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NSERC-CMIC FOOTPRINTS

NSERC-CMIC Mineral Exploration Footprints Research Network:

Data Integration for the Next Generation of Mineral Exploration Models

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uOttawa

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

Problems

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- **Volume of data**: Surveys are being conducted faster than ever before, frequently exceeding the capacity to assemble and interpret them, leaving vast amounts of quantitative information unused
- **Subjective data selection**: Conventional methods of handling the data are no longer sufficient to extract their full value and expensive data are regularly dismissed on the basis of subjective evaluations
- **Consistency**: Lack of consistency in the quality and resolution of different data sets creates problems in comparing and integrating data
- **Incomplete quantitative analysis**: Most exploration models have typically not been populated with quantitative data for more than a few parameters or at the range of scales necessary for effective exploration
- **Data interrogation/relationships**: Even where data are abundant, they are often interrogated individually or without qualification that may emphasize their relationship to an economic deposit

Goals

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- **Enhance the ability of the Canadian mining industry to recognize the entire footprint of an ore deposit** from its high-grade (minable) core to most distant cryptic margin
- **Develop methods that truly integrate** (not just layer) **the wide range of complex geological-structural-lithological-mineralogical-geochemical-petrophysical-geophysical data** that define the footprint of an ore deposit
- **Formalized methodologies for how specialists in each of those areas need to interact** in order to accomplish these goals

Specific Objectives

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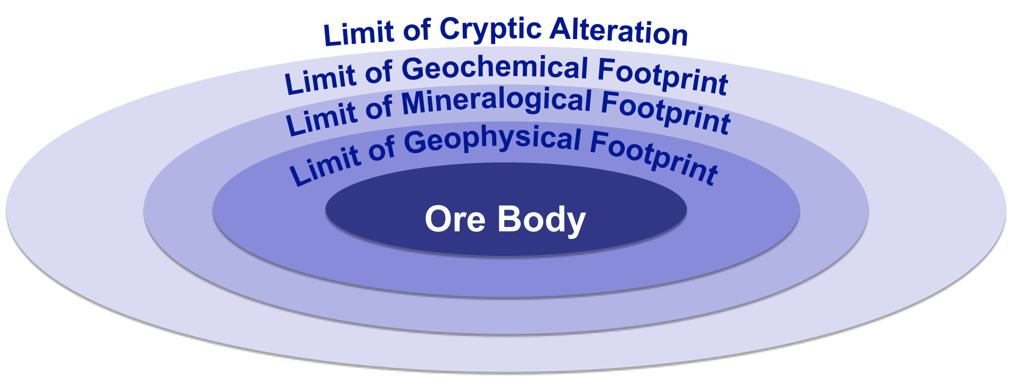
- **Develop comprehensive and robust models of the footprints of large-scale ore-forming systems** at three integrated study sites, combining geological, mineralogical, geochemical, geophysical, and physical rock properties from the local to the camp scale
- **Develop novel methods for integrating and 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
- **Identify the best combinations of geological, geophysical, petrophysical, mineralogical, and geochemical tools** to detect the footprints of major ore-forming systems



Research Network

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30 Faculty Researchers at 24 Canadian Universities

80 HQP Trained

- **15 Research Scientists**, **9 PhD Students, 16 MSc Students**
- **6 BSc Hons Students, 17 BSc Lab Assistants**, **17 BSc Field Assistants**

33 Sponsors:

- **16 Mining and Mineral Exploration Companies**: Agnico-Eagle (2014-2018), AngloGold Ashanti, Areva/Orano, Barrick, Cameco, Denison Mines, Franklin Geosciences, Gedex (2013-2014), Goldfields, HudBay, Iamgold, Japan-Canada Uranium (2013-2016), Kinross, Osisko (2013-2014), Teck, Yamana Gold (2014-2018)
- **4 Geochemical Service Companies**: Actlabs, ALS, SGS, SRC
- **6 Geological and Geophysical Service Companies**: Abitibi Geophysics, Fugro/CGG, DGI, PGW, Rekasa Rocks (2017), SRK
- **7 Software Service Companies**: BearingPoint, Dassault Systèmes, Geosoft, MIRA Geoscience, Paradigm, Pitney-Bowes, Reflex

4 Collaborators: GSC TGI-4, MRNQ, SGS, GSBC

Study Sites

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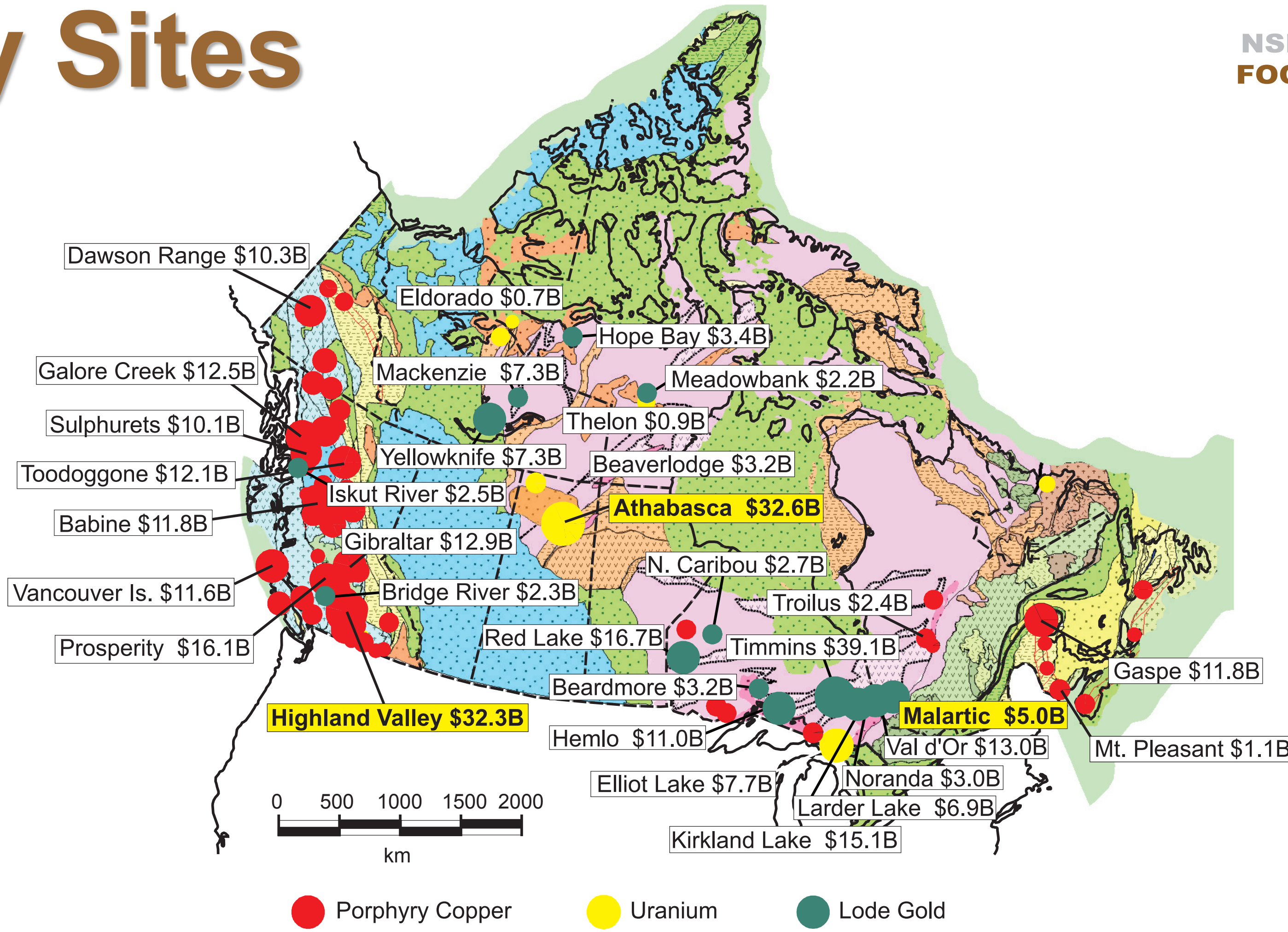

Research Methodologies

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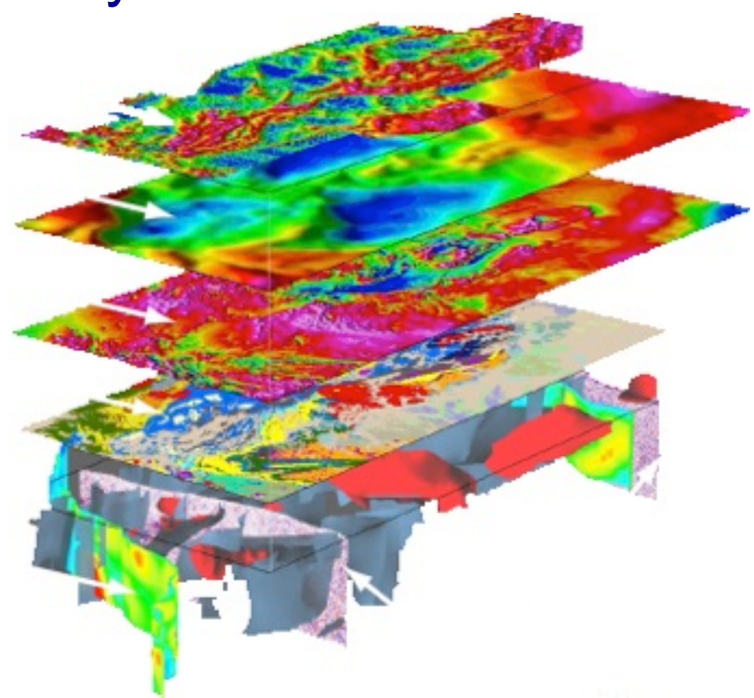
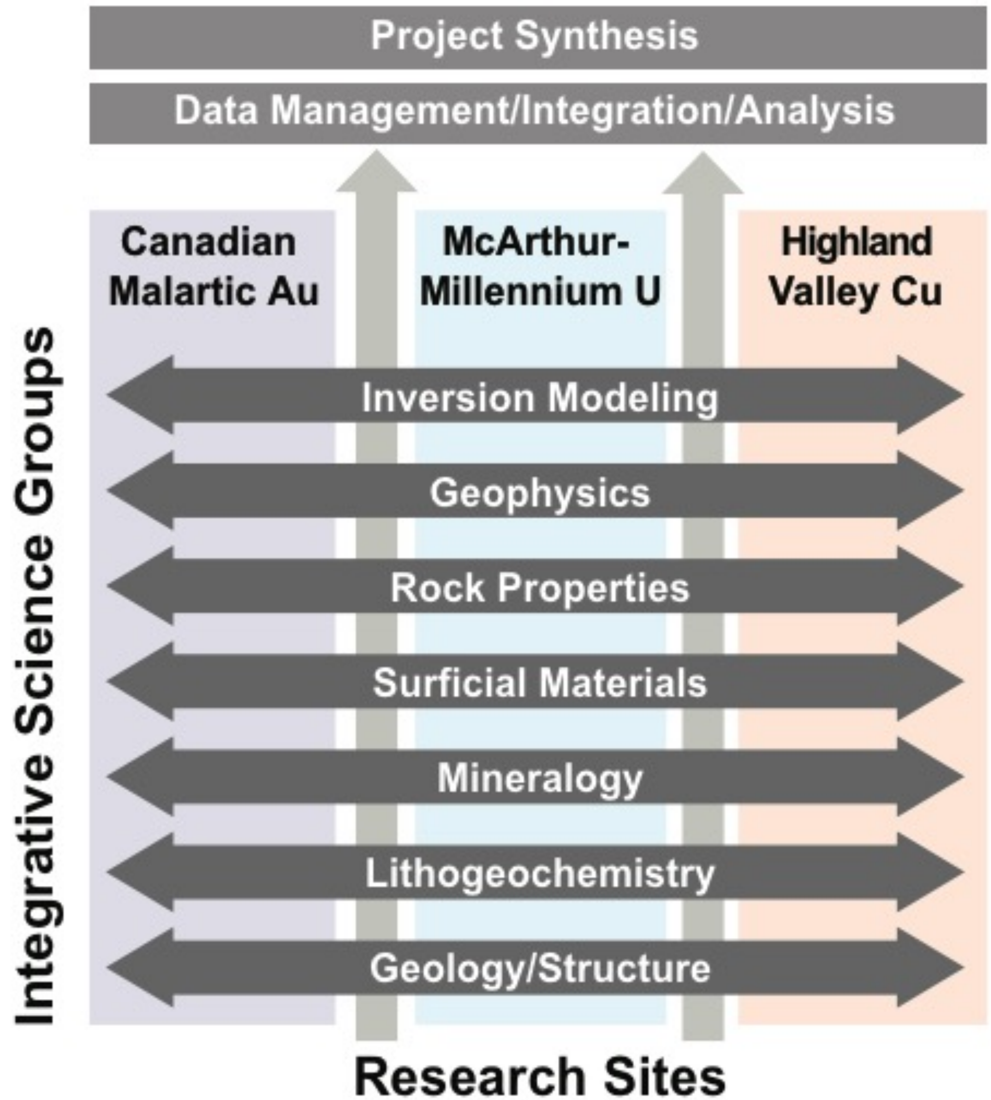
- **Full ore systems from distal edges to ore zones**, both at surface and at depth, and including the highest density of data and sampling opportunities
- **New and legacy data**, with emphasis on high-quality multi-parameter measurements on the same samples at each site
- **3D data constrained using multi-parameter data from representative cross sections and surface/level plans** through each ore system



Site/Technology Groups

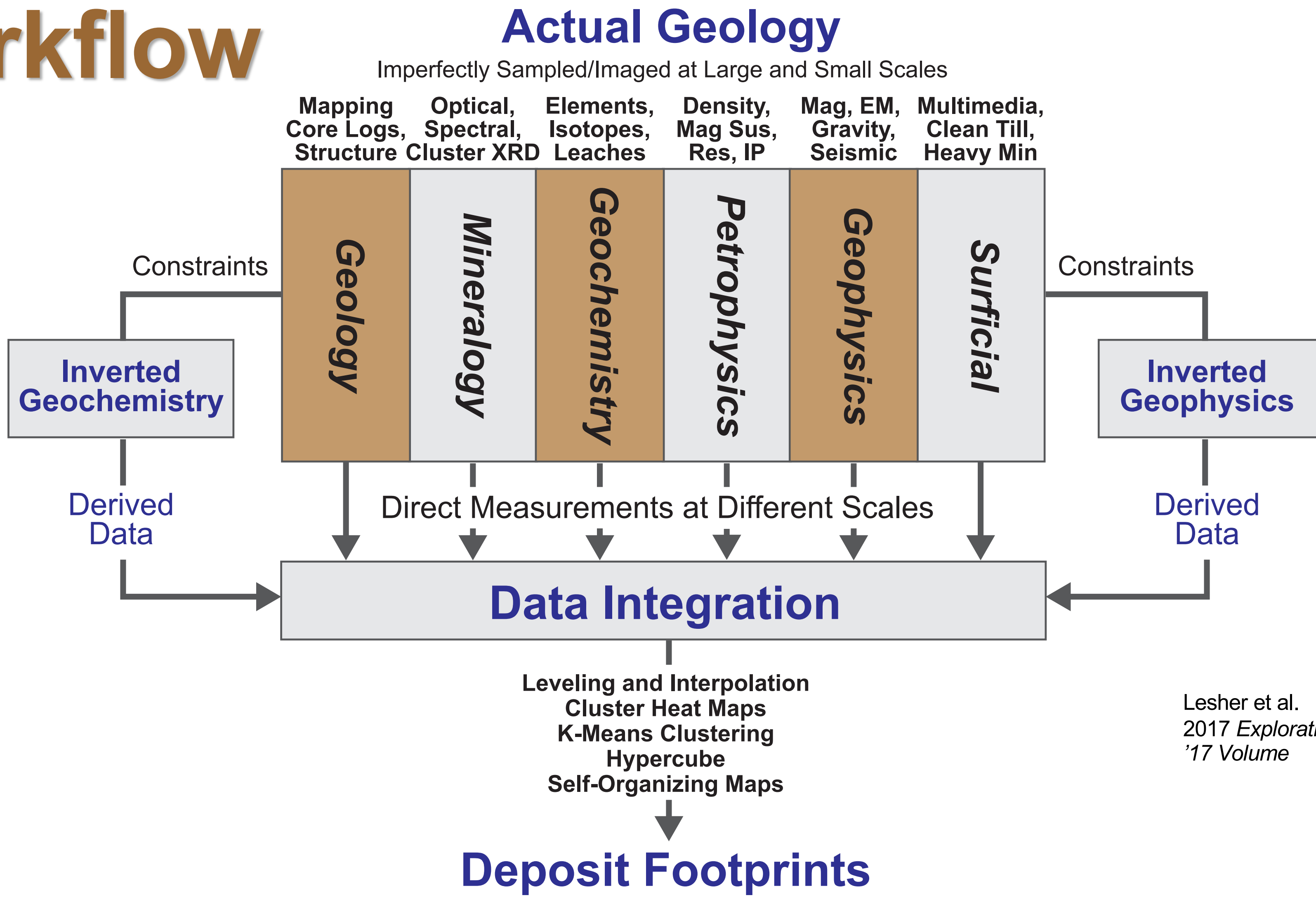
- Same teams of researchers working on all three sites to ensure a uniform approach to defining the ore-system footprints



Common Focus of Subprojects

- Collate and integrate existing data sets
- Identify key sections to characterize the deposit footprint
- Select new analyses to fill critical gaps in multi-parameter data sets
- Identify unique combinations of parameters at the appropriate scales

Workflow



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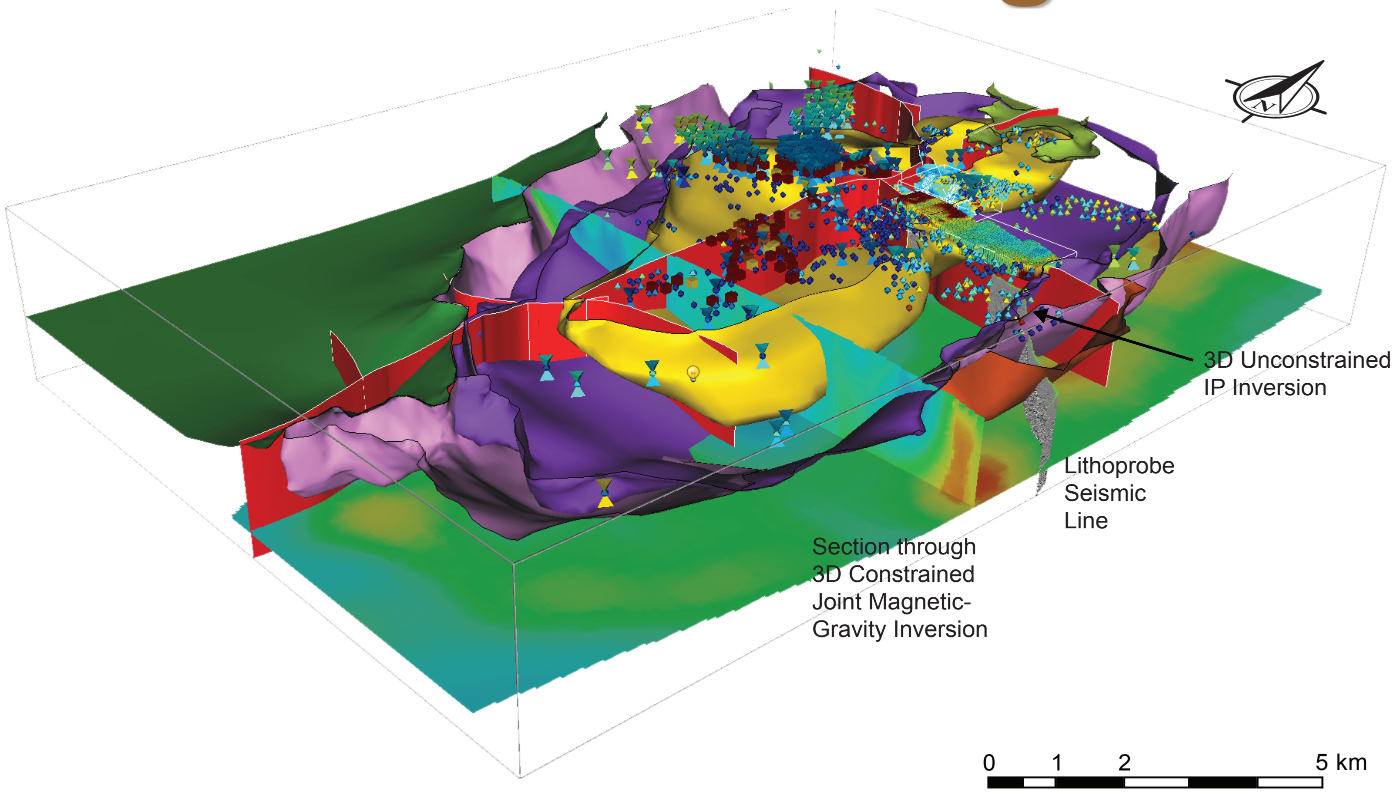
Common Data Integration Model



GOCAD/SKUA and MIRA Mining Suite used to provide a common framework for 2D/3D geology, physical properties, borehole logs, assay data, structural/geophysical/geochemical models, and inversions

Major Deliverables

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- **Fully integrated, multiparameter footprint models** of three major types of ore systems in Canada and the workflows needed to creating them
- **Maps and sections of the detectable features** of the ore systems, including full geological, mineralogical, geochemical, petrophysical, geophysical, and derived attributes
- **Database of physical rock properties** linked to the mineralogical and geochemical attributes of ore-hosting lithologies and alteration
- **Geophysical survey data reprocessed** with new software and constrained by new geological information and physical property measurements specific to the ore system
- **Modifications of existing tools or methods** to enhance the measurement and detection of footprints at a range of scales

Footprints and Vectors Identified

- **Au Site**
  - **98 vectors** (35 in metasedimentary rocks, 63 in mafic dikes)
  - **20 footprints** (9 in metasedimentary rocks, 11 in mafic dikes)
  - **4 halos** in Quaternary sediments
- **U Site**
  - **18 vectors and 7 footprints at Millennium**
  - **14 vectors and footprints at McArthur River**
  - **Vary with stratigraphy, strongly controlled by structure**
- **Cu Site**
  - **15 vectors and footprints**

Au Site Database and CEM

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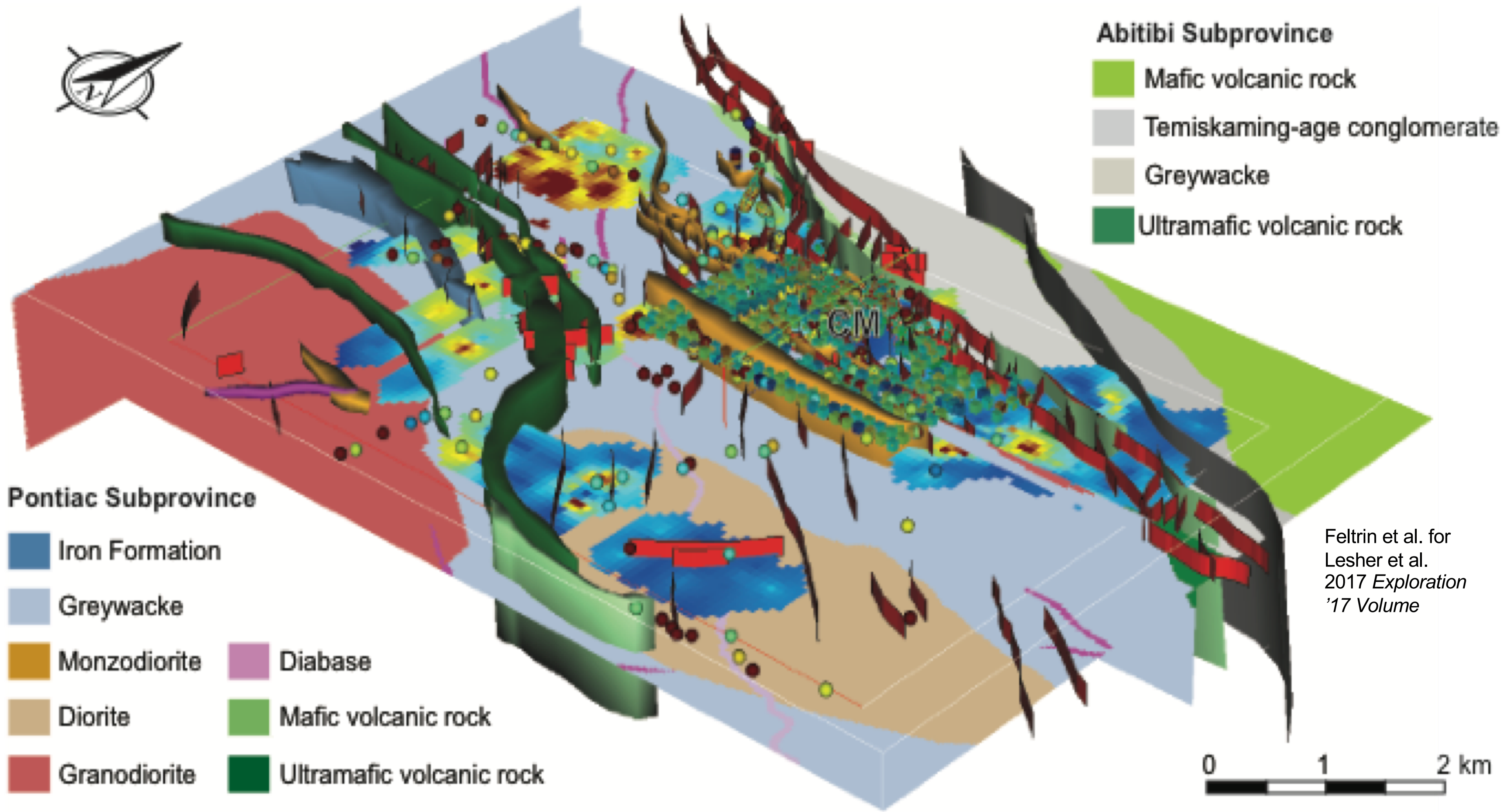
- **5 local** (40 cm resolution) **and 1 regional** (90m resolution) **DEMs**
- **Overburden thickness model and regional till map**
- **161 historic mine sections, 6045 DDH logs, and 14 downhole petrophysical logs**
- **Regional geological model and 14 local outcrop geology maps**
- **2322 structural measurements and 2888 regional mineral occurrences**
- **2 airborne MAG and EM, 19 IP, and 3 satellite/ground gravity surveys**
- **863 petrophysical** and **1011 gamma-ray spectrometric measurements**
- **4382 pXRF, 1103 WR lithogeochem,** and **272 WR and mineral H-O-C-S isotope analyses**
- **347 XRD mineralogy determinations**
- **7539 WD-XRES** (EPMA) **mineral analyses**
- **Hyperspectral data for 1639 samples and over 1000m of drill core**
- **Derivative products:** stitched 1D inversions of AEM data for resistivity and susceptibility at different frequencies, forward magnetic models, inversions for IP resistivity and chargeability, and gridded geochemistry, mineralogy, petrophysics
- **Supporting data**: >2000 photographs, photomicrographs, backscattered electron SEM maps, hyperspectral mineral chemistry maps, WD-XRES EPMA and LA-ICP-MS elemental maps, and mineral liberation analytical maps


Abitibi Subprovince
Mafic volcanic rock
Temiskaming-age conglomerate
Greywacke
Ultramafic volcanic rock
CM
Pontiac Subprovince
Iron Formation
Greywacke
Monzodiorite
Diorite
Granodiorite
Diabase
Mafic volcanic rock
Ultramafic volcanic rock
0
1
2 km
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Lesher et al.
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'17 Volume

Au Site Footprints/ Vectors I.

Type/Lithology/Phase/Property				Mineralized <0.1 km	Proximal 0.1 - 0.5 km	Medial 0.5 - 1 km	Distal 1 - 5 km	Least Altered > 5 km	Method / Instrument
Mineralogy and Petrophysics	Metabasic dikes	**Anorthite**	Presence				OUT	IN	Petrography
		Hornblende	Presence		OUT	IN			Petrography
			Proportion			—→	—→	—→	XRD
		Biotite	Presence				IN	OUT	Petrography
			Proportion	←—	←—	←—	←—		XRD
		Epidote (Allanite)	Presence	OUT	IN		IN	OUT	Petrography
			Ca/(REE+Y)		—→	—→			EPMA (WD-XRES)
			Al/(Mg+Fe)		┈→	┈→			EPMA (WD-XRES)
			F/Cl		←┈				EPMA (WD-XRES)
		Calcite	Presence			IN	OUT		Petrography
			Proportion	←—	←—	←—			XRD / Petrography
		Density		—→	—→	—→	—→		Balance
	All Lithologies	**Iron carbonates**	Presence	IN	OUT				Staining
		Fluoro-carbonates (Parisite)	Presence		IN	OUT			SEM
			Proportion	←┈	←┈				SEM
		Ilmenite	Presence		OUT	IN			SEM
		Rutile	W-Sb-Nb	←—	←—	←—			EPMA (WD-XRES)
		Pyrite	Presence			IN	OUT		Petrography
			Proportion	←┈	←┈	←┈			SEM
		Pyrrhotite (metamorphic)	Presence	OUT	IN		IN	OUT	Petrography
			Proportion		┈→	←┈	←┈		SEM / Petrophysics
			Ratio Po/Py		—→	—→			SEM
		Magnetic Susceptibility			—→	←—	←—		Susceptibility meter
	Metasedimentary rocks	**Albite**	Presence	IN	OUT				Petrography
		Microcline	Presence	IN	OUT				Petrography / Staining
		Biotite (hydrothermal)	Wavelength	—→	—→				SWIR Imagery
			Mg #		High | Low *(metamorphic)*				EPMA / SWIR Imagery
		Biotite (metamorphic)	Si-K-Ti-F	←┈	←┈	←┈	←┈	←┈	EPMA
			Na-Al	┈→	┈→	┈→	┈→	┈→	EPMA
		White mica (hydrothermal)	Wavelength	←—	←—	←—			SWIR Imagery
			Al^{VI}			Low	High		EPMA
		White mica (metamorphic)	Si-Fe-Mg-K-Ti	←┈	←┈	←┈	←┈	←┈	EPMA
			Na-Al	┈→	┈→	┈→	┈→	┈→	EPMA
			Wavelength	←—	←—	←—	←—	←—	SWIR Imagery
		Calcite	Presence		IN	OUT			Petrography
			Proportion	←┈	←┈				XRD / Petrography
		Pyrite	Au-Te	←—	←—	←—	←—		ICP-MS

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Type/Lithology/Phase/Property				Mineralized <0.1 km	Proximal 0.1 - 0.5 km	Medial 0.5 - 1 km	Distal 1 - 5 km	Least Altered > 5 km	Method / Instrument
Mineralogy and Petrophysics	Metabasic dikes	**Anorthite**	Presence				OUT	IN	Petrography
		Hornblende	Presence Proportion		OUT	IN			Petrography XRD
		Biotite	Presence Proportion				IN	OUT	Petrography XRD
		Epidote (Allanite)	Presence Ca/(REE+Y) Al/(Mg+Fe) F/Cl	OUT	IN		IN	OUT	Petrography EPMA (WD-XRES) EPMA (WD-XRES) EPMA (WD-XRES)
		Calcite	Presence Proportion			IN	OUT		Petrography XRD / Petrography
		Density							Balance
	All Lithologies	**Iron carbonates**	Presence	IN	OUT				Staining
		Fluoro-carbonates (Parisite)	Presence Proportion		IN	OUT			SEM SEM
		Ilmenite	Presence		OUT	IN			SEM
		Rutile	W-Sb-Nb						EPMA (WD-XRES)
		Pyrite	Presence Proportion			IN	OUT		Petrography SEM
		Pyrrhotite (metamorphic)	Presence Proportion Ratio Po/Py	OUT	IN		IN	OUT	Petrography SEM / Petrophysics SEM
		Magnetic Susceptibility							Susceptibility meter

Type/Lithology/Phase/Property			Mineralized <0.1 km	Proximal 0.1 - 0.5 km	Medial 0.5 - 1 km	Distal 1 - 5 km	Least Altered > 5 km	Method / Instrument
Metasedimentary rocks	**Albite**	Presence	**IN**	**OUT**				Petrography
	Microcline	Presence	**IN**	**OUT**				Petrography / Staining
	Biotite (hydrothermal)	Wavelength						SWIR Imagery
		Mg #		**High**	**Low** *(metamorphic)*			EPMA / SWIR Imagery
	Biotite (metamorphic)	Si-K-Ti-F						EPMA
		Na-Al						EPMA
	White mica (hydrothermal)	Wavelength						SWIR Imagery
		Al^{VI}			**Low**	**High**		EPMA
	White mica (metamorphic)	Si-Fe-Mg-K-Ti						EPMA
		Na-Al						EPMA
		Wavelength						SWIR Imagery
	Calcite	Presence		**IN**	**OUT**			Petrography
		Proportion						XRD / Petrography
	Pyrite	Au-Te						ICP-MS

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Schematic Au Site Footprint

* metabasic dikes only
** metasedimentary rocks only

Distance	In	Out
<200m	Pyrite, Calcite**, Albite, Microcline**, Hydrothermal Mica**, Fluorocarbonate	Hornblende*
<1 km	Calcite*	Ilmenite
<5 km	Biotite*, Epidote*	Anorthite*

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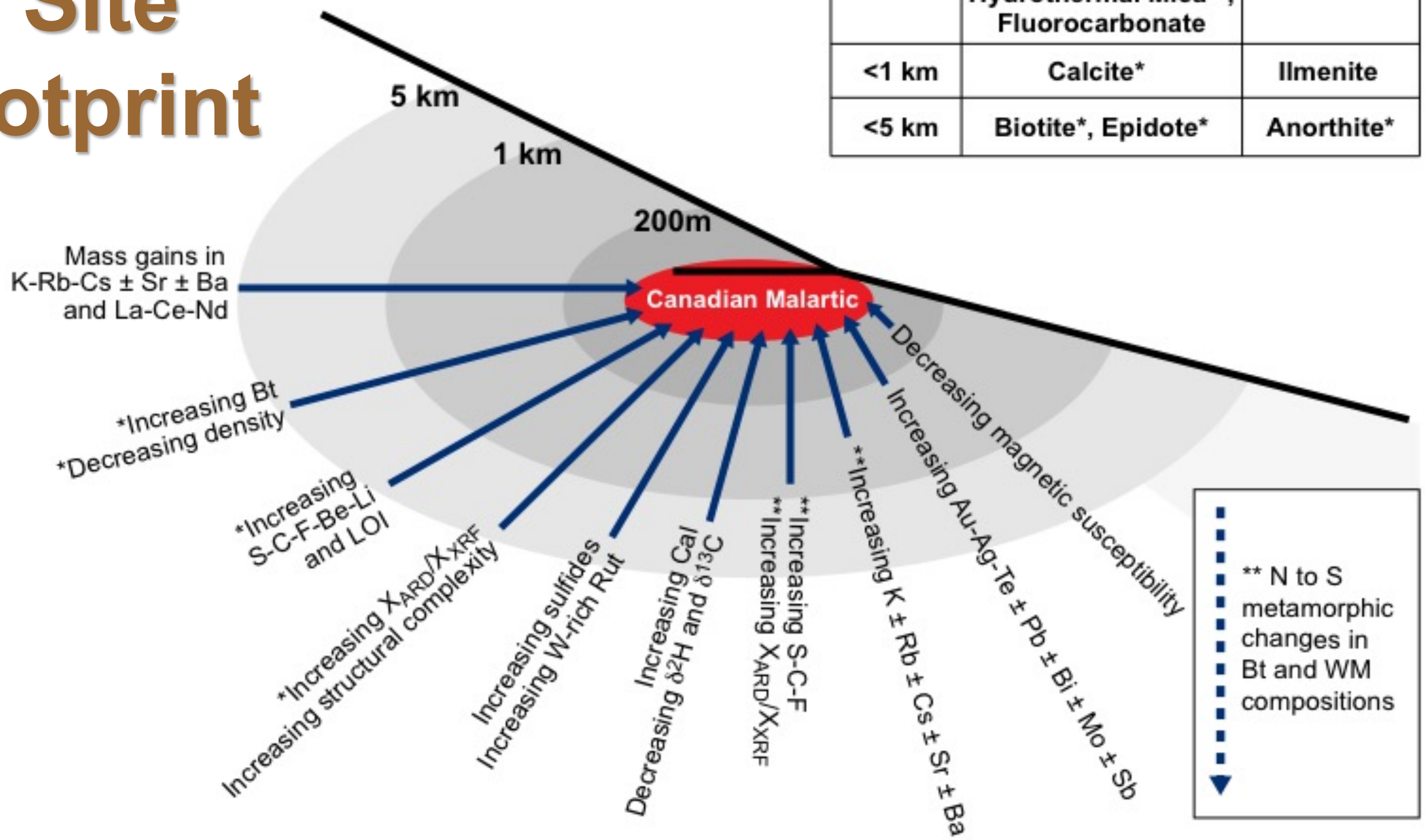

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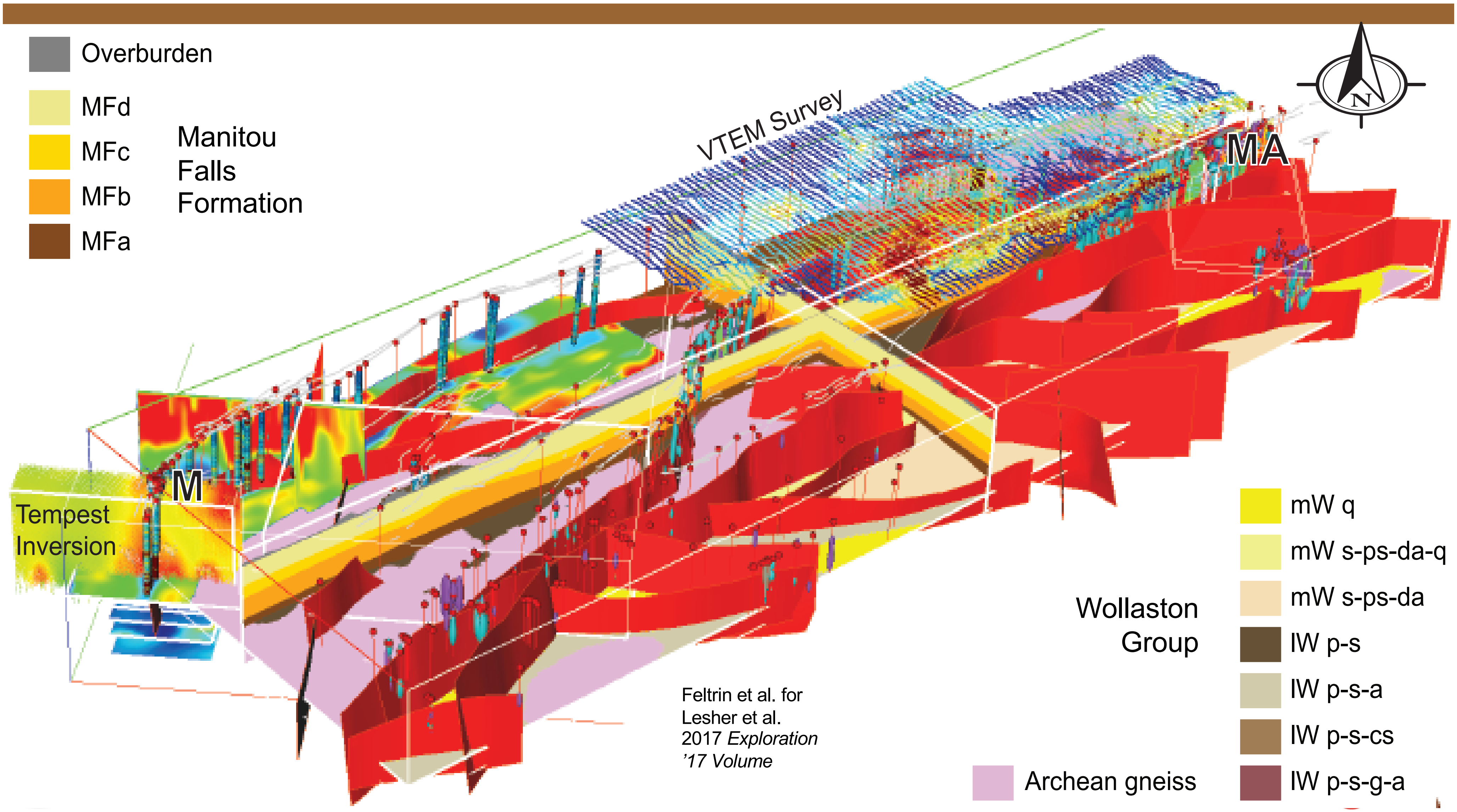
U Site Database and CEM

NSERC-CMIC FOOTPRINTS

- **50m-spaced DEM and overburden thickness map**
- **Basin and basement geology with fault traces**
- **Regional radiometrics; seismic**
- **1 km-spaced ground gravity and gravity forward model**
- **100m** (Millennium) **and 300m** (McArthur River) **spaced airborne gravity gradiometry and inversions**
- **300m-spaced AEM survey and magnetic inversion,** and **AMT survey**
- **EM conductor traces; airborne electromagnetic surveys, 3D resistivity inversion, and 1D resistivity inversion of all survey lines**
- **~1440 drill cores with lithologies, geochemistry** (>47,000 analyses)**, SWIR, and structural data** (12 with new lithogeochemistry, mineralogy, and petrophysics)
- **5 GPR lines** and **74 till samples** (geochemistry and pebble counts)
- **Surficial geochemistry** (~2140 soil horizons, ~580 tree cores, ~270 boulders)
- **~250 petrophysical measurements** (saturated bulk density, porosity, magnetic susceptibility, resistivity, chargeability)


Overburden
MFd
MFc
MFb
MFa
Manitou Falls Formation
VTEM Survey
MA
M
Tempest Inversion
mW q
mW s-ps-da-q
mW s-ps-da
lW p-s
lW p-s-a
lW p-s-cs
lW p-s-g-a
Wollaston Group
Archean gneiss
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U Site Footprint Components

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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

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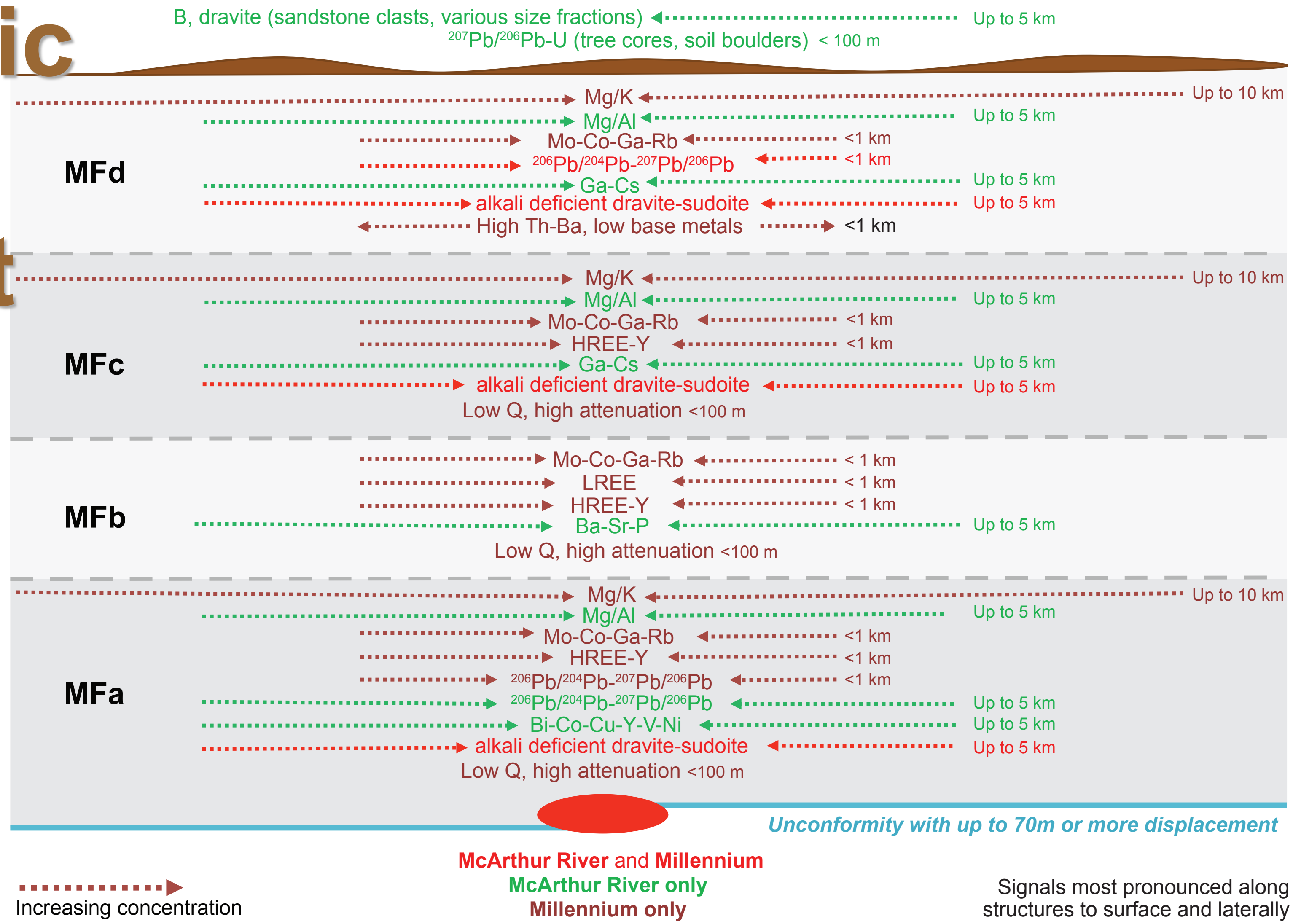
Schematic U Site Footprint



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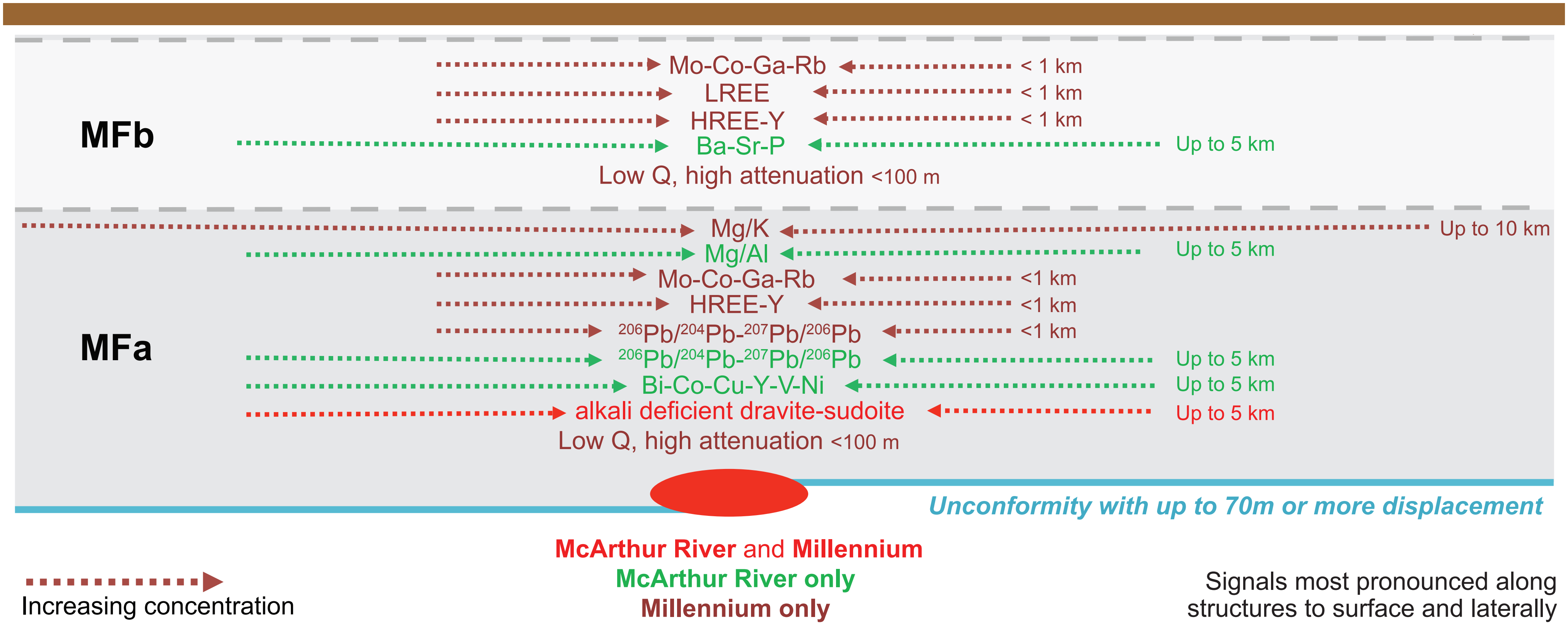

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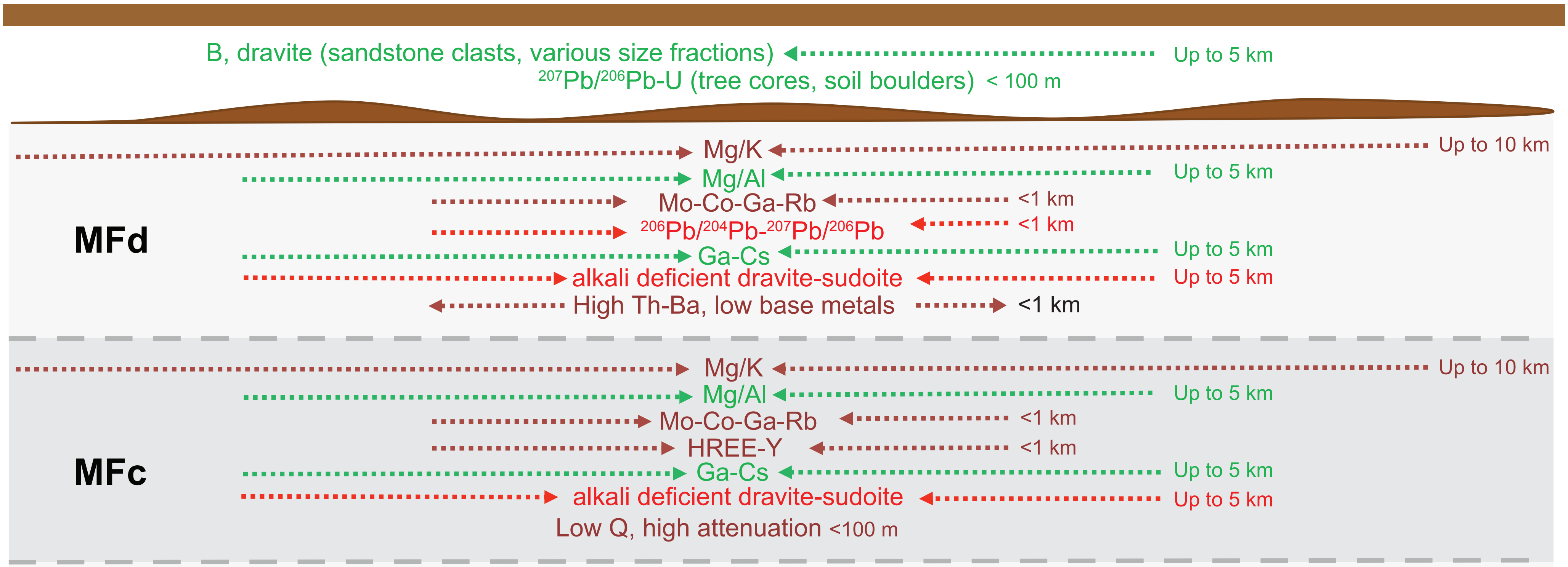

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Cu Site Database and CEM

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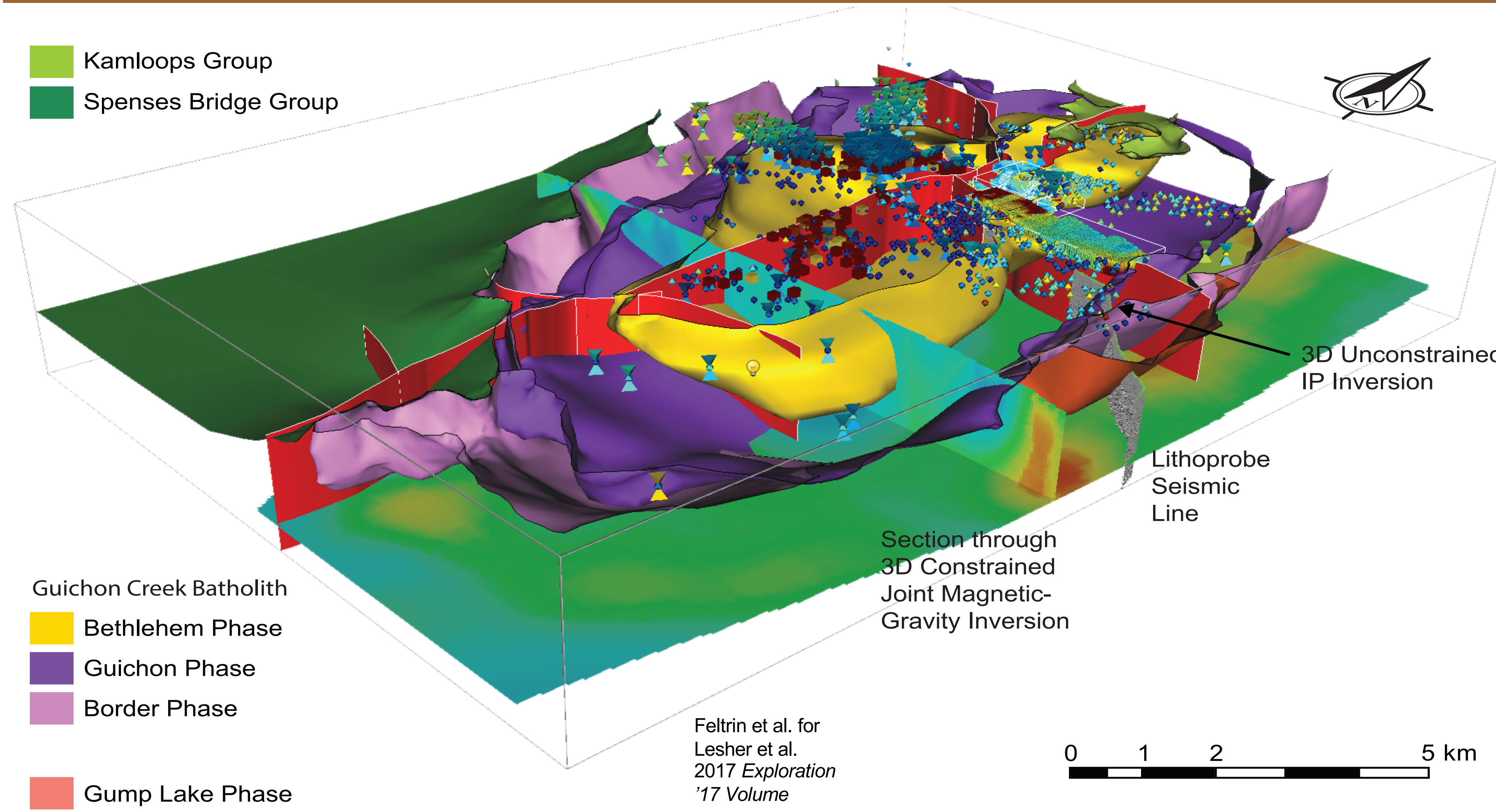
- **90m-resolution DEM** and **compilation of DDH overburden thickness**
- **HR orthophotography** and **regional/local geological maps including ~1640 outcrop/DDH stations, ~2350 bedding and structural measurements, ~750 mag sus measurements**
- **Compilation of Cu-Au-Ag-Zn-Pb mineral occurrences**
- **250m-spacing airborne mag and radiometrics,** and **2 km-spacing airborne gravity**
- **3D compilation of chargeability/resistivity** (20 DCIP surveys ea. with 2D or 3D inversion)
- **2 ft-resolution satellite grav survey** and **200-station ground grav survey**
- **~1400 petrophysical** (density/porosity/mag sus/remanence/electric) **measurements**
- **~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; wide range of WD-XRES** (EPMA) **and LA-ICP-MS microanalyses of hornblende, plagioclase, epidote, biotite, chlorite, white mica, tourmaline, apatite, zircon, and oxides**
- **380 pebble-mineral counts and geochemical analyses of till samples** (80 with petrophysical measurements)



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Cu Site Vectors

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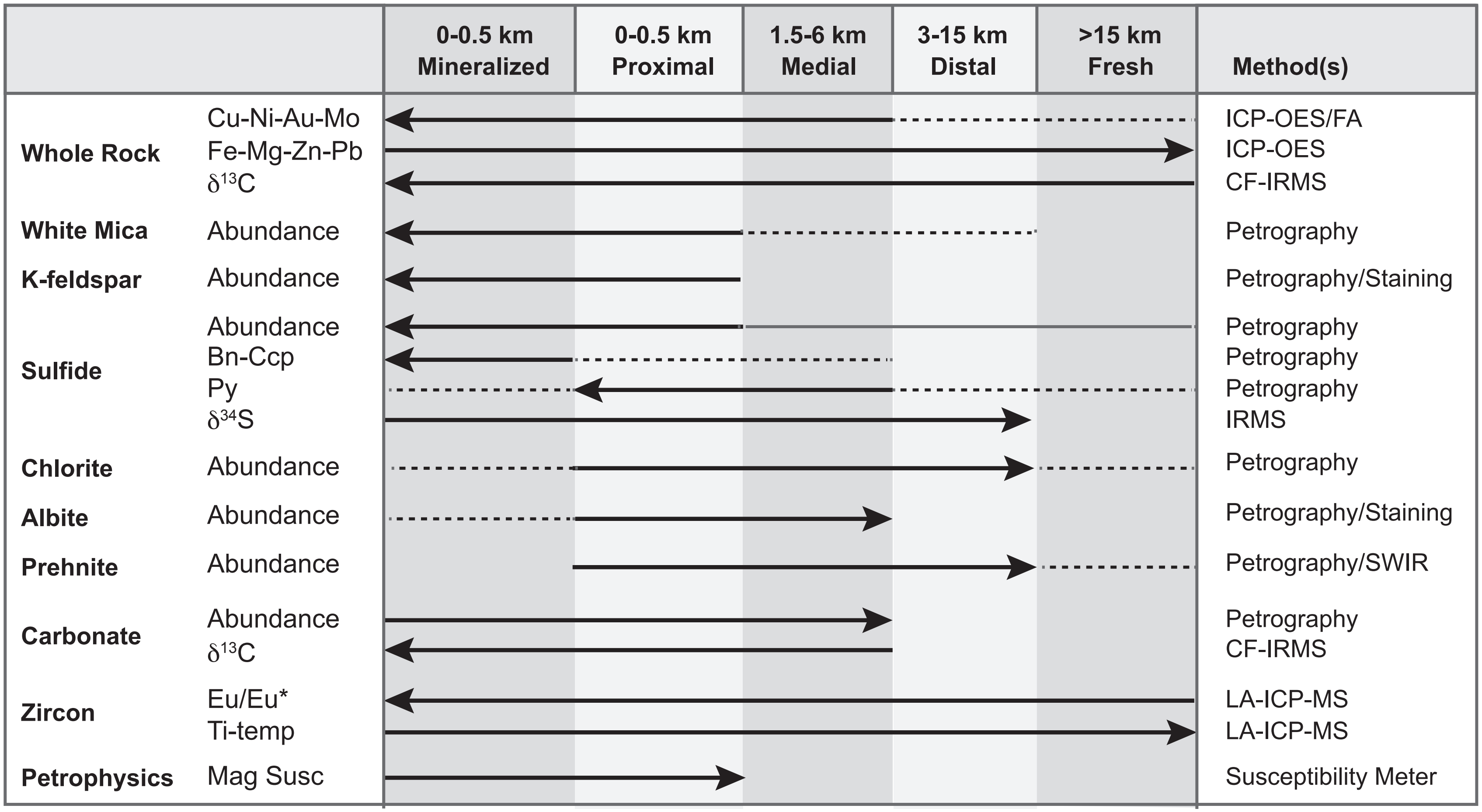
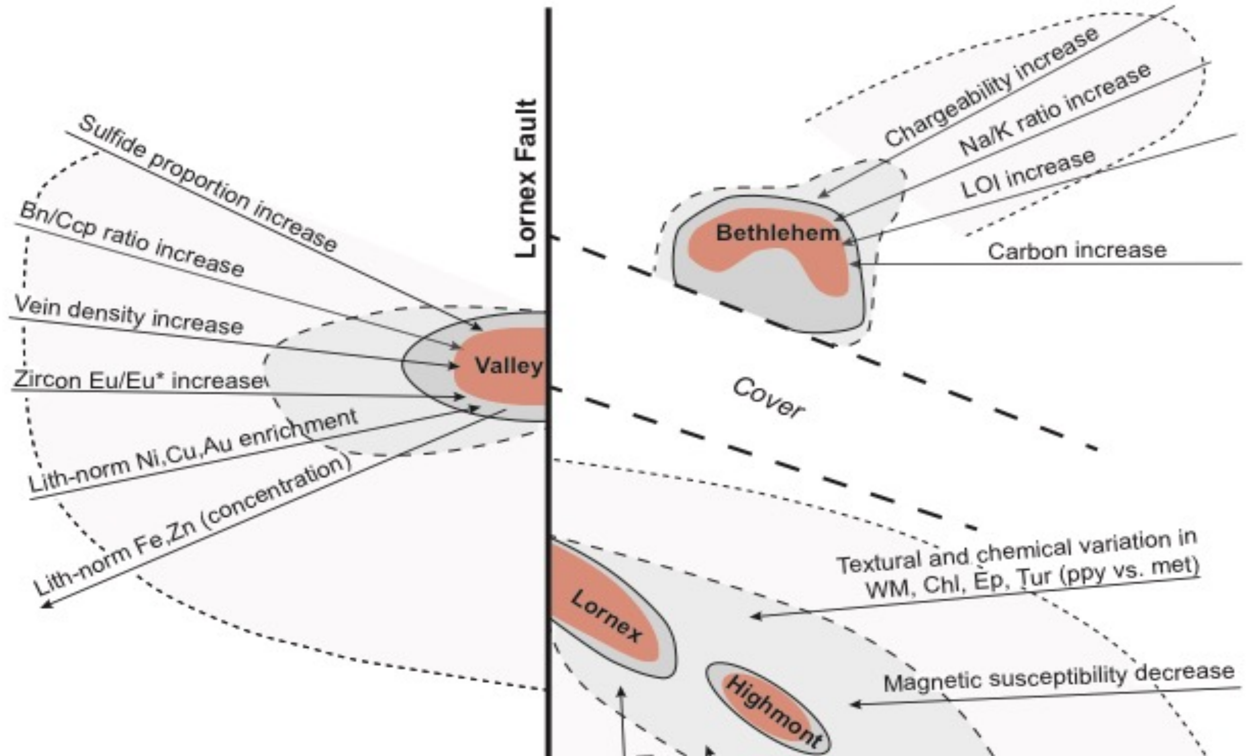


Schematic Cu Site Footprint



Legend	Distance from mineralization center	Alteration mineral assemblage
———— (solid line)	0.5-1.5 km	Qtz, Ms, Ksp, Bt, Bn, Ccp, Py, Chl, Kln, Mnt
– – – – (dashed line)	3.0-5.5 km	Qtz, Ksp, Bt, Py, Ccp, Bn, WM, Ab, Chl, Act, Ep, Tur
········· (dotted line)	8.0-12 km	WM, Chl, Prh, Ab, Ep, Tur

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Common Footprints and Vectors I.

	Au	Cu	U
Structure			
Variance in bedding footprint	◉		◉
Vein/fracture density footprint		◉	◉
Petrophysics			
Mag Sus vector	◉	◉	
Resistivity and chargeability footprint	◉	◉	◎
Mineralogy			
Hydrothermal zircon footprint	◉	◉	
Silicification/desilicification vector	◉	◉	◉
Mineral Chemistry			
Epidote footprint	◉	◉	
Feldspar composition vector	◉	◉	
Ilmenite footprint	◉	◉	
Phyllosilicate (mica/chlorite/clay) compositional vector	◉	◉	◉
Pyrite footprint	◉	◉	
Sulfide chemistry footprint	◉	◉	
W in rutile footprint	◉	◉	

Common Footprints and Vectors II.

	Au	Cu	U
Lithogeochemistry			
Au footprint	◉	◉	McA only
B vector	◎	◉	◉
Ba-Sr vector	◉	◉	
C (carbonate/graphite)	◉	◉	◉
Cs-Rb-K vector	◉	◉	◉
Cu-Ag footprint	◉	◉	◉
LOI footprint	◉	◉	◉
REE vector	LREE	REE	◉
Mo ± Bi ± Pb footprint	◉	◉	◉
Ni-Zn vector		◉	◉
S footprint	◉	◉	◉
Selective leaching footprint	◉	◉	◉
U vector	◉		◉
Isotopes			
H-C-O isotope vector	◉	◉	◎
S isotope vector	◉	◉	◎
Pb isotope vector	◎	◎	◉

Key Theme: Variance

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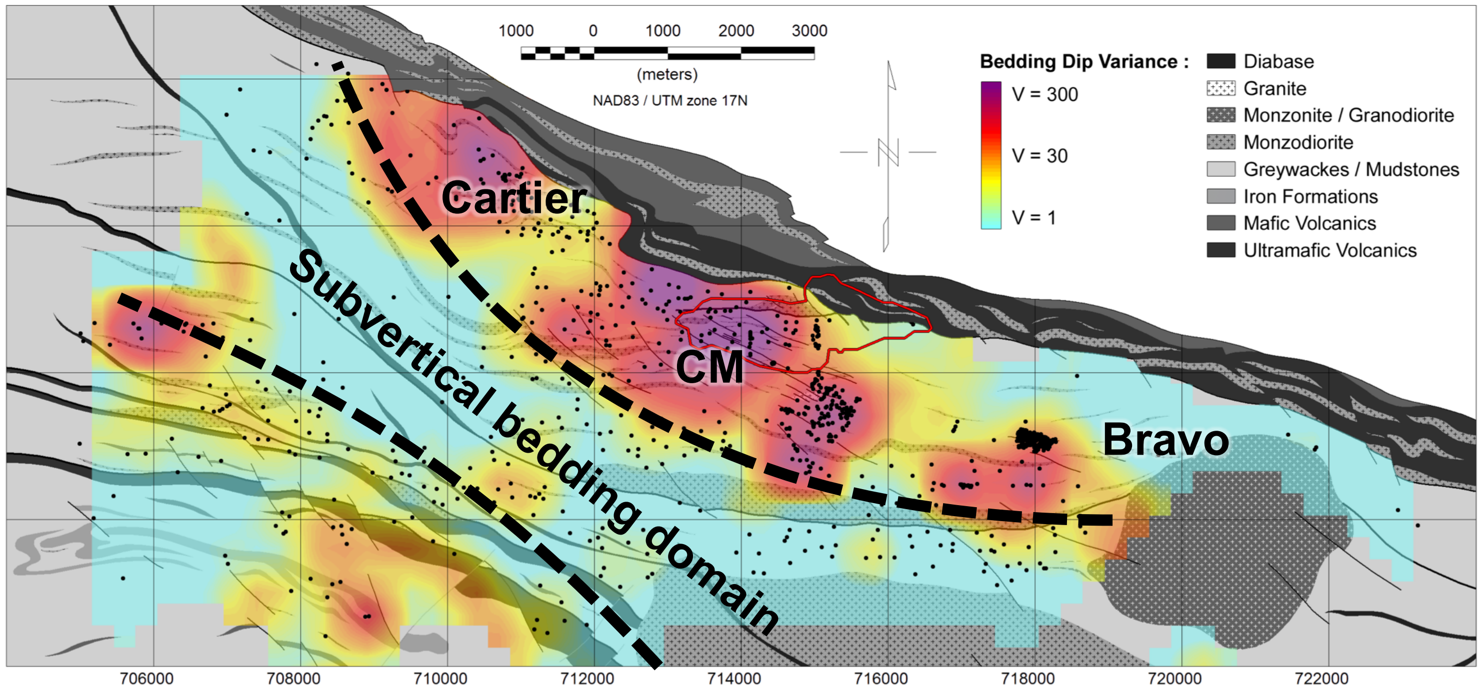
- **The variance of most parameters** (structure, physical properties, mineralogy, mineral chemistry, lithogeochemistry, and isotopes) **increases toward mineralization**
- **Ore zones are characterized by small-scale variations**



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Highlights: Geophysics

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- **Seismics**
  - **Image enhancement**
  - **Physical property derivatives**
  - **Q factor** (anelastic attenuation) to define alteration
- **Magnetics**
  - **High-frequency anomalies** (e.g., fault geometry, alteration)
  - **Derived signals from borehole navigation logs**
  - **3D inversions**
- **Electromagnetics**
  - **Surface mag sus from AEM**
  - **3D multi-electrode BH resistivity and IP**
  - **Merged res and spectral IP**
- **Inversions**
  - **Constrained and joint inversions** for overburden stripping
  - **Open source code** for multi-model inversions
  - **Instrumental/model limitations** (e.g., low Mag Sus contrasts)

Highlights: Petrophysics

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- **Physical properties** aided geological correlation and alteration mapping
- **IP responses** of altered, mineralized, and barren lithologies
- **Multiparameter magnetics** to detect syn-mineralization pyrrhotite
- **Inversion of WR geochemical data** to derive physical properties
- **Derived physical properties** from 3D geophysical data

Highlights: Structural Geology

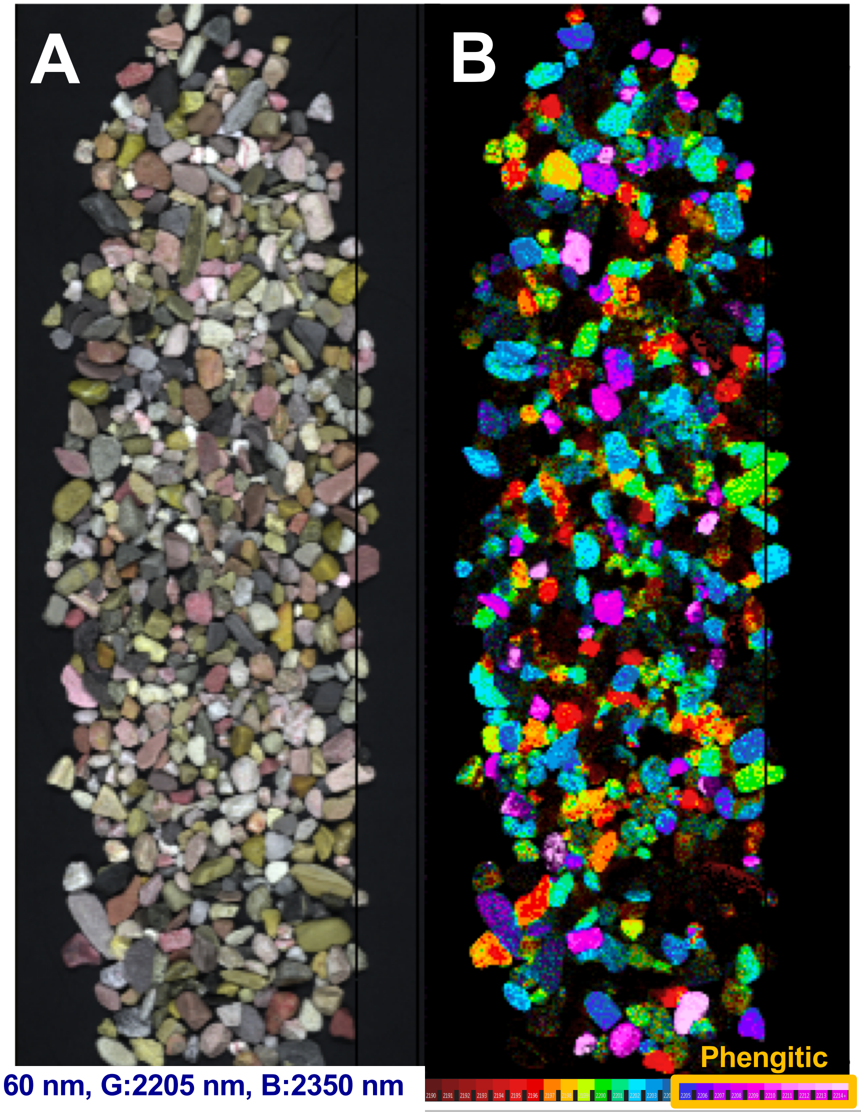
- **Quantitative analysis** of bedding attitudes to identify favourable structural domains
- **Application of variograms** to establish spatial continuity in structural analysis, petrophysics, and geochemistry

Highlights: Geochemistry

- **Whole-Rock Geochemistry**
  - **pXRF analysis** of outcrop and assay pulps
  - **Molar element ratios** eliminate closure issues
  - **Variable leach techniques** for mineral-specific geochemistry
  - **Fluid pathways from fracture mineralogy and geochemistry**
  - **High-sensitivity, low-cost C, O, and Pb isotopic analysis**
- **Mineral Chemistry**
  - **Hyperspectral mapping** of mine faces/samples/cores/surficial materials
  - **Pathfinder models** based on mineral-chemical data
  - **Cluster analysis Rietveld XRD** for alteration mapping
  - **Modernization of field techniques** (e.g., spectral analysis of stained core)

Highlights: Surficial

- **Multi-media** (soil, fractured rock, vegetation, etc.)
- **Glacial stratigraphic controls** on detrital minerals
- **“Clean” silt and sand-sized till samples** used for geochemical analysis
- **Mineral-chemical signatures** of heavy minerals (e.g., W in rutile)
- **Hyperspectral analysis of glacial materials** (e.g., phengitic mica)
- **Supervised classification of radiometrics** in surficial materials



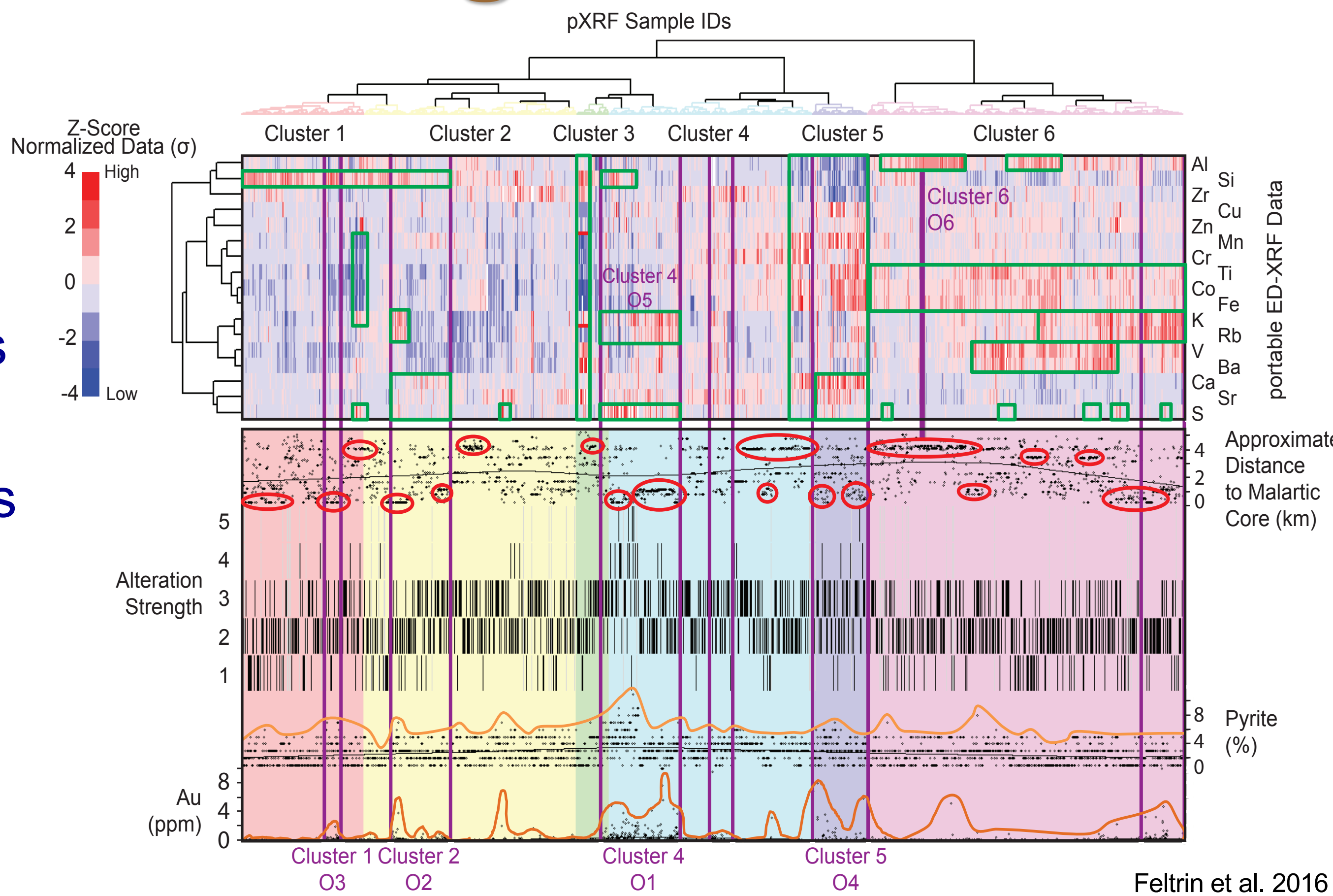
Taylor et al. *in prep*

R:2160 nm, G:2205 nm, B:2350 nm

Highlights: Data Integration

NSERC-CMIC FOOTPRINTS

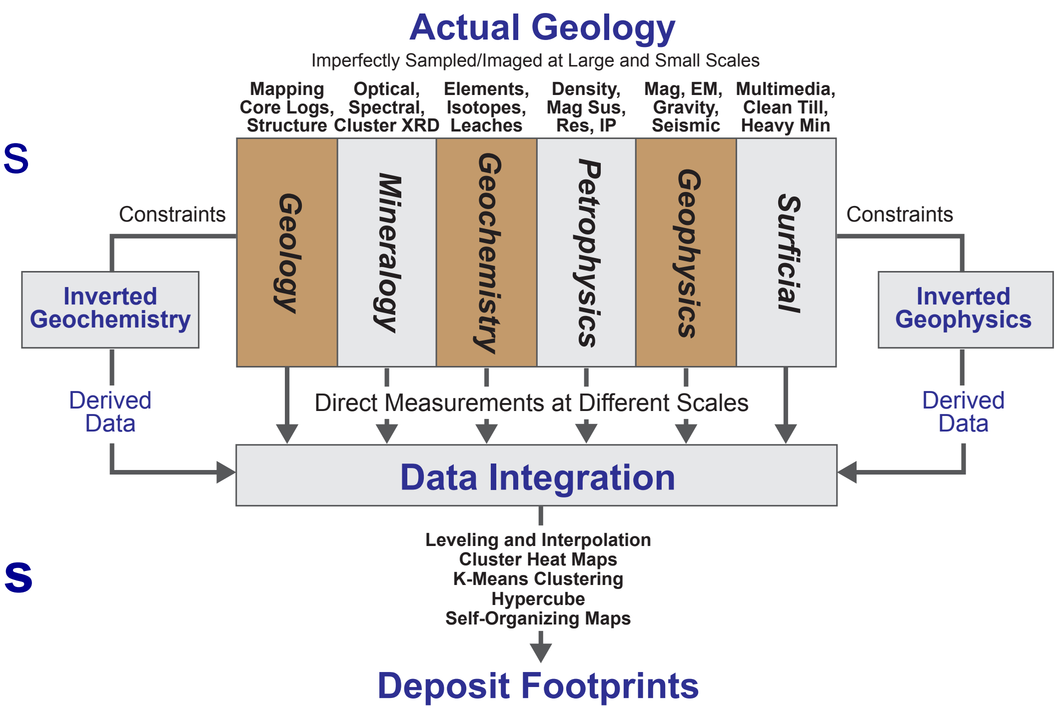
- **QA/QC protocols**
- **Custom workflows for data integration**
- **Machine learning**
  - Clustered heat maps
  - K-means clustering
  - Self-organizing maps
  - Hypercube
- **Geoscience INTEGRATOR**
- **Common Earth Models**



Feltrin et al. 2016 *PDAC;* Lesher et al. 2017 *Expl '17 Vol*

Highlights: Project Management

- **First project of its kind in the minerals industry in Canada** to involve so many researchers and industry partners
- **New policies and workflows** to facilitate collaboration across the various technological disciplines (more than Lithoprobe, Metal Earth, or most AMIRA projects) and across the different research sites
- **May well be among the longest-lasting of the innovations resulting from the project**



Project Closure and Data Release

- **Preliminary Final Scientific Report** submitted to Sponsors in **Sept 2018**
- **"Glossy" Final Scientific Report** and **Final NSERC Report** will be submitted in **March 2019**
- **Project-generated data will be stored at the Mining Observatory Data Control Centre** (MODCC) **at the Sudbury Neutrino Observatory and will be available to the public in March 2019 – links will be provided on** *http://merc.laurentian.ca/footprints (alias cmic-footprints.ca)*
- **All project-generated data, metadata, and products will be provided in a Geoscience INTEGRATOR database, which can display data using the free Geoscience ANALYST 3D data visualizer and which can easily export data into other databases**

Sponsors/Collaborators

NSERC-CMIC FOOTPRINTS

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

Supporters: Fullagar Geophysics
Rekasa Rocks
UBC Geophysical Inversion Facility