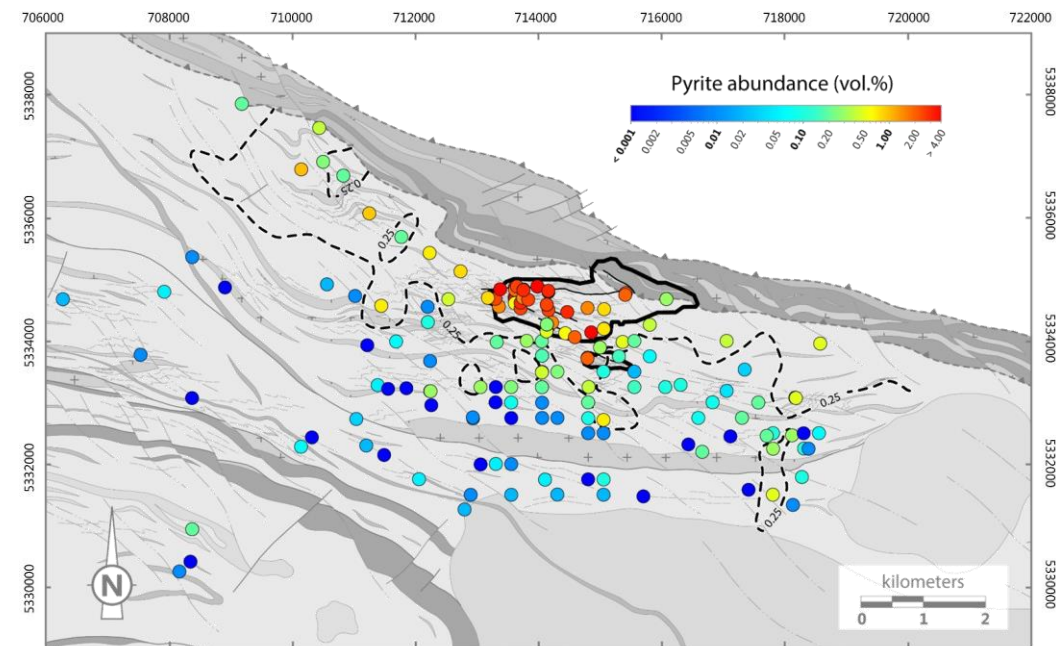
Rutile

- Rutile occurs as a minor to trace phase in all lithologies; in and near the deposit, rutile replaces ilmenite in the sulfidized alteration halo.
- Rutile associated with mineralization exhibits elevated W concentrations, similar to other Archean gold deposits. Sb and Nb are also elevated (to a lesser extent) at Canadian Malartic.



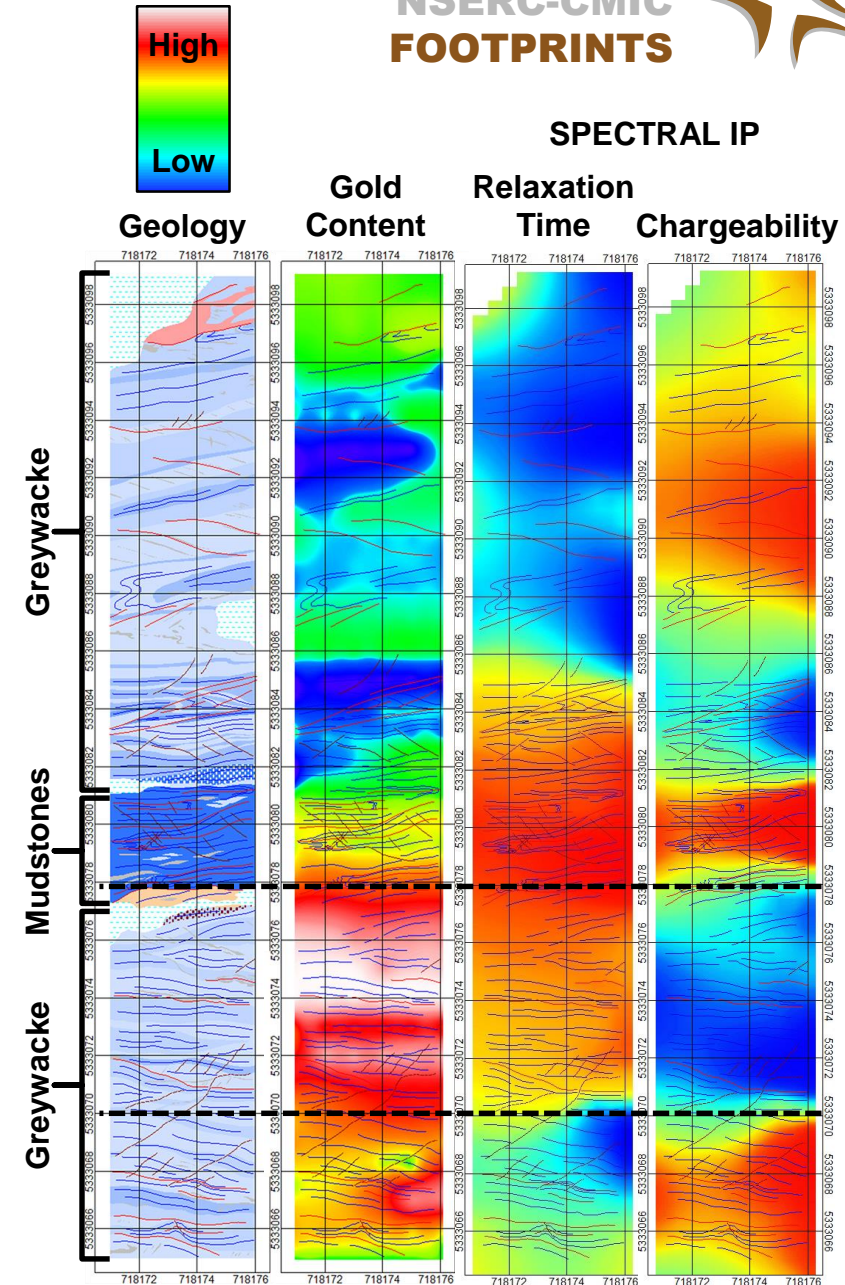
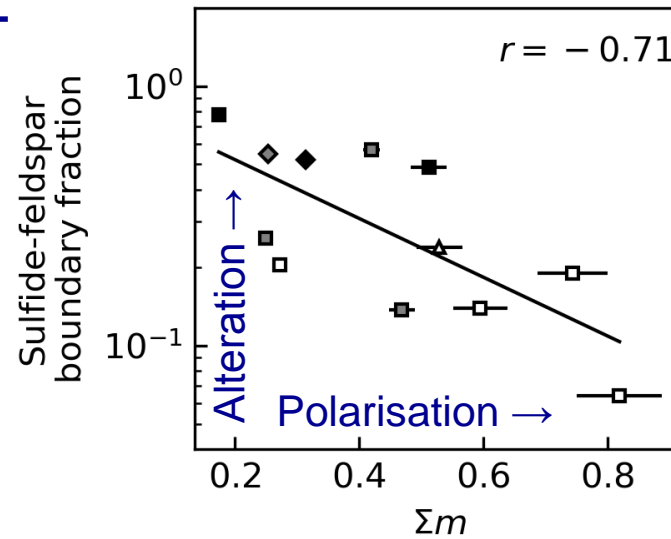
Sulfide Minerals

- **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.**



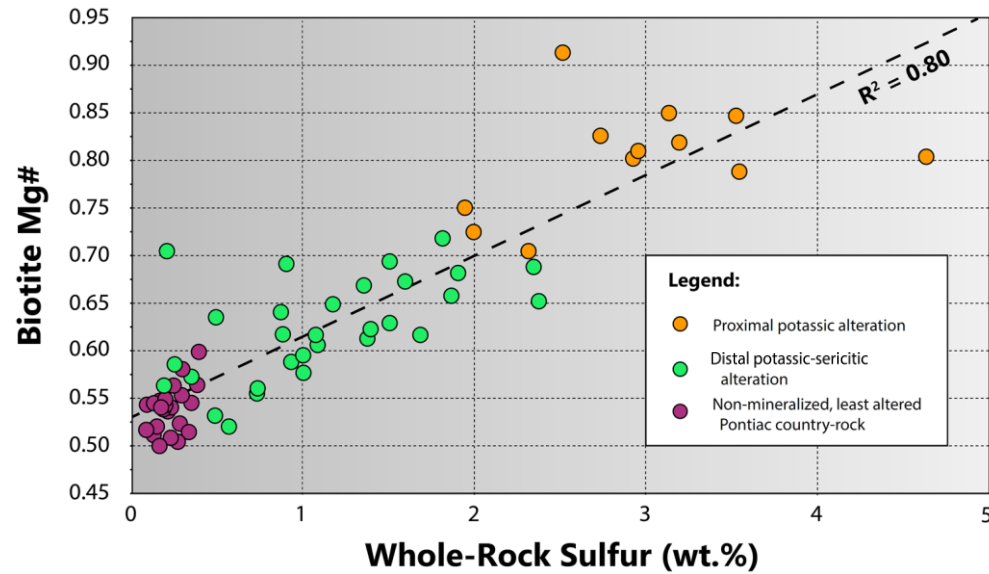
Geophysical Implications

- ~~More pyrite \Rightarrow 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.

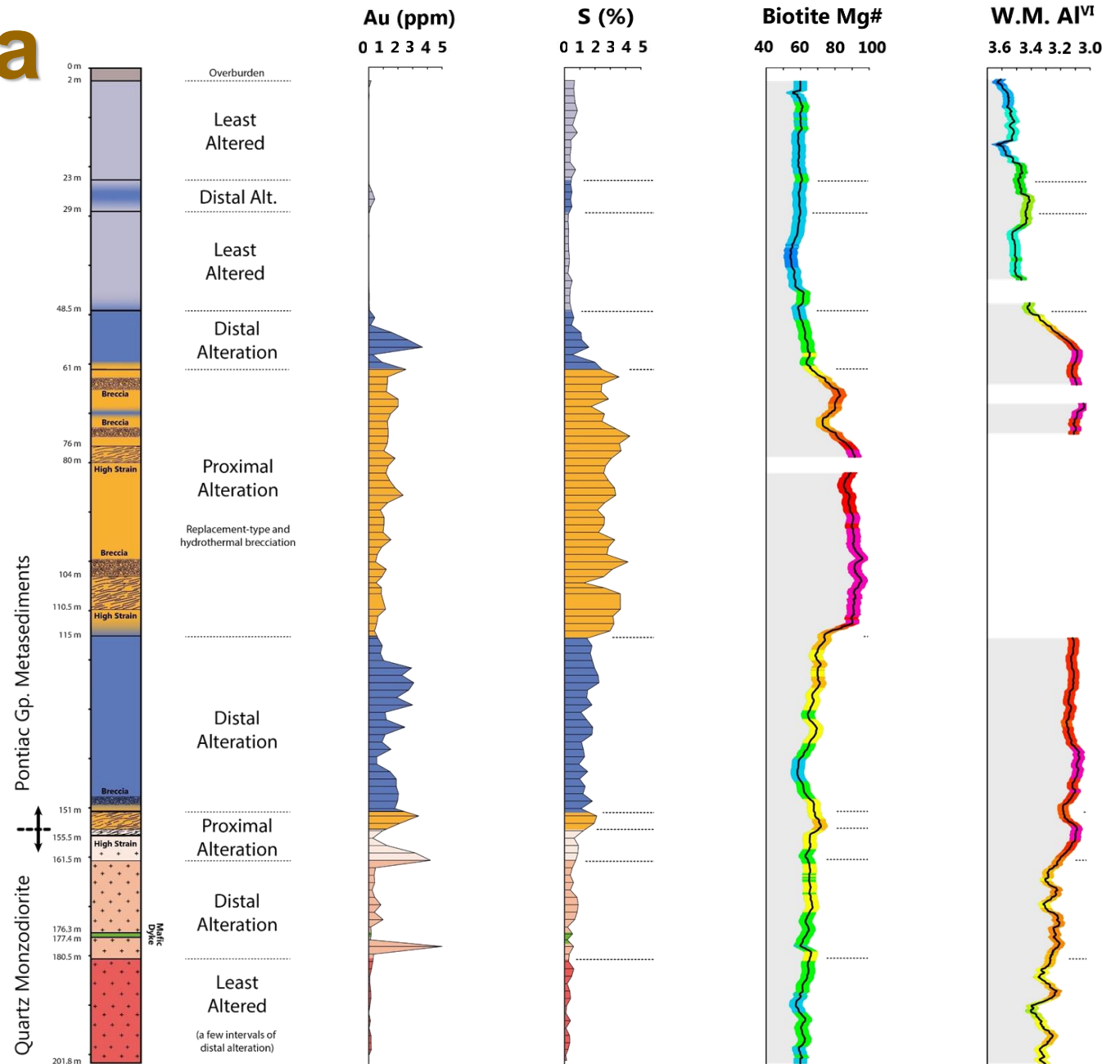


Biotite and White Mica

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

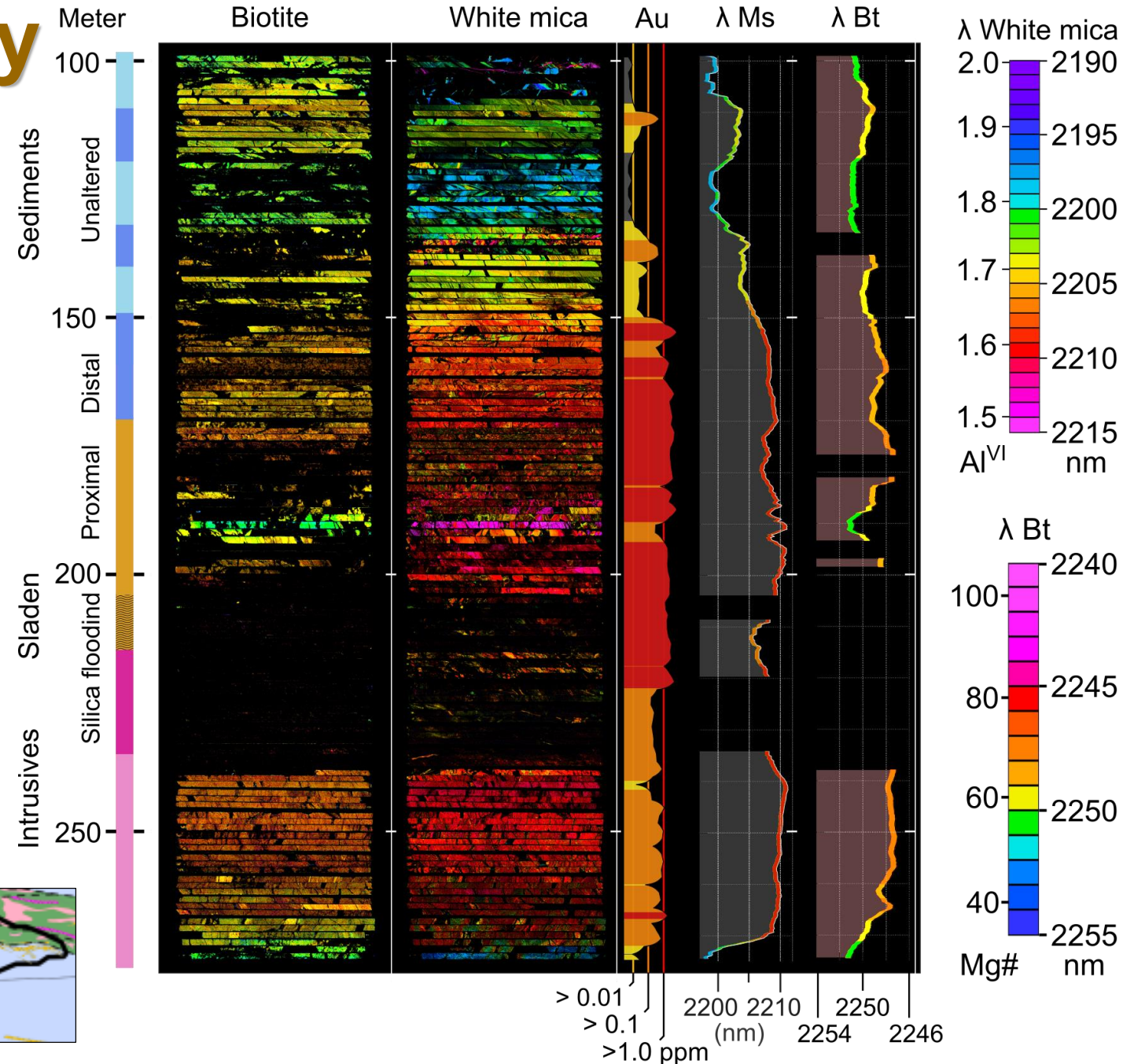
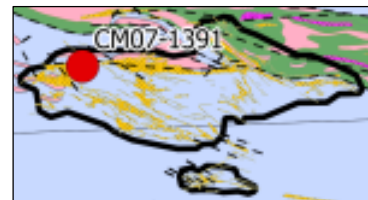


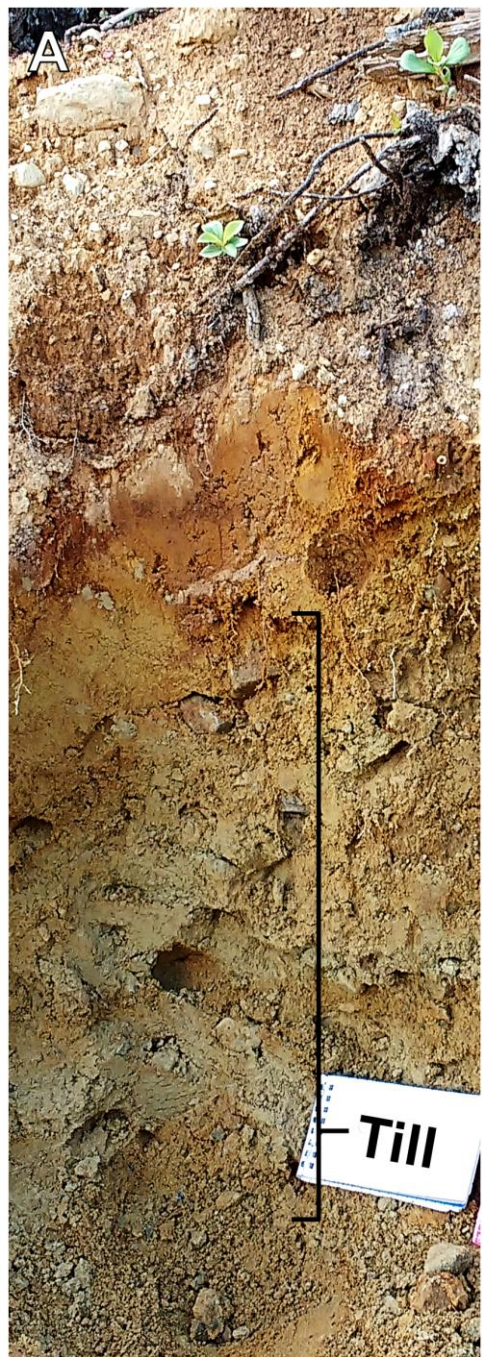
- Mg-enrichment of ore-zone biotite was caused by Fe-buffering by pyrite under increasing $\Sigma aS-fO_2$ conditions.
- Tschermak exchange in mica from proximal and distal alteration zones was controlled by variations in $a(K^+)$ and/or pH.



Hyperspectral Imagery

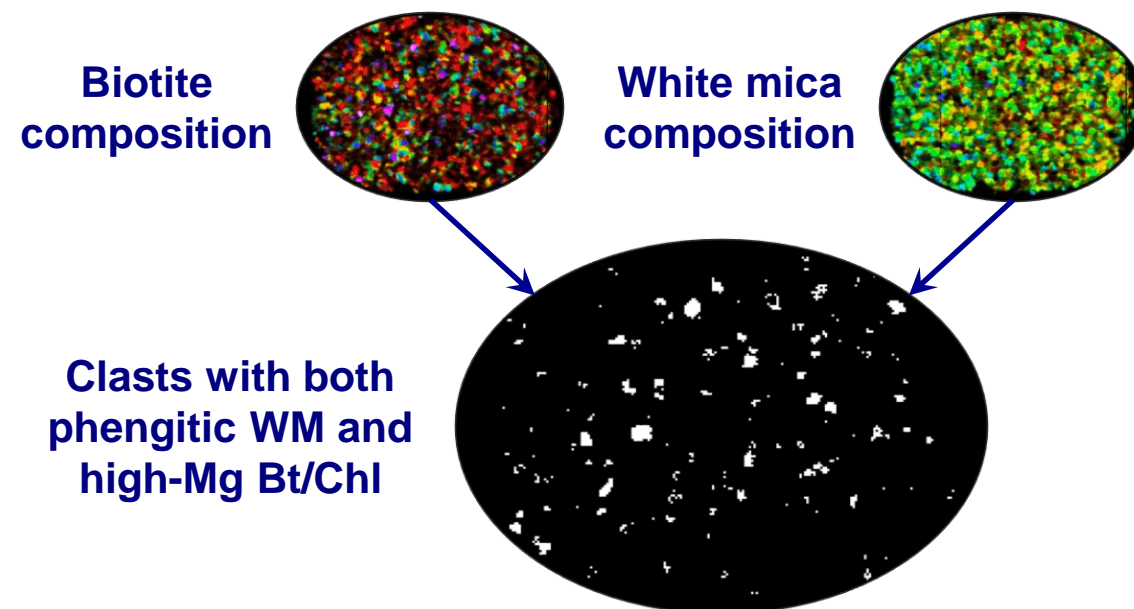
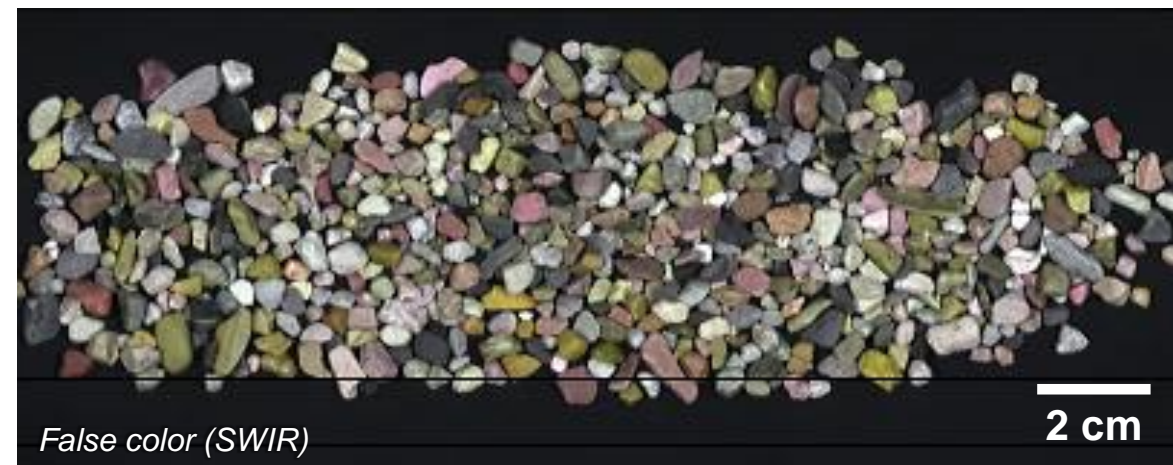
- Chemical analysis of biotite and white mica using hyperspectral imagery:
- Can be used as a proxy for alteration in metasedimentary and intrusive rocks.
- Enables the rapid delineation of altered intervals.
- Minimizes assaying barren intervals.





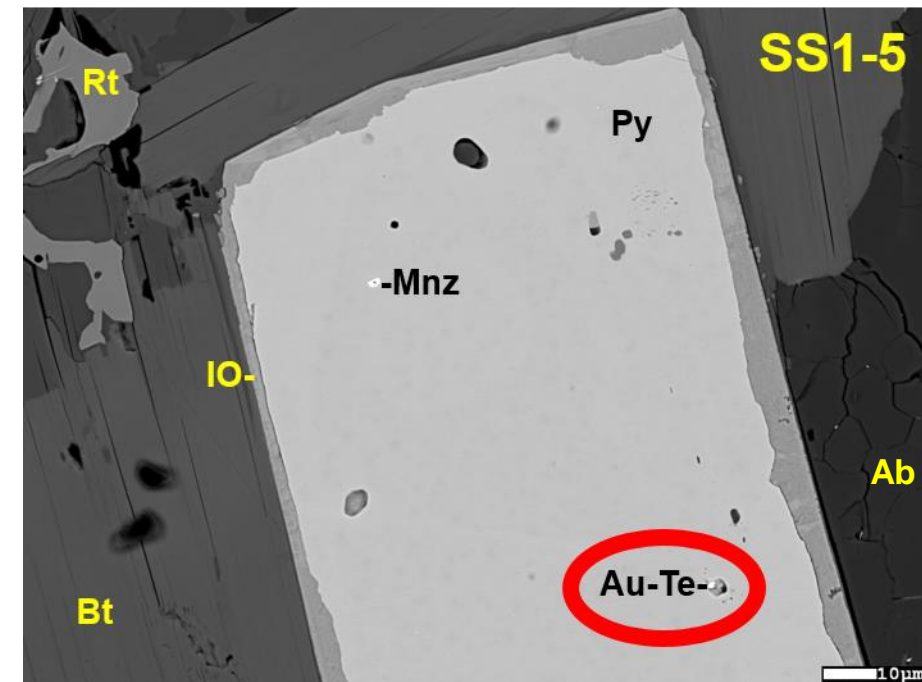
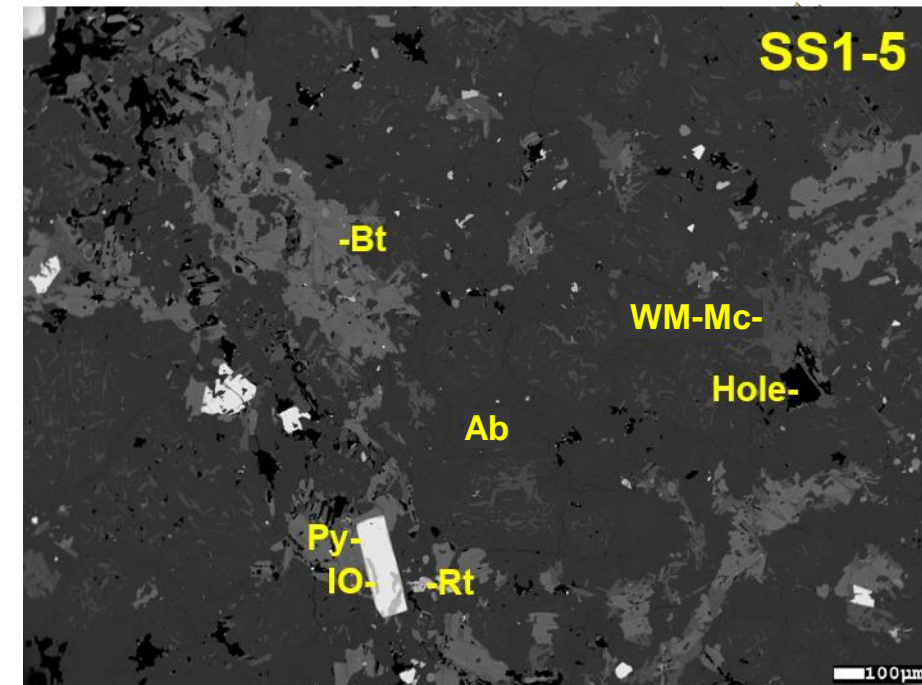
Surficial Exploration Approach NSERC-CMIC FOOTPRINTS

- Sampling of till and separation of the 4-8 mm clast fraction.
- **Hyperspectral-sorting of thousands of clasts.**
- Validation through petrographic analyses of possibly altered clasts.
- Mapping of the proportion of clasts with both phengitic white mica and high-Mg biotite.



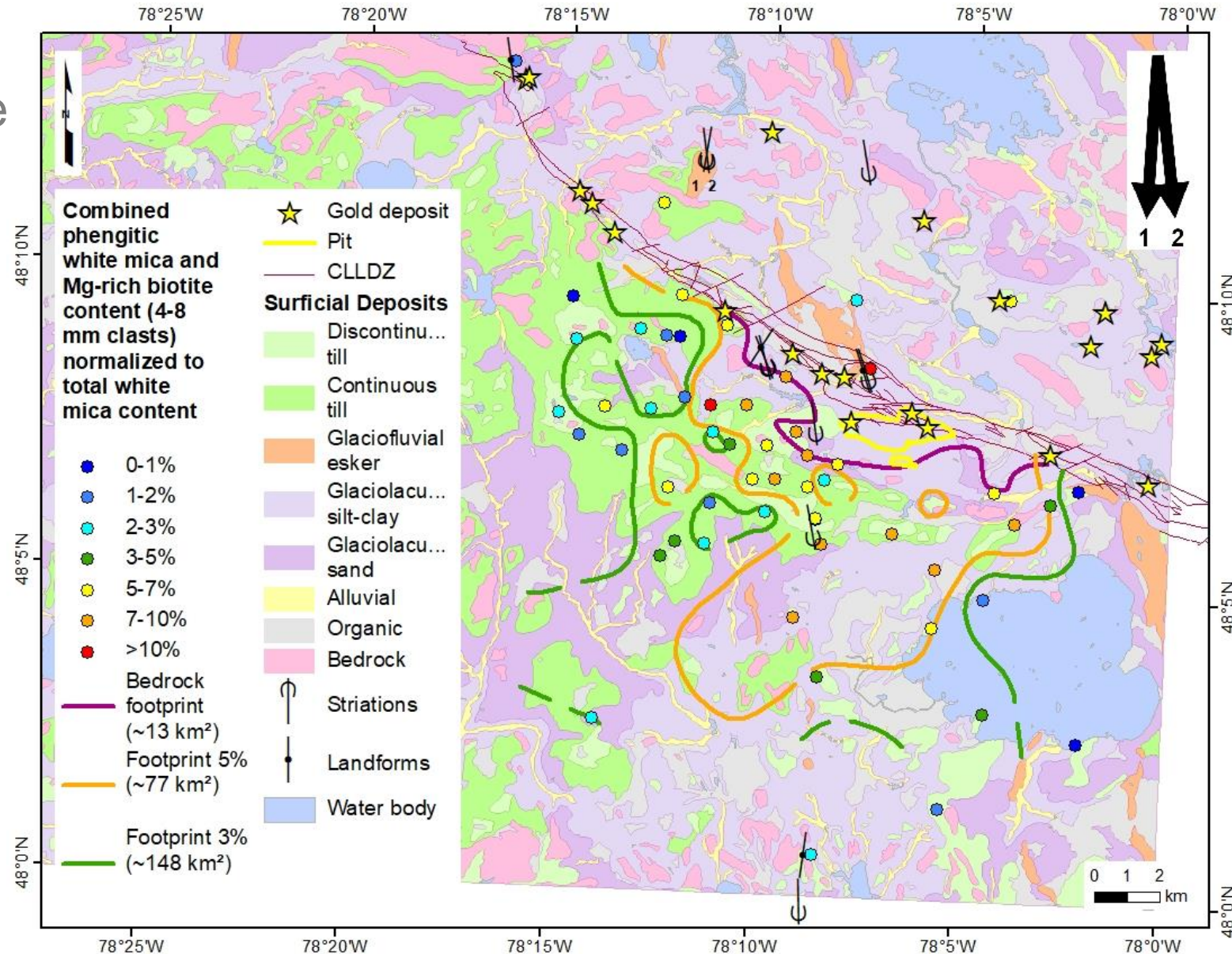
Validation by Petrography

- Objective is to determine if the clasts with phengitic white mica and high-Mg biotite may belong to the Canadian Malartic deposit.
- Typical mineralogy of a selected clasts:
 - Biotite, white mica, microcline, albite, pyrite, quartz, rutile (W-rich), iron oxide minerals.
 - Holes may represent dissolved carbonates.
 - Clasts of intrusive and metasedimentary rocks display similar texture and mineralogy to the rocks from the Canadian Malartic deposit.
- The finding of gold-telluride inclusions validate this hyperspectral-sorting approach.



Quaternary Dispersion of the Footprint

- Interpolated glacial dispersion of the footprint based on biotite and white mica compositions (4-8 mm clasts):
- Fan-shaped dispersion toward the SSE, at least 5 times bigger than the footprint in the bedrock.**
- Background map after Veillette (2004). (1) and (2) on map represent older and younger ice flows, respectively.*



Summary

- ◉ **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.

Sponsors/Collaborators



Collaborators: GSC TGI4 Program
MRNQ
Saskatchewan Geol Survey
BC Geological Survey

Supporters: Fullagar Geophysics
Rekasa Rocks
UBC Geophysical Inversion Facility

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<https://cmic-footprints.laurentian.ca/>