NSERC-CMIC

FOOTPRINTS

PROJECT

Mine wall imaging using SisuRock hypespectral camera.
Dr. Benoit Rivard (right) and Dr. Jilu Feng (left).

"NSERC is pleased to have supported Footprints, a unique collaboration and the largest mineral exploration research project ever undertaken in Canada. The new knowledge and improved methods developed under the project will help Canadian mining companies identify ore-system footprints at their most distant edges and depths. It will give Canadian mining companies an edge when it comes to exploring for new deposits.

I would like to thank Dr. Michael Lesher for his scientific leadership and all of the researchers involved in the project for their dedication and hard work. I would also like to acknowledge the important coordination and leadership role played by the Canadian Mining and Innovation Council (CMIC) and the support and engagement of the numerous mining companies and provincial and federal agencies involved in the Footprints project."

Dr. Marc Fortin,
Vice-President of Research Partnerships,
Natural Sciences and Engineering Research Council of Canada

Introduction

Au Site

U Site

Cu Site

Data Integration

Closing

The Creation and Success of the NSERC-CMIC Footprints Project

François Robert, Ph.D., Ing.
Barrick Gold Corp.

Richard Tosdal, Ph.D., P.Geo
PicachoEx LLC

Alan Galley, Ph.D., P.Geo.
Malleus Consulting Inc.

The NSERC-Footprints initiative must be considered the most successful and extensive industry-led mineral exploration research project in Canadian history. It's creation first came about in January, 2010 when François Robert, Richard Tosdal and six industry visionaries came together to define the critical needs of Canada's mineral exploration sector. This was a breakthrough for Canada's mineral exploration business, and set a new standard for creating and supporting collaborative R&D. This group became the Exploration Innovation Consortium (EIC), the first component of the Canada Mining Innovation Council (www.cmic-ccim.org).

As a result of a series of meetings the continually expanding industry group designed a 10-year road map to increase mineral discovery in Canada based on the need for new discovery criteria, exploration techniques, and better data management and analysis *(Fig. 1)*. The road map focused on the exploration challenge associated with deep and mature mining camps, remote areas, and covered terrains *(Fig. 2)*.

Once defined by industry, the roadmap challenged Canada's research community to develop a multi-disciplinary approach towards the generation of integrated exploration approaches and methodology that would result in more effective and efficient mineral exploration.

Themes	**Discovery Criteria**	**Discovery Technology**	**Data to Knowledge**
Focus	**Knowledge and Models**	**Detection**	**Interpretation**
Key Questions	• Where to look? • What to look for?	• How to detect?	• What does it mean?
Challenges	• Terrane selection • Area selection • Vectoring to ore	• Mapping and detection tools • Cheaper drilling	• Visualization and integration • Using physical property models
Education and Technology Transfer			

10-year roadmap developed in 2010 by the CMIC-EIC industry representatives as a conceptual guideline for future direction of mineral exploration research in Canada.

Looking back at the project in hindsight, we clearly have a landmark project in terms of collaboration among and between minerals industry, service providers, Universities, and Government institutions.

Deep Mature Camps	Remote and Covered Areas
Theme 1: Multi-parameter footprints and 3D vectoring • *Detecting edges and vectoring to ore*	**Theme 4:** Characteristics of fertile terranes and districts • *Identification of most fertile areas*
Theme 2: Techniques to unravel deep 3D geology • *Deep-penetrating detection and mapping techniques*	**Theme 5:** Techniques to map subsurface geology • *Drilling, data integration* • *Data density for detection*
Theme 3: Real-time down-hole data collection • *Real-time decision*	**Theme 6:** Secondary dispersion • *Understand mechanisms* • *Develop techniques*

Building on the roadmap in Figure 1, the CMIC-EIC committee further defined the exploration areas to be prioritized and themes on which specific programs should focus. Whereas Footprints was defined around Theme 1, the $104M Metal Earth project (merc.laurentian.ca/research/metal-earth) is focused on Theme 4 and planning for another EIC project is focused on Theme 6.

Under the university leadership of Drs. Michael Lesher and Mark Hannington over 40 university researchers from 20 Canadian universities embraced the vision set forth by the industry. Together with industry sponsors, they established a major collaborative R&D project proposal at a scale that has never been attempted.

After 2 years of dedicated work the result was a National Science and Engineering Research Council (NSERC) 5-year, initial $12M proposal: *Footprints: Integrated multi-parameter footprints of ore systems: The next generation of ore deposit models.*

A key to the acceptance by NSERC of the Footprints proposal was the funding support of 27 mineral exploration and sector service companies. These collaborators, over the course of the project, eventually expanded to over 30 companies. Whereas the quality and proposed innovations of the proposal, along with the original industry support resulted in this NSERC-CMIC project being implemented, it was the intellectual buy-in and support by industry that helped make the project an international success. The sponsor companies understood that their collective experiences and intellect had to form a critical input in ensuring the project research paths were new and innovative, thereby setting a new standard for collaborative mineral exploration R&D for Canada and around the world.

The project exceeded expectations on a number of fronts, including:

1. How it all came together and delivered on the initial objectives, largely on time and on budget, with credit to the project leaders, industry sponsors especially the site sponsors, the Board of Directors, and Science Advisory Board;
2. The quality and practical technical outcomes of the research at all the sites, some of which are being currently applied in active exploration programs, whereas others provide a basis for future development;
3. The enhanced scientific knowledge of the scale and manifestations of the hydrothermal systems investigated;
4. Having a significant number of students and postdocs working in a real-life Industry environment and being exposed to Industry imperatives and drivers;
5. Development of a template for the design, management, and implementation of large collaborative R&D programs in the mineral discovery environment.

This project illustrates that with an ambitious vision, leadership, and real collaboration across Industry and institutions, game-changing results can be achieved and pave the way for future exploration successes and future R&D.

Message from the Project Directors

CM LESHER
Principal Investigator
and Project Director

MD HANNINGTON
Co-Principal Investigator
and Co-Director

Mineral exploration in Canada is increasingly focused on concealed and deeply buried targets, requiring more effective tools to detect large-scale ore-forming systems and to vector from their most distal margins to their high-grade cores. A new generation of ore system models is required to achieve this.

This document summarizes the design and key results of the $13M Mineral Exploration Footprints project, which was funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Canada Mining Innovation Council (CMIC) between April 2013 and March 2019.

This was Canada's largest multidisciplinary, collaborative mineral exploration research network, involving 70 faculty, research associates, and student researchers at 20 Canadian universities working with 30 mining, mineral exploration, and mining service provider sponsors.

The goal of the project was to significantly improve our knowledge of the "footprints" of 3 major ore deposit types in Canada, an Archean disseminated gold system, typified by the Canadian Malartic deposit in Québec, an unconformity-related uranium system, typified by the McArthur River – Millennium corridor in Saskatchewan, and a porphyry copper-(molybdenum)-(gold) system, typified by the Highland Valley deposit in British Columbia.

Over 118 footprint components and vectors were identified at Canadian Malartic, 40 at McArthur-Millennium, and over 83 at Highland Valley. They were integrated using self-consistent 3D Common Earth Models and geostatistical/machine learning technologies.

Project results and publications are posted on **merc.laurentian.ca/footprints**.

CM Lesher and MG Hannington

Project Objectives and Design

PROJECT OBJECTIVES

The project had three key objectives:

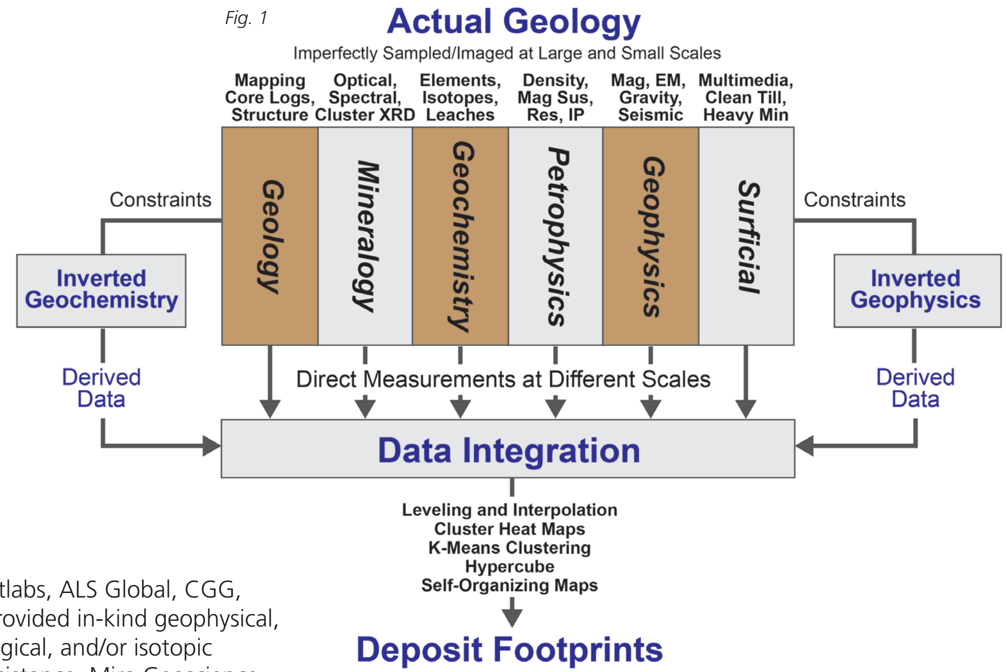
1. To enhance the ability of the Canadian mining industry to recognize the entire "footprint" of an ore deposit from its high-grade core to the most-distant cryptic margin (which, if deeply buried, is the only part detectable on the surface).
2. To develop methods that fully integrate the wide range of complex geological, structural, lithologic, mineralogical, geochemical, petrophysical, and geophysical data that define the "footprint" of an ore deposit.
3. To formalize methodologies for how specialists in each of those areas will effectively interact in order to accomplish those targets.

PROJECT DESIGN

A key aspect to the success of the project was the use of Site Groups, which included Site Sponsor Representatives, to coordinate and focus the research at each site, and Technical Groups to coordinate and drive the geological, structural, mineralogical, mineral chemical, lithogeochemical, petrophysical, geophysical, and surficial layers at all three study sites *(Fig. 1)*. Annual work plans were reviewed by Sponsor Subject Matter Experts, the Scientific Advisory Board, and they and the budget were approved by the Board of Directors.

Another key aspect was the creation of a workflow *(Fig. 2)* that ensured data were collected and treated in the same way for the entire project and that knowledge gained at one site was quickly transferred to the other sites. A dedicated Data Integration Team explored the best methods for data integration, working with the Site Groups and Technical Groups.Mine Canadian Malartic, Cameco Resources, and Teck Resources provided access to the research sites and a wide variety of proprietary geological, geophysical, and geochemical data.

Fig. 1

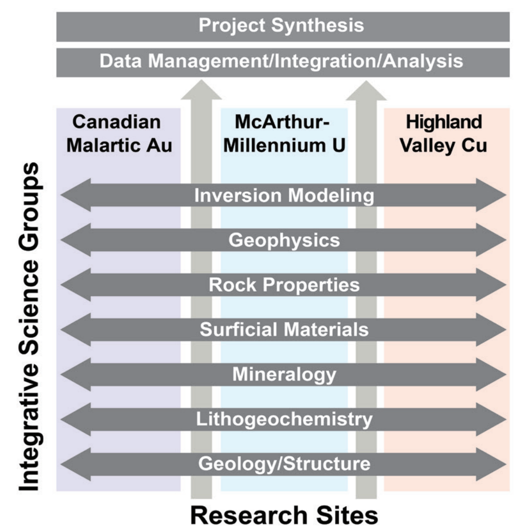


Abitibi Geophysics, Actlabs, ALS Global, CGG, PGW, SGS, and SRC provided in-kind geophysical, geochemical, mineralogical, and/or isotopic analyses/processing/assistance. Mira Geoscience, Bearing Point, Reflex, and SRK provided in-kind 3D modelling, machine learning, geochemical plotting/analysis, and structural workshops. GSC-Sydney provided in-kind petrophysical data.

Geophysical data processing, gridding and interpretation were performed using Geosoft Oasis Montaj. Geophysical Inversions were performed using codes from Fullagar Geophysics, Geosoft, Mira Geoscience, and the University of British Columbia Geophysical Inversion Facility. Geochemical plotting and analysis were performed using Reflex ioGAS and other spreadsheet/plotting software. 2D mapping was done using Pitney Bowes MapInfo and other mapping software. Data were compiled in Mira Geoscience's INTEGRATOR and visualized in Mira Geocience's ANALYST. Self-consistent 3D Common Earth models were constructed using GOCAD/SKUA Mining Suite from Emerson/Paradigm and Mira Geoscience.

Statistical analyses and machine learning were done using Bearing Point Hypercube and a variety of open-source and custom codes.

Fig. 2



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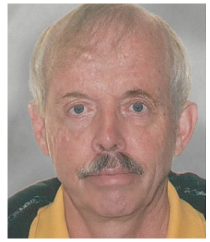

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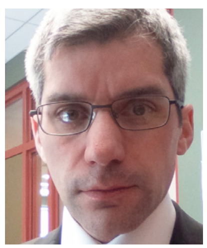

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Gerard Zaluski *(Cameco)*


DEERE

Au Site

Key Numbers

21
HQP (10 RA/PDF, 3 PhD, 5 MSc, 3 BSc) trained

64
Researchers and Collaborators

10
New geophysical surveys

1,540
days (18,500 hours) of field work

2,300
structural measurements

1,700
SWIR analyses

1,200
whole rock lithogeochemical analyses

4,400
pXRF analyses

7,500
mineral analyses

350
XRD analyses

900
thin-sections

850
petrophysical measurements

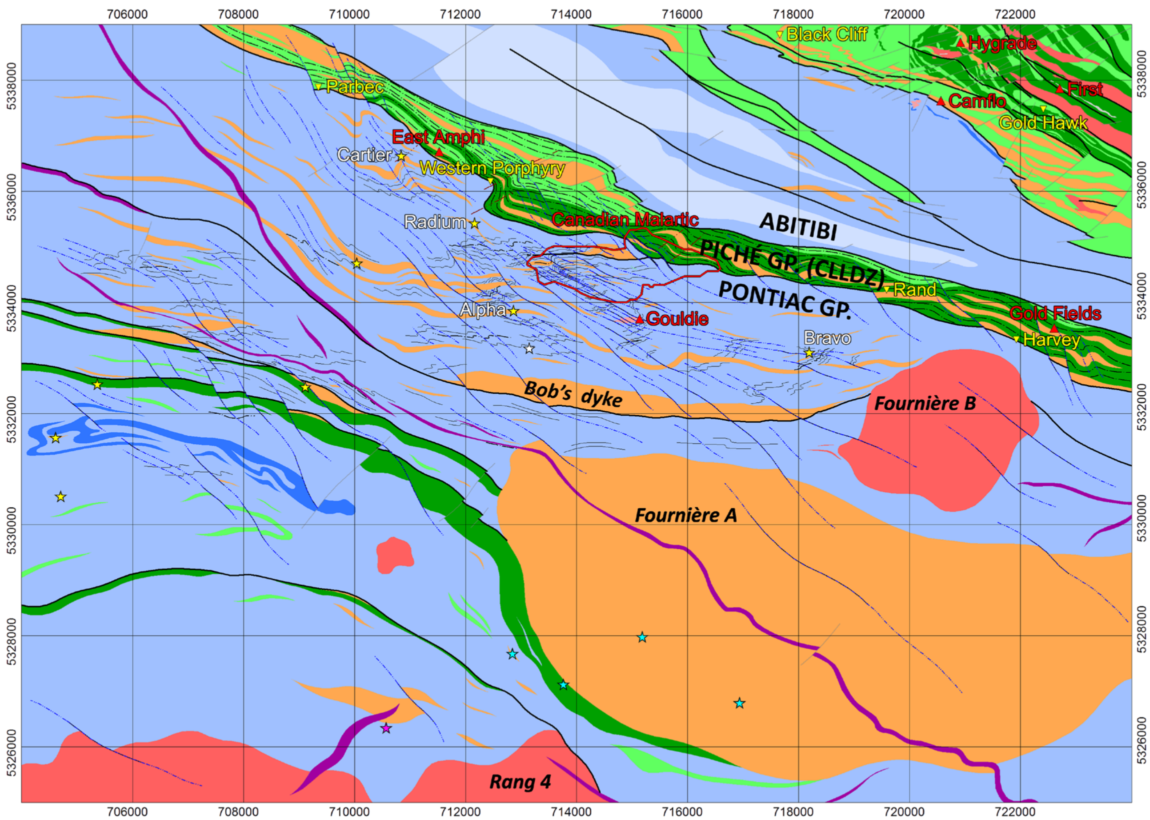
Au

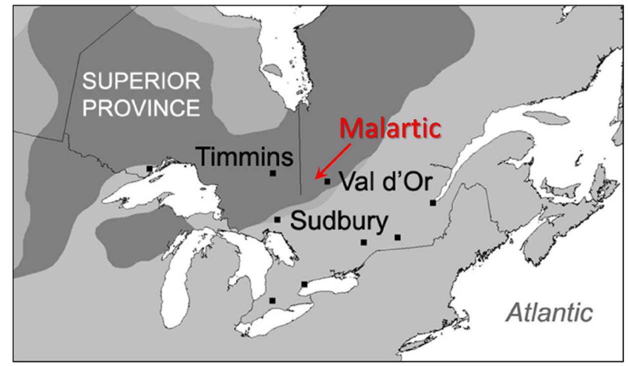
Canadian Malartic provided 20 geophysical surveys, 3600 historical maps and cross-sections, >100000 drillcore photographs, and >500,000 gold assays

118
structural, geophysical, geochemical, mineralogical, and petrophysical footprints and vectors identified

Multiple alteration centers were identified (Canadian Malartic, Cartier, Bravo/Odyssey). Their sizes range from 0.5 to 6 km from the core of the system. New structural, metamorphic, and hydrothermal models were proposed.

Geological Map

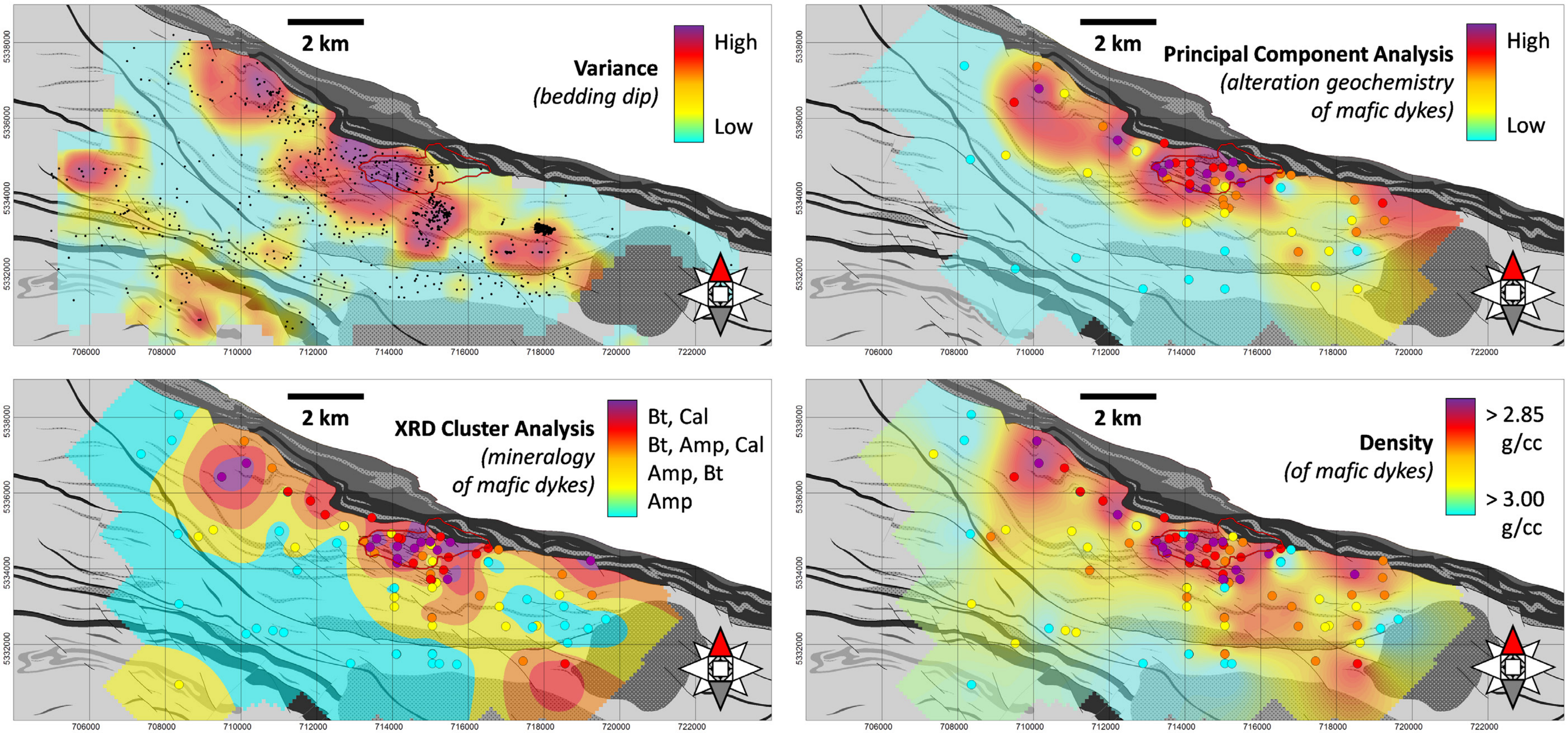




- Diabase
- Granite (i.e. Gouldie)
- Monzonite / Granodiorite
- Monzodiorite
- Greywackes
- Iron Formations
- Mafic Volcanic rocks
- Ultramafic Volcanic rocks
- Pit outline (active mine)
- S_0 (bedding)
- S_1 (foliation)
- S_2 (foliation)
- Fault
- Au old mine
- Au prospect
- Au occurrence
- Ag, Cu, Be occurrences

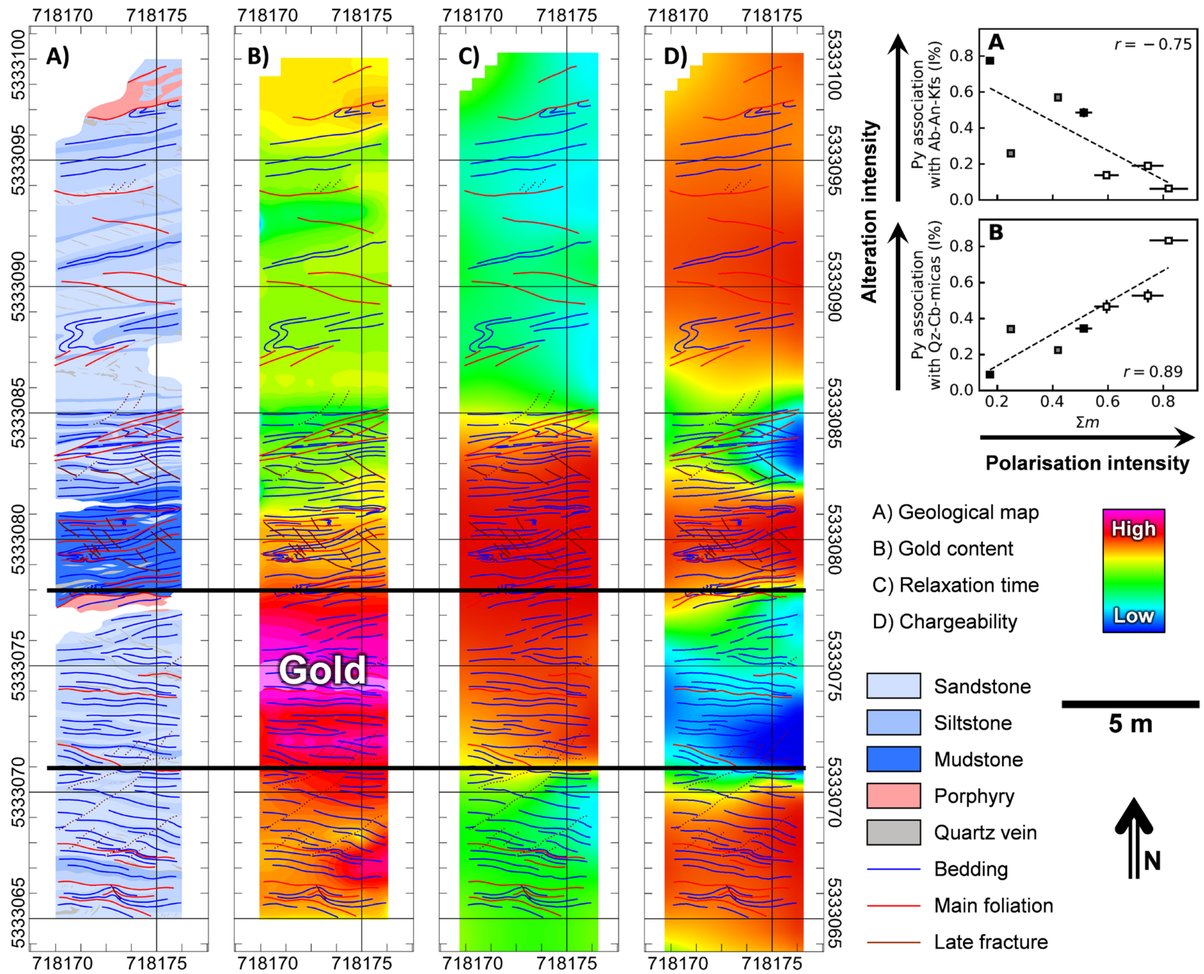
Geological map of the Canadian Marlartic area (modified after Perrouty et al., 2017).

Key Mineral Exploration Footprint Maps



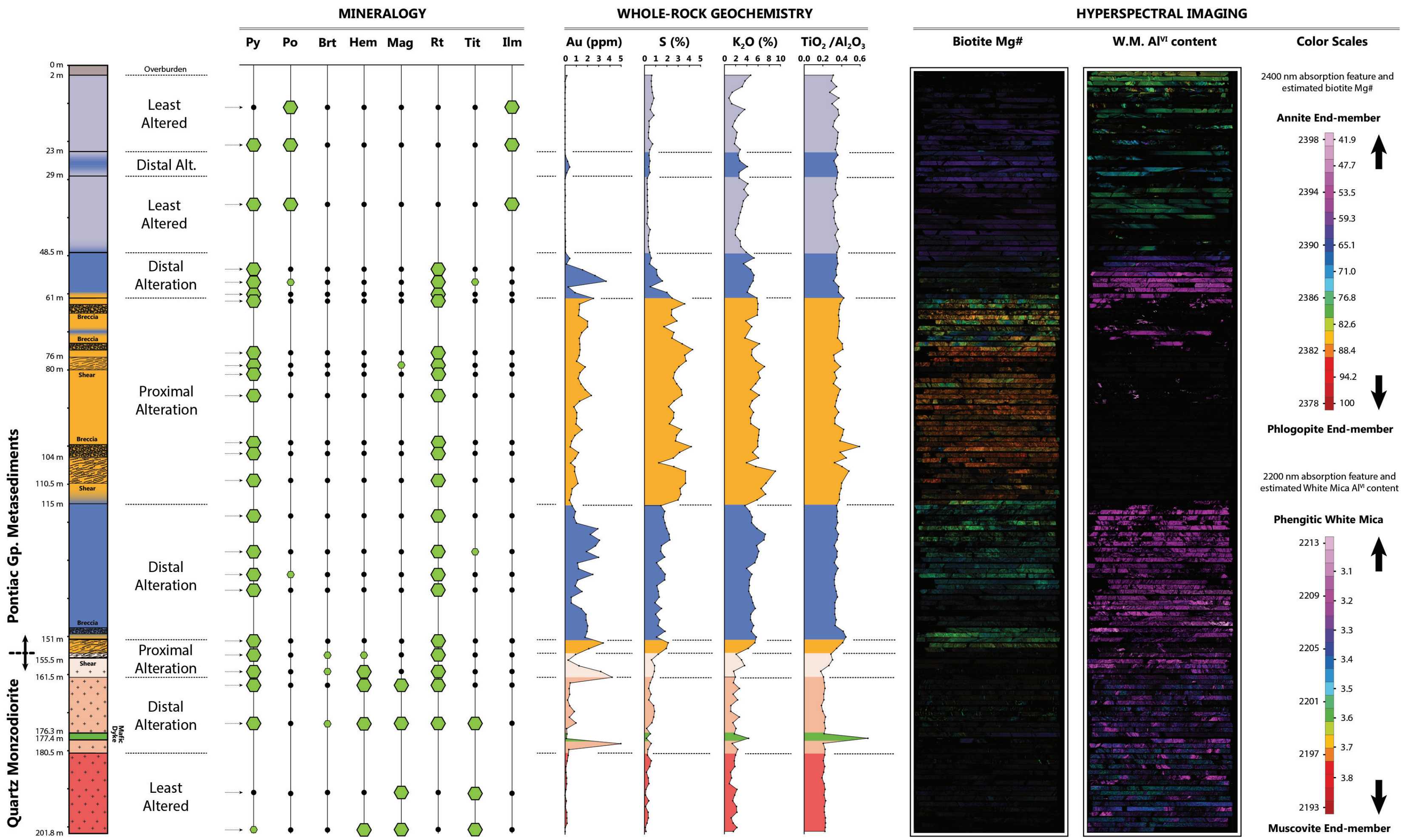
Variants in bedding dip, principal component analysis, XRD cluster analysis, and density maps for the Canadian Malartic area (modified after Perrouty et al., 2018).

Petrophysical Maps



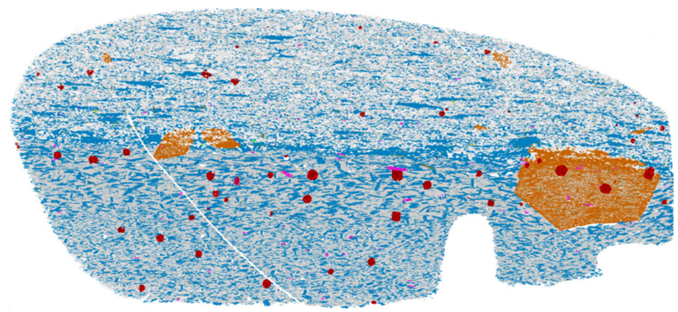
Geological and petrophysical maps of the Bravo outcrop (modified after Bérubé et al., 2017). At Canadian Malartic, the zones of pervasive hydrothermal alteration are characterized by low chargeability. This is due to pyrite being encapsulated in feldspar (microcline and albite), which diminishes the surface of contact between sulfides and porosity and therefore the chargeability.

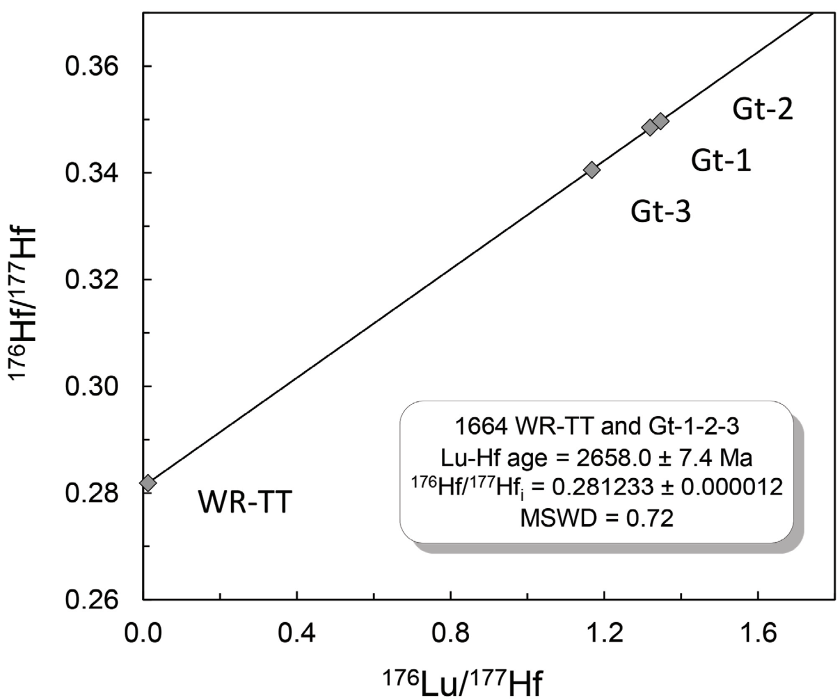
Mineralogy-Geochemistry-Hyperspectral

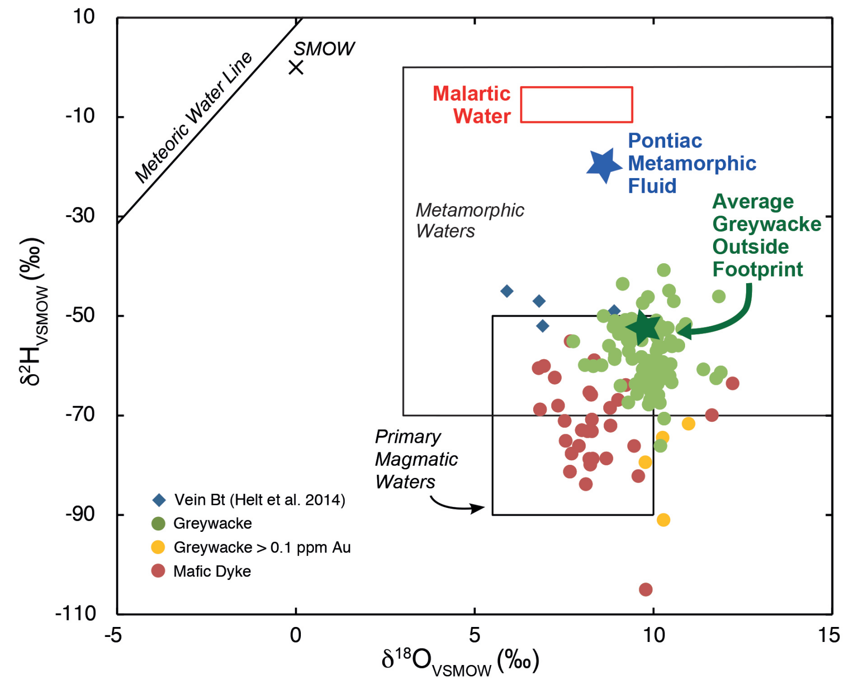


This drillhole intersects the main structural control of the Canadian Malartic system (i.e., the Sladen Fault). The zonation of the alteration proximal to fluid pathways is expressed in the lithogeochemistry (gold, sulfur, potassium enrichment), mineralogy (proximal Fe-dolomite-calcite and distal calcite-only assemblages), and mineral chemistry (biotite Mg# and AlVI in white mica, measured using Short Wavelength InfraRed imaging) (modified after Gaillard et al., 2018).

Metamorphism / Isotopes



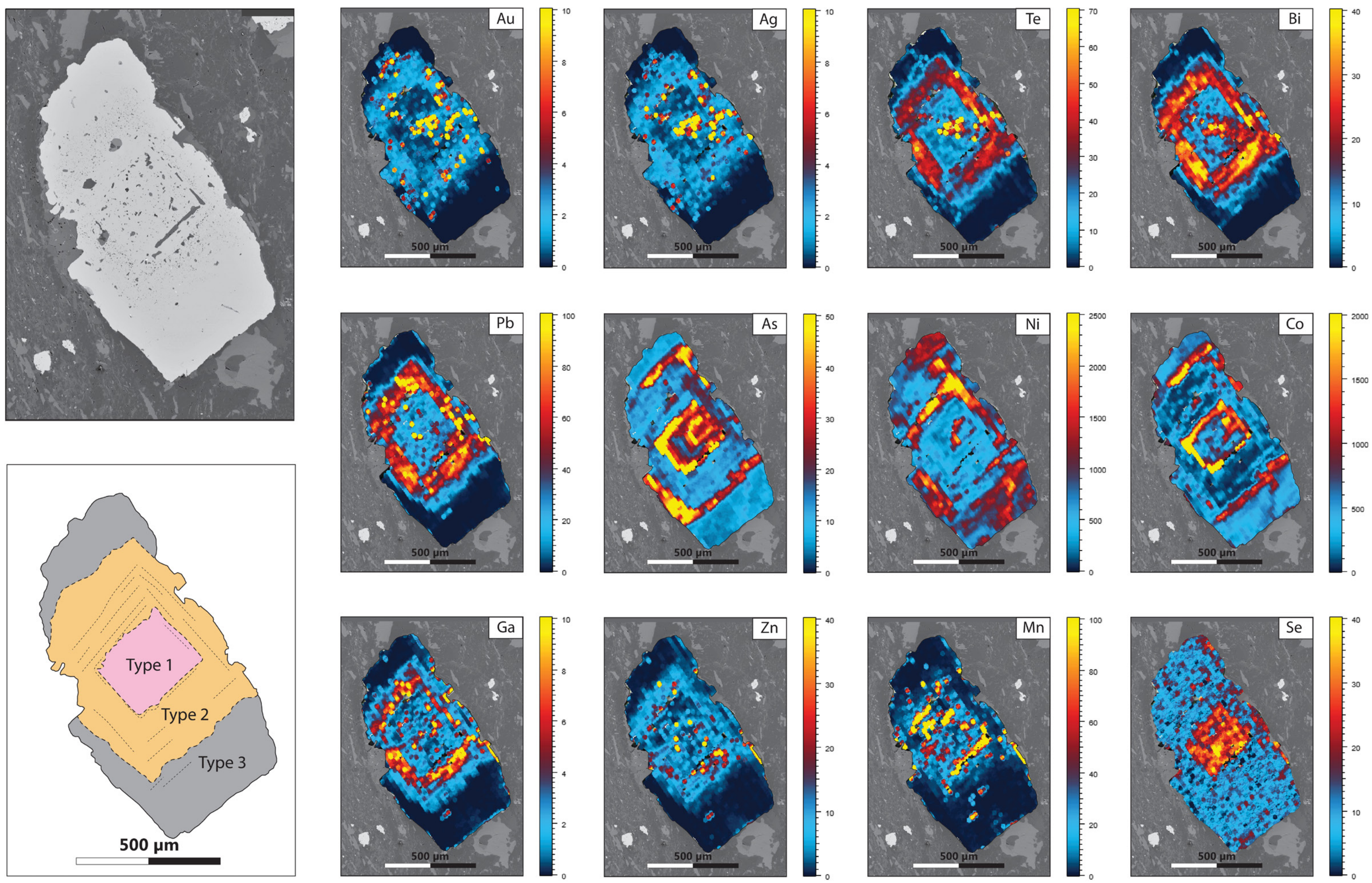




Left: Isochron on garnet. The photo is a SEM/MLA map of the sample (garnet in red, staurolite in orange, mica in blue). The metamorphic overprint of the Canadian Malartic footprint has been investigated using structural observation (metamorphism is syn to late mineralization), mineral chemistry (Tschermak substitution in mica). Lu-Hf age on garnet at 2657 Ma is the first reliable metamorphic age to be obtained for the Pontiac Subprovince. (modified after Piette-Lauzière et al., 2018).

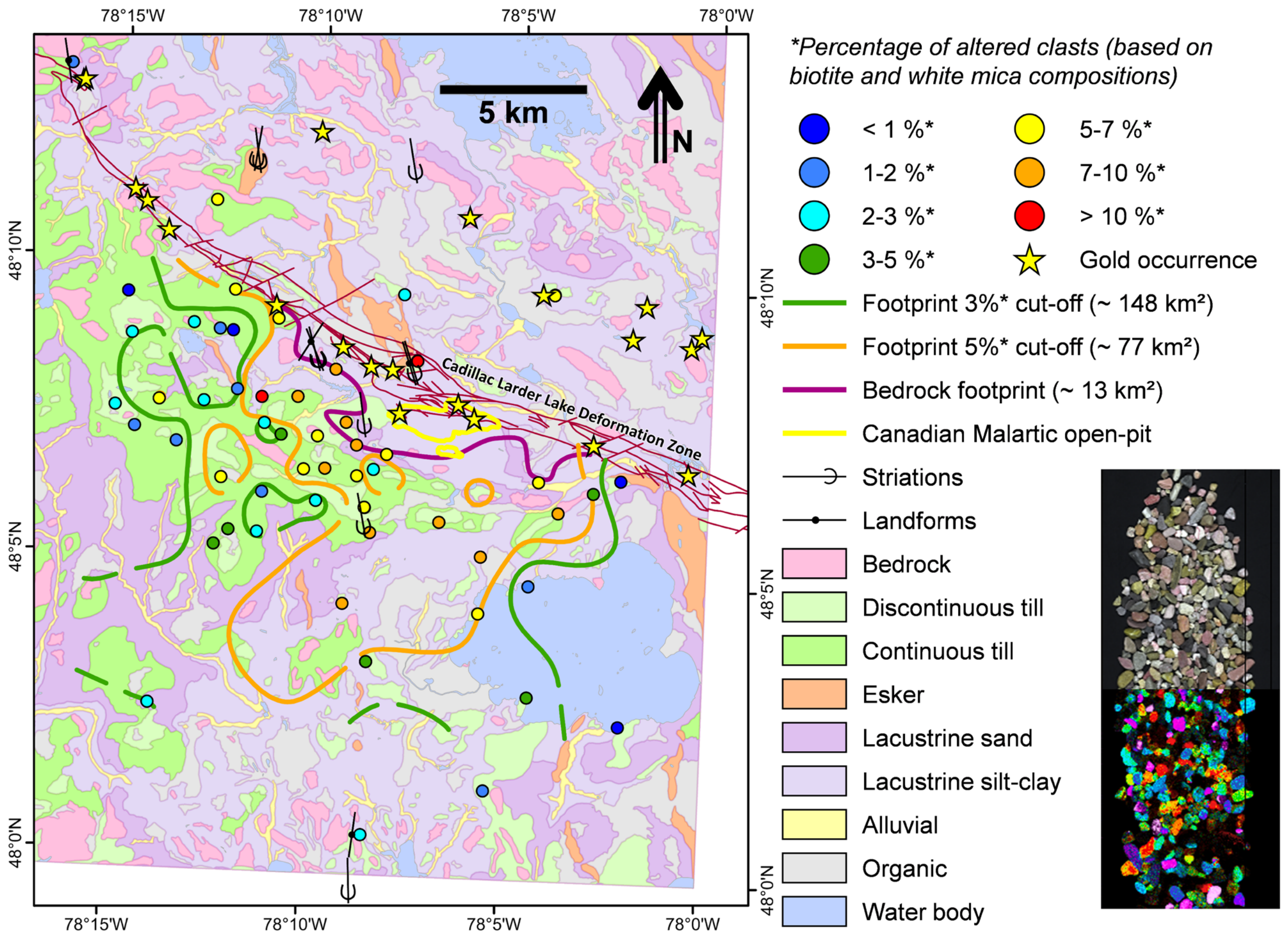
Right: $\delta^{18}O$ and $\delta^{2}H$ stable isotope geology. (Stable isotope compositions are in equilibrium with upper greenschist to amphibolite conditions of ca. 550°C) (modified after Raskevicius et al., submitted).

Mineral Chemistry



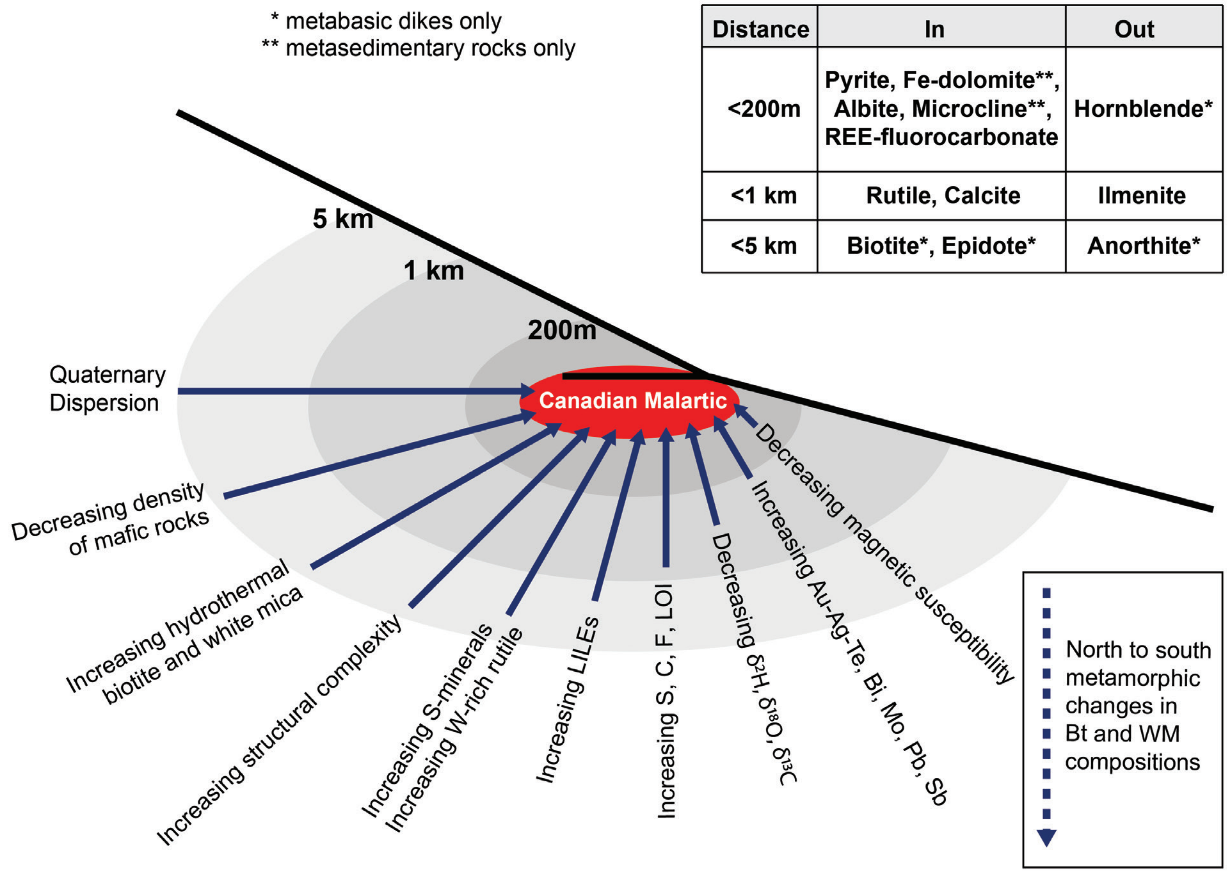
LA-ICP-MS maps showing three generations of hydrothermal pyrites (Gaillard et al., submitted).

Quaternary Footprint



The quaternary dispersion of the Canadian Malartic footprint (map above) was estimated using SWIR analyses of glacial till clasts (modified after Taylor et al., in preparation).

Schematic Footprint

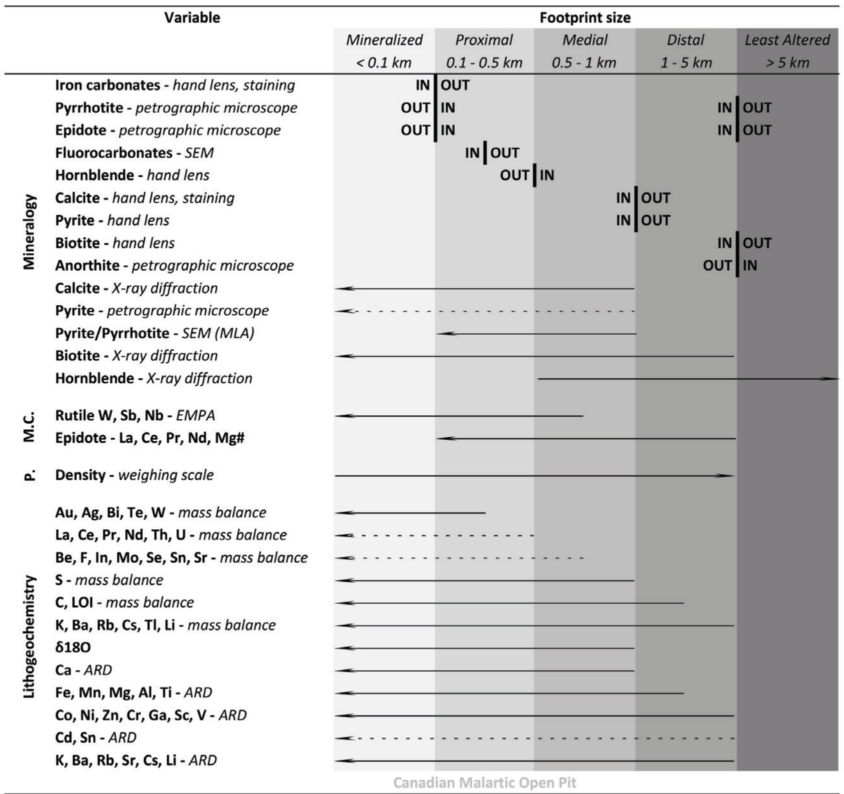


Distance	In	Out
<200m	Pyrite, Fe-dolomite**, Albite, Microcline**, REE-fluorocarbonate	Hornblende*
<1 km	Rutile, Calcite	Ilmenite
<5 km	Biotite*, Epidote*	Anorthite*

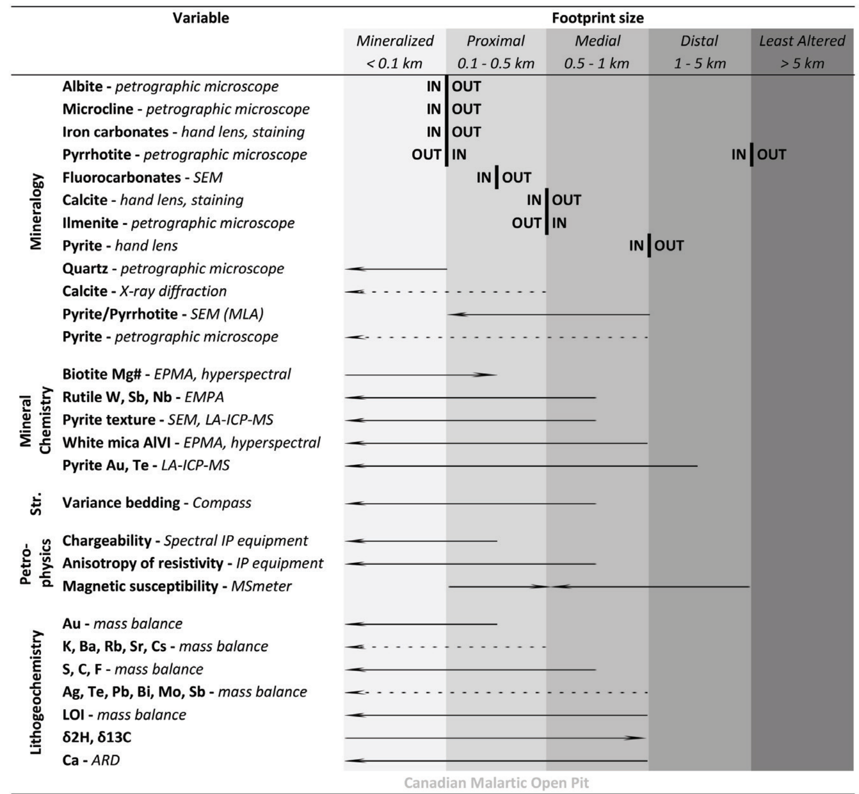
Schematic map of Canadian Malartic area summarizing some of the footprint components (upper right) and vectors in the Pontiac Group (modified from Lesher et al., 2017).

Footprints and Vectors

Mafic Dykes



Metasedimentary Rocks



Footprints (In/Out) and vectors (arrows) in mafic dykes (left) and metasedimentary rocks (right).


Cameco
U Site

Key Numbers

18

HQP (9 RA, 2 PhD, 6 MSc, 1 BSc, 5 Field Assistants) trained

18

Researchers and Collaborators

17

Industry Collaborators

1,440

drill-hole lithology logs, and associated structural (~140,000 interval, and ~450,000 point structures), geochemical (> 10,000 analyses), SWIR data

2,775

geochemical analyses used for the Millennium geochemical study, and 7,774 for the McArthur River area

233 new samples collected from 13 drill-holes in the McArthur River area – SWIR, and geochemical data obtained from all samples, 123 polished thin sections, 23 hyperpectral images obtained from thin section chips from one hole, for comparison. New LA-ICP-MS

253 samples collected adjacent to samples above, and underlying basement, for new rock property data (density and porosity, magnetic susceptibility and remanence, electric resistivity and chargeability)

82 fracture samples collected from these drill-holes, optical and SEM mineralogy, stable and Pb isotopes, CL-ICP-MS

New Rn, Ra, and U in glacial till and soil, groundwater, and fracture coatings, and He, H, and O in groundwater

580 tree cores (older than 1970), **270** sandstone boulders, and **2140** soil samples, with a focus on the A-horizon, from **4** grids above the McArthur River deposit – geochemistry, Pb isotopes, SWIR

9 km of new ground penetrating radar sections along 5 lines to determine thickness and stratigraphy of glacial sediments

Surficial ice flow and stratigraphic measurements, including **74** till samples for geochemistry, mineralogy, pebble counts, and density resulting in a new predictive map

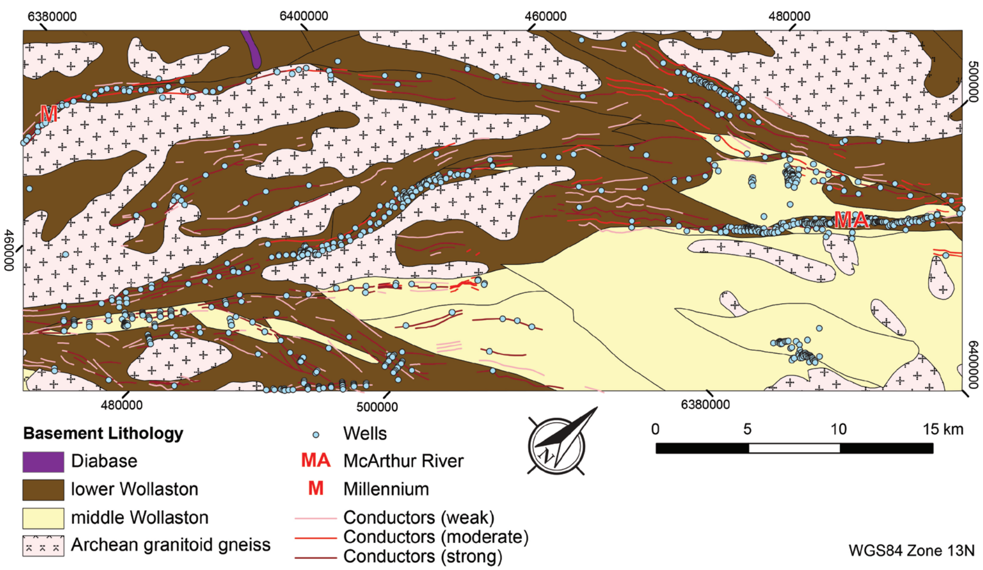
Cameco provided a database that included 1,440 drill-hole lithology logs with structural, geochemical, and SWIR data, interpreted basement geology map, and geophysical data - regional and around the Millennium and McArthur River area - triaxial magnetics, airborne and ground gravity gradiometry, 3D-3C seismic, TEM, VTEM surveys and 50m-spaced Digital Elevation Model

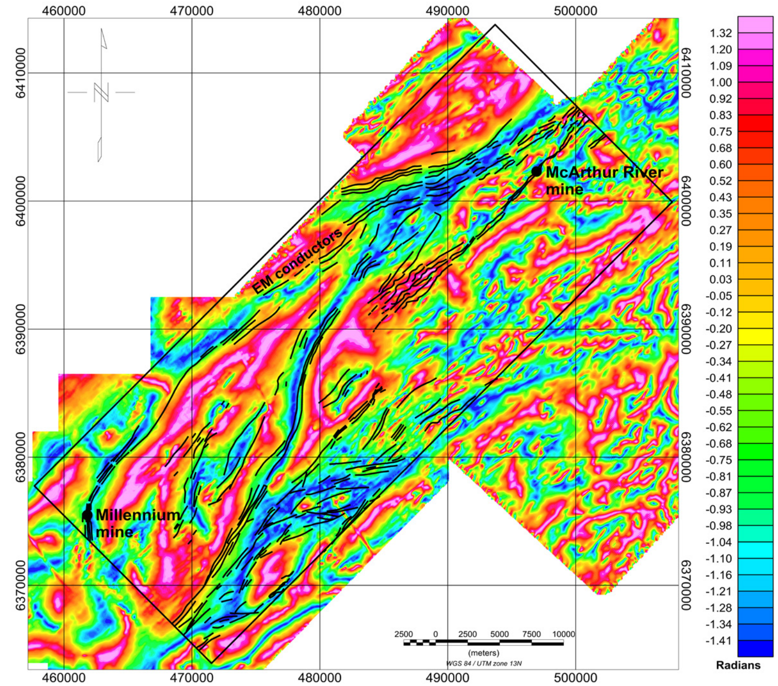
CGG provided VTEM data from 92 profile lines to obtain conductivity-depth slices

~ 20

individual footprint components and vectors have been identified at McArthur River and ~30 at Millennium. Some are similar at both sites, but some are different, highlighting multiple factors/processes involved in the mineralizing systems in the Athabasca Basin.

Geology and Geophysics

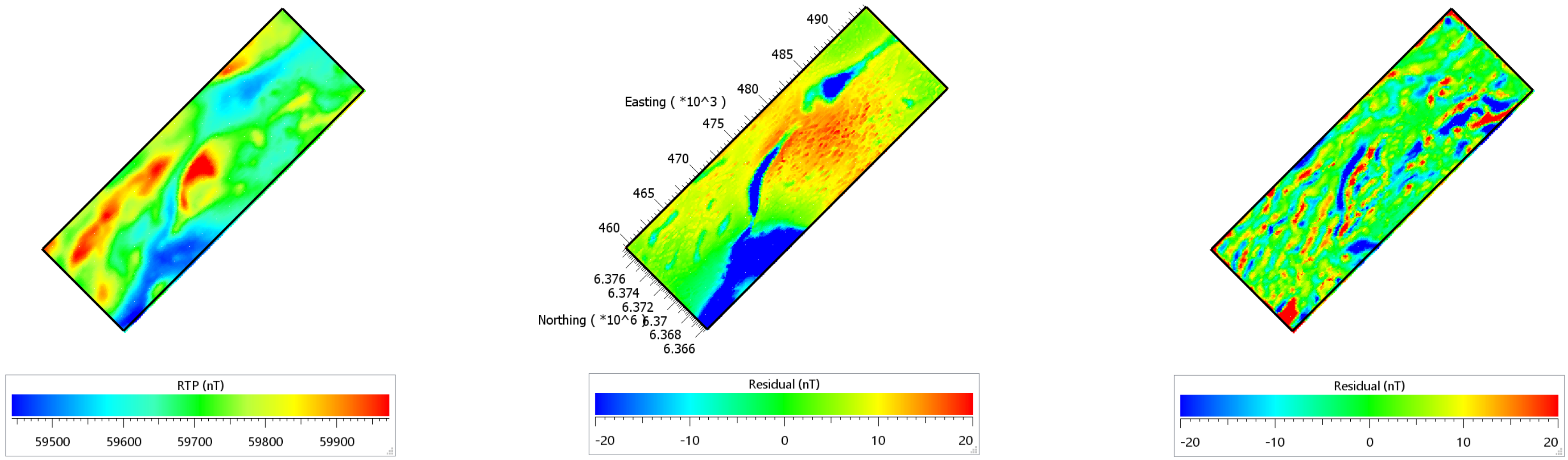


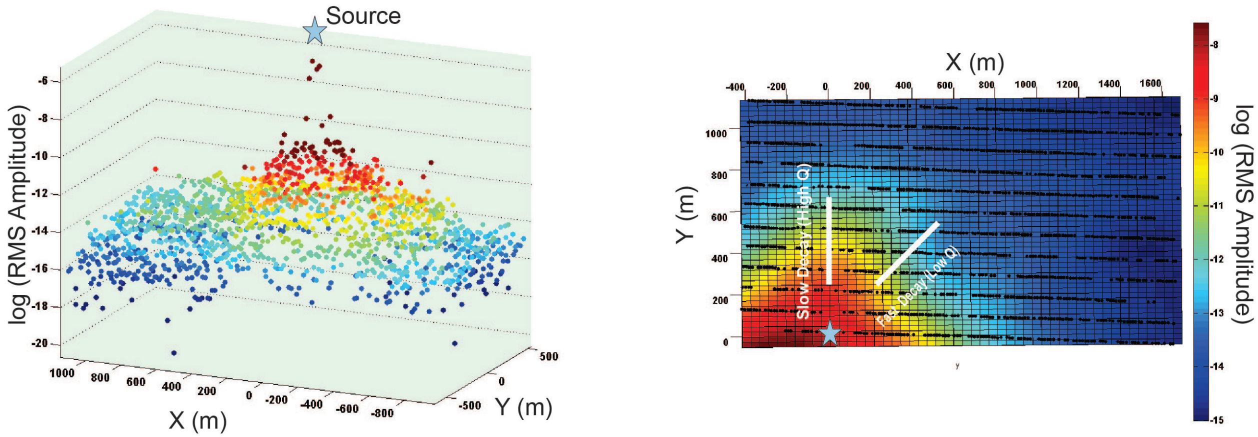


Left: Simplified geological map of the interpreted basement geology underneath the southeast part of the Athabasca Basin (after G. Zaluski, Cameco), showing the location of electromagnetic conductors, drillholes, the McArthur River mine, and the Millennium deposit.

Right: A map of tilt-angle derivative calculated from a combined airborne triaxial magnetic data set obtained by stitching three surveys together (by Reza Mir RA). The map is overlain with interpreted conductors from ground and airborne electromagnetic surveys defining structures. The magnetic signature can be broadly correlated with rock units in the basement rocks below the unconformity and the sandstones in the Athabasca Basin.

Inversion and Seismics

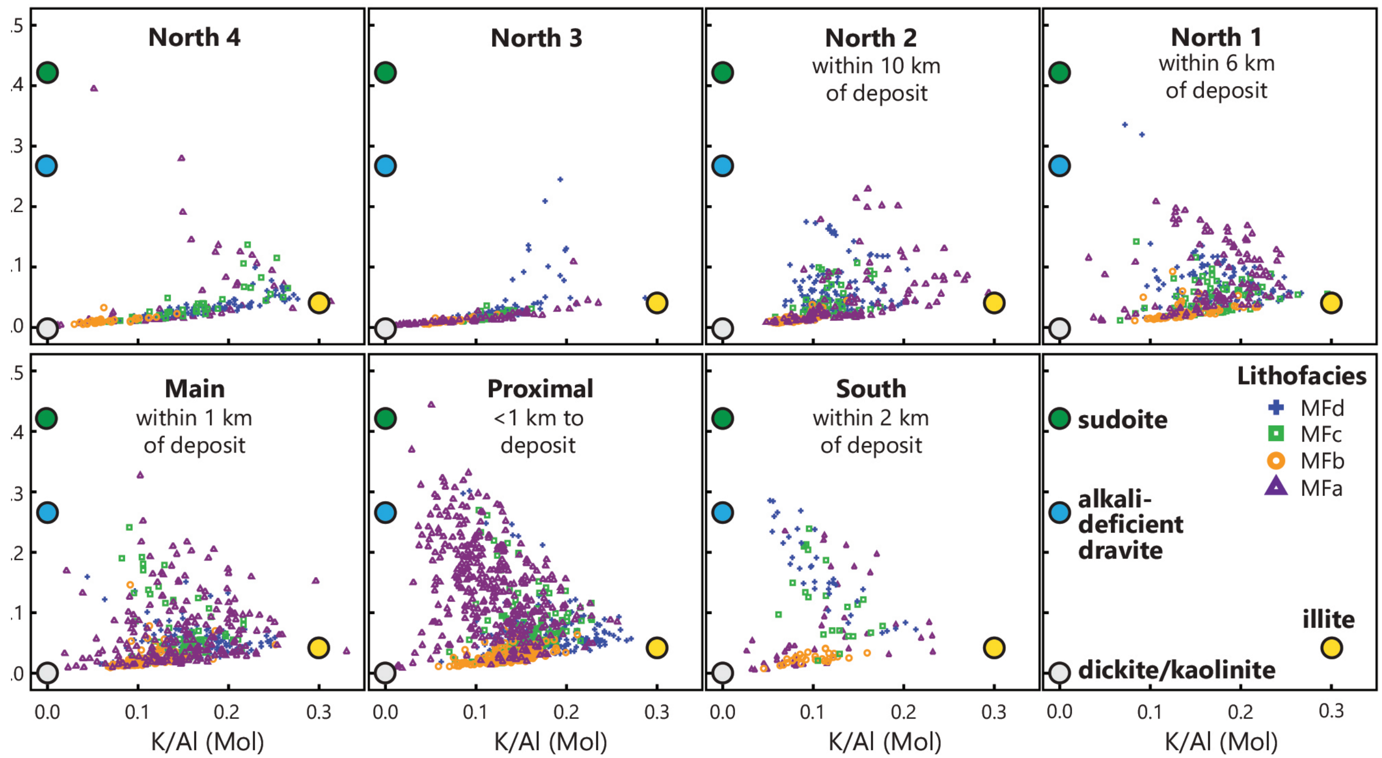




Top: Compilation of total aeromagnetic field reduced to pole over the whole of the U Site area. Marc Vallee (RA) attempted to make the available magnetic data consistent with the geological model using Vpmg inversion software. The middle figure shows the residuals from an unconstrained inversion, whereas the right figure shows the results of a constrained inversion utilizing the most reasonable geological model and physical properties of the rock units in the basement. The geology of the basement below the unconformity with the sandstones is complicated, although the constrained inversion has been the most successful at reducing the residuals

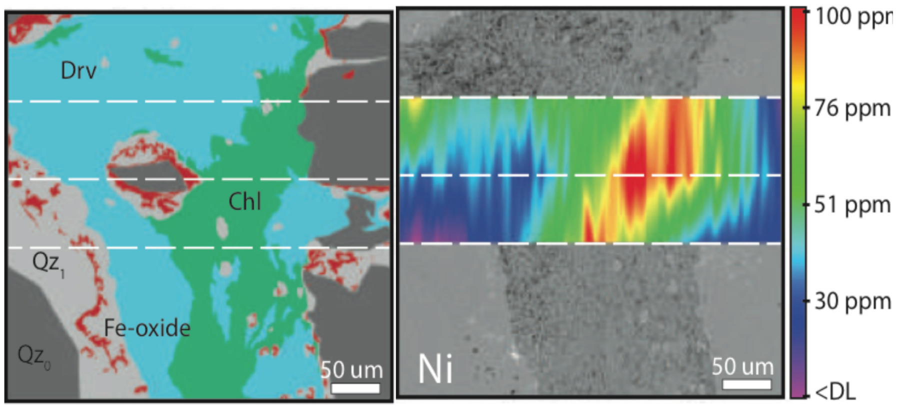
Bottom: First break amplitude of seismic waves, measured by Dong Shi (PhD), from the Millennium deposit area has been used to calculate attenuation (Qp). The values are very low, and are interpreted to be imaging subtly altered rocks in the sandstones, vertically above the deposit ("seismic footprint").

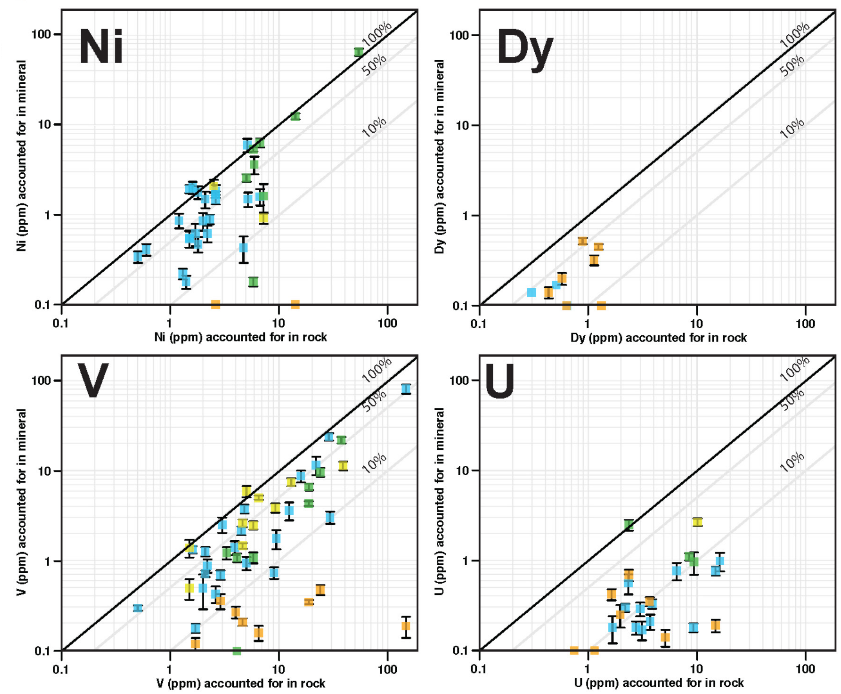
Geochemistry

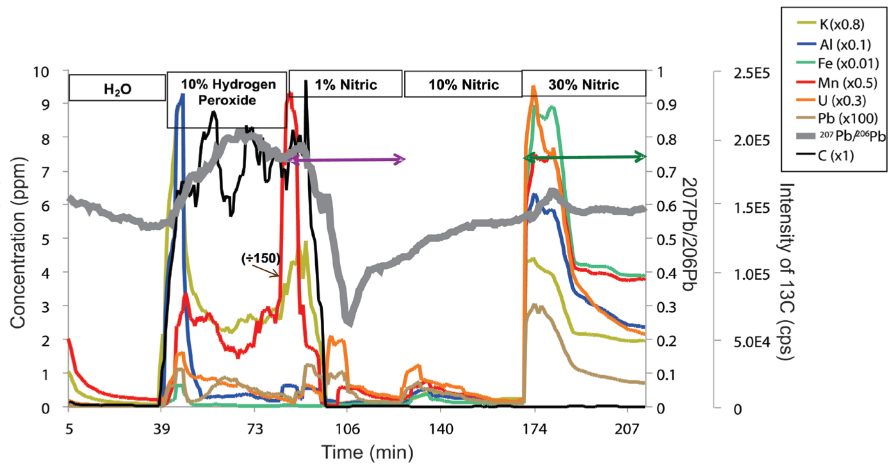


Molar element ratio plots, constructed by Shannon Guffey (MSc), demonstrate the varying contents of Mg and K in the sandstones (MFa, which is above the unconformity, to MFd below the glacial deposits) relative to the location of the Millennium deposit. In the least-altered locations, greater than 10 km from the deposit (North 4 and North 3), samples plot on the trend between the kaolin group and illite nodes almost exclusively. Within 10 km of the deposit (North 2), samples shift toward the alkali-deficient dravite and sudoite nodes in the MFd, MFc, and MFa lithofacies. This shift intensifies with proximity to the deposit in all lithofacies but the MFb. The use of molar element ratios has expanded the footprint of a uranium mineralizing system

Mineralogy and Fractures





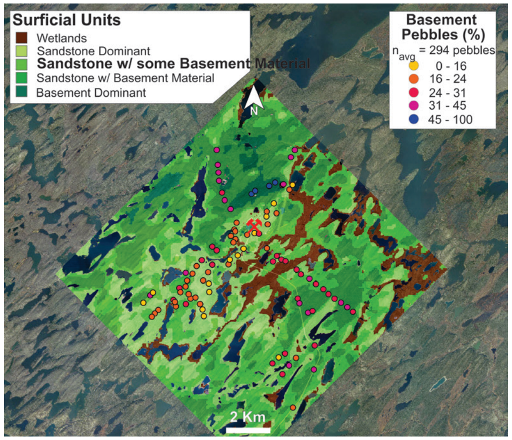


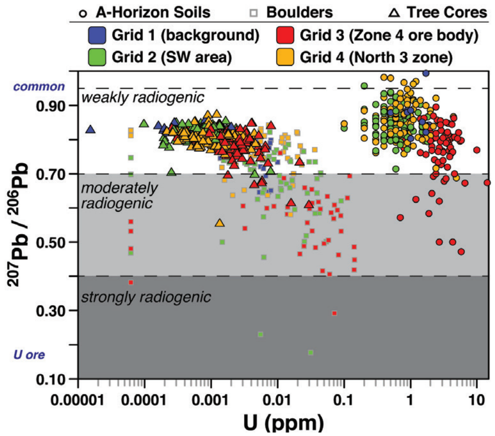
Top left: LA-ICP-MS map showing the distribution of nickel, and interpretative alteration mineral assemblages obtained by Nick Joyce (MSc) from a polished thin section of a core sample from the McArthur River area. The Ni map is superimposed on a SEM-BSE image of the thin section.

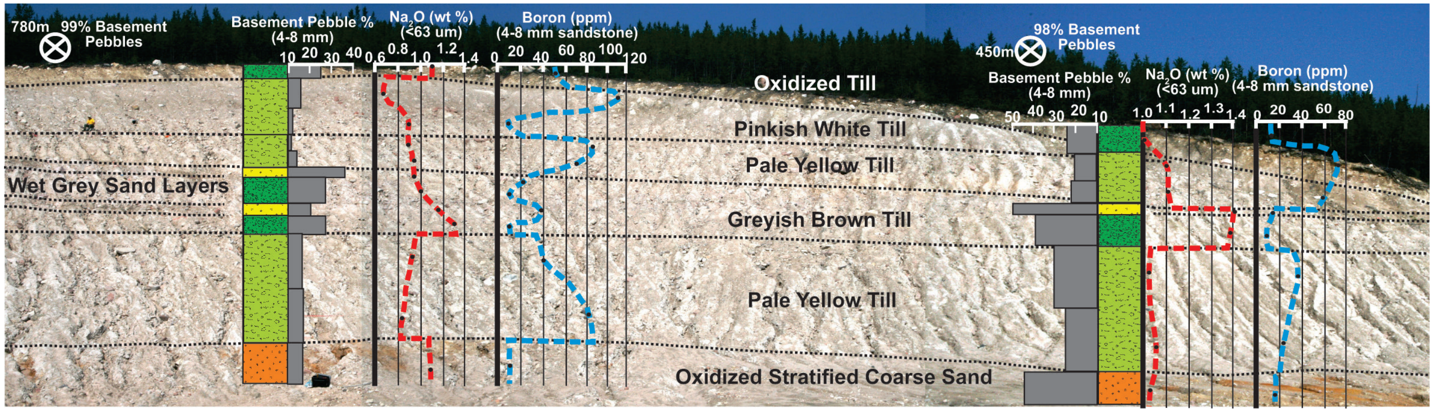
Top right: The inventory of trace elements, such as Ni, in the minerals present in altered rocks was determined by comparing the concentration of elements in the minerals obtained by LA-ICP-MS (normalized on the basis of whole-rock clay proportions determined by SWIR analysis) with the concentration of the element in the whole rock sample (determined by ICP-MS total digestion lithogeochemistry). It was found that much of the Ni can be accounted for by chlorite in the alteration mineral assemblages.

Bottom left: An example of continuous leach-ICP-MS data collected by Marissa Valentino (MSc) from a fracture in the sandstones, which is coated by illite, kaolinite, and goethite, and Mn-oxides, interacts with leaching solutions of increasing strength. The 10% hydrogen peroxide leach removes elements associated with organics, whereas the strongest acid leaches elements within the minerals that coat the fracture. This type of data suggests that brown fractures record secondary dispersion of elements from the McArthur River deposit throughout the sandstone column, and may thus be a useful vector to mineralization.

Surficial





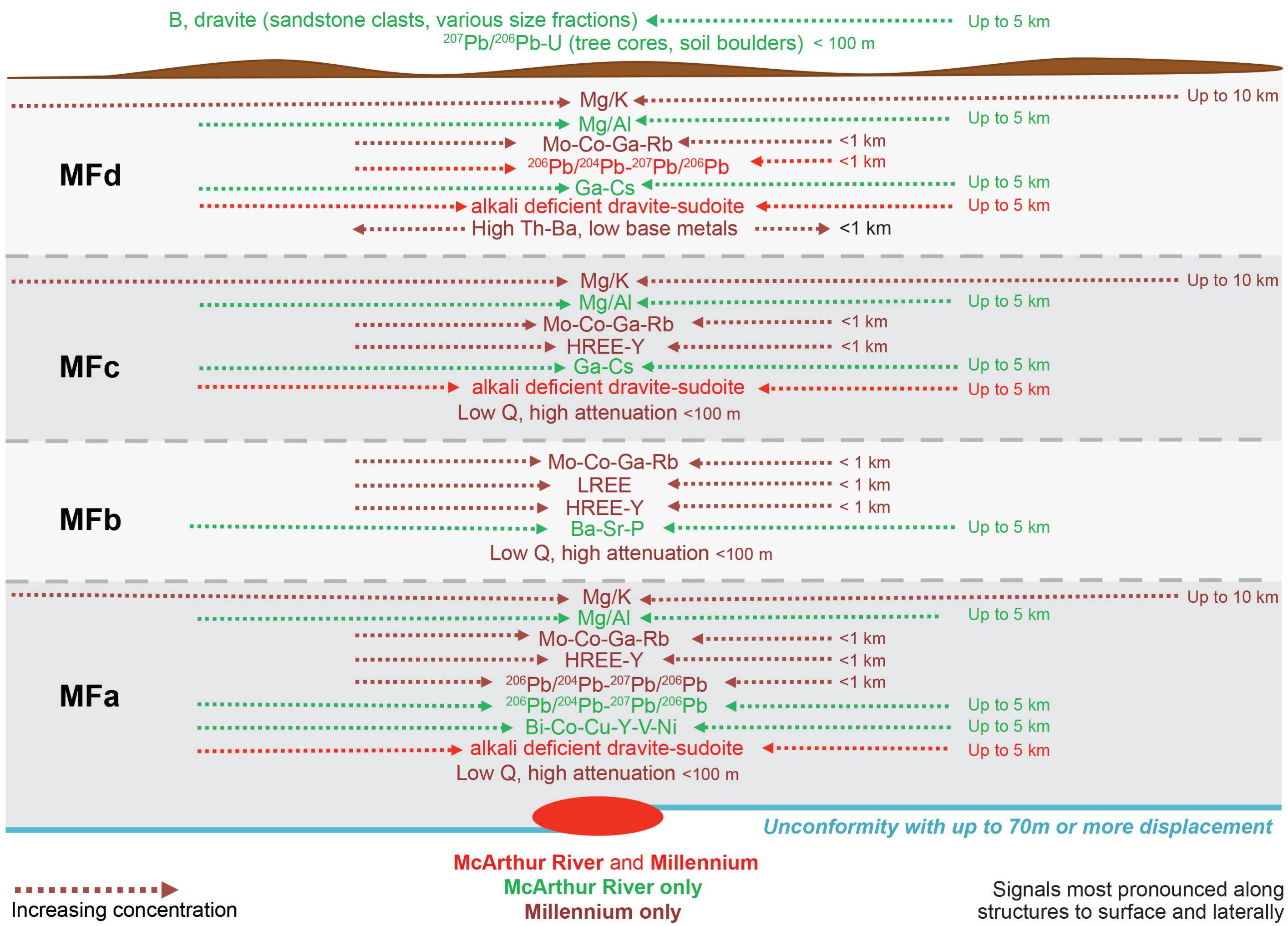


Top left: Predictive map of the different surficial materials in the McArthur River area, developed by Shawn Scott (MSc), based on the positive relationship between radiometric potassium and the proportion of basement pebbles at the locations shown on the map. The distribution of the surficial units was estimated based on their radiometric signature from public domain airborne radiometric data, and could be applied throughout the Athabasca Basin in order to target surficial materials with the most local sources.

Top right: U concentration and Pb isotope data obtained from soils, boulders, and tree cores collected by Steve Beyer (RA) and students from grids above the McArthur River deposit, which is approximately 500 m below the surface. The samples with high $^{207}Pb/^{206}Pb$ ratios suggest that the Pb has come from a common background sources, whereas the samples with lower $^{207}Pb/^{206}Pb$ ratios suggest that the Pb may have come from a more radiogenic source, such as the McArthur River deposit. The samples from the grid directly above the Zone 4 orebody yield the most radiogenic $^{207}Pb/^{206}Pb$ values.

Bottom: Two stratigraphic sections through a large, 50 m high, drumlin near McArthur River, measured and sampled by Shawn Scott (MSc), showing complex internal till stratigraphy. The lighter coloured tills are dominated by local sandstone material are interpreted to have been altered during the mineralization event, as shown by high boron indicative of dravitic tourmaline. The darker coloured tills have the highest proportion of basement pebbles, with elevated Na_2O, that were derived from a distal source.

Schematic Footprint



U Site footprint indicators in the Athabasca Group sandstones (MFa-MFd), and glacial till (brown), above the unconformity with the basement rocks (from Lesher et al., 2017).

Footprints and Vectors

Method	Indicator/Vector	Notes	Stratigraphic Unit	Distribution	Extent
McArthur River					
Lithogeochem	molar Mg/K	indicative of clay mineralogy	MFa, MFd	above economic mineralization	1-5 km
Lithogeochem	chlorite, kaolinite		MFa, MFd	above economic mineralization	1-5 km
Lithogeochem	Ba-Sr-P		MFa, MFb, MFc	above economic mineralization	1-5 km
Lithogeochem	Ga-Cs		MFa, MFd	above economic mineralization	1-5 km
Lithogeochem	Bi-Co-Cu-Ni-Mo-Pb	traditional pathfinders	MFa	restricted to lower sandstone above all mineralization	<1 km
Lithogeochem	$^{207}Pb/^{206}Pb$		MFa	restricted to lower sandstone above all mineralization	<1 km
Lithogeochem	$^{206}Pb/^{204}Pb$		MFd	fractures	<1 km
Surfical geochem	$^{207}Pb/^{206}Pb$		trees, boulders in A-horizon soils	most radiogenic Pb above ore	<0.1 km
Surfical geochem	U		trees, boulders in A-horizon soils	highest U conc. above ore	<0.1 km
Surficial geochem	B, dravite (norm)	dispersal pattern in locally-derived till	altered sandstone clasts in till (various size fractions)		up to 5 km

Method	Indicator/Vector	Notes	Stratigraphic Unit	Distribution	Extent
Lithogeochem	molar Mg/K	indicative of clay mineralogy	MFa, MFc, MFd		up to 10 km
Lithogeochem	Mo-Co-Ga-Rb		MFa, MFb, MFc, MFd		<1 km
Lithogeochem	HREE-Y		MFa, MFb, MFc		1-2 km
Lithogeochem	LREE		MFb		<1 km
Lithogeochem	$^{206}Pb/^{204}Pb$, $^{207}Pb/^{206}Pb$		MFa	possibly in fractures	<1 km
Machine Learning	High Th-Ba, low base metals		MFc	background?	>1 km
Machine Learning	High Zn-Mn-Ca		MFd		<1 km
Machine Learning	High LREE		MFb, MFc, MFd		<1 km
Machine Learning	High Ni-Co-V-Mo-Bi-B		MFc		<1 km
Machine Learning	late Carb, epigentic Chl		MFb		<1 km
Isotopes	high $^{206}Pb/^{204}Pb$, low $^{207}Pb/^{206}Pb$		MFa, MFb		>1 km
Geophysics	Seismic Q	anelastic attenuation factor		may detect alteration in sandstone in restricted survey	TBD

Preliminary footprint components and vectors for McArthur River (left), and Millennium (right) (from Lesher et al., 2017). Seismic Q: anelastic attenuation factor. Carb: carbonate, Chl: chlorite.

Teck

Cu Site

Key Numbers

17

HQP (9 RA, 3 PhD, 3 MSc, 2 BSc) trained

13

Researchers and Collaborators

8

Industry Collaborators

1,200

new samples collected from the Guichon Creek batholith region including rock, soil, till, and drill core. New lithochemistry, feldspar staining, SWIR, petrophysical properties, and hyperspectral imaging obtained from all samples.

200

polished thin sections, and new LA-ICP-MS mineral chemistry and isotopic composition.

12

new age dates define new temporal evolution of the Guichon Creek batholith and Highland Valley Copper porphyry deposits.

8,000

new lithochemistry, mineral isotopic and chemical analyses, soil and biochem, SWIR, and hyperspectral imaging.

74

till samples collected with GSC and BCGS outlining new glacial dispersion trains of indicator minerals. Trace element chemistry on indicator minerals fingerprints mineralized zones in Guichon Creek batholith and Highland Valley Copper distribution.

Surficial geology – new soil sample survey lines over Highmont South and J.A. targets used to identify best sampling methods and indicator chemical response.

Deionized water, aqua regia, and sequential leaching collected on soil B-horizon samples. Pine needle biogeochem and hydrocarbon sampling collected along same soil transects also define clear mineral indicator response from blind structures and over buried mineralized zones.

Teck provided access to their properties, drill cores, and core-logging facilities; geological information to guide field work; and access to legacy geophysical data sets and historic drill logs.

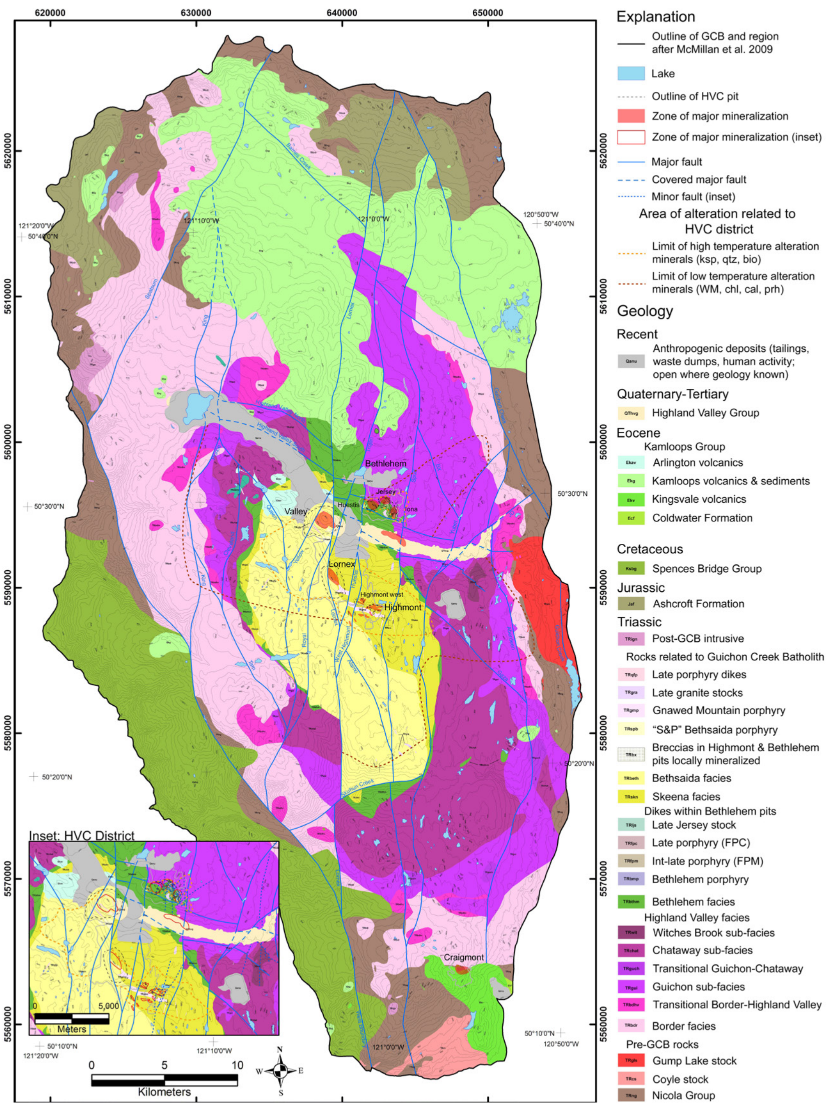
Over 20 new footprints and vectors have been identified.

Regional airborne geophysical data used for new structure interpretation and model of the Guichon Creek batholith.

The new regional lithochemistry defines the petrogenetic evolution of the magmatic phases that host and produced the porphyry Cu mineralization and illustrates the relationships between petrogenetic processes, magma fertility, and formation of ore deposits.

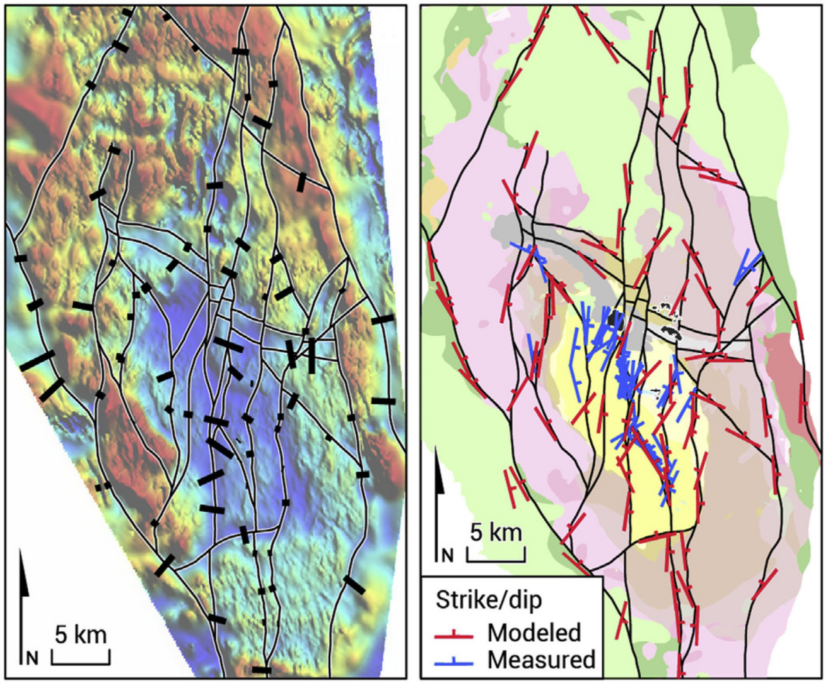
Rock property data (density and porosity, magnetic susceptibility and remanence, electric resistivity and chargeability) from all rock samples constrain new geophysical inversions. Outcrop magnetic susceptibility measurements highlight regional alteration zones and used to correlate with airborne magnetic survey.

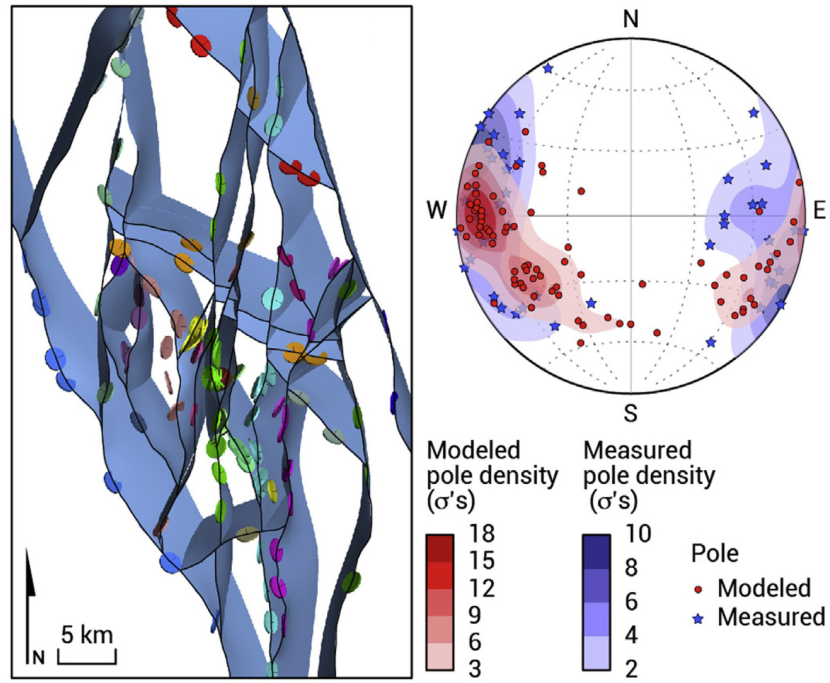
Geological Map



Geologic map for the Guichon Creek batholith from new field mapping, chemistry, and geophysical processing (Lee et al., 2018).

Geophysics and Structure

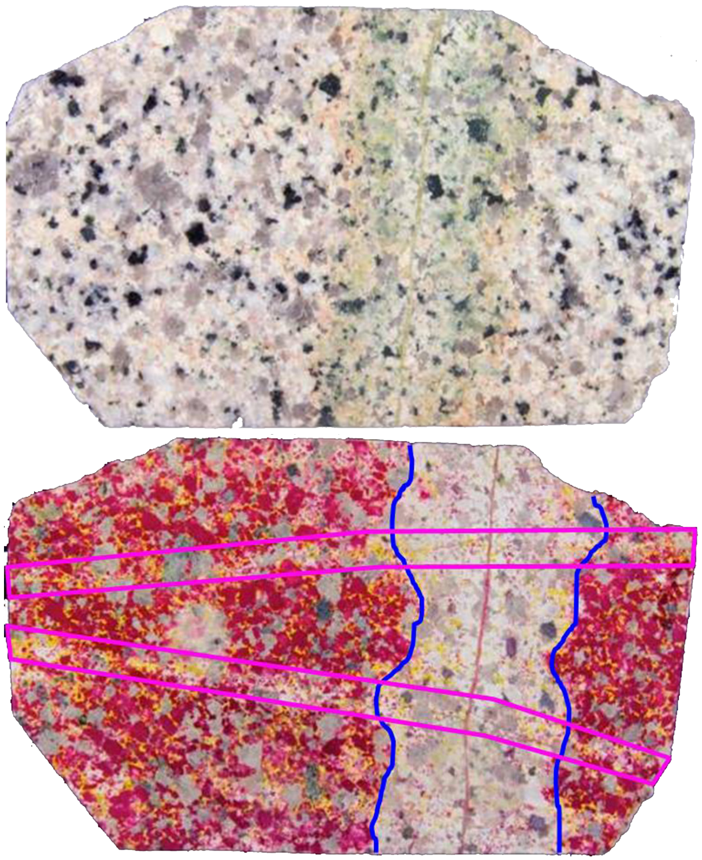


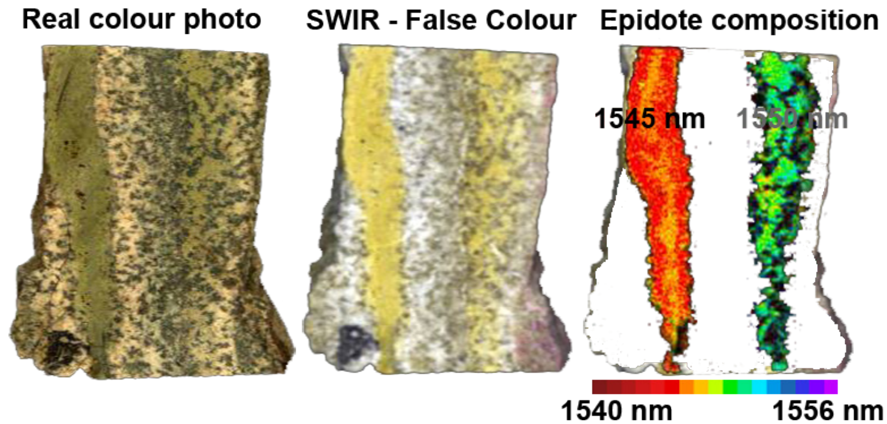


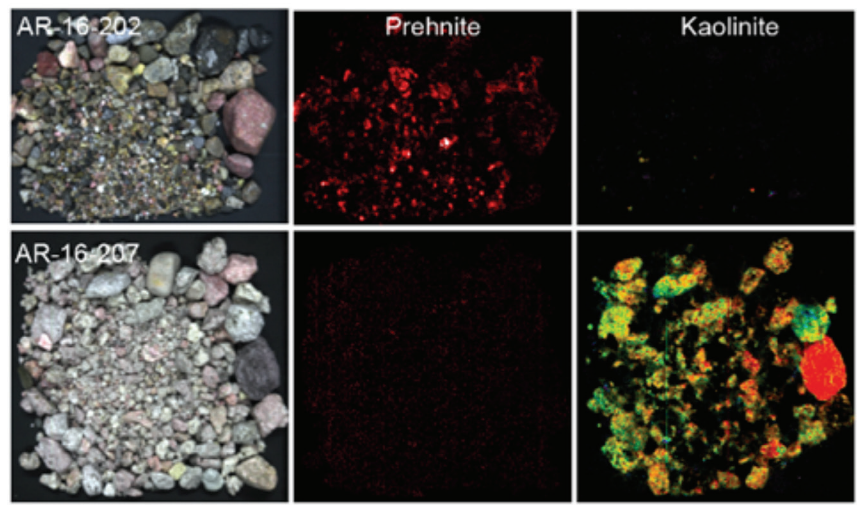
Left: Magnetic field intensity and updated lithology of the Guichon Creek batholith with new structure model. 2D profiles of modeled and measured dips were used to determine fault dips for 3D common earth model (modified from Lesage et al., 2019).

Right: Final 3D fault network interpretation with the measured strikes and dips and comparison of modeled and measured pole densities for the new Guichon Creek batholith structural model (modified from Lesage et al., 2019).

Staining and Hyperspectral





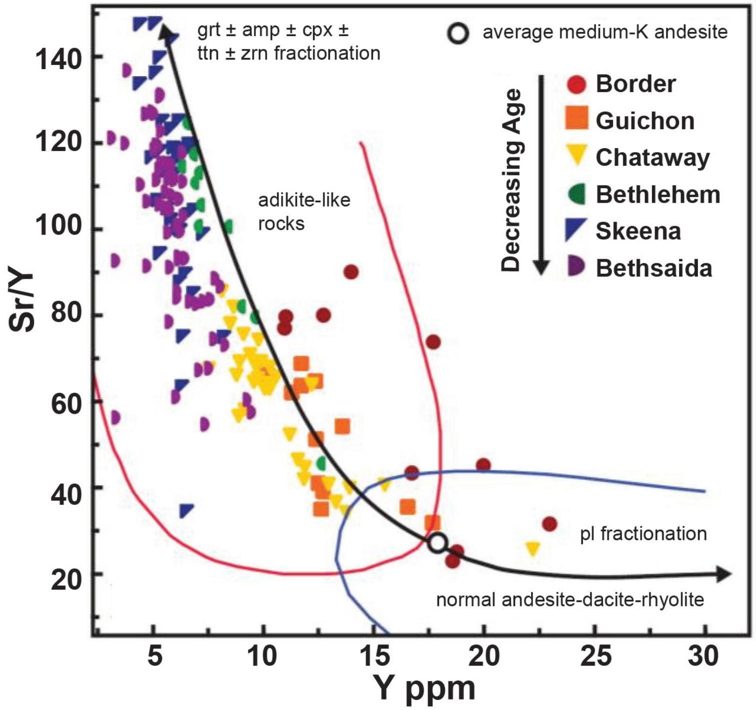


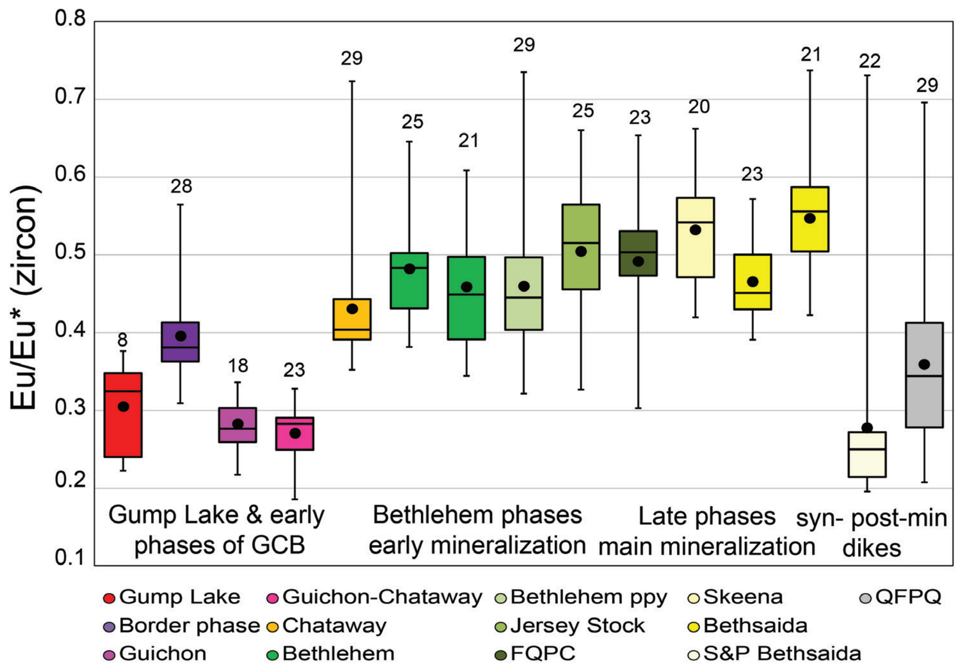
Left: Feldspar staining is simple effective tool to identify early high temperature potassium feldspar veining overprinted by chlorite-albite veins (modified from Lesage, 2018).

Upper right: Hyperspectral imaging highlights variation in epidote composition from Highland Valley Copper deposit. Imaging identifies multiple vein generations in the sample that are not evident visually (modified from Byrne, 2019).

Lower right: Hyperspectral images of till from drill core highlighting distal alteration minerals from the upper section and proximal alteration minerals from the basal section (Reaman, 2018).

Geochemistry

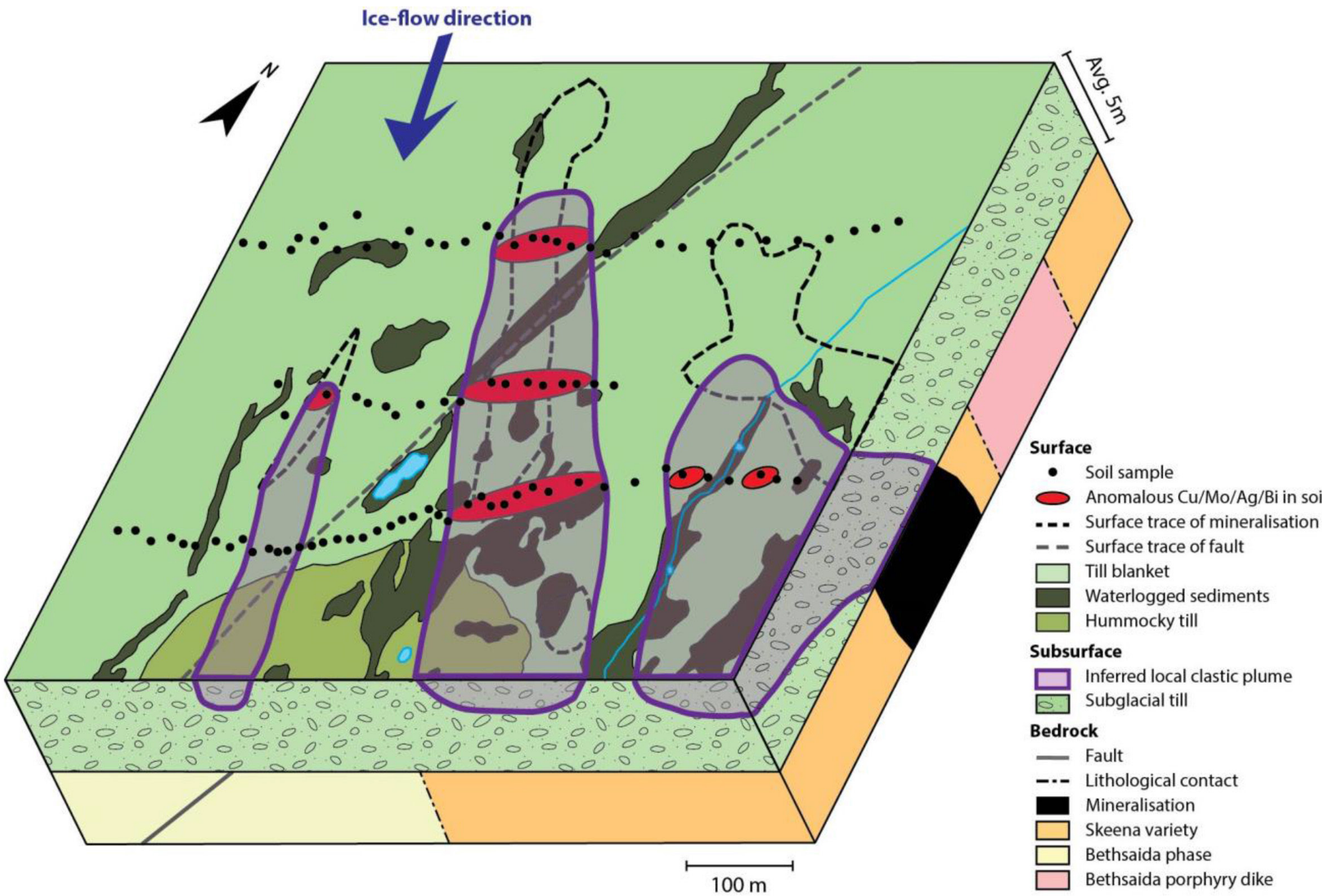




Left: Magma fertility diagrams for the Guichon Creek batholith. Whole rock composition of Sr/Y vs Y diagram highlights the elevated Sr/Y values indicative of high magmatic water contents (~5-6 wt.% H_2O) (D'Angelo et al., 2017).

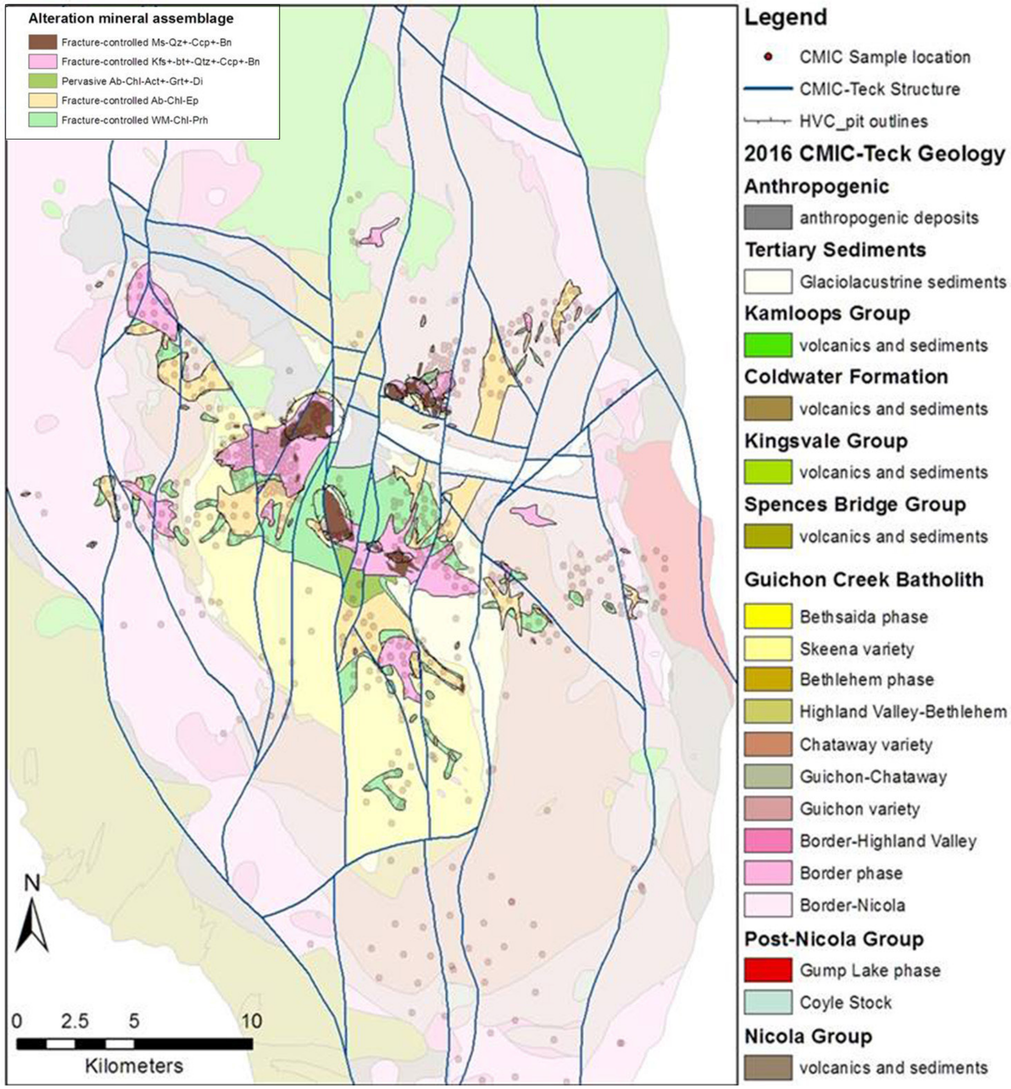
Right: Europium anomalies increase in zircon from the earlier Guichon Creek rocks to the younger core rocks which host mineralization. Elevated Eu/Eu have been observed in other porphyry copper systems. These chemical signals along with other chemical factors highlight the fertility of the region and can be used as a vectoring tool for mineral exploration (Lee et al., 2018).*

Surficial Chemistry



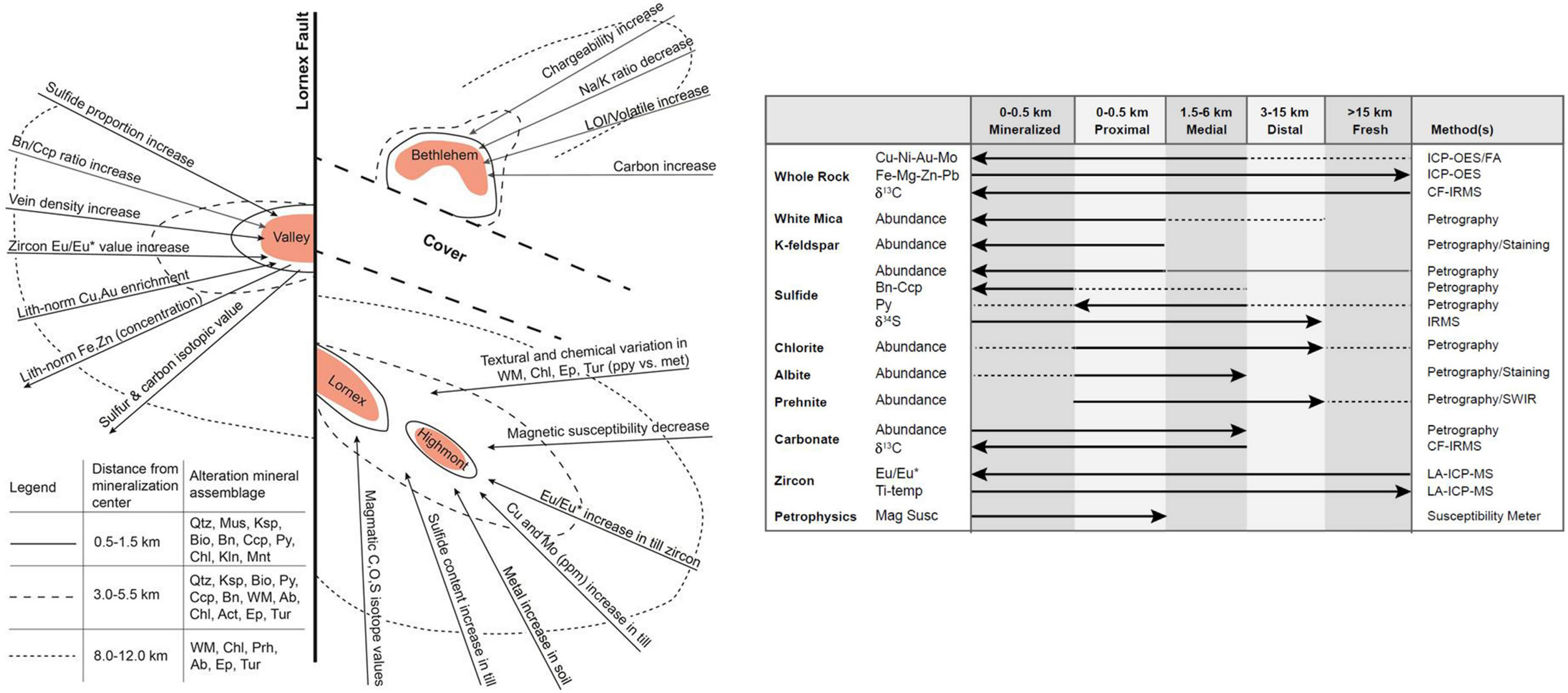
Schematic model of local clastic transport for fragments of bedrock mineralisation at Highmont South target of Highland Valley Copper deposit. Main anomalous elements in upper B horizon soil (<180 microns, aqua regia, ICP-MS) are Cu, Mo, Ag, and Bi, with lesser Sb, As, and W. Till blanket is thin at Highmont South (2-10 metres) and dispersal trains are inferred to be close to their bedrock source (modified from Chouinard, 2018).

Hydrothermal Alteration

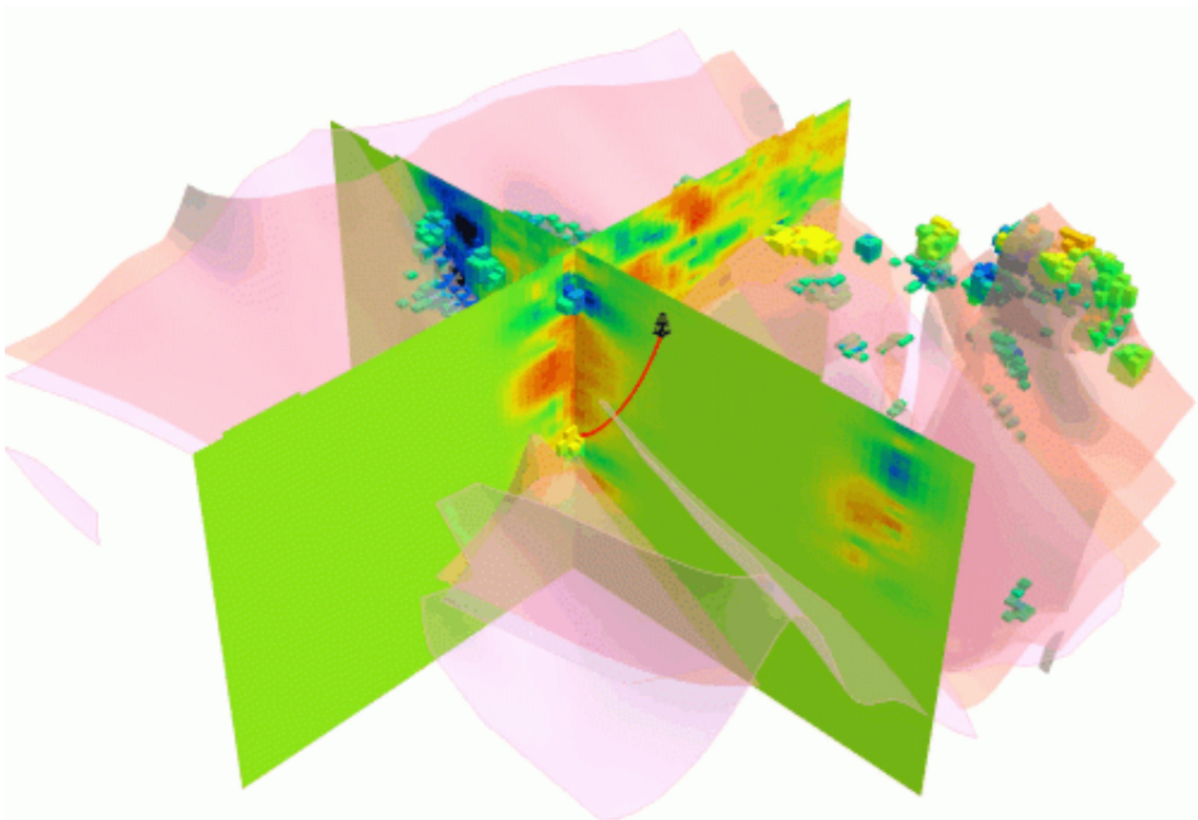


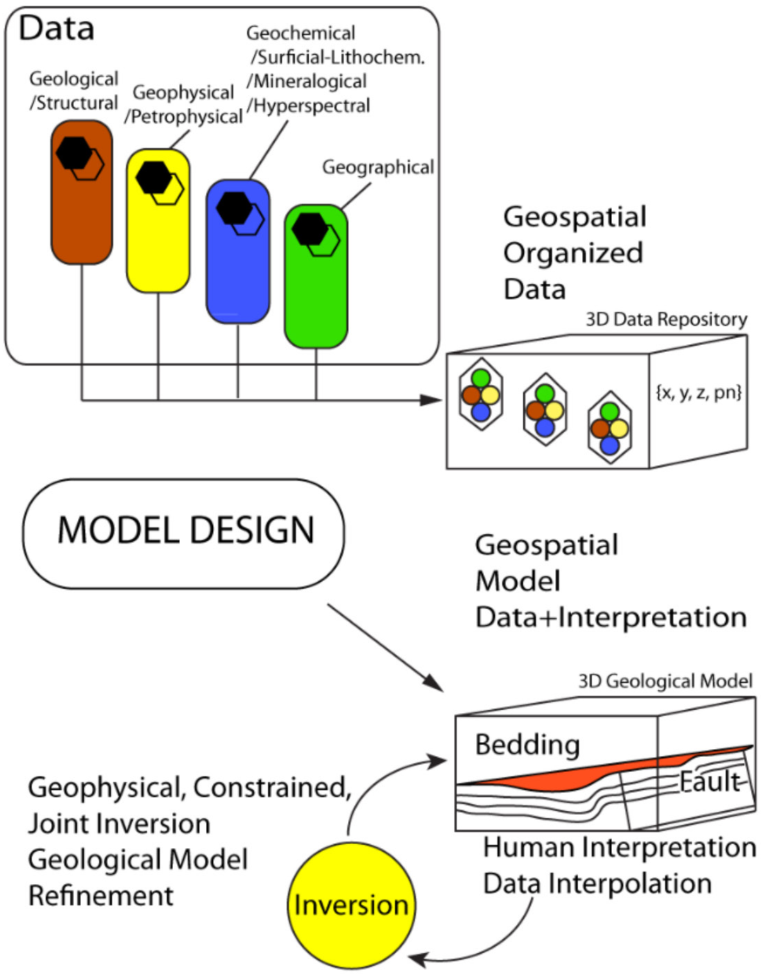
Alteration assemblage map of the Guichon Creek batholith and Highland Valley Copper deposit (modified from Lesage et al., 2016). Alteration compiled from new field mapping and over 1000 samples. Detailed petrographic analyses were conducted to identify the new alteration assemblages in the district including; lithochemistry, petrophysical properties, mineral chemical and isotopic composition, and geophysical response.

Footprints and Vectors

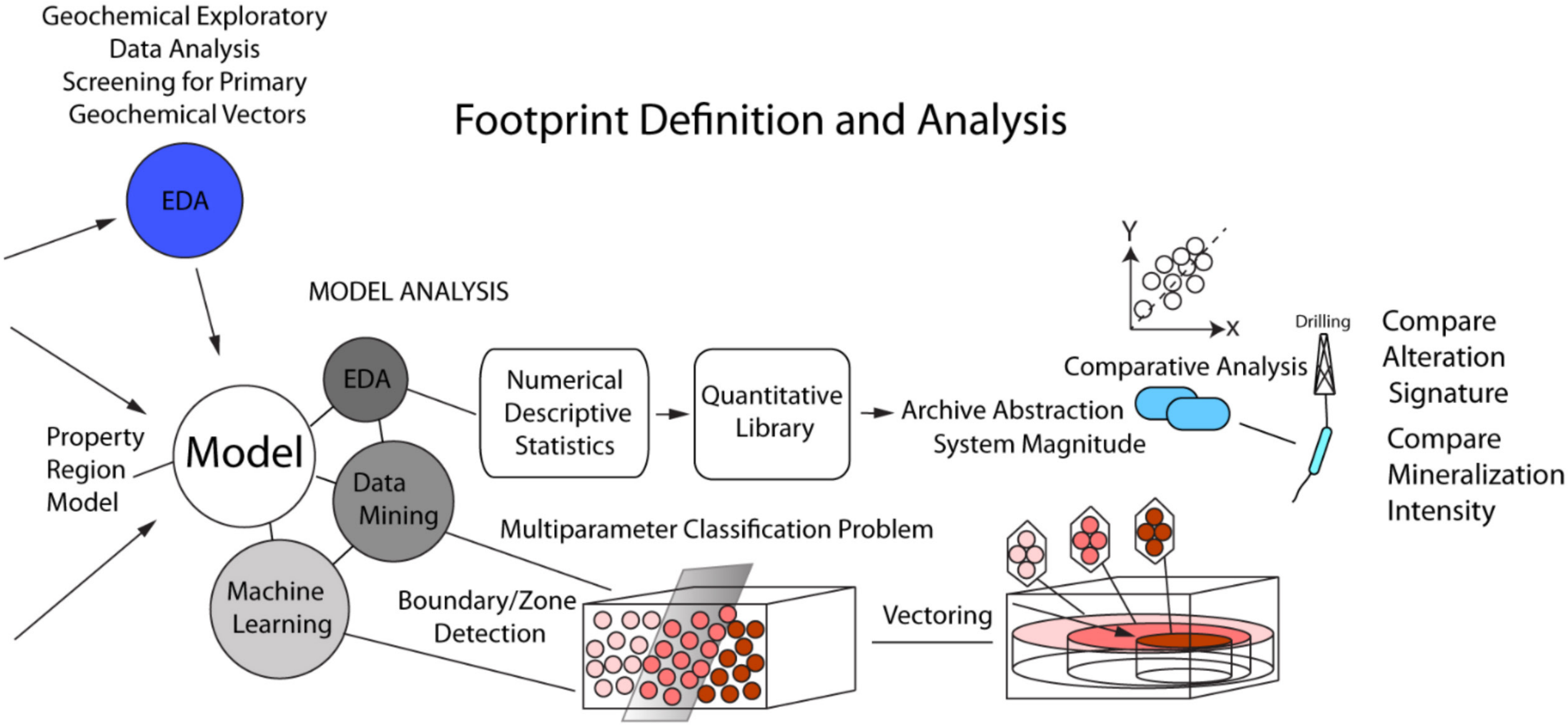


Cu-site footprint and vector cartoon of the Highland Valley Copper district, highlighting the properties and features related to mineralization distally and adjacent to the deposit (modified from Lee, 2018 and Lesher et al., 2017).




Data
Geological /Structural
Geophysical /Petrophysical
Geochemical /Surficial-Lithochem. /Mineralogical /Hyperspectral
Geographical
Geospatial Organized Data
3D Data Repository
{x, y, z, pn}
MODEL DESIGN
Geospatial Model Data+Interpretation
3D Geological Model
Bedding
Fault
Geophysical, Constrained, Joint Inversion Geological Model Refinement
Inversion
Human Interpretation Data Interpolation

Data



Integration

Data Integration Objectives

Data Management and Exploratory Data Analysis

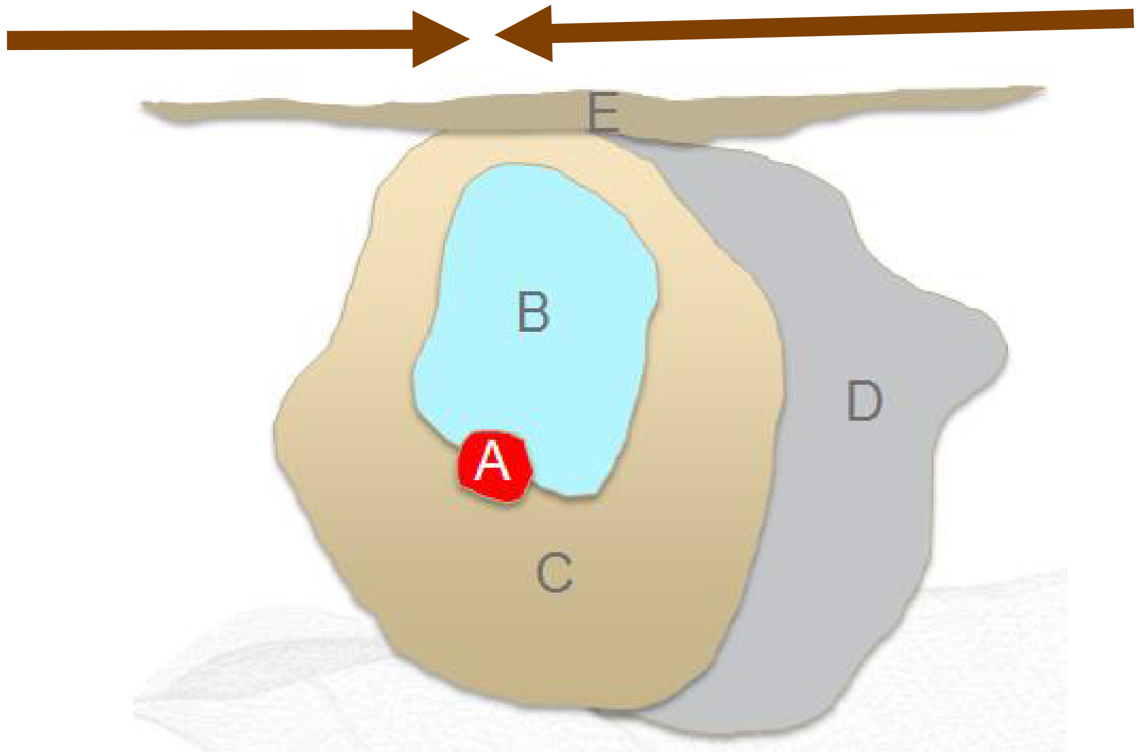
Research and develop innovative strategies for managing large, multi-disciplinary, multi-site, multi-user databases of spatial data and metadata to facilitate quantitiative data integration. Use novel EDA approaches to assess data quality and statistics.

3D Modelling

Research and develop innovative workflows for the construction and validation of self-consistent 3D "Common Earth Models" to serve as spatial data and interpretation containers supporting data fusion for machine learning.

Machine Learning

Research and develop innovative methods for recognizing previously unknown correlations or patterns within large, complex, multi-disciplinary data sets that characterize the zonal footprint structure of a mineral system.

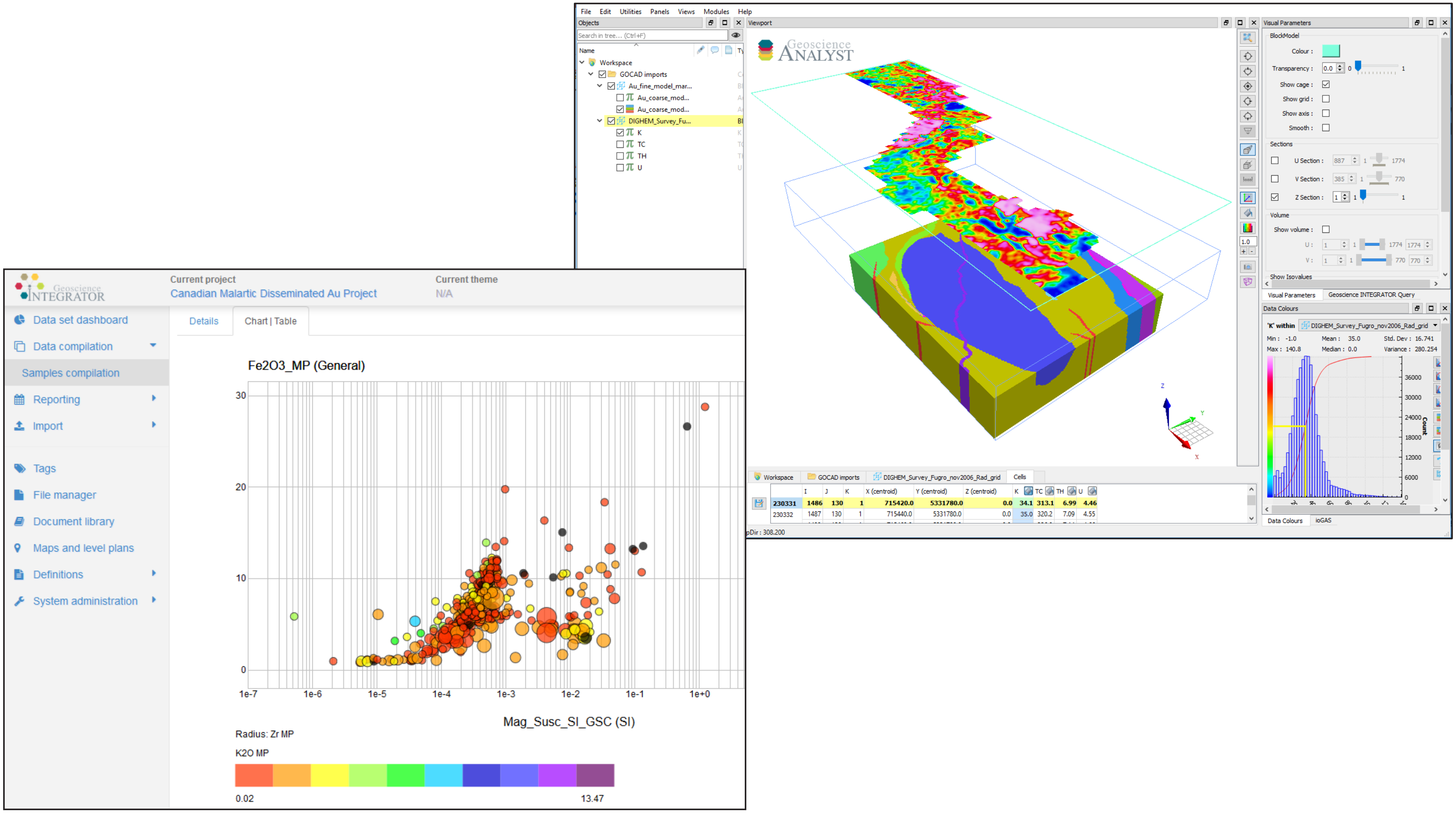


We framed the data integration problem with this conceptual cross-section, depicting a hypothetical ore system footprint from the deposit at its core (A) through a series of zones from proximal to most distal (B through D), primarily correlated to hydrothermal alteration, plus overburden (E). The arrows represent our research goal of recognizing vectors towards the system centre from exploration data.

The Common Earth Model is the 3D container for spatial data and spatial interpretations, such as geostatistical interpolations and geophysical inversions. It provides a visual framework for communication, interpretation, and conceptual validation.

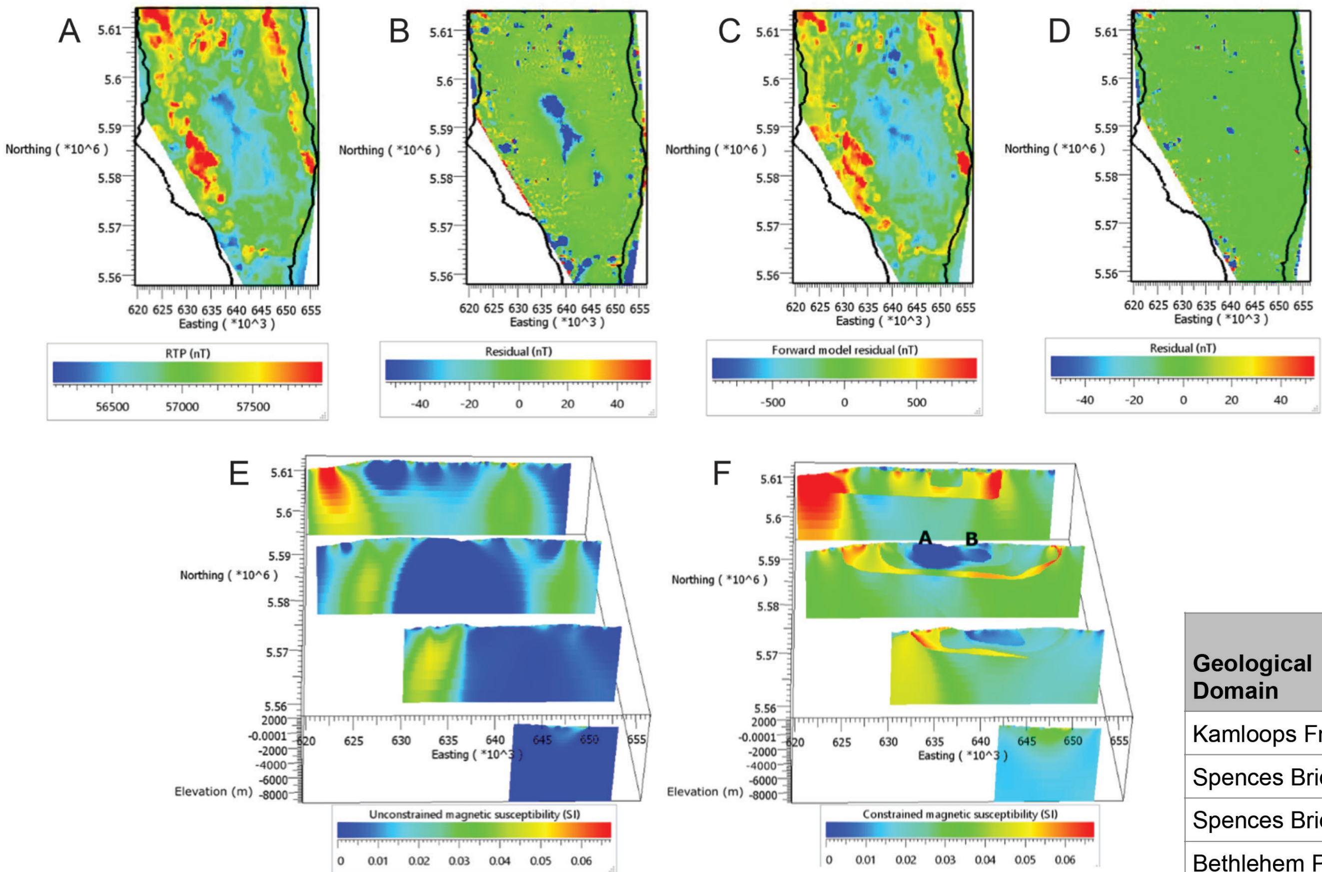
More importantly for the objectives of the Footprints project, it provides the input data structures for the spatial "data fusion" workflows that follow, in which multiple data sets are combined into the simpler data structures that can be acted upon by machine learning tools.

Data Management and Repository



The project presented a unique opportunity to analyze the requirements and build a system for effective multi-site, multi-user information organization, query, visualization, and retrieval that would support quantitative analysis. This was achieved for the benefit of future academic research projects, industry needs, and as a final, public repository for project-generated data, models, documents, and metadata.

Geophysical Inversion

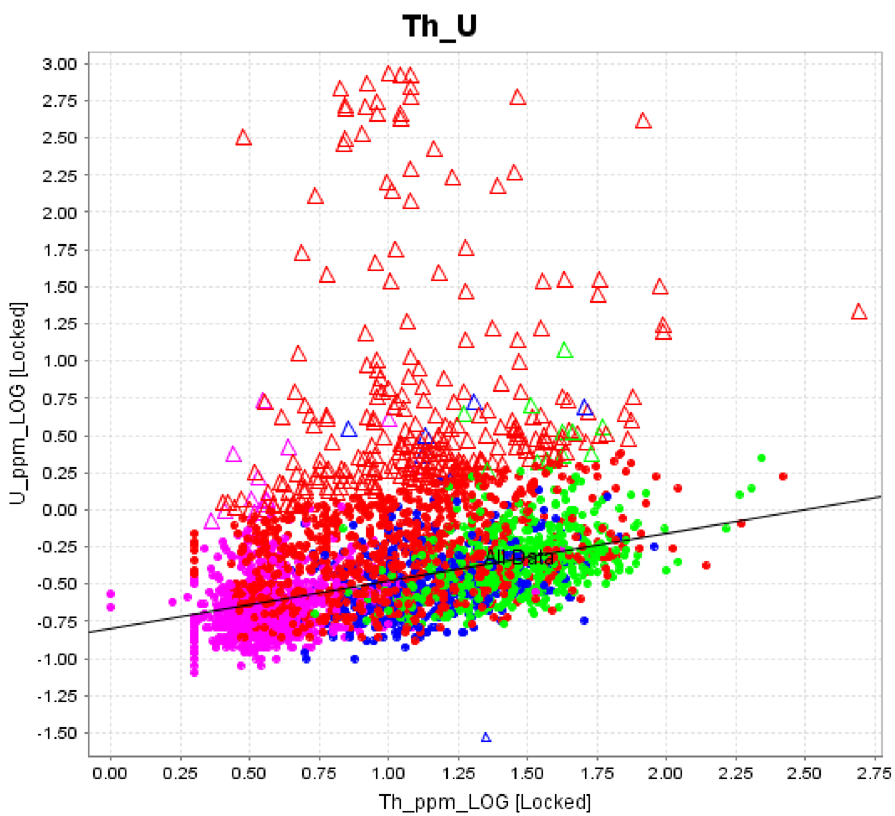


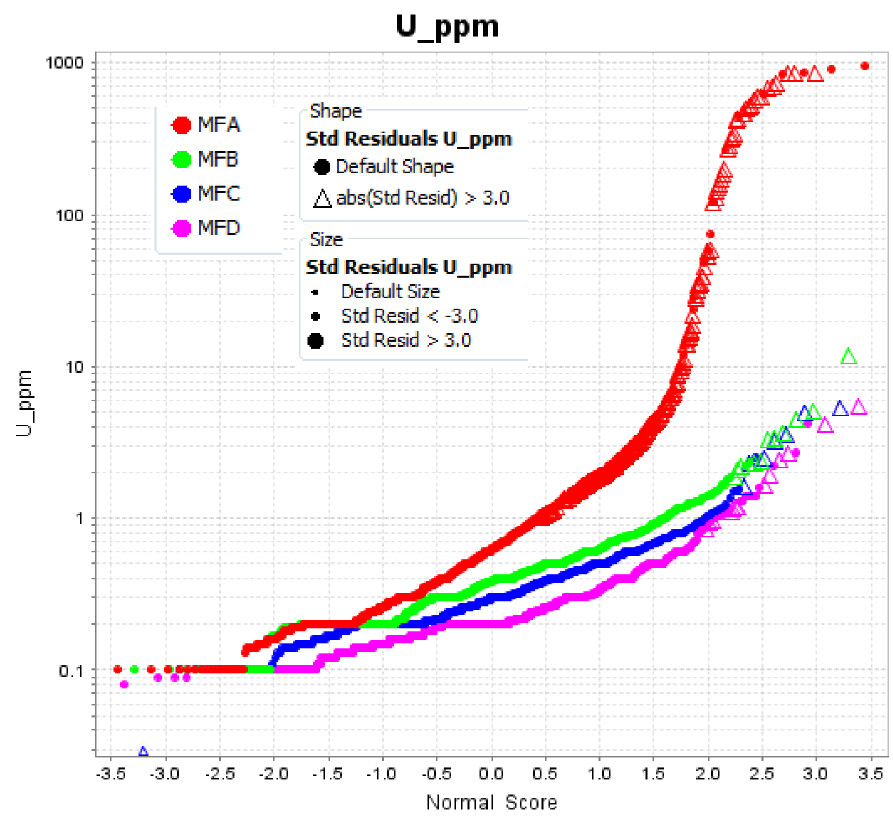
Geological Domain	Density (kg m^{-3})	Magnetic Susceptibility (SI x 10^{-3})
Kamloops Fm.	2670	1.0
Spences Bridge Spius Fm.	2670	44
Spences Bridge Pimainus Fm.	2670	29
Bethlehem Phase	2649	3.3
Guichon Phase	2741	28
Border Phase	2811	44.3
Nicola Fm.	2670	20

Inversion of magnetic data (A) for Highland Valley models. The modeling workflow involved assigning physical properties to mapped lithologies (see pages 37 and 42), unconstrained inversion (B and E), addition to CEM, input of geological constraints, constrained inversion (C and F), iterative adjustment of model bounds, minimization of residuals (D), and optimization of geology in CEM.

In unconstrained inversion (E) the outer layers of the Guichon Batholith are modeled as extending to infinite depth and changing in dip direction. In contrast the constrained inversion (F) limits depth extent based on regional seismic data and has consistent dip between adjacent sections.

Exploratory Data Analysis



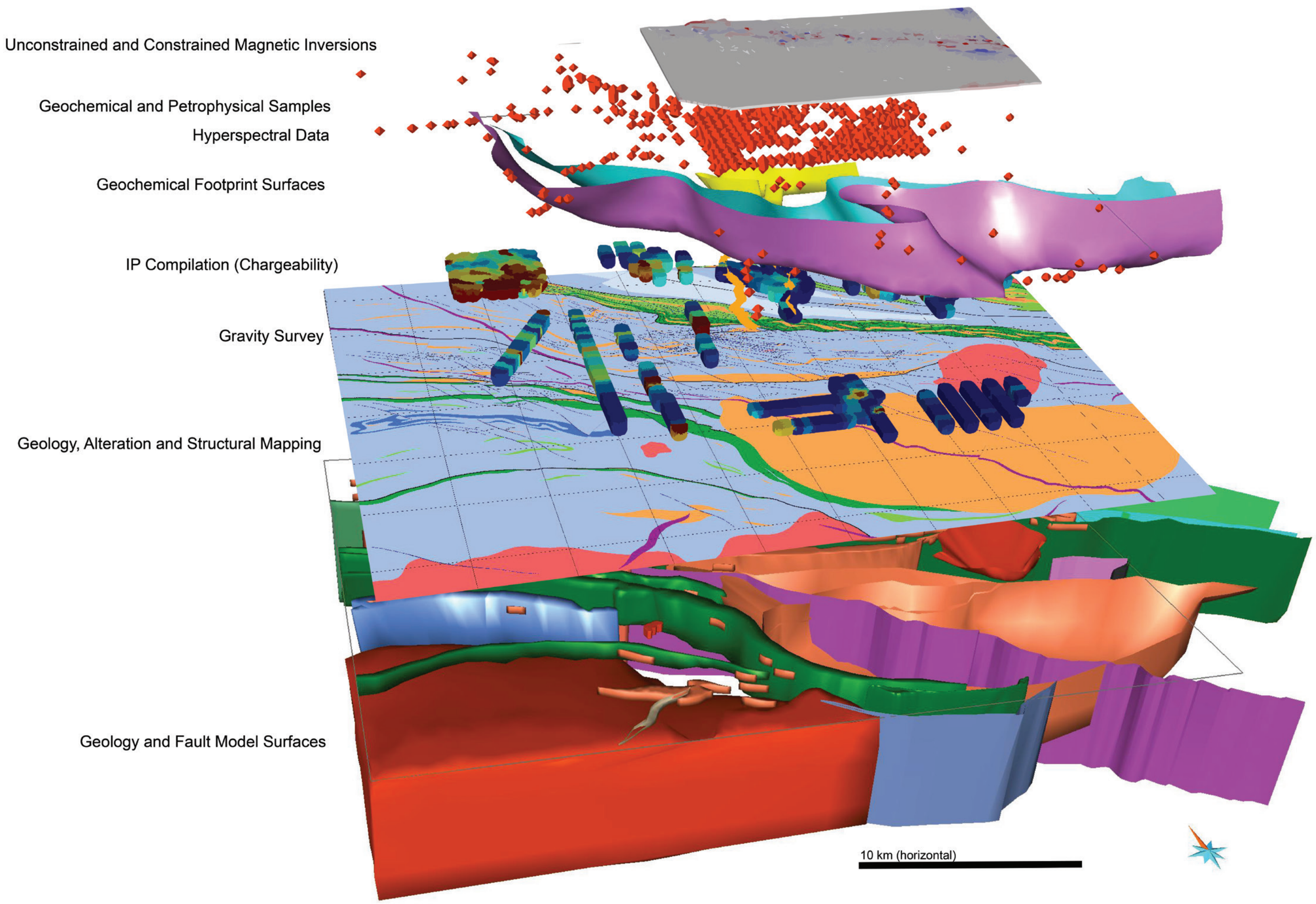


Validation and assessment of the quality of all geochemical data available to the project, including public, legacy, and project-generated data, was an important and intensive area of work. This was critical to ensuring that data quality was sufficient to support the interpretations and conclusions of individual researchers sharing the geochemistry database.

Left: U-Th Correlation – Sandstones (by M. Bertelli).

Right: Exploring U/Th relationships in the a, b, c, and d members of the Manitou Falls formation at the uranium case study site.

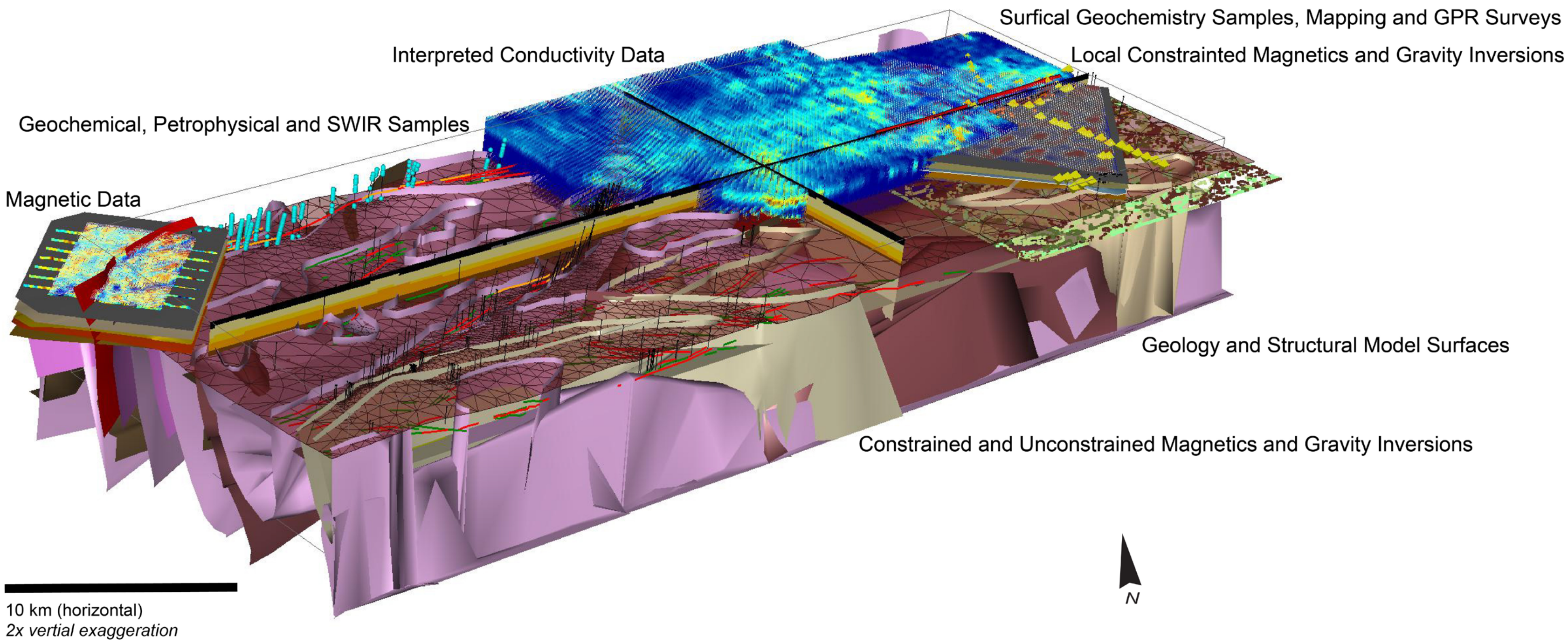
Canadian Malartic Common Earth Model



The database for Canadian Malartic contains a regional (90 m resolution) digital elevation model; an overburden thickness model; a regional till map; a regional geological model; 14 local outcrop geology maps; 2322 structural measurements; 2888 regional mineral occurrences; 2 airborne magnetic and electromagnetic surveys; 19 induced polarization surveys; 3 satellite and ground gravity surveys; 863 petrophysical measurements; 1011 gamma-ray spectrometric measurements, 4382 portable XRF analyses; 1103 whole-rock lithogeochemical analyses, 272 H-O-C-S stable isotope analyses; 347 XRD mineralogy determinations; 7539 wavelength-dispersive X-ray emission spectrometric (EPMA) mineral analyses; and hyperspectral data for 1639 samples and over 1000 m of drill core, as well as a variety of derivative products including stitched 1D inversions of airborne electromagnetic data for resistivity and susceptibility at different frequencies, forward magnetic models, inversions for induced polarization (IP) resistivity and chargeability, and gridded geochemistry, mineralogy, petrophysics, and a wide range of supporting data including over 2000 photographs, photomicrographs, backscattered electron SEM maps, hyperspectral mineral chemistry maps, WDS-EPMA and LA-ICP-MS elemental maps, and mineral liberation analytical maps. We also had access to 161 historic mine sections, 6045 diamond drill core logs, and 14 downhole petrophysical logs.

The CEM above shows locations of geochemical and petrophysical samples, geology and fault model surfaces, geology-alteration-structural mapping, a gravity survey, an IP (chargeability) compilation, unconstrained and constrained magnetic inversions, and several geochemical footprint surfaces.

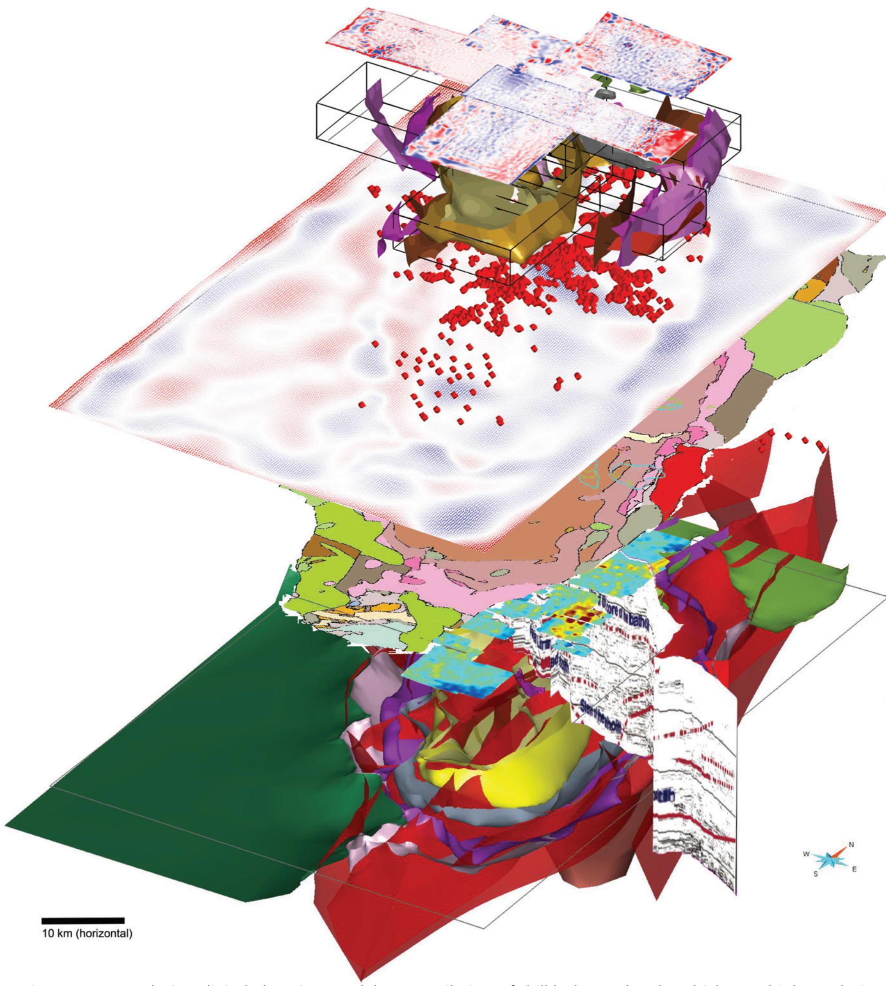
McArthur River Millennium Trend Common Earth Model



The database for the McArthur-Millennium corridor contains 50m-spaced digital elevation map; overburden thickness map; basin and basement geology with fault traces; regional radiometrics; seismic; 1 km-spaced ground gravity and gravity forward model; 100 m (Millennium) and 300 m (McArthur River) spaced airborne gravity gradiometry and inversions; 300m-spaced aeromagnetic survey and magnetic inversion; audio magnetotelluric (AMT) survey; electromagnetic conductor traces; airborne electromagnetic surveys, 3D resistivity inversion, and 1D resistivity inversion of all survey lines; diamond drill core lithologies, geochemistry, shortwave infrared spectroscopy (SWIR), and structural data (12 with new lithogeochemistry, mineralogy, and petrophysics); 5 ground-penetrating radar lines; 74 till samples (geochemistry and pebble counts); surficial geochemistry (~2140 soil horizons, ~580 tree cores, ~270 boulders), and ~250 petrophysical measurements (saturated bulk density, porosity, magnetic susceptibility, resistivity, chargeability). The image from the CEM in Figure 12 shows basin and basement geology, a TEMPEST® inversion at Millennium (greens-yellow-red volume in lower left), a VTEM® survey over and north of McArthur River (multicolour lines in upper right), and the locations of some of the many drill core samples analyzed for geochemistry, SWIR mineralogy, and petrophysical properties.

The CEM above shows geology and structural model surfaces, magnetic data, interpreted conductivity data, constrained and unconstrained magnetics and gravity inversions, local constrained magnetics and gravity inversions, GPR surveys, and the locations of geochemical, petrophysical, SWIR, and surficial geochemistry samples.

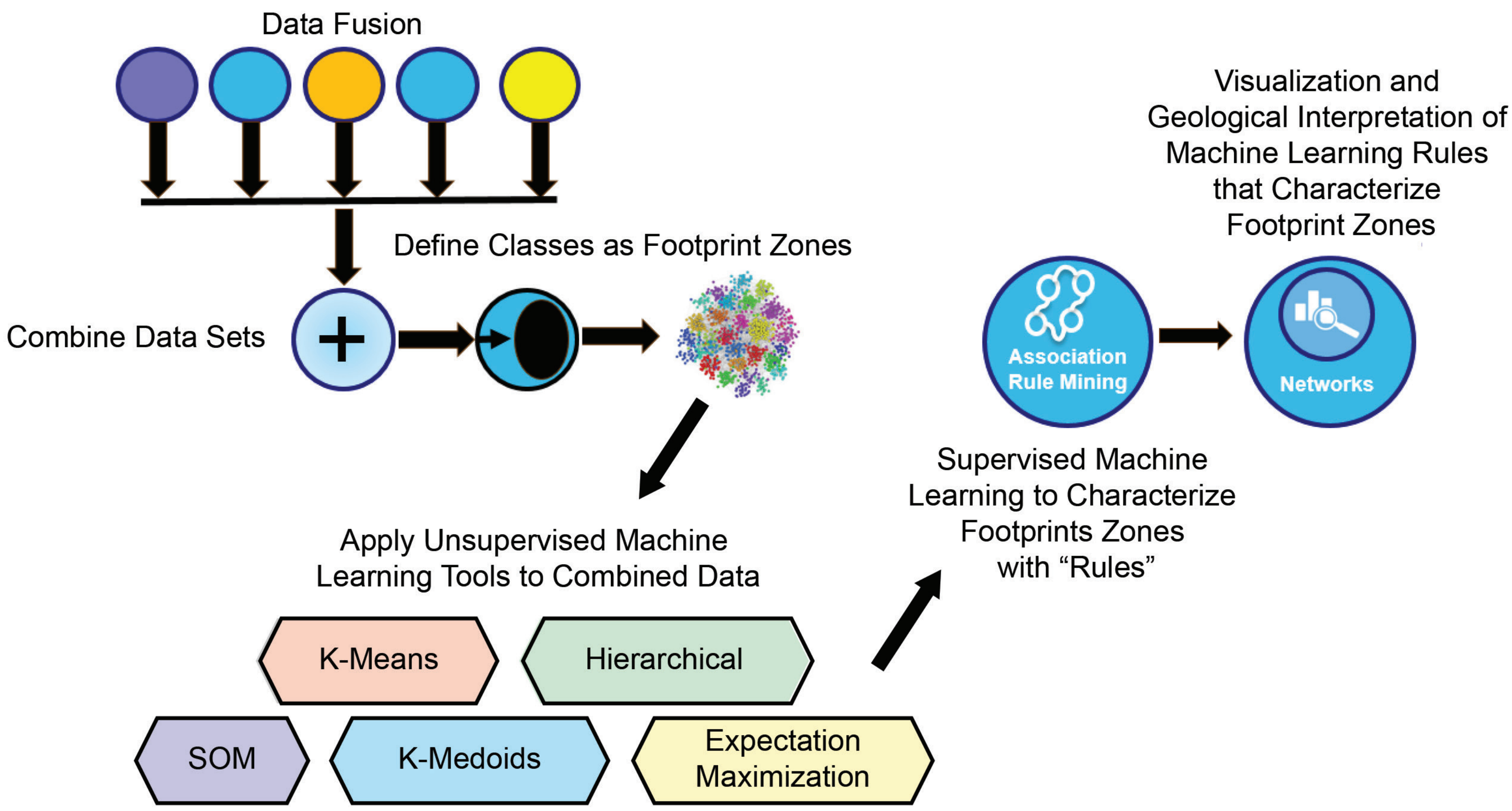
Highland Valley Copper Common Earth Model



The database for the Highland Valley district contains a 90 m-resolution digital elevation model; a compilation of drill hole overburden thickness; high resolution orthophotography; regional and local geological maps including ~1640 outcrop/DDH stations, ~2350 bedding and structural measurements, ~750 magnetic susceptibility measurements; a compilation of Cu-Au-Ag-Zn-Pb mineral occurrences; a 250 m-spacing airborne magnetic and radiometric survey for the entire batholith; a 2 km-spacing airborne gravity survey; a 3D compilation of chargeability and resistivity made up of 20 DCIP surveys, each with a 2D or 3D inverted model; a 2′-resolution satellite gravity survey and a 200-station ground gravity survey; density, porosity, magnetic susceptibility, remanence, and electric measurements on more than 1070 petrophysical samples (GSC) and more than 300 additional samples with density, porosity, magnetic susceptibility, and electric properties (Poly), ~1200 legacy and ~1200 new lithogeochemical, ~235 soil geochemical, and 125 biogeochemical (tree) analyses; ~250 whole-rock and ~180 soil pXRF analyses; ~3200 field and ~700 laboratory hyperspectral analyses; 100 C-O, 70 S, 7 Cu, and 14 Rb-Sr and Sm-Nd isotopic analyses; over 3000 electron probe X-ray emission spectrometric and laser ablation ICP-MS microanalyses of hornblende, plagioclase, epidote, biotite, chlorite, white mica, tourmaline, apatite, zircon, and oxides; and 380 pebble-mineral counts and geochemical analyses of till samples, 80 with petrophysical measurements.

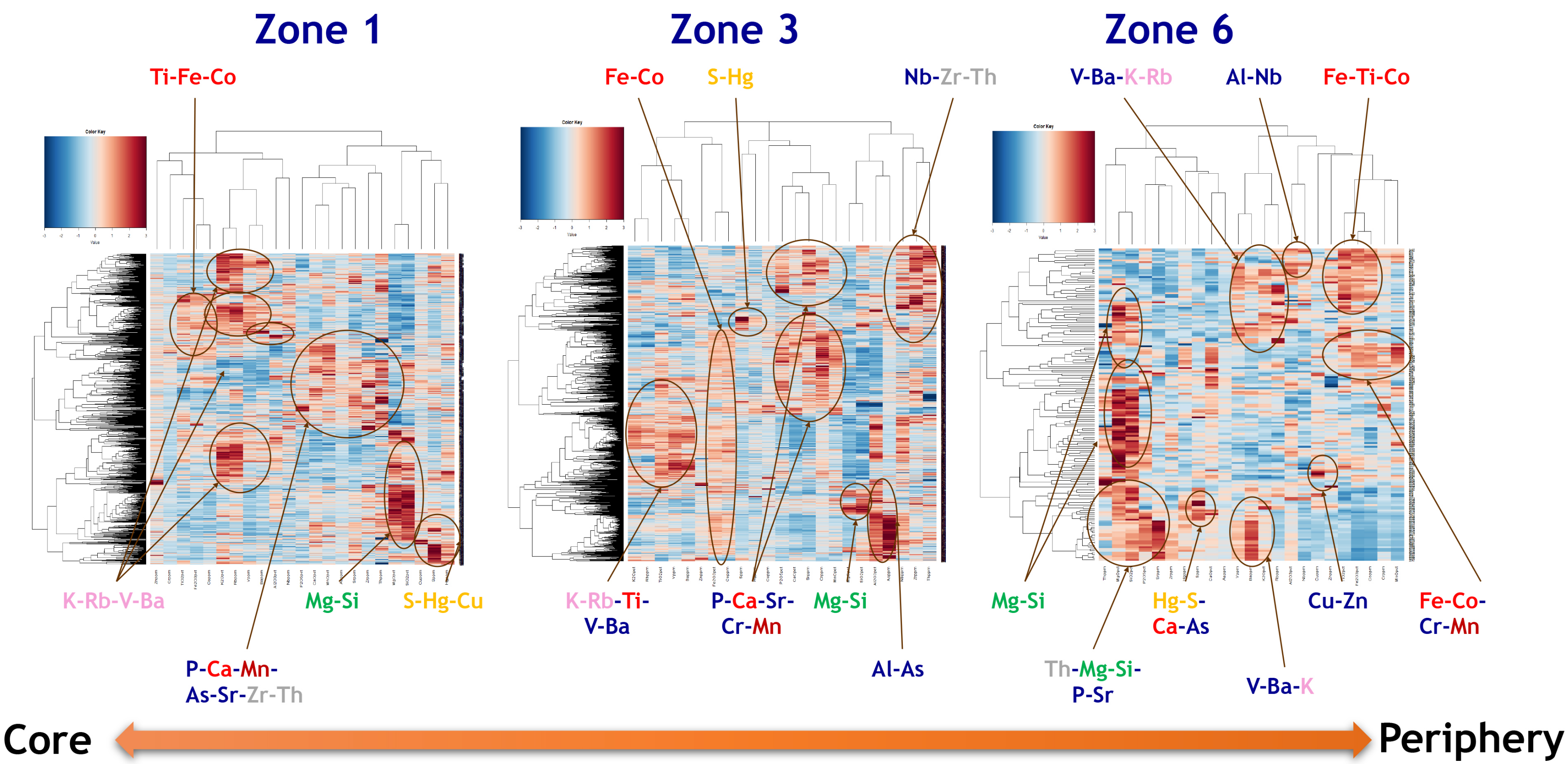
The CEM shown here shows geology and structural model surfaces, geology and alteration mapping, seismic data, reprocessed IP data, constrained and unconstrained magnetics and gravity inversions, local constrained magnetics inversions, and the locations of geochemical, petrophysical, and biological samples.

Workflows for Machine Learning



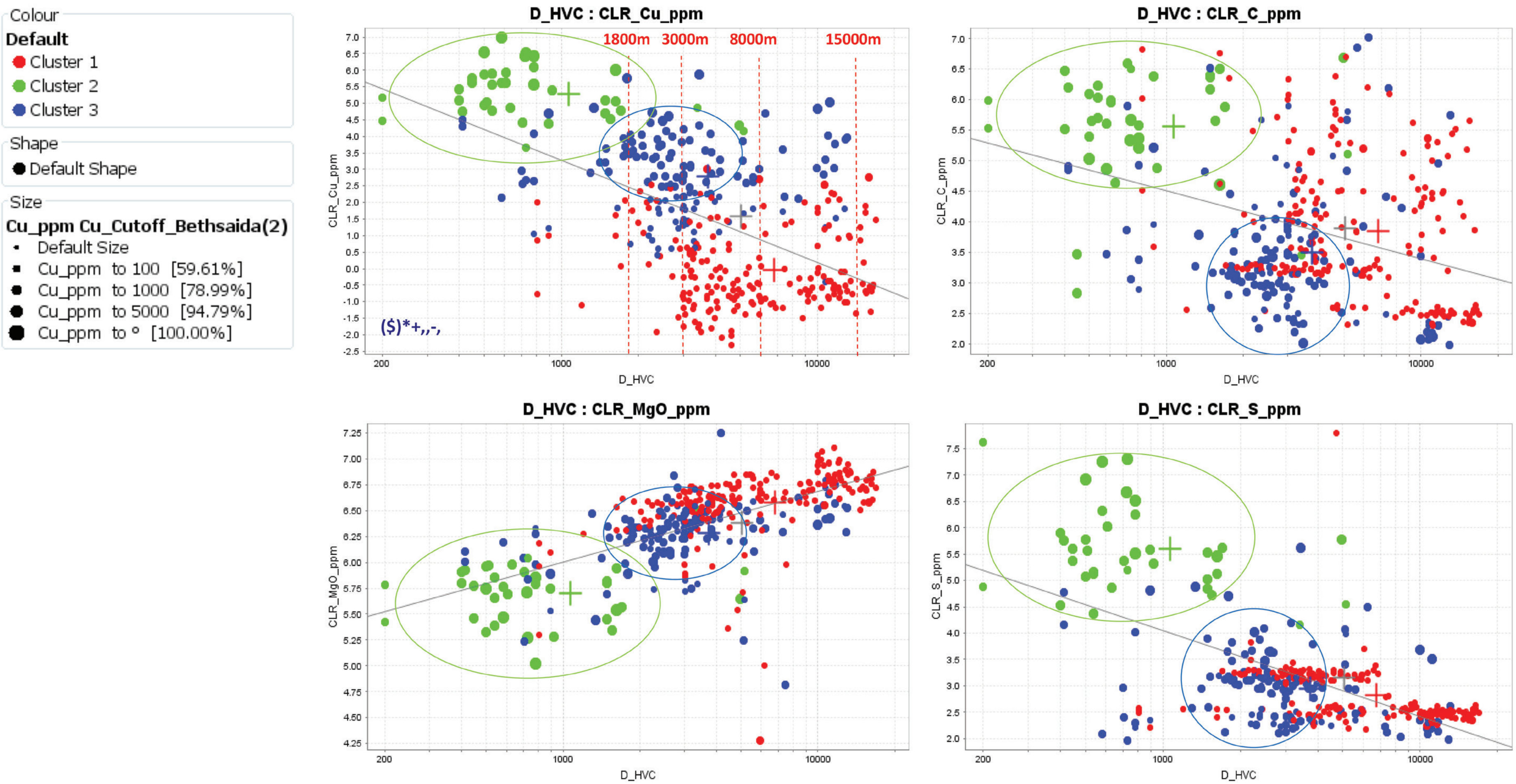
Workflows were developed by Leo Feltrin for application of machine learning to explore relationships among multi-disciplinary data within the Common Earth Model. “Data fusion” processes were developed to upscale, downscale, co-locate, and combine data sets into a single data structure for application of machine learning tools. Several unsupervised machine learning approaches were used to establish and test the validity of identified groupings of data into natural footprint zones that could be defined by distance from the deposit at the core of the system. Supervised machine learning approaches were then used to individually characterize each of the identified footprint zones in terms of “rules” of association among variables drawn from multiple data types. This was followed by selection or “mining,” interpretation, and visualization of the most meaningful rules.

Cluster Heat Maps



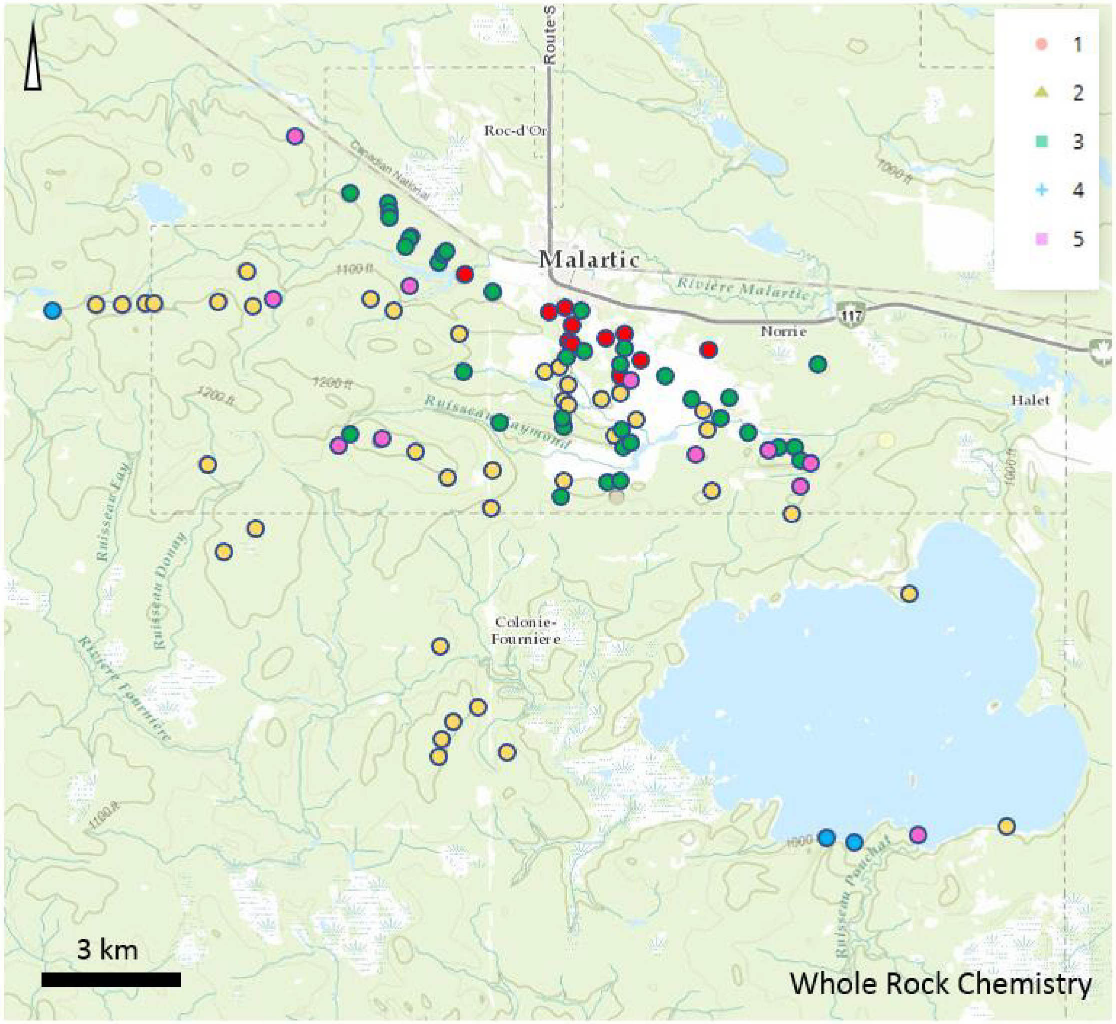
One of the machine learning tools deployed by Leo Feltrin was hierarchical classification displayed as "clustered heat maps," which show variation across a great amount of data in a compact visual space. In the three plots above, relative strength (red high, blue low) of geochemical variables from pXRF measurements in greywacke from possible footprint zones at the Au site is shown. Columns correspond to measured geochemistry parameters; rows are sample numbers. The algorithm sorts the data in each plot so that more similar variables (columns), across all samples, are more adjacent in the plot, and more similar samples (rows), across all variables, are similarly more adjacent. The patterns of clusters of red (circled) or blue across columns and rows of the heat map may be considered diagnostic of the footprint zone under investigation.

Zone Recognition with Machine Learning



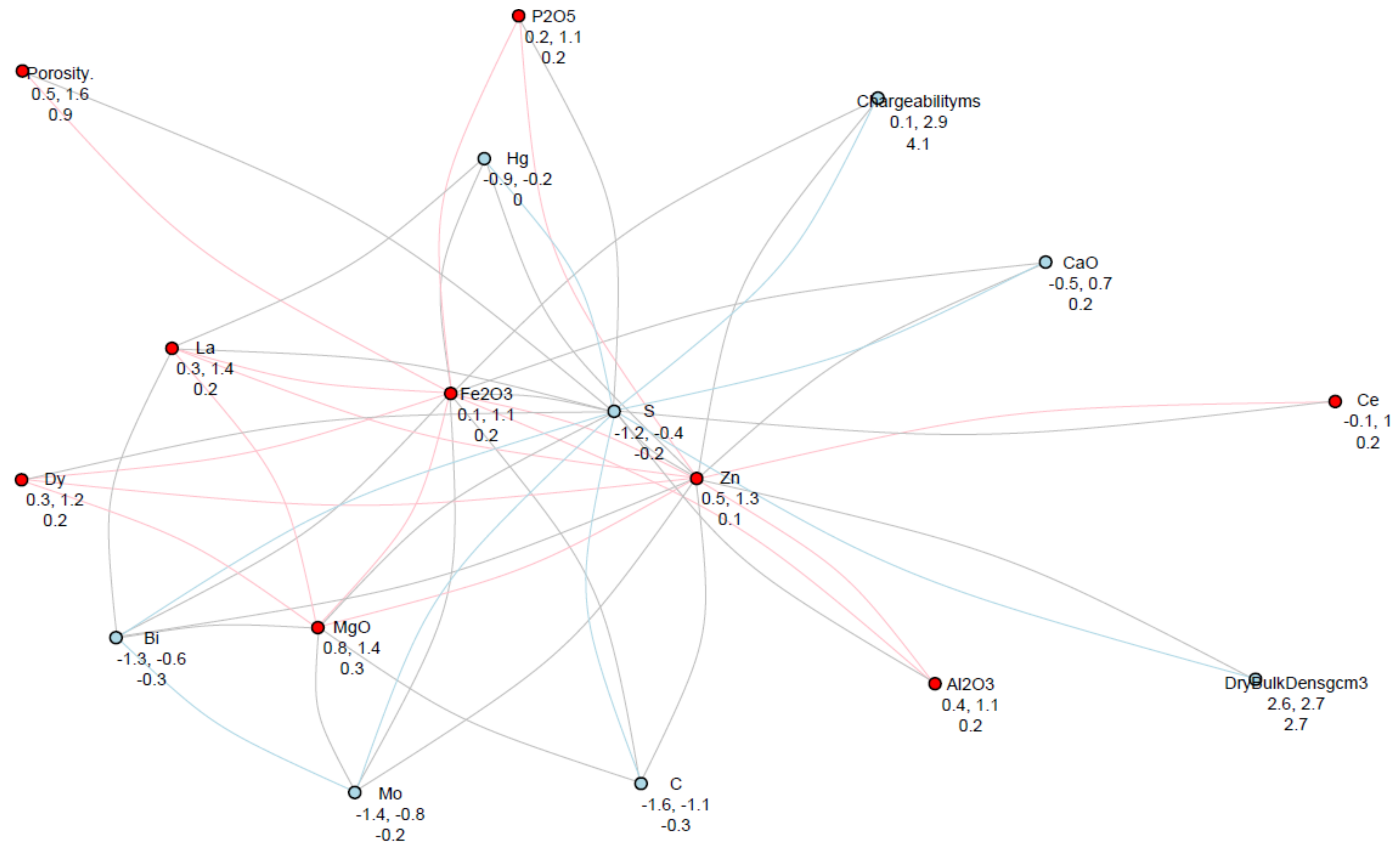
One of the unsupervised machine learning tools deployed by Martina Bertelli was k-means clustering, in which a group of samples is sorted into k sub-groups, within which samples are more similar to each other than to samples in the other sub-groups. In the example shown, a sampling of centre-log-ratio-transformed geochemistry data is shown as a function of distance from the Bethsaida orebody at Highland Valley Copper, with individual samples coloured by cluster number resulting from a test with k=3. An interpretive overlay on one of the plots suggests possible footprint zone limits.

Zone Recognition with Machine Learning



An ensemble of unsupervised machine learning tools (including self-organizing maps, k-means, k-medoids, herarchical clustering, and expectation maximization) were used by Leo Feltrin to determine possible natural clustering of samples. This map, developed using only whole rock geochemistry data as an example from the Au site, shows a result in which the multiple methods "voted" on cluster membership, with the resulting cluster nomination membership shown. A proximal-to-distal trend is evident. Such results were used in combination with others to interpret footprint zone boundaries.

Visualization of Hypercube Results



Supervised machine learning was used by Leo Feltrin to characterize individual footprint zones that had been previously interpreted from the unsupervised machine learning results. Learning how to recognize what relationships among data make each footprint zone distinct and recognizeable was accomplished principally with the HyperCube machine learning tool, which employs a brute-force algorithm to search through high-dimensional data space to find where in that space data from individual zones tend to be concentrated. The resulting "hypercube" volumes that correspond to individual footprint zones can be defined by sets of "rules" that define bounds within that high-dimensional data space. Shown here is a "network diagram" used to visualize a set of three-variable rules defining the location in data space where the samples from a particular footprint zone occur (Lornex Valley Zone 5 from the Cu site). The diagram combines physical properties such as chargeability, density, and porosity with metal concentration and lithogeochemical data to define muliti-disciplinary characteristics of a distal footprint zone, a key project objective.

Technology Transfer

Numerous technologies and methodologies developed to provide better exploration data interpretation were transferred to Sponsors.

Some of these transfers are summarized below:

Geophysics

1. Construction of 3D subsurface magnetic field variations from borehole navigation logs
2. Estimation of near-surface magnetic susceptibility from airborne EM data
3. Application of 3D multi-electrode borehole-to-borehole and borehole-to-surface resistivity and chargeability (IP) imaging
4. Methods to merge multiple generations of IP and resistivity surveys
5. Use ground-penetrating radar, high-frequency or resistive-limit electromagnetic methods, and seismic methods to map Quaternary cover thickness variations so that its influence on geophysical signatures can be stripped
6. Use of the seismic anelastic attenuation factor (Q) to define extent of hydrothermal alteration
7. New migration noise attenuation software for 3D seismic image enhancement
8. Extraction of physical property information from seismic 3-component data to aid in identifying alteration and vertical structures
9. Use of anisotropy of resistivity to characterize structural complexity associated with mineralization
10. Transformation of data by kriging using a gravimetric model of covariance, factorial kriging for noise reduction and separation of regional and residual components, and interpolation using non-stationary covariances

Geophysical Inversion

11. Application of 3D stochastic magnetic inversion methods to airborne and borehole magnetic data at both regional and local scales
12. Incorporation of downhole susceptibilities or magnetic data as constraints to reduce the non-uniqueness characteristic of magnetic inversions
13. Evaluation of current instrument and inversion methods to detect the low magnetic susceptibility contrast of disseminated mineralization
14. Use of high frequency magnetic anomalies to define 3D fault geometry and quantify alteration intensity by comparison with petrophysical and mineralogical data
15. Stochastic modelling of spectral IP data
16. Constrained and joint inversion of complementary geophysical data types for overburden stripping
17. Fast 3D inversion of airborne electromagnetic data for detecting conductors and alteration

Petrophysics

18. Establishment of best practices for measuring complex conductivity in the lab
19. Stochastic inversion of laboratory complex resistivity measurements using Markov-chain Monte Carlo simulation to obtain SIP parameters and their uncertainties from Cole-Cole and Dias models or from Debye and Warburg decomposition approaches
20. Extraction of petrophysical indicators from modelling SIP responses to discriminate vein/disseminated mineralization from alteration and unmineralized wall rocks
21. Use of multiple magnetic property measurements (susceptibility, coercivity, anisotropy of susceptibility, remanence) to identify the presence and structural timing of pyrrhotite in large-scale surveys, directly determining the timing and spatial distribution of footprints and mineralization
22. Use of physical property data from routinely collected whole-rock geochemistry to better constrain geophysical inversions

23. Joint analysis of physical properties at different scales and sampling distances, including estimation of physical properties from 3D geophysical data and geologically-constrained inversions to find the physical properties of rock units that best reconcile with observed geophysical responses
24. Use of magnetic susceptibility, resistivity, chargeability, and gamma spectrometry (bore holes, drill cores, and outcrops) to facilitate correlations with geology, foliation, and alteration to calculate average physical properties
25. Assessment of the capabilities/effectiveness of physical property-based joint inversion for mineral exploration and application to real-life data to mineral exploration scenarios

Structural Geology

26. Quantification of bedding attitude variance to detect the complex structural domains that host mineralization
27. Use of orientations, densities, lining compositions, and relative timings of fractures to identify variations related to mineralization along regional fault systems

Mineral Assemblage Mapping and Mineral Chemistry

28. Development of workflows to integrate mineral chemical and other measured parameters on the same samples
29. Use of hyperspectral mineral mapping at a wide range of scales, including scanning of field outcrops and open pit walls to map alteration, more efficient use of SWIR in measuring mica compositions, and applications to glacial material to identify the secondary dispersion of the alteration footprint
30. Use of mineral chemical data to link pathfinder elements to specific minerals, so that geochemical enrichments can be inferred from field data
31. Use of cluster analysis of Rietveld X-ray diffraction data to generate mineralogical data at the same rate and scale as standard whole-rock geochemical data
32. Modernization of carbonate and feldspar rock surface staining procedures using digital image analysis methods.

Lithogeochemistry and Isotope Chemistry

33. Analysis of field/core rock powders and old assay pulps via pXRF to provide rapid, fit-for-purpose data for footprint definition
34. Use of element ratios to eliminate data closure issues leading to more reliable delineation of alteration footprints.
35. Use of partial/total leach ratios to map mineral abundance variations
36. Development of more cost-effective stable C-O and radiogenic Pb isotope analyses

Surficial Methods

37. New methods to handle till samples to ensure that "clean" silt and sand-sized fractions are produced consistently for geochemical analysis
38. Use of fracture fillings, soil fractions, and tree cores to trace secondary element migration
39. Mapping of internal glacial stratigraphy of drumlins and correlation with units exposed at surface to understand the effect of stratigraphy and erosion on the secondary detrital dispersion of mineral indicators and their pathfinder elements
40. Detection of alteration signatures in glacial sediment cover using hyperspectral analysis of pebbles
41. Mapping units of contrasting composition (provenance) in surficial Quaternary sediment cover using supervised classification of radiometrics and other remotely sensed imagery to constrain the analysis and interpretation of surficial secondary dispersion
42. Use of W contents of rutile in tills to map footprint dispersion

Data Visualization, Integration, and Analysis

43. Construction of Common Earth Models that included a much wider variety of self-consistent geological, structural, mineralogical, mineral hemical, lithogeochemical, surficial, petrophysical, and geophysical data
44. Workflows for QA/QC of various types of exploration data
45. Modification of Geoscience INTEGRATOR to accommodate the wide range of data used in the project
46. Application of various data clustering algorithms to identify spatial patterns that cannot be detected using traditional geostatistical methods.
47). Workflows to facilitate fusion (import, collocate and resample) of varied data sets (lithogeochemical, mineralogical, mineral chemical, surficial, petrophysical, geophysical, and inversion outputs) for input into machine learning method
48. Geostatistical methods to combine geological-structural-mineralogical-lithogeochemical-surficial-petrophysical-geophysical variables to expand the outermost limits of footprint detection, and to identify smaller combinations of elements that can be analyzed less expensively by pXRF
49. Use of correlations between co-located petrophysical, geochemical, mineralogical, and hyperspectral data to permit statistical analyses of the relationships existing between lithology, alteration, ore, and petrophysical properties
50. Use of Machine learning methods to quantify uncertainties in the classification of petrophysical data
51. Methods to better visualize the output from machine learning tools like HyperCube.
52. Integration of lithogeochemical, geophysical, and surficial geochemical data to more clearly define footprints and to guide geophysical inversions
53. Use of relationship between spectral IP response and ore type, grain size, and distribution to determine the impact of these factors on the parameters from the physical models, allowing fine-tuning of the IP method in prospecting for ores

Project Management

54. Policies and workflows to facilitate collaboration across the various technological disciplines and across multiple research sites, which will be among the longest-lasting of the innovations resulting from the project

IN MEMORIAM

Kurt Kyser

The Footprints team was very saddened by the sudden loss of Professor T Kurtis Kyser, who died doing something he loved – teaching and interacting with students - while on a field school in Bermuda on 29 August 2017. Kurt was born in Montana, grew up in California, and completed his BSc at the University of California - San Diego, and earned his MA and PhD from the University of California - Berkeley.

His first professorial position was in the Department of Geological Sciences at the University of Saskatchewan, which he joined in 1981, after completing post-doctoral fellowships in Denver and Paris. He progressed through the ranks to full Professor, and was a recipient of the EWR Steacie Fellowship in 1993, which he held until his move to the Department of Geological Sciences and Geological Engineering at Queen's University in 1995. He then created and directed one of the leading geochemistry laboratories in North America, the Queen's Facility for Isotope Research. Kurt's work was recognized by numerous awards and accolades, including Fellow of the Royal Society of Canada, Willet G Miller Medal from the RSC, Killam Research Fellowship from the Canada Council, Past President's Medal of the Mineralogical Association of Canada, and the Duncan R Derry Medal and Past President's Medal from the Geological Association of Canada. In addition, at the time of his death, he was the Editor-in-Chief of the Geological Society of London's journal *Geochemistry: Exploration, Environment, Analysis*.

Kurt was a world-renowned researcher whose creativity and gift for solving scientific problems produced more than 500 peer-reviewed papers, books, book chapters, and technical reports. In particular, he was a recognized expert on the elemental and isotope geochemistry of uranium deposits and worked with many companies in applying geochemical techniques to the exploration for mineral deposits.

He collaborated with colleagues worldwide and believed strongly that field geology is fundamental to geochemical research. Many close friendships were born from these collaborations. Beyond these seminal contributions, his lasting legacy is the hundreds of former students and post-doctoral fellows that he mentored and who will remember his impact on their careers.

Acknowledgements

The Researchers are very grateful to Alan Galley, Thomas Hynes, François Robert, Dick Tosdal, and Carl Weatherell of CMIC for their leadership in designing the project; to Reginald Thériault and Robert Therrien of NSERC for their assistance in developing the proposal and strong support during the project; to the Scientific Advisory Board and Board of Directors for keeping our scientific and work plans on track; to the Sponsor Representatives and Subject Matter Experts for their scientific and logistical contributions to the project; to all of the Research Associates, Students, and Research Staff who did most of the science; and to Cathy Nadjiwon and the rest of the Office Staff who kept us organized, on budget, and on time.

Sponsors

Collaborators:
GSC TGI4 Program, MERN Québec, Saskatchewan Geological Survey, BC Geological Survey

Supporters:
Fullagar Geophysics; Rekasa Rocks; UBC Geophysical Inversion Facility

Charles L. Bérubé conducting IP mapping of a mineralized outcrop in the Canadian Malartic footprint.

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