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Mineral Exploration Research Centre
at the HARQUAIL SCHOOL OF EARTH SCIENCES

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Integrated Multi-Parameter Footprint of the Canadian Malartic Gold Deposit

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LaurentianUniversity UniversitéLaurentienne

MINE CANADIAN MALARTIC

Western UNIVERSITY · CANADA

Queen's UNIVERSITY

Footprint Project Objectives

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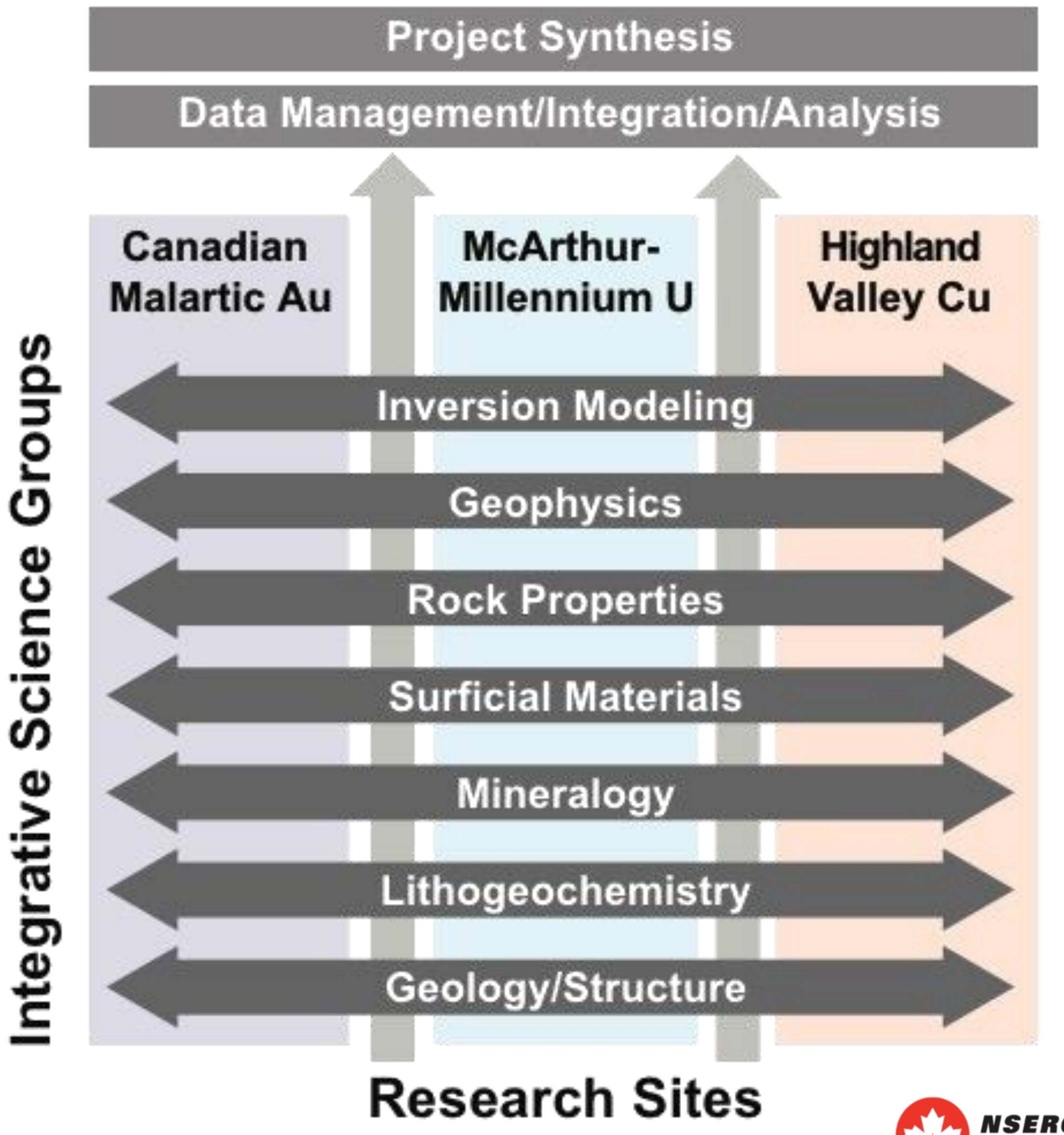
- **Develop comprehensive and robust models of the footprints of large-scale ore-forming systems at three integrated study sites**, combining geological, mineralogical, geochemical, geophysical and physical rock properties from the local to the camp scale

- **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



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Location of Footprint Sites

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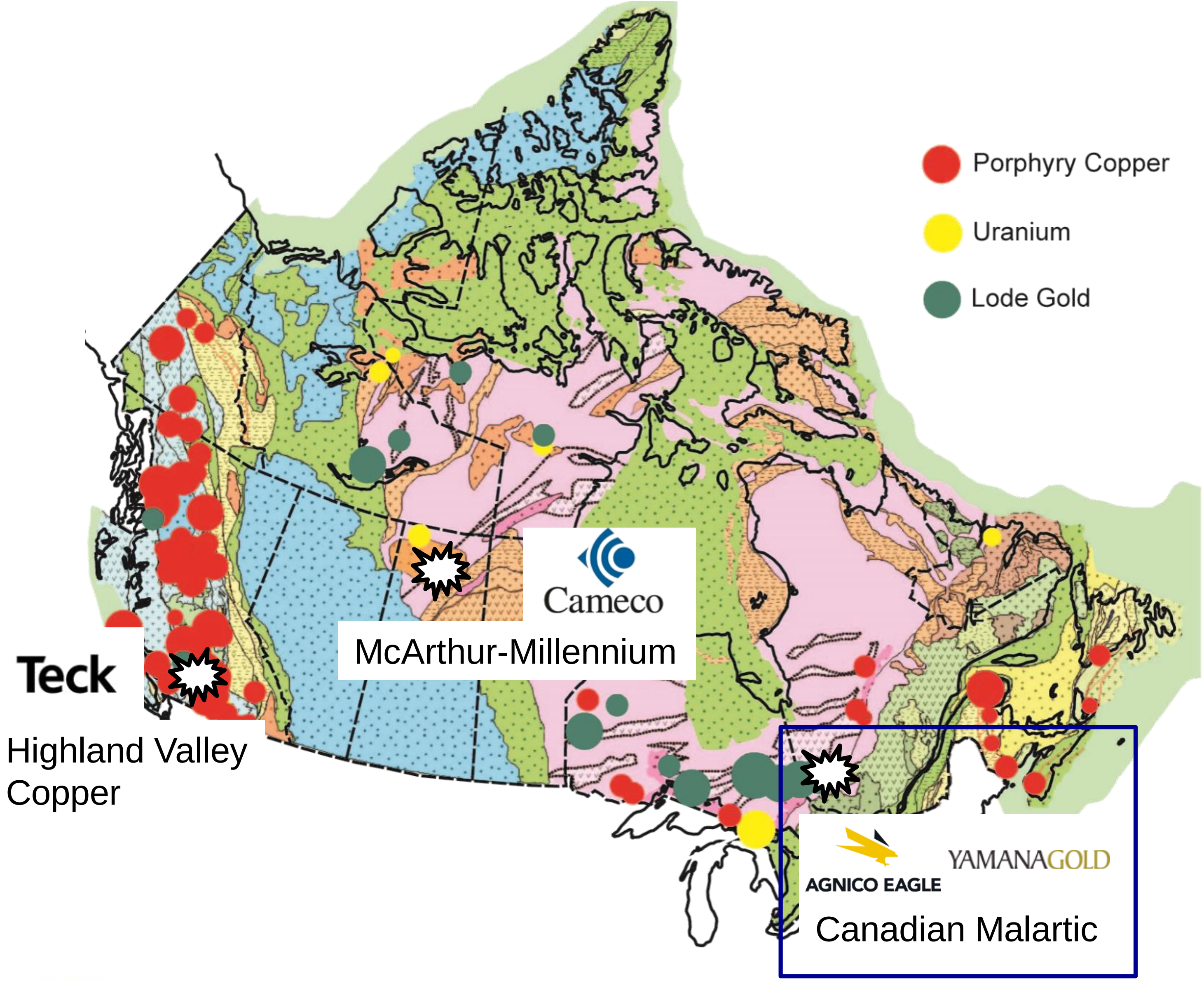
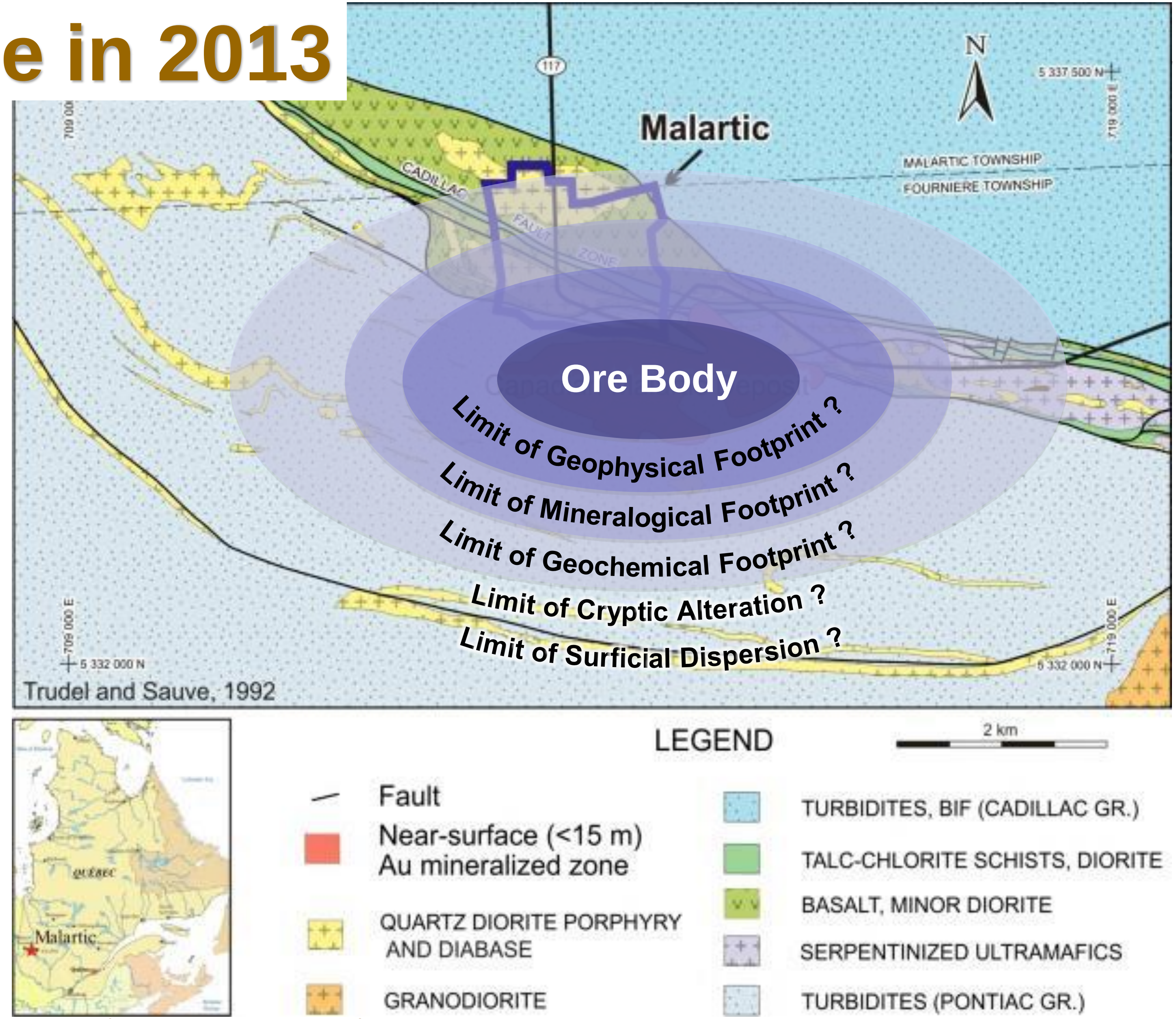


- **Canadian Malartic:**
  - **>18.6 Moz Au**
  - **South of the Cadillac - Larder Lake Deformation Zone, Québec**
  - **Oxidized intrusion-related deposit** (Helt et al., 2012, *Economic Geology*)
  - **Stockwork-disseminated system** (De Souza et al., 2016, *Economic Geology*)

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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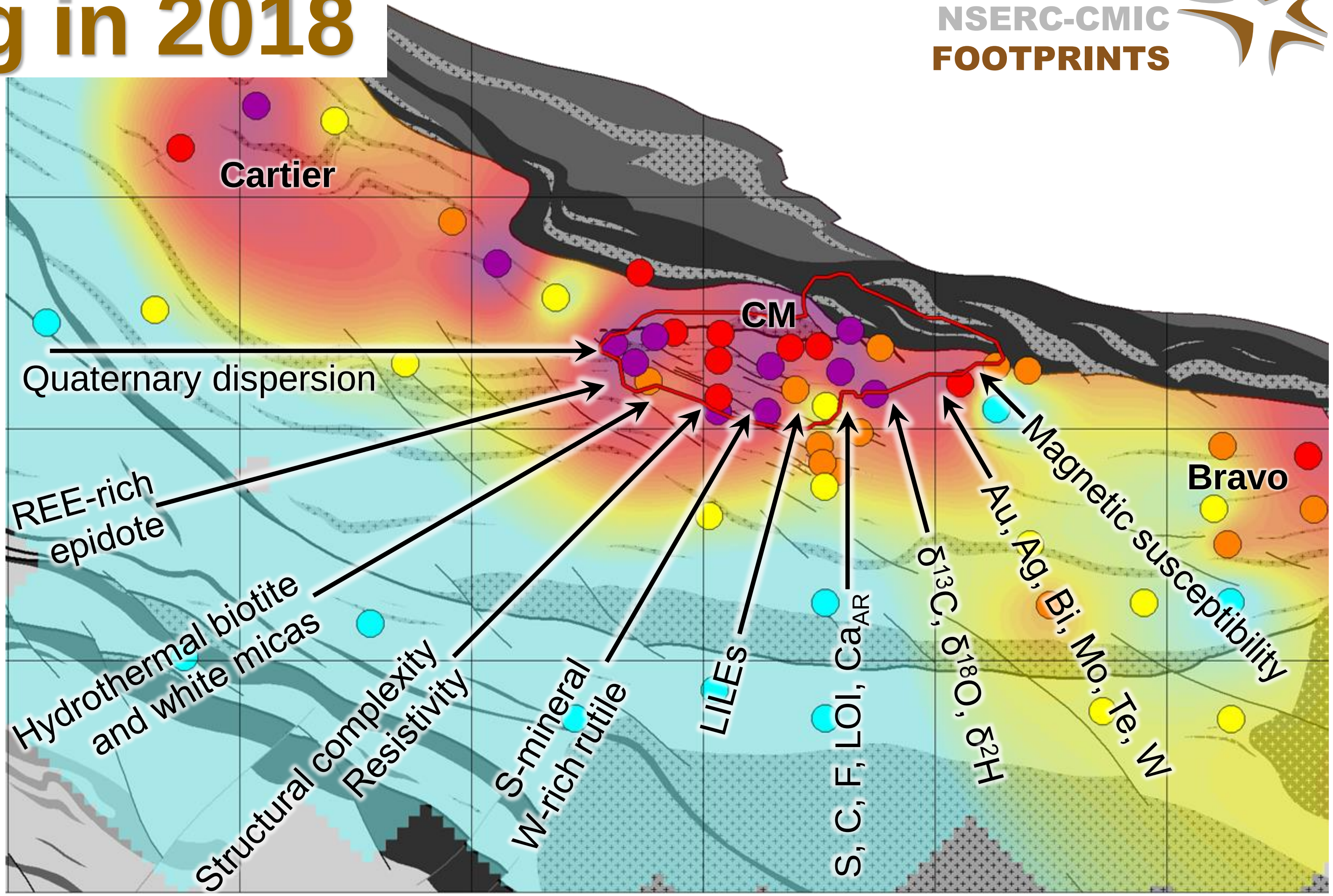
- **118 structural, geophysical, geochemical, mineralogical, and petrophysical halos**
- **Sizes range from 0.5 to 6 km from the core of the system**
- **Multiple alteration centers** (CM, Cartier, Bravo/Odyssey)
- **New models: structural/ metamorphic/hydrothermal**
- **New techniques applicable to gold exploration**



Main vectoring tools in the Canadian Malartic footprint

Major Results

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- **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 ($\delta^{2}H$, $\delta^{18}O$, $\delta^{13}C$, $\delta^{34}S$) halos in mafic dykes and metasedimentary rocks
- **Mineral chemistry halos in metasedimentary rocks**
- **New geophysical approaches: spectral IP**, anisotrophy of resistivity, variance
- Multi-parameter integration through PCA and machine learning approaches
- **New surficial exploration approach using mica compositions**

Geological Setting

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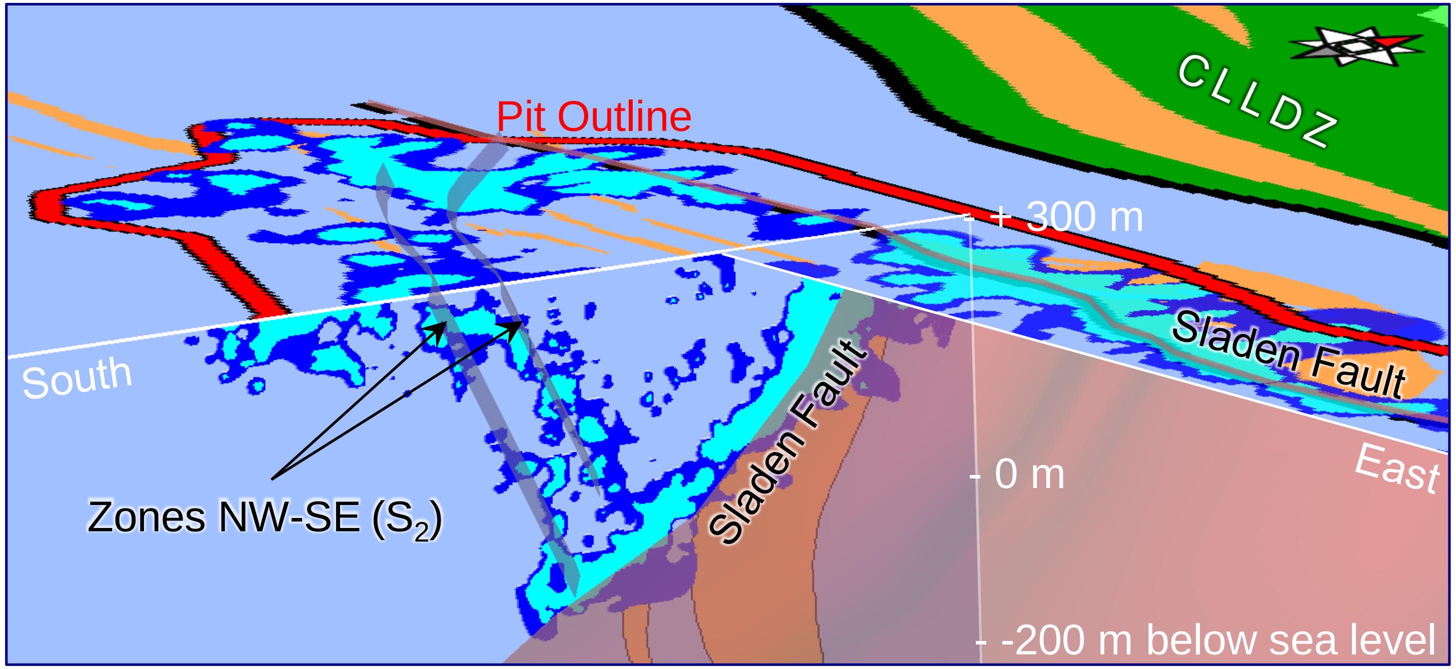
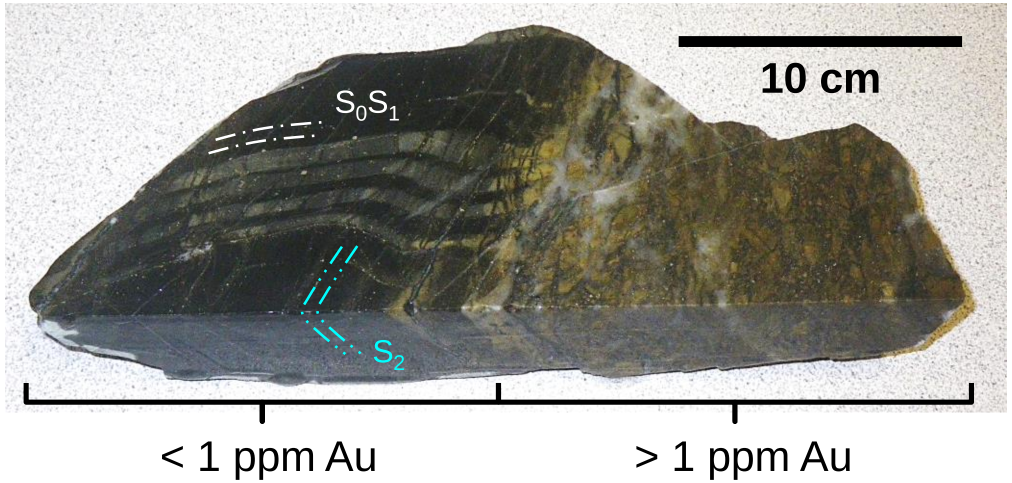
- **3 deformation events:** **D_1** - isoclinal F_1 folds, pressure-solution cleavage (S_1)
  D_2 - close s-shaped F_2 folds, NW-SE biotite cleavage (S_2)
  D_3 - subtle crenulation cleavage (S_3)
- **2 structural controls: E-W Sladen fault and NW-SE high-strain zones (in F_2 fold hinges)**





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

Structural Footprint

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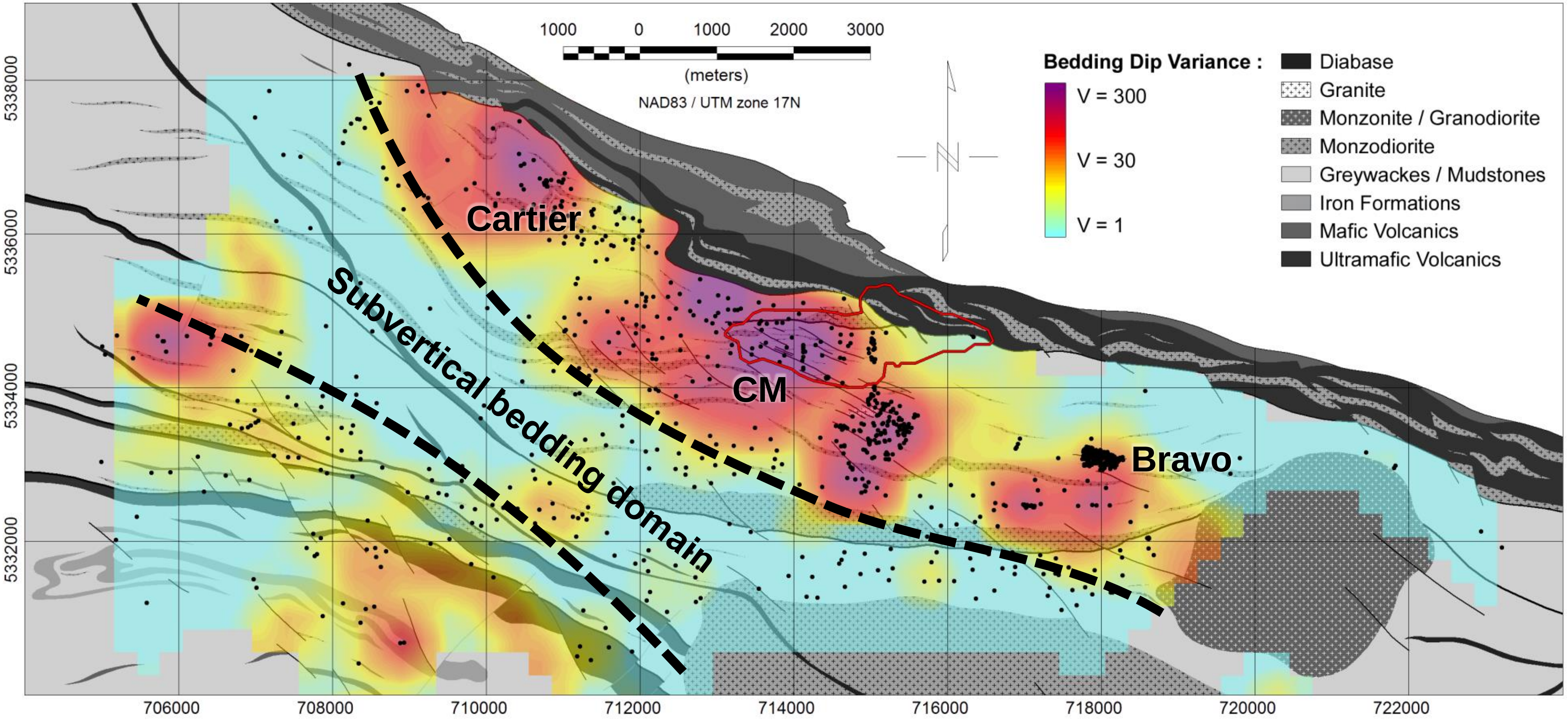
- Field mapping suggests that alteration zones are spatially associated with structurally complex zones (F_1 and F_2 fold hinges).
- The variance of the bedding dip highlights these fold interference zones.



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

Geochemical Halos *(in mafic dykes)*

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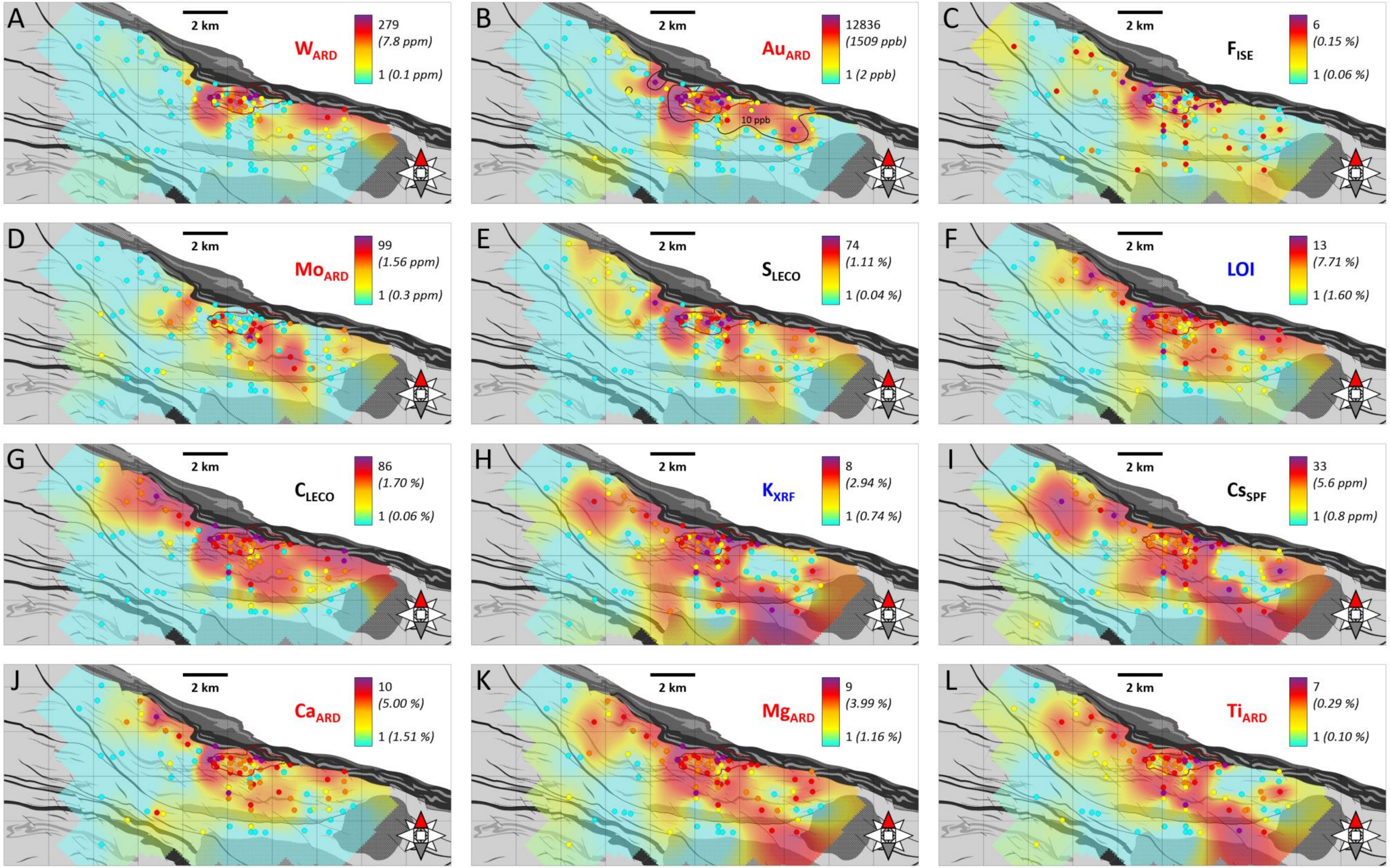
- **Whole-rock (partial and total digestion) lithogeochemical halos are controlled by structures.**

- Concentration gain factors are calculated using the method of Gresens (1967) and MacLean (1990).



Mineralogical Halos *(in mafic dykes)*

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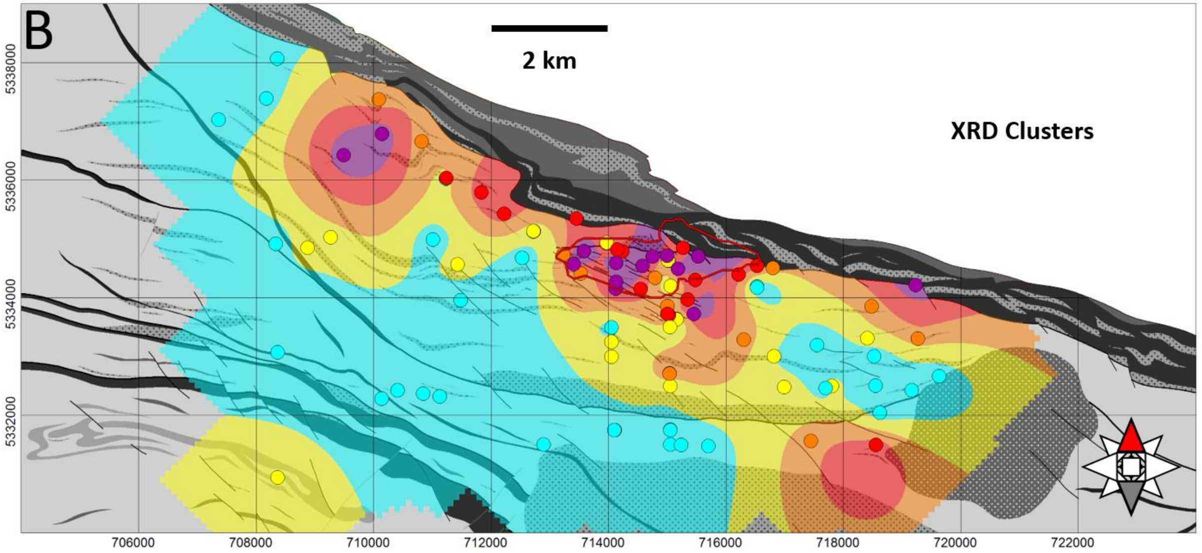
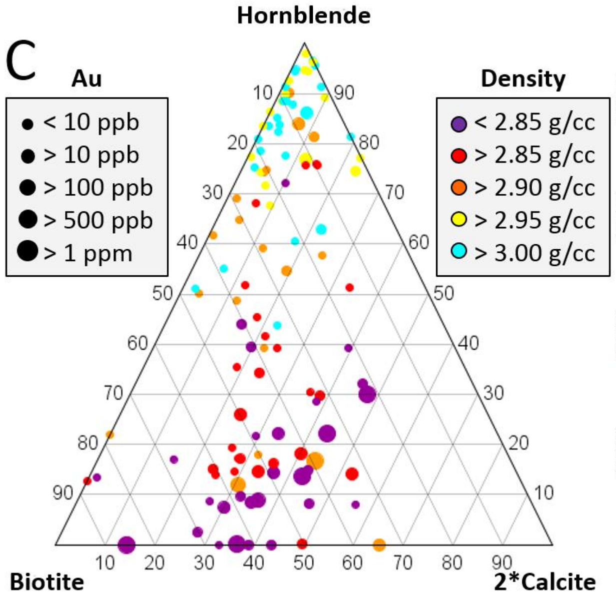
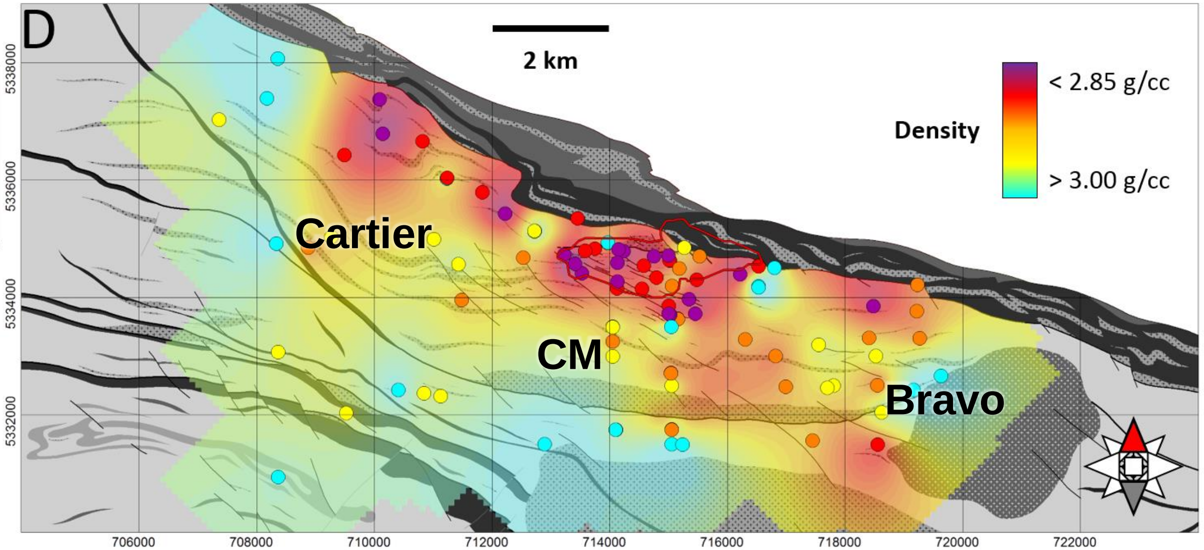
A

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



- **Lithogeochemical changes are reflected in the mineralogy and rock density.**
- XRD cluster analysis was performed to quantify and outline mineralogical changes.

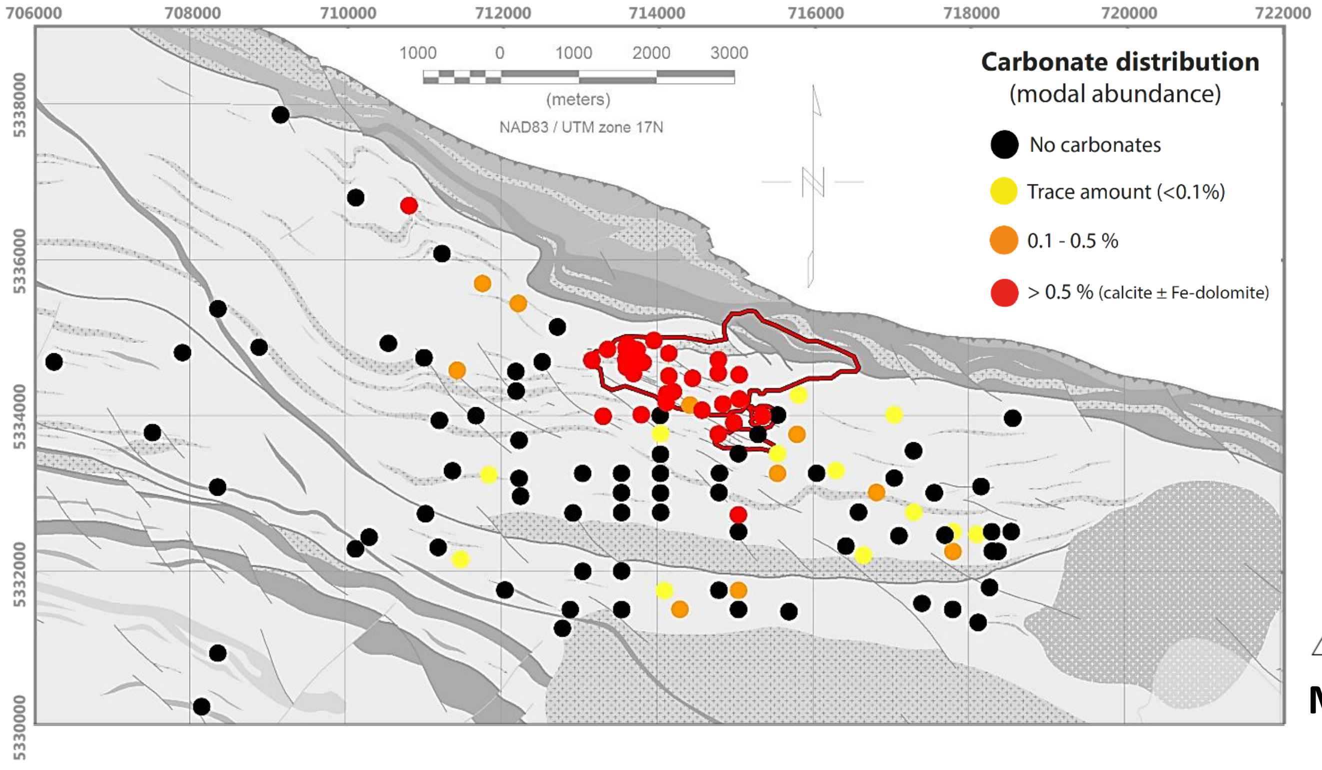


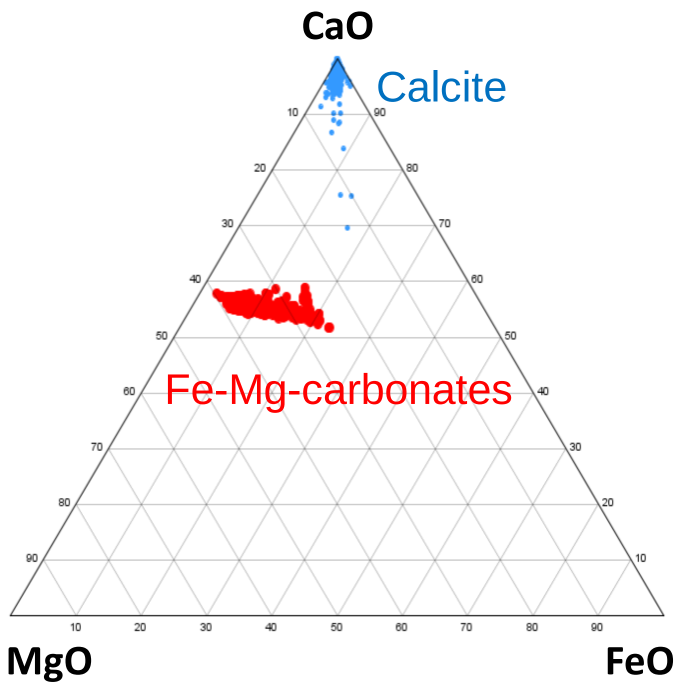


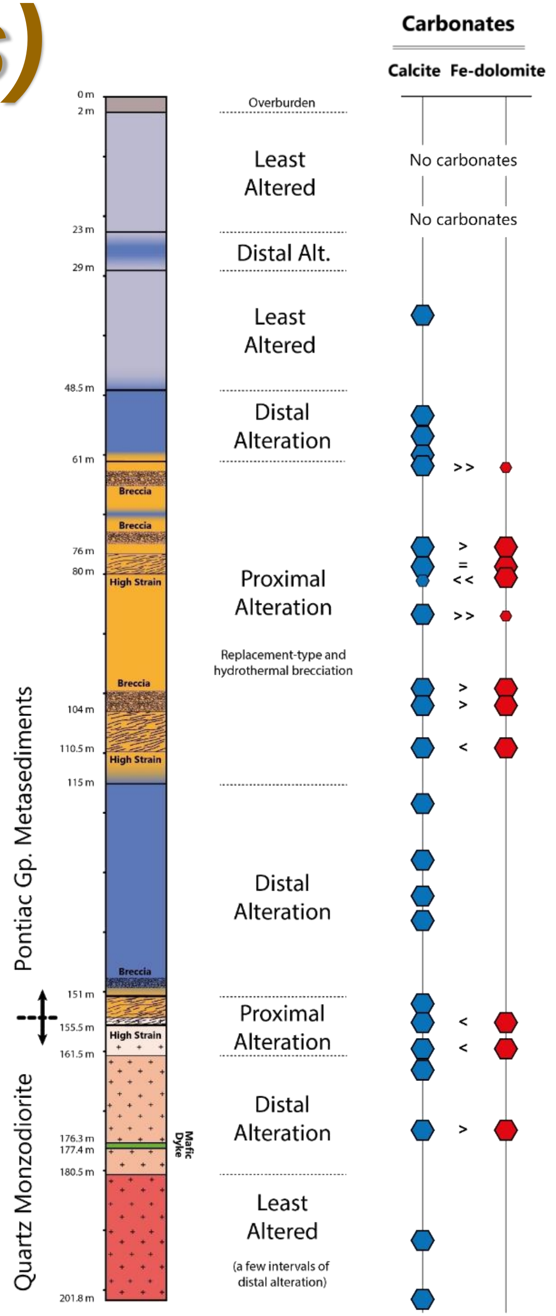
Perrouty et al. *(2018, Mineralium Deposita)*

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.







Gaillard et al. *(in prep)*

Rutile

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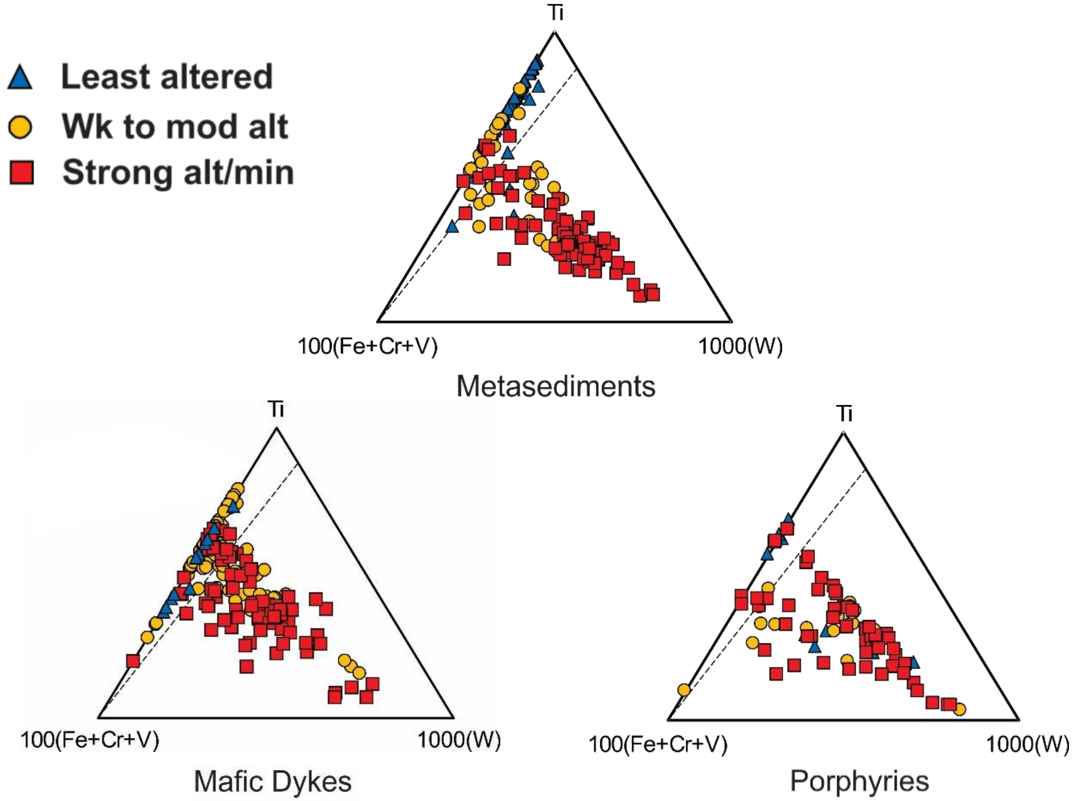
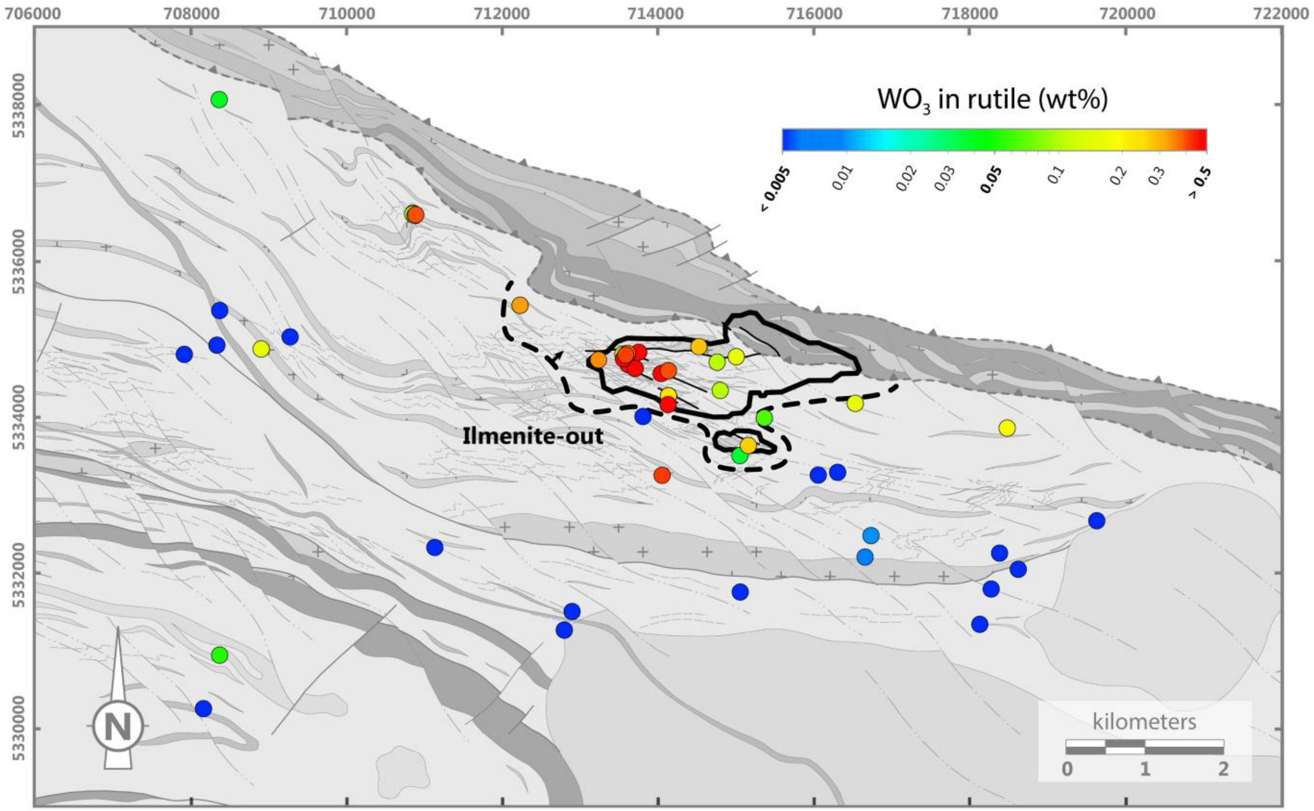
- **Rutile occurs as a minor to trace phase in all lithologies; in and near the deposit, rutile replaces ilmenite in the sulfidized alteration halo.**
- **Rutile associated with mineralization exhibits elevated W concentrations**, similar to other Archean gold deposits. Sb and Nb are also elevated (to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

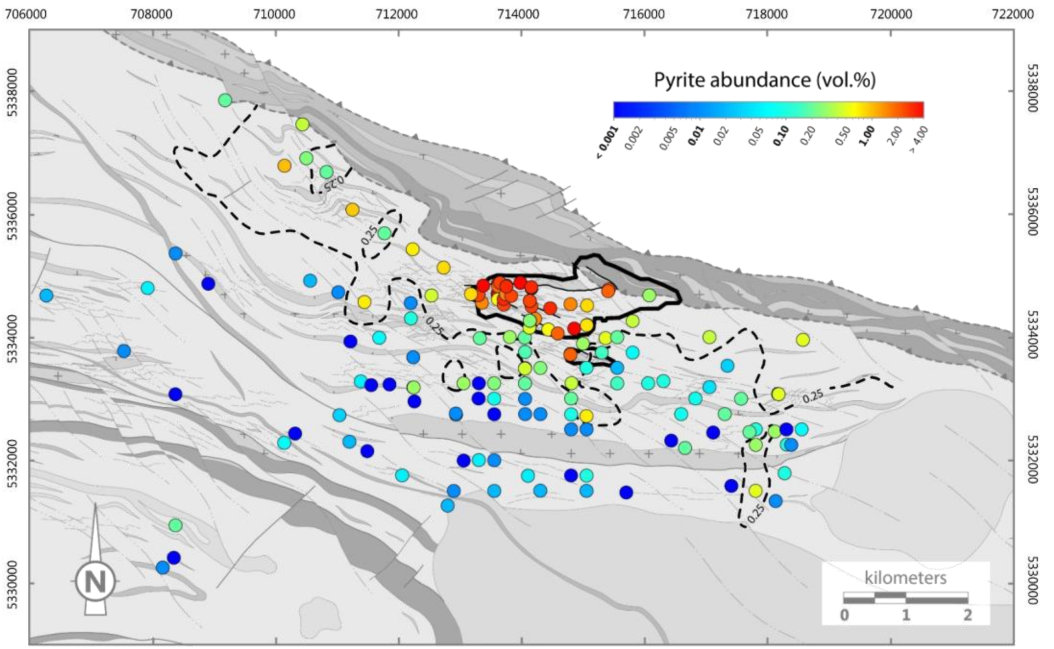


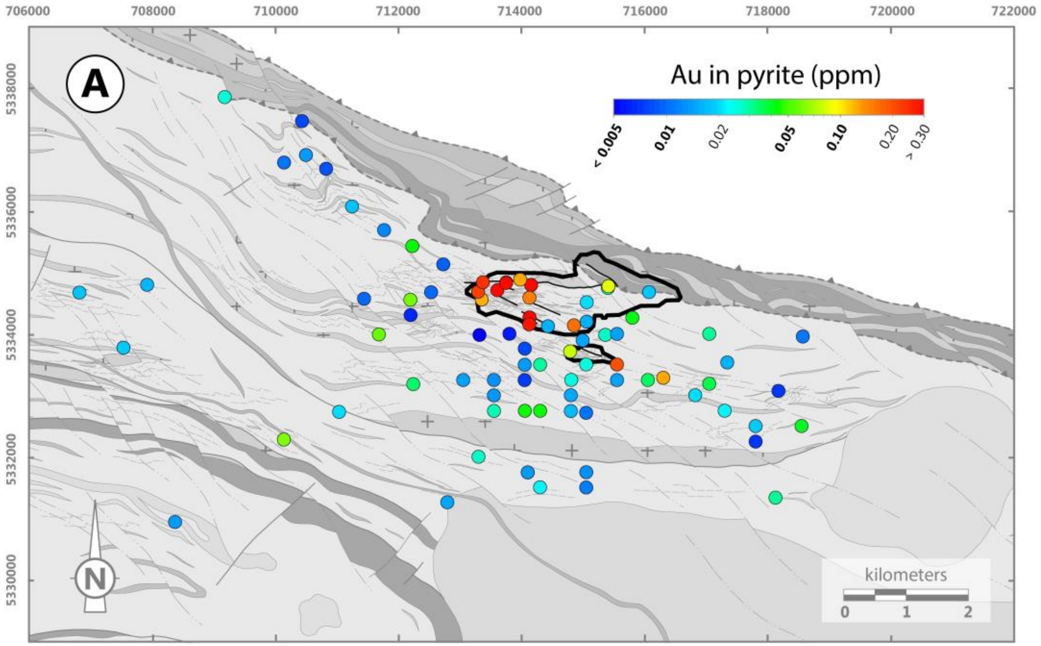


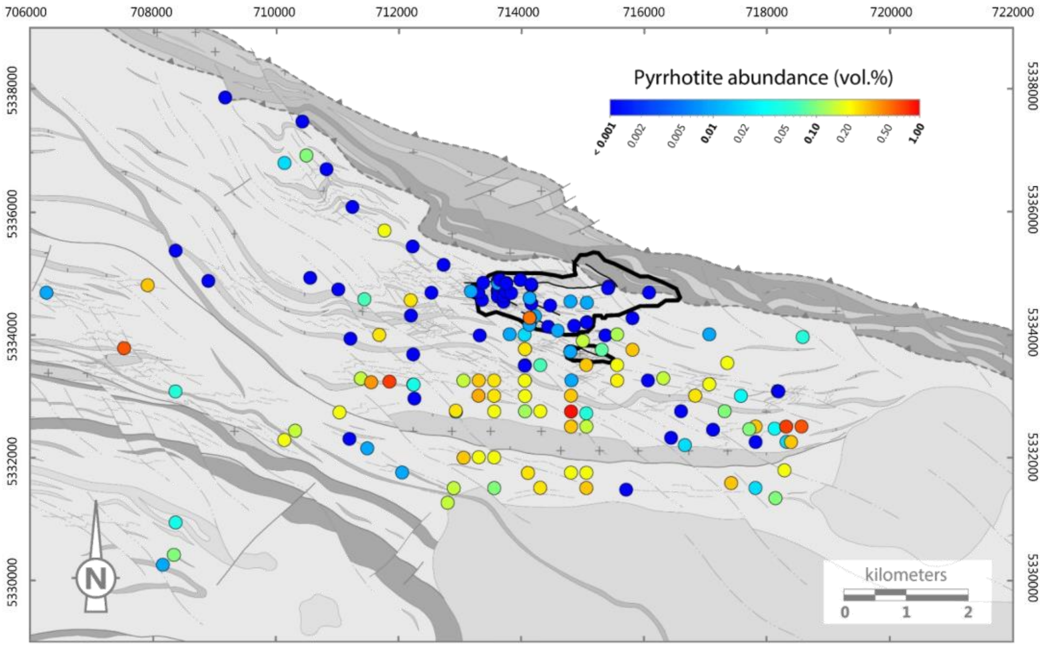
Clark et al. *(in prep)*

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.





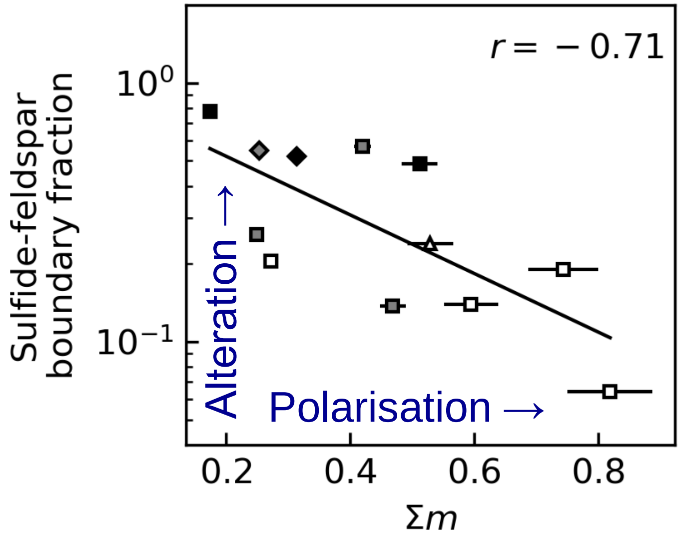


Gaillard et al. *(submitted)*

Geophysical Implications

- ~~**More pyrite => more chargeability?**~~

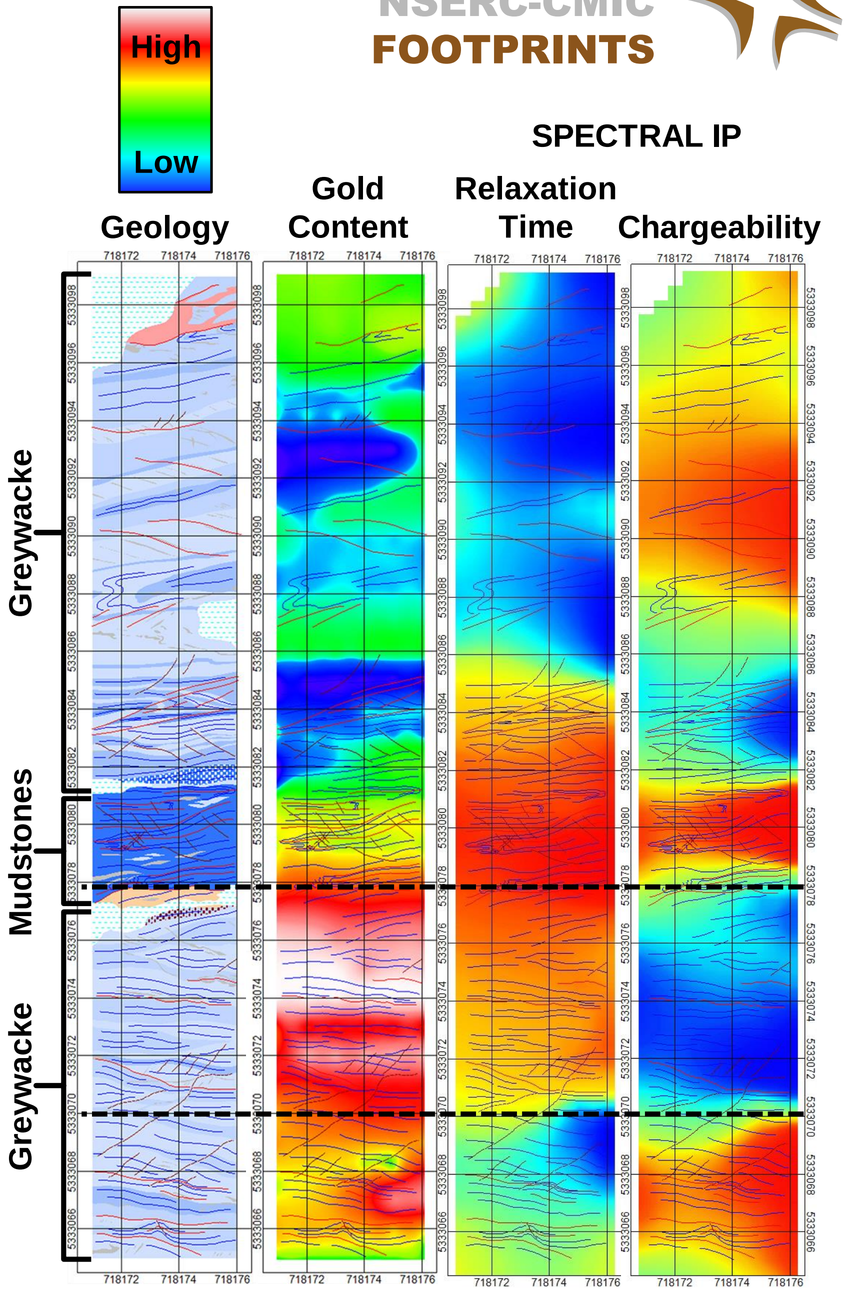
- **Chargeability increases with increasing surface of contact between sulfide minerals and porosity:**



- 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.

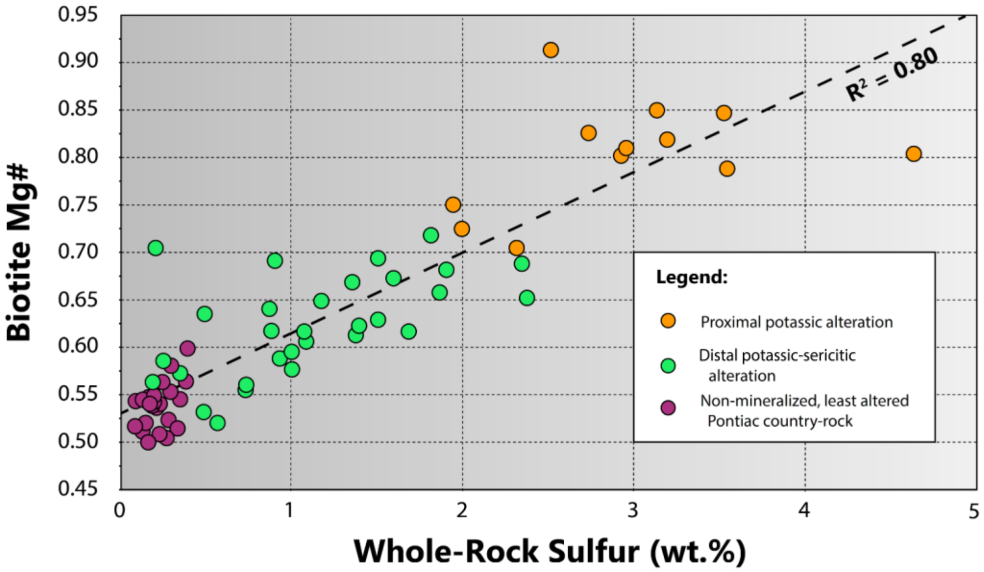
- **At Canadian Malartic, zones of pervasive hydrothermal alteration are characterized by low chargeability.**



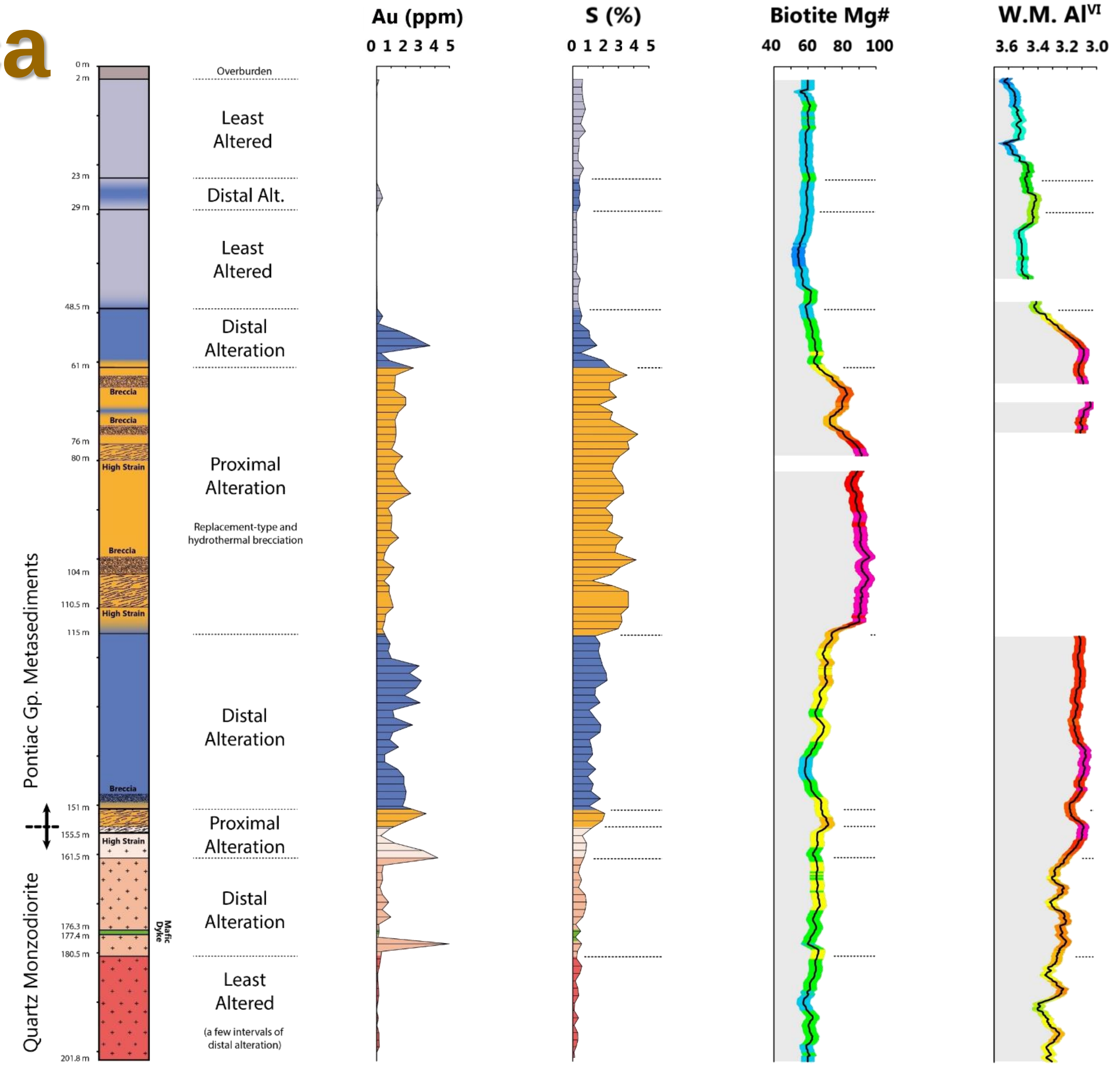
Bérubé et al. *(in prep)*

Biotite and White Mica

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



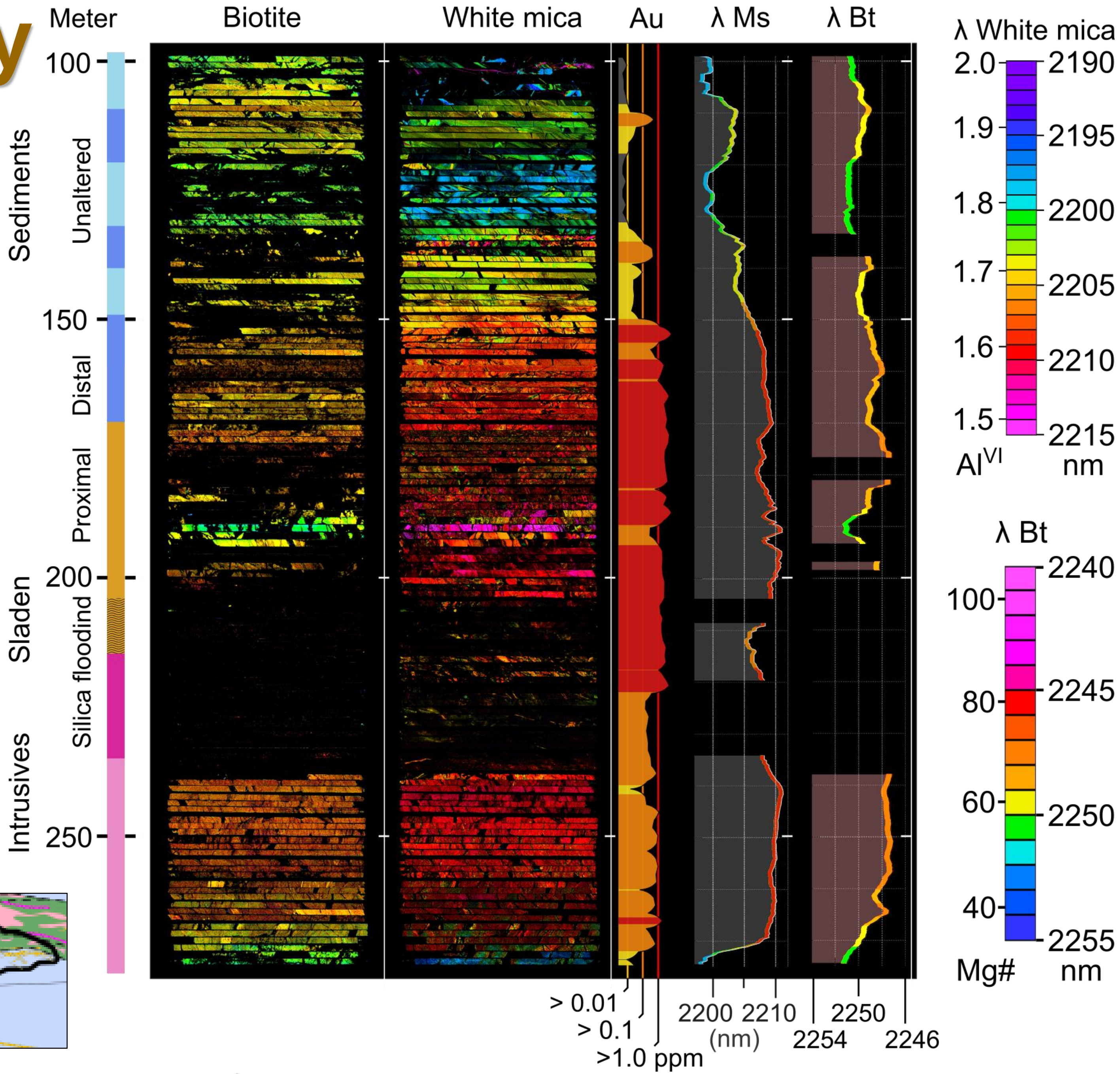
- Mg-enrichment of ore-zone biotite was caused by Fe-buffering by pyrite under increasing $\sum aS\text{-}fO_2$ conditions.
- Tschermak exchange in mica from proximal and distal alteration zones was controlled by variations in $a(K^+)$ and/or pH.

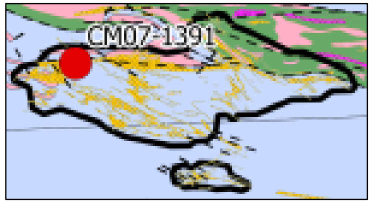


Gaillard et al. *(2018, Ore Geology Reviews)*

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. *(in prep)*

Surficial Exploration Approach

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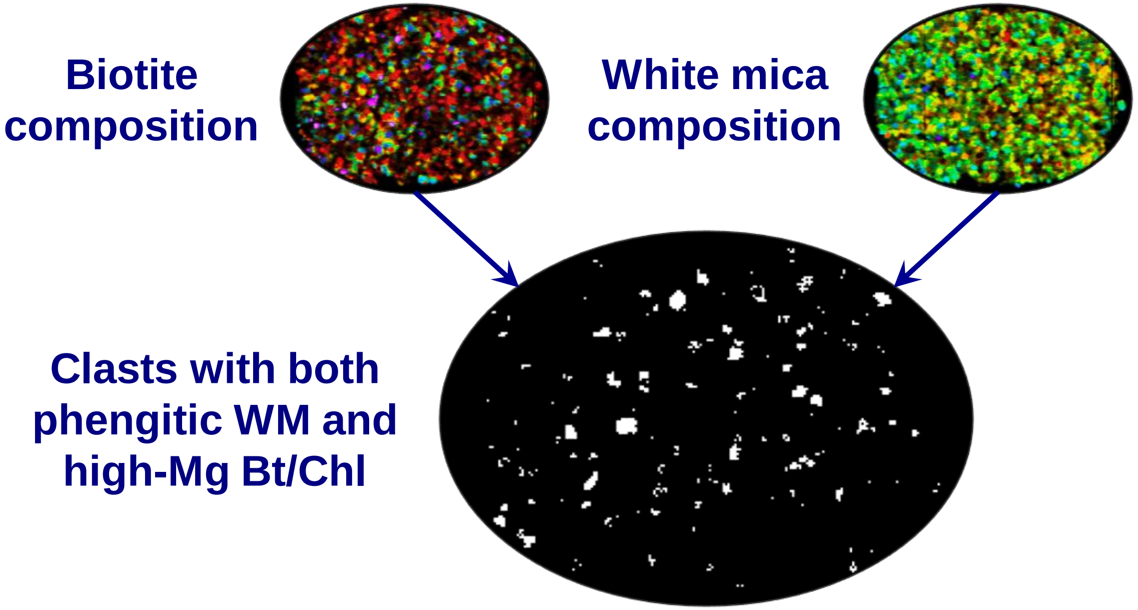
- Sampling of till and separation of the 4-8 mm clast fraction.
- **Hyperspectral-sorting of thousands of clasts.**
- Validation through petrographic analyses of possibly altered clasts.
- Mapping of the proportion of clasts with both phengitic white mica and high-Mg biotite.

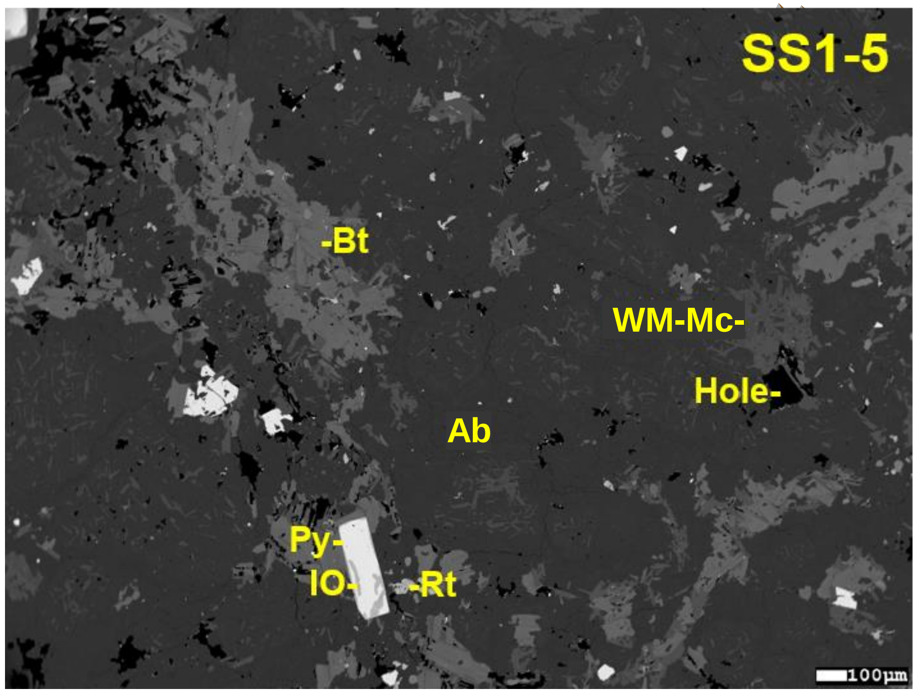


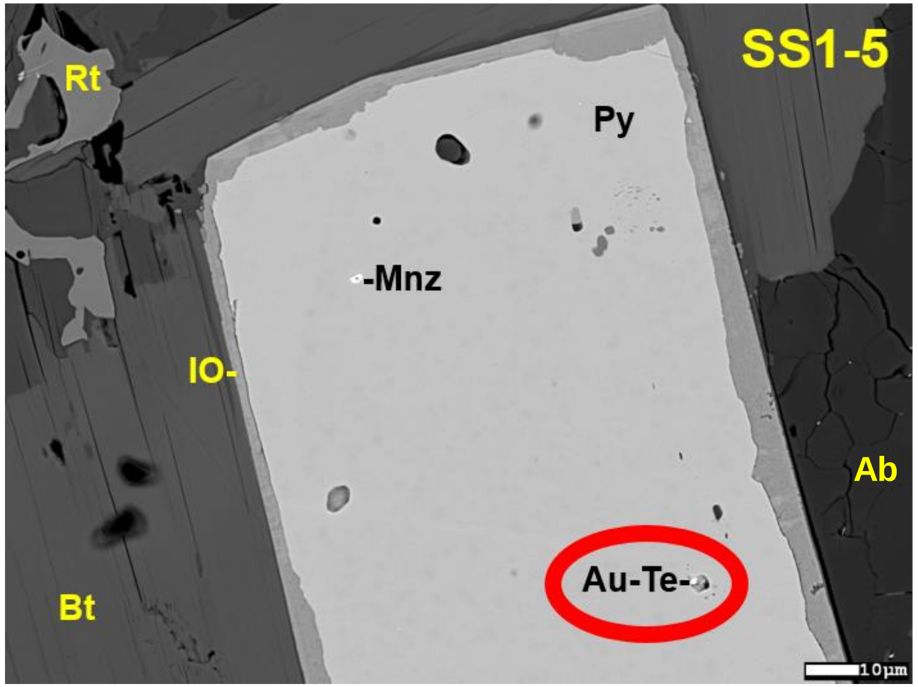
Validation by Petrography

- **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.**





Taylor et al. *(in prep)*

Quaternary Dispersion of the Footprint

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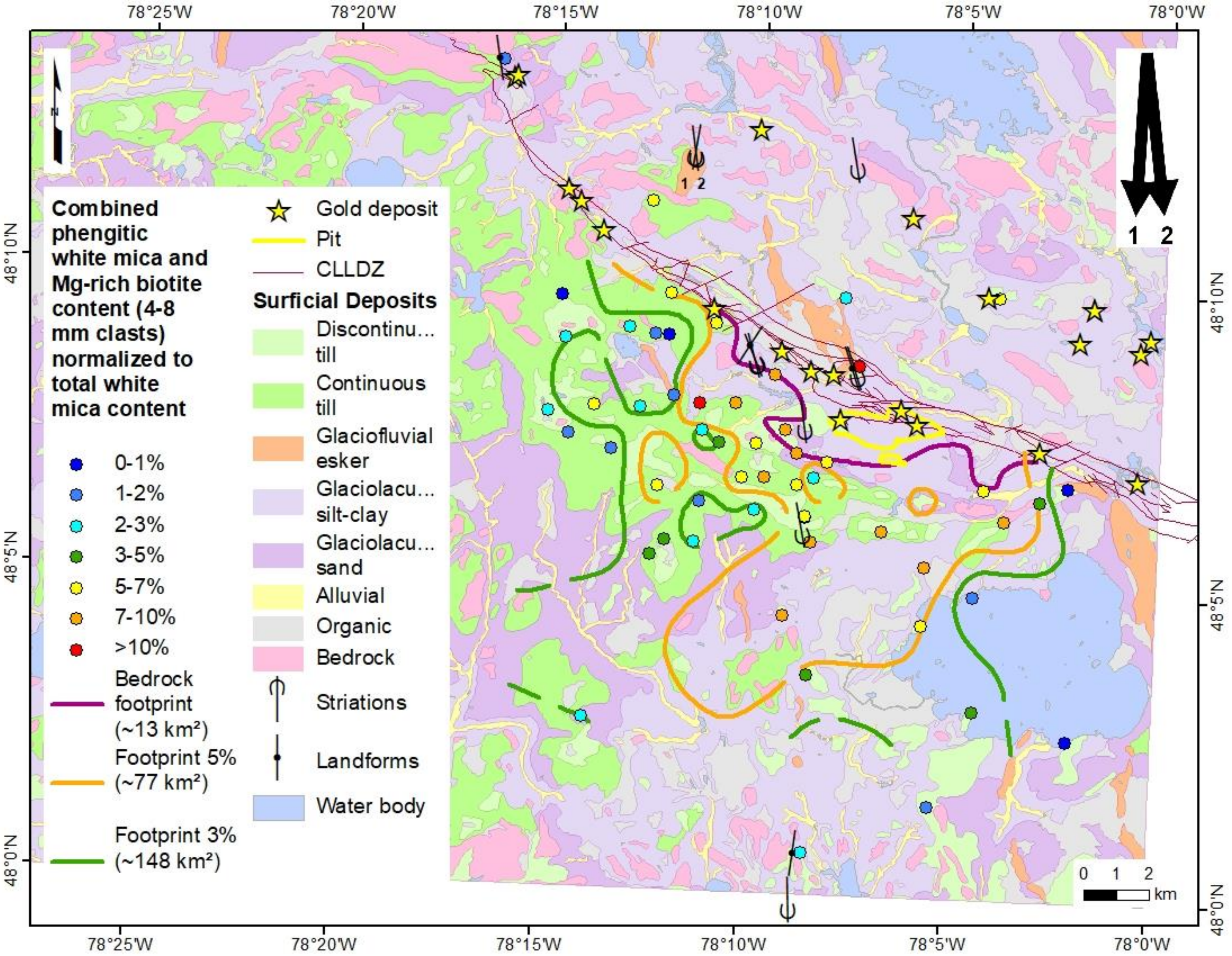
- Interpolated glacial dispersion of the footprint based on biotite and white mica compositions (4-8 mm clasts):
- **Fan-shaped dispersion toward the SSE, at least 5 times bigger than the footprint in the bedrock.**
- ***Background map after Veillette (2004). (1) and (2) on map represent older and younger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



Taylor et al. *(in prep)*

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

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

Supporters: Fullagar Geophysics
Rekasa Rocks
UBC Geophysical Inversion Facility

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