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Metasomatic iron and alkali-calcic (MIAC) system frameworks: a TGI-6 task force to help de-risk exploration for IOCG, IOA and affiliated primary critical metal deposits

L. Corriveau, J.-F. Montreuil, O. Blein, E. Potter, M. Ansari, J. Craven, R. Enkin, R. Fortin, B. Harvey, N. Hayward, D. Kellett, M. Ouellet, S. Paradis, D. Regis, A.-A. Sappin, V. Tschirhart, S. Péloquin, R.M. Easton, B. Maity, J. Conliffe, A. Moukhsil, G. Baldwin, K. Neyedley, C. Wade, A. Reid, A. Fabris, S. Hore, K. Robertson, V. Lisitsin, C. Dhnaram, P. Acosta-Góngora, E. Mansur, R. Quentin de Gromard, D. Kesley, F. Korhonen, P. Duuring, T. Ivanic, R. Goad, E. Adlakha, F. Daliran, S. Dare, F. Gervais, X.-W. Huang, M. Kiefer, N. Piette-Lauzière, D. Savard, and X.-F. Zhao

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The first author also acknowledges contributors to this workshop, in particular all those who dedicated long hours before or after work to see this research happens. We hope that through time significant funding will be allotted by all surveys to MIAC research.

Additional acknowledgments can be found at slide 99 concerning current and past contributions to MIAC related activities under the Targeted Geoscience Initiative and Geomapping for Energy and Minerals programs.

Notes

Previously published figures and photos included in this workshop presentation are veiled by a figure caption referring to their source publication. This editorial choice is prompted to avoid potential copyright issues and to link provided information to the detailed published description and discussion of the systems. Additional references have been included to further inform on available publications from the Geological Survey of Canada and its collaborators.

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Acronyms and abbreviations in Annex 1

Abstract

Australia's and China's resources (e.g. Olympic Dam Cu-U-Au-Ag and Bayan Obo REE deposits) highlight how discovery and mining of iron oxide copper-gold (IOCG), iron oxide±apatite (IOA) and affiliated primary critical metal deposits in metasomatic iron and alkali-calcic (MIAC) mineral systems can secure a long-term supply of critical metals for Canada and its partners. In Canada, MIAC systems comprise a wide range of undeveloped primary critical metal deposits (e.g. NWT NICO Au-Co-Bi-Cu and Québec HREE-rich Josette deposits). Underexplored settings are parts of metallogenic belts that extend into Australia and the USA. Some settings, such as the Camsell River district explored by the Dene First Nations in the NWT, have infrastructures and 100s of km of historic drill cores. Yet vocabularies for mapping MIAC systems are scanty. Ability to identify metasomatic vectors to ore is fledging. Deposit models based on host rock types, structural controls or metal associations underpin the identification of MIAC-affinities, assessment of systems' full mineral potential and development of robust mineral exploration strategies.

This workshop presentation reviews public geoscience research and tools developed by the Targeted Geoscience Initiative to establish the MIAC frameworks of prospective Canadian settings and global mining districts and help de-risk exploration for IOCG, IOA and affiliated primary critical metal deposits. The knowledge also supports fundamental research, environmental baseline assessment and societal decisions. It fulfills objectives of the Canadian Mineral and Metal Plan and the Critical Mineral Mapping Initiative among others.

The GSC-led MIAC research team comprises members of the academic, private and public sectors from Canada, Australia, Europe, USA, China and Dene First Nations. The team's novel alteration mapping protocols, geological, mineralogical, geochemical and geophysical framework tools, and holistic mineral systems and petrophysics models mitigate and solve some of the exploration and geosciences challenges posed by the intricacies of MIAC systems. The group pioneers the use of discriminant alteration diagrams and barcodes, the assembly of a vocab for mapping and core logging, and the provision of field short courses, atlas, photo collections and system-scale field, geochemical, rock physical properties and geophysical datasets are in progress to synthesize shared signatures of Canadian settings and global MIAC mining districts. Research on a metamorphosed MIAC system and metamorphic phase equilibria modelling of alteration facies will provide a foundation for framework mapping and exploration of high-grade metamorphic terranes where surface and near surface resources are still to be discovered and mined as are those of non-metamorphosed MIAC systems.

Résumé

Les ressources minérales australiennes et chinoises (p. ex. mine à Cu-U-Au-Ag d'Olympic Dam et à ETR de Bayan Obo) illustrent que la découverte et l'exploitation de gisements à oxyde de fer-cuivre-or (IOCG), oxyde de fer±apatite (IOA) et à métaux critiques affiliés au sein de systèmes métasomatiques alcali-calciques et à fer (MIAC) pourraient assurer un approvisionnement à long terme en métaux critiques au Canada et à ses partenaires. Les systèmes MIAC canadiens comprennent un large éventail de gisements de métaux critiques primaires non développés tels que NICO (Au-Co-Bi-Cu) aux T.N.O. et Josette (ETR) au Québec. Les régions d'intérêt font partie de vastes ceintures métallogéniques dont certaines s'étendent jusqu'en Australie et aux États-Unis. Certains secteurs, comme le district de la rivière Camsell exploré par les Premières Nations dénées aux T.N.O., disposent d'infrastructures et de centaines de kilomètres de carottes de forage. Pourtant, le vocabulaire nécessaire pour cartographier les systèmes MIAC est absent des lexiques des commissions géologiques. La capacité des divers intervenants d'identifier les vecteurs d'exploration métasomatiques est souvent embryonnaire. Les modèles de gisement basés sur les types de roches hôtes, les contrôles structuraux ou les associations de métaux limitent l'identification des affinités MIAC des gîtes et systèmes hôtes, et affaiblissent les évaluations de potentiel minéral et les stratégies d'exploration minière.

Cette présentation d'atelier résume les recherches menées, et les outils développés, par le programme de l'Initiative géoscientifique ciblée pour établir des cadres MIAC pour des systèmes métallifères canadiens et districts miniers mondiaux et ainsi aider à réduire les risques à l'exploration des gisements IOCG, IOA et à métaux critiques primaires affiliés. Ces connaissances appuient également la recherche fondamentale, les évaluations environnementales et des prises de décisions sociétales. Elles répondent, entre autres, aux objectifs du Plan des Minéraux et des Métaux du Canada et de l'Initiative de cartographie des minéraux critiques.

L'équipe de recherche MIAC, dirigée par la CGC, comprend des membres des secteurs universitaire, privé et public canadiens, australiens, européens, américains, chinois et des Premières Nations des Dénés. Ses protocoles de cartographie d'altération, et nouveaux outils et bases de données géologiques, minéralogiques, géochimiques et géophysiques, et modèles gîtologique et pétrophysique atténuent et résolvent certains des défis d'exploration et de compréhension posés par la complexité des systèmes MIAC. Le groupe pilote l'utilisation de diagrammes d'altération discriminants et de codes-barres, monte un vocabulaire de cartographie de terrain et de carottes de forage, et prépare la publication de cours intensif, d'atlas, de collections de photos et d'ensembles de données à l'échelle de systèmes, afin de synthétiser les signatures communes des environnements canadiens et des districts miniers MIAC. La recherche sur un système MIAC métamorphisé et la modélisation de l'équilibre des phases métamorphiques des faciès d'altération fourniront une base plus robuste pour la cartographie et l'exploration des terranes métamorphiques à haute grade (faciès amphibolite supérieur et granulite) où les ressources de surface et proches de la surface sont encore à découvrir et à exploiter, tout comme celles des systèmes MIAC non métamorphisés.

TGI- 6 MIAC systems scientific workshop contributions

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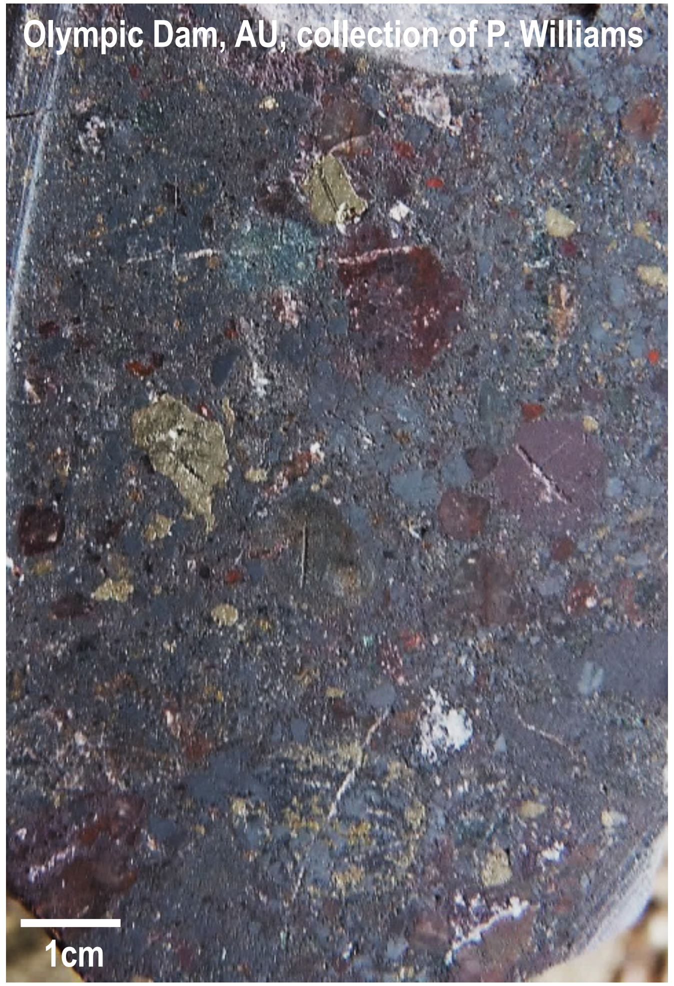
Public geoscience task force to de-risk exploration for IOCG, IOA and affiliated primary critical metal deposits in Canadian metasomatic iron and alkali-calcic (MIAC) mineral systems

Discovering and mining primary critical deposits of MIAC systems is critical for Canada's long term supply in critical metals!
These systems lead to supergiant deposits with critical metals as primary commodities and global mining districts (e.g. Olympic Cu-Au province, AU). Such deposits exist but remain undeveloped in Canada.

Research Question: How can we help de-risk MIAC-related exploration and secure critical metal resources considering that Canada's MIAC systems are underexplored and MIAC affinity of prospects commonly unrecognized?

Goal: This provincial, territorial, federal and international survey, First Nations, private sector and academic collaboration will provide MIAC frameworks for selected Canadian systems anchored on some global mining districts.



TGI – GEM data + new research on available data →

- **Publication of datasets + footprints as support for a future synthesis**
- **Establish MIAC framework for selected Canadian settings**
- **Synthesize results**

← **Canadian and international data, knowledge, collaborations**

Acronyms and abbreviations in Annex 1

Foundation of wealth: well funded public geoscience research on IOCG and critical metal deposits has helped secure extensive metal resources and reserves in Australia (see Huston et al. 2012)

Olympic Copper-Gold Province MIAC resources (examples)

Olympic Dam (discovered in 1975)
9,730 Mt at 0.62% Cu, 0.20 kg/t U_3O_8, 0.27 g/t Au, 1.0 g/t Ag open pit ore
997 Mt at 1.68% Cu, 0.49 kg/t U_3O_8, 0.64 g/t Au, 4 g/t Ag underground ore (+ ~0.3% LREE, 0.01% HREE)

Prominent Hill (discovered in 2001)
210 Mt at 1.2% Cu, 0.5 g/t Au, 2.8 g/t Ag + 31 Mt at 0.1% Cu, 1.5 g/t Au, 1.1 g/t Ag (+U, + REE)

Carrapateena (discovered in 2005)
970 Mt at 0.5% Cu, 0.2 g/t Au, 3 g/t Ag (+U)

Hillside (discovered in 2009)
337 Mt at 0.6% Cu, 0.14 g/t Au, 15.7% Fe (+Ag, U)

Khamsin (discovered in 2012)
202 Mt at 0.6% Cu, 0.1 g/t Au, 1.7g/t Ag, 86 ppm U

Oak Dam East (discovered in 1976; Oak Dam West IOCG discovered in 2019)
~560 Mt at 41–56% Fe, 0.2% Cu, 690 ppm U; Oak Dam West resources estimate in ~2021, e.g. 425.7 m at 3% Cu, 0.59 g/t Au, 346 ppm U_3O_8

Fremantle Doctor:
104 Mt at 0.7% Cu, 0.5 g/t Au, 3 g/t Ag

First global IOA to IOCG model: Hitzman et al. 1992
MIAC-related deposits discovery largely post 1975;
most other deposit types have been mined for centuries

Mt Isa Province MIAC resources (examples)

Ernest Henry (discovered in 1990)
167 Mt at 1.1% Cu, 0.5 g/t Au (+ Co)

Mt Dore (Cloncurry)
111 Mt at 0.53% Cu, 0.09g/t Au, 0.06% Pb 0.31% Zn

Mt Elliot-Swan (**1880–2013**, Cloncurry)
353.7 Mt at 0.6% Cu, 0.35 g/t Au

Merlin (**2008**, Cloncurry)
6.4 Mt at 1.5% Mo, 26 g/t Re (reserves)

Rocklands (**2006**, Cloncurry)
55.4 Mt at 0.64% Cu, 290 ppm Co, 0.15ppm Au, 5.1% Mag **227 Mt** at 16% Mag

Osborne (Cloncurry)
12 Mt at 1.4% Cu, 0.88g/t Au

Monakoff (Cloncurry)
2.4 Mt at 0.95% Cu, 0.3 g/t Au (112 ppm U_3O_8)

Valhalla (Mt Isa)
34.7 Mt at 830 ppm U_3O_8

Mary Kathleen, Elaine 1, Elaine-Dorothy
9.5 Mt at 1300 ppm U_3O_8
0.83 Mt at 280 ppm U_3O_8, 3200 ppm TREE
26.1Mt at 0.56% Cu, 0.09 g/t Au

Citation of references in Annex 2; see also Skirrow and Davidson 2007; Ehrig et al. 2017; Huston et al. 2012; Reid 2019; Skirrow et al. 2019; King 2020; Porter Geoconsultancy, 2021

Foundation of wealth: Brazil, Chile, Peru, China, India, Vietnam, Iran and Turkey resources

Carajás district, Brazil

Salobo
789 Mt at 0.96% Cu, 0.52 g/t Au, 55g/t Ag (+ 16-26ppm U)
Cristalino
500 Mt at 1.0% Cu, 0.3 g/t Au
Igarapé Bahia/Alemão
219 Mt at 1.4% Cu, 0.86 g/t Au + U, REE
Sossego
245 Mt at 1.1% Cu and 0.28 g/t Au
Alemao
161 Mt at 1.3% Cu, 0.86 g/t Au + U, REE
Gameleira
100 Mt at 0.7% Cu
Pedra Branca
2.4 Mt at 0.94% Cu, 0.27 g/t Au
Alvo 118
170 Mt at 1.0% Cu, 0.3 g/t Au

Citation of references for resource figures in Annex 2

Central and High Andes, Chile and Peru

Candelaria and Ojos des Salado
501Mt at 0.54% Cu, 0.13 g/t Au, 2.06 g/t Ag
Cerro Negro Norte
377 Mt at 32.8% Fe
El Laco
734 Mt at 49.2% Fe
Los Colorados
943 Mt at 34.7% Fe
Mantoverde
400 Mt at 0.52% Cu, 0.11 g/t Au
Marcona
~1940 Mt at 55.4% Fe, 0.12% Cu
Mina Justa
347 Mt at 0.71% Cu, 0.03 g/t Au, 3.83 g/t Ag
Romeral
454 Mt at 28.3% Fe
Santo Domingo and Iris
514 Mt at 0.31% Cu, 0.04 g/t Au, 25.8% Fe
El Espino
123 Mt at 0.66% Cu, 0.24 g/t Au

Asia

Bayan Obo, China (reserves)
57.4 Mt at 6% REE_2O_3 ; **2.2 Mt** at 0.13% Nb_2O_5
1500 Mt at 35% Fe

Dahongshan, China
458.3 Mt at 41% Fe; **1.35 Mt** at 0.78% Cu + (16t Au, 141t Ag, 18,156 t Co, 2.1t Pd+Pt)

Lala, China
163 Mt at 14% Fe, 1.02% Cu, 0.02% Mo, 0.17 g/t Au

Luodang, China
73.5 Mt at 15% Fe, 0.8% Cu, 0.16 g/t Au, 1.87 g/t Ag, 0.02% Co, 0.02% Mo, 0.14% REE

Yinachang, China
20 Mt at 41.9-44.5% Fe
15 Mt at 0.85-0.97% Cu + REE (~1127 ppm)

Washan, MLYRMB, China, ~214 Mt at 50% Fe

Khetri belt, India, 140 Mt at 1.1-1.7% Cu, 0.5 g/t Au

Sin Quyen, Vietnam, ~ 50 Mt at 0.9% Cu, 0.4 g/t Au

Chador-Malu, Bafq district, Iran, 400 Mt at 55% Fe

Divriği, Turkey, 133.8 Mt at 56% Fe, 0.5% Cu

Foundation of wealth: MIAC resources in Africa, Scandinavia, USA, Mexico and Canada

Africa

Phalaborwa, South Africa
~ 1200 Mt at 0.59% Cu

Kitumba, Zambia
38.8 Mt at 2.2% Cu, 222 ppm Co, 0.03 g/t Au, 0.9 g/t Ag, 27 ppm U

Guelb Moghrein, Maurita nia
31.3 Mt at 0.92% Cu, 0.69g/t Au (reserves)

Vergenoed, South Africa
122 Mt fluorine, 42% Fe (+REE)

USA

Blackbird (Idaho Co belt)
16.8 Mt at 1.04 g/t Au, 0.73% Co, 0.14% Cu

Boss (SE Missouri)
40 Mt at 0.83% Cu, 0.035% Co (historic)

Pea Ridge (SE Missouri)
160.6 Mt at ~ 53-55% Fe
0.2Mt at 12% TREE (historic)

Coles Hill (Virginia; indicated resources)
119 Mt at 0.056% U_3O_8

Scandinavia

Kiirunavaara (Kiruna district, Norrbotten)
682 Mt at 47.5% Fe

Malmberget (Kiruna district, Norrbotten)
271 Mt at 41.8% Fe

Kaunisvaara (Norbotten)
164.9 Mt at 32.7% Fe

Grangesberg (Bergslagen district)
115.2 Mt at 40.2% Fe, 0.78% P (indicated)

Hangaslampi (Kuusamo deposit)
0.4 Mt at 0.06% Co, 5.1 g/t Au, ≤260 ppm U

Juomasuo (Kuusamo deposit)
2.3 Mt at 0.13% Co, 4.6g/t Au, ≤260 ppm U

Hannukainen (Pajala district)
187 Mt at 30.0% Fe, 0.18% Cu, 0.11 g/t Au

Kaunisvaara (reserves) (Pajala district)
164.9 Mt at 32.7% Fe

Citation of references for resource figures in Annex 2

Mexico

Peña Colorada
300 Mt at 50-60% Fe

Canada (undeveloped advanced projects)

NICO (NWT, reserves)
33 Mt at 1.02 g/t Au, 0.12% Co, 0.14% Bi, 0.04% Cu

Sue Dianne (NWT)
8.4 Mt at 0.80% Cu, 0.07 g/t Au, 3.2 g/t Ag

Josette (QC)
6.9 Mt at 2.7% REE_2O_3
(= 1.83% LREE, 0.89% HREE)

Fostung (ON)
12.4 Mt at 0.2% WO_3

Michelin (NFL)
42.7 Mt at 0.098% U_3O_8

Upper C, Moran Lake (NFL)
6.92 Mt at 0.034% U_3O_8, 0.078% V_2O_5

Historic mine: Marmoraton (ON)
28 Mt at 42% Fe

MIAC mineral systems as sources of primary critical metal deposits: summary and context

In summary, MIAC systems:

1. Generate a wide range of economic deposit types with base, precious and critical metals as primary commodities
2. Include economic resources in Ag, Au, Bi, Co, Cu, F, Fe, Mo, Nb, Ni, Pb, Pd, Pt, Re, REE (both LREE and HREE), U, V, W and Zn
3. Are enriched in Al, As, Ba, Cd, Rb, Sb, Sc, Se, Sn, Sr, Ta, Te, Th, Y and Zr
4. Encompass resources and potential resources for a total of 24 of the 31 critical metals on the Canadian list and 30 of the 51 critical metals of the combined American, European, Japanese, Australian and Canadian lists (lists in Emsbo et al. 2021; Natural Resources Canada,2021; criticality concepts and Canadian list discrepancy discussed in Simandl et al. 2021)

Context for the team's research

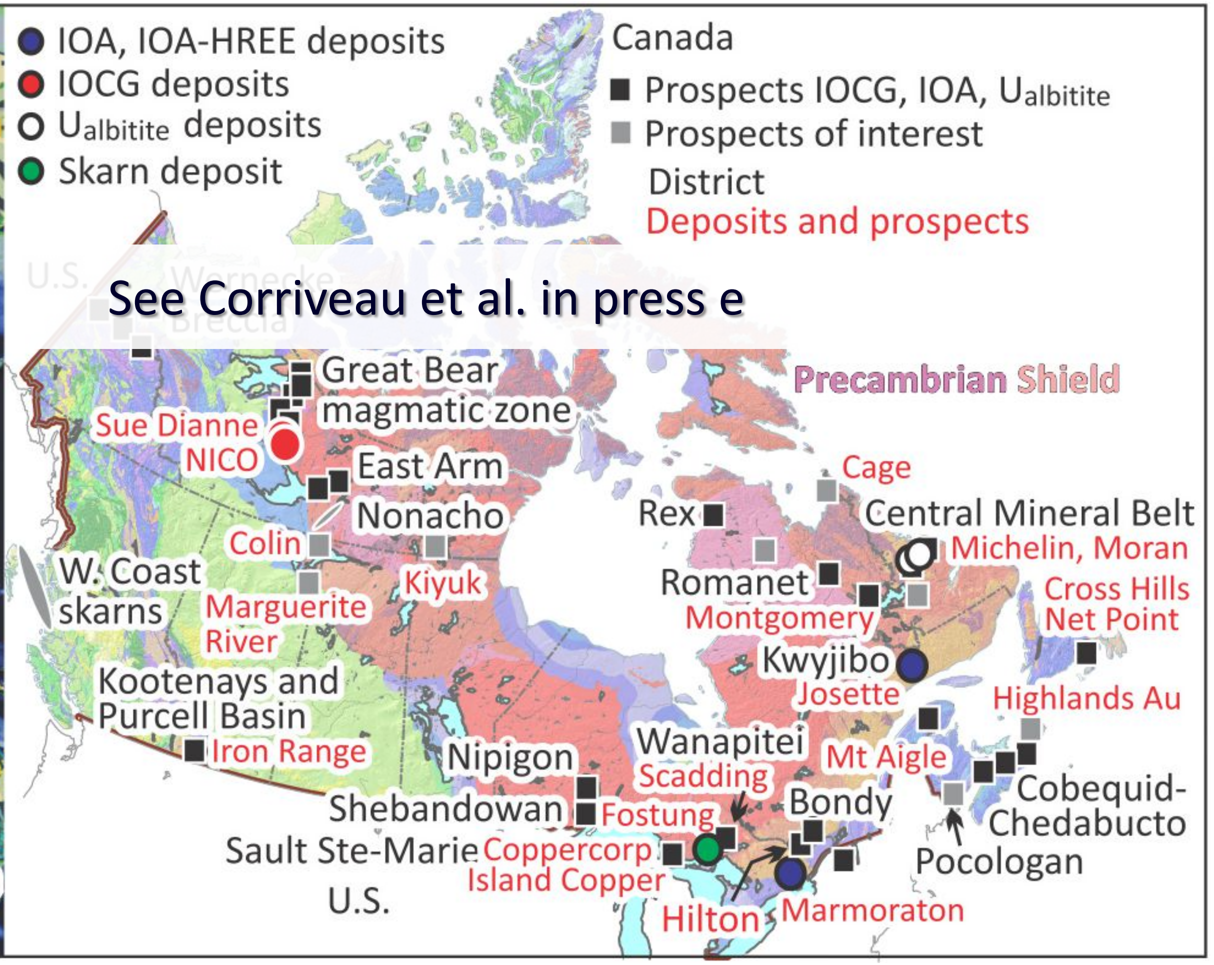
1. Atypical associations of base, precious and critical metals in ores enhance the resilience of MIAC primary critical metal deposits to market changes
2. Identifying, mapping, and exploring MIAC systems are fundamental to securing critical metal resources in Canada and globally
3. Exploration and mining are taking place, in Canada, across federal, provincial, territorial and municipal jurisdictions, built across traditional indigenous lands
4. The Geological Survey of Canada led MIAC team includes members from the Canadian and international academic, private and public sectors and the Denendeh Exploration and Mining Company (DEMCo; DEMCo Ltd, 2015; Canadian Mining Journal, 2016) to optimize current and future MIAC-related resources development in Canada with and among First Nations (cf. Beaulieu, 2018, 2019)

See Porter 2000, 2002, 2010a, b; Lentz 2007; Skirrow and Davidson 2007; Corriveau and Mumin 2010; Slack 2013; Slack et al. 2016; Schutesky et al. 2021; Corriveau et al. in press e

Research goal: refine MIAC framework of prospective settings in Canada

aided by a refined framework of selected mining districts (e.g. Australia)

Including in terranes metamorphosed to high grades (Grenville, Curnamona, western Australia)



Canadian settings are parts of metallogenic belts that extend into Australia and the USA (e.g. Verbaas et al. 2018; Corriveau et al. in press e)

Of the 15 framework tools presented, which one will YOU apply to your local areas of interest?

Framework tool #1: the team itself

Connecting globally to optimize the public geoscience of MIAC systems

Geological Survey of Canada

GSC-North+Central
M. Ansari
J. Craven
R. Enkin
R. Fortin
B. Harvey
M. Ouellet
J.B. Percival
E. Potter
D. Regis
V. Tschirhart

GSC-Québec
F. Aucoin
L. Corriveau
N. Jacob
K. Lauzière
F. Létourneau
A. Morin
J.-L. Pilote
A.-A. Sappin

GSC-Atlantic
D. Kellett

GSC-Pacific
R. Enkin
N. Hayward
S. Paradis

Participants

+ Contributions to the Critical Mineral Mapping Initiative
(GA-USGS-GSC)

Provincial surveys

British-Columbia
F. Katay
G. Simandl

MRNQ
A. Moukhsil

New Brunswick
A. Park

New Foundland-Labrador
J. Conliffe

Nova Scotia
G. Baldwin
K. Neyedley

OGS
M. Easton
B. Maity
S. Péloquin

International surveys

BRGM
O. Blein

GSQ
C. Dhnaram, V. Lisitsin

GSWA
P. Duuring, T. Ivanic
D. Kesley, F. Korhonen
R. Quentin De Gromard

GSSA
A. Fabris, A. Reid
C. Wade

NGU
P. Acosta-Góngora
E. Mansur

USGS
A. Hofstra, D. Kreiner

Research organization

CSIRO
T. Schlegel

Industry

BHP-Olympic Dam
K. Ehrig

Fortune Minerals
R. Goad

DEMCo
D. Beaulieu
C. Bowdidge

Minotaur
A. Belperio

NextSource Materials
C. Scherba

Red Pine Exploration
J.-F. Montreuil

Resources Maxima
M. Belisle
J . Pelletier

Zonte
T. Christopher

Others
N. Lavoie

Academia

Brandon U.
A. H. Mumin

UBC
N. Piette-Lauzière

Chinese Academy of Sciences
H. Chen, X.-W. Huang

China U. of Geosciences
X.-F. Zhao

Karlsruhe U.
F. Daliran

Laval U.
C. Laflamme, G. Beaudoin, E. Santos

Missouri U. of Sci. & Tech.
M. Locmelis

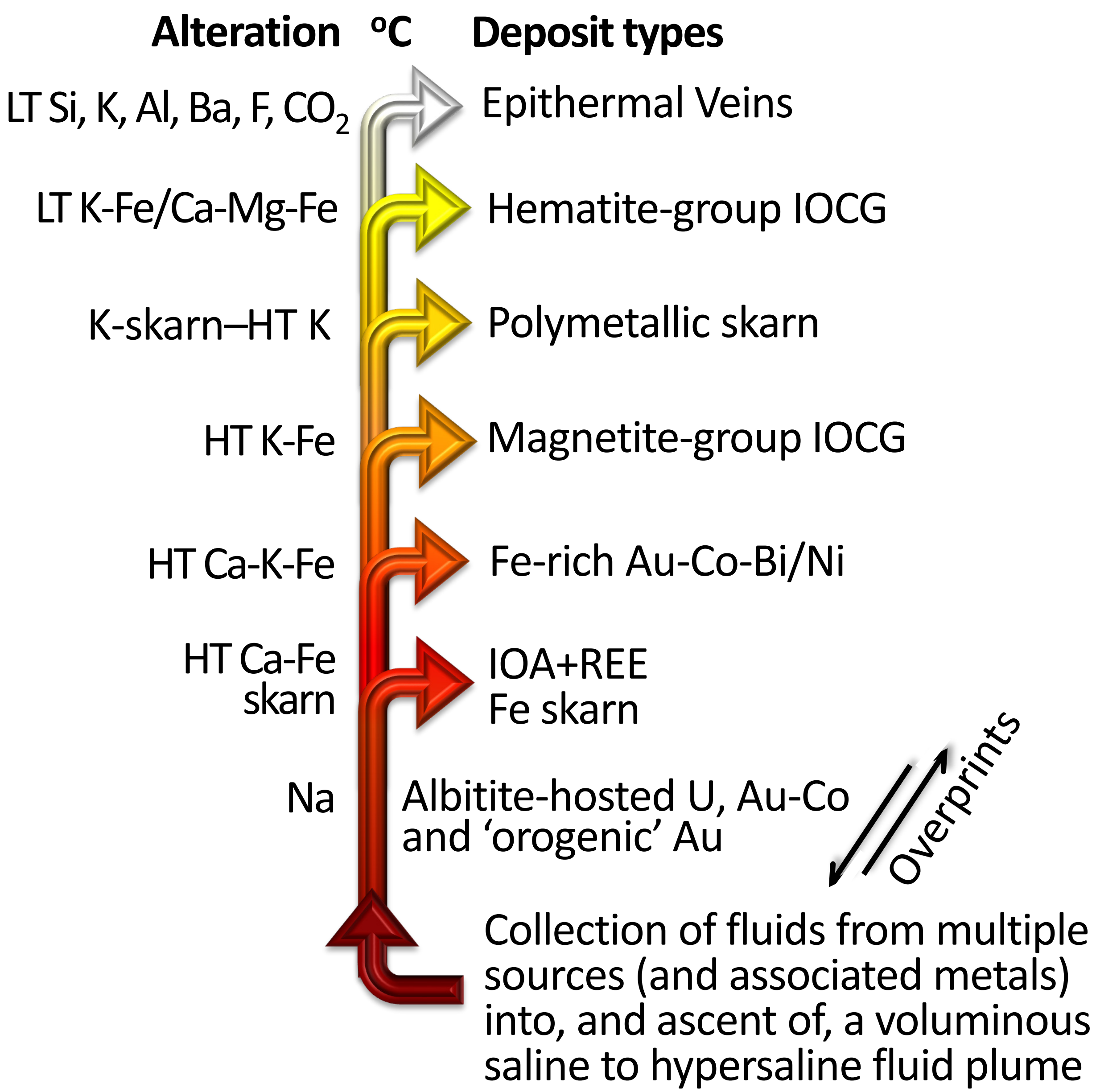
Polytechnique
F. Gervais

Ste Mary's U.
E. Adlakha, K. Landry

UQAC
S. Dare, M. Kiefer, D. Savard

University of Würzburg
A. Kawohl

Framework tool #2: MIAC system ore deposit model as a mineral potential framework tool

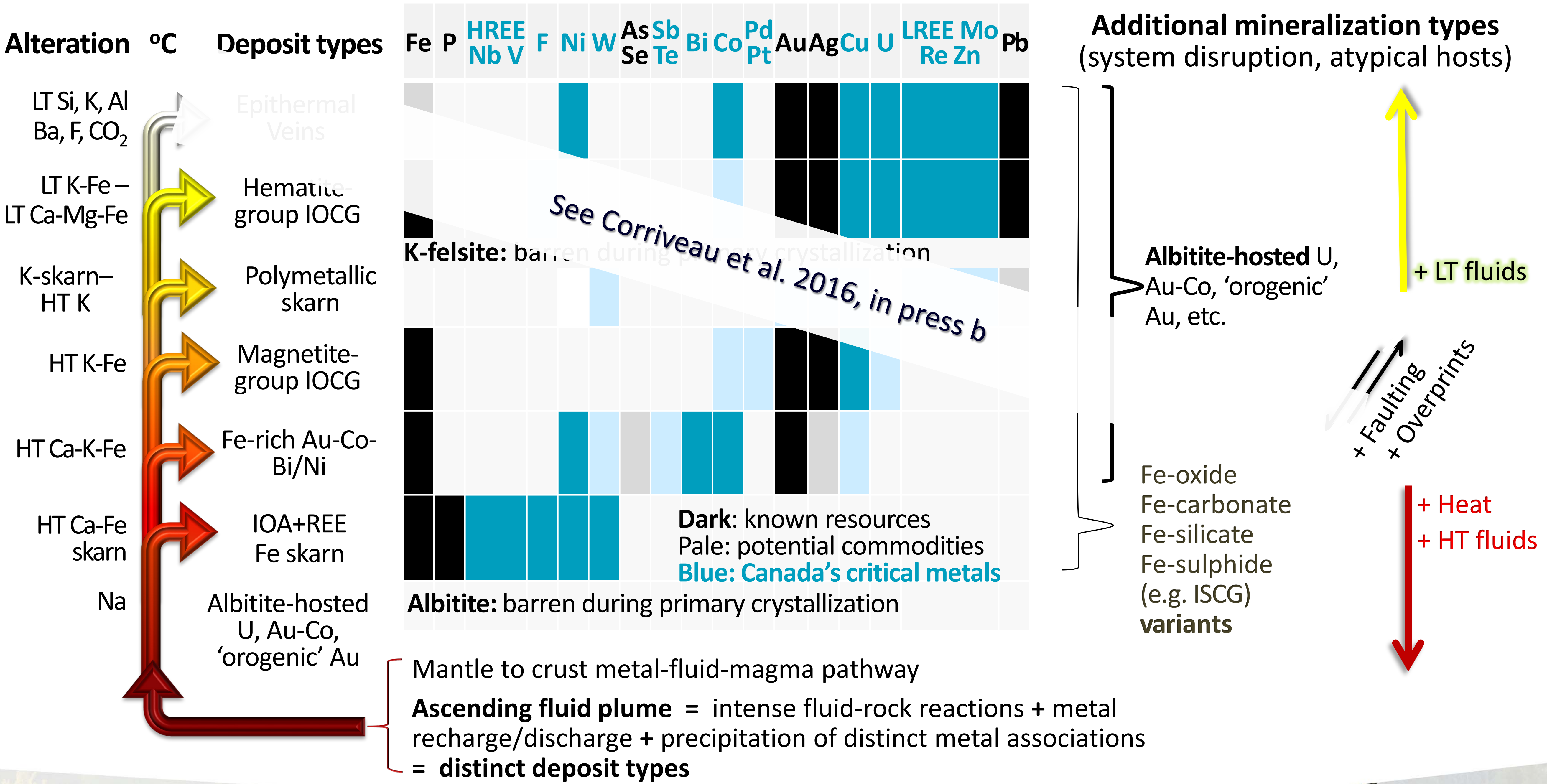


Acknowledging that disruption of systems, and repetition and telescoping of facies are common due to repeated heat and fluid ingress within the main fluid plume, this simple system-scale ore deposit model helps:

1. Frame critical metals resources and metal associations in MIAC systems
2. Unravel distribution of critical metal mineralization in space and time, including due to disruptions and remobilization associated with tectonic and magmatic events
3. Assess potential new sources of critical metals within known systems
4. Provide tools to identify potential fault zones in the field
5. Advance geological criteria for regional to deposit-scale mineral exploration
6. Illustrate the intrinsic metasomatic controls on critical metal precipitation
7. Model systems transformations through high-grade metamorphism, identify them in the field and then map and explore them
8. Develop mineral prospectivity mapping criteria
9. Conduct national scale mineral resource assessment

See Corriveau et al. 2011, 2016, in press a–e; Wilde 2013; Montreuil et al. 2015, 2016a–c; Potter et al. 2019, 2020; Wade 2019; Tornos et al. 2021; Chen and Zhao in press; Zhao et al. in press

Framework tool #2a: MIAC system evolution and genesis of iron oxide-rich to iron-poor deposit types



Framework tool #2b: MIAC system evolution and critical metal resources and associations

Alteration	°C	Deposit types	Examples
LT Si, K, Al, Ba, F, CO_2		Epithermal Veins	Merlin: 6.4 Mt @ 26 g/t Re, 1.5% Mo **Past-producing Norex, Terra, Eldorado, Echo Bay mines[1]**
LT K-Fe/Ca-Mg-Fe		Hematite-group IOCG	Olympic Dam: 10 000 Mt @ 0.6% Cu, 0.2 kg/t U_3O_8, 0.3 g/t Au, 1 g/t Ag (+ ~0.3% LREE, 0.01% HREE) (605 Mt @ 0.02% Co, not publically updated since Williams and Pollard, 2001) Mt Dore: 111 Mt @ 0.5% Cu, 0.09 g/t Au, 0.06% Pb, 0.3% Zn
K-skarn–HT K		Polymetallic skarn	Punt Hill (Cu, Au ± Ag, Zn, Pb) **Miles (Cu, Zn, Pb, Ag, Mo, W ± Mn)[1]**
HT K-Fe		Magnetite-group IOCG	Ernest Henry: 166 Mt @ 1.1% Cu, 0.5 g/t Au; Dahongshan: 2.1 t Pd+Pt Salobo: 789 Mt @ 0.96% Cu, 0.52 g/t Au, 55 g/t Ag **Sue Dianne: 8.4 Mt @ 0.8% Cu, 0.07 g/t Au, 3.2 g/t Ag[1]**
HT Ca-K-Fe		Fe-rich Au-Co-Bi/Ni	**NICO: 33 Mt @ 1g/t Au, 0.1% Co, 0.14% Bi, 0.04% Cu (+W, Sb, Se, Te)[1]** Blackbird: 17 Mt @ 1g/t Au, 0.7% Co, 0.14% Cu
HT Ca-Fe skarn		IOA+REE Fe skarn	**Josette: 6.9 Mt @ 2.7% REE_2O_3 (i.e. 1.83% LREE, 0.89% HREE)[1]** Pea Ridge: 0.2 Mt @ 12% REE_2O_3 (historic, not 43-101 compliant resource) Jaguar: 59 Mt @ 0.95% Ni; Grangesberg: 115 Mt @ 40% Fe, 0.78% P Bayan Obo: 800 Mt @ 6% REE_2O_3 (+Nb) **Fostung: 12.4 Mt @ 0.2% WO_3 [1]**
Na		Albitite-hosted U, Au-Co and 'orogenic' Au	Valhalla: 34.7 Mt @ 830 g/t U_3O_8; Juomasuo: 2.3 Mt @ 0.13% Co, 4.6 g/t Au **Michelin: 42.7 Mt @ 0.098% U_3O_8; Moran: 6.92 Mt @ 0.034% U_3O_8, 0.078% V_2O_5[1]**

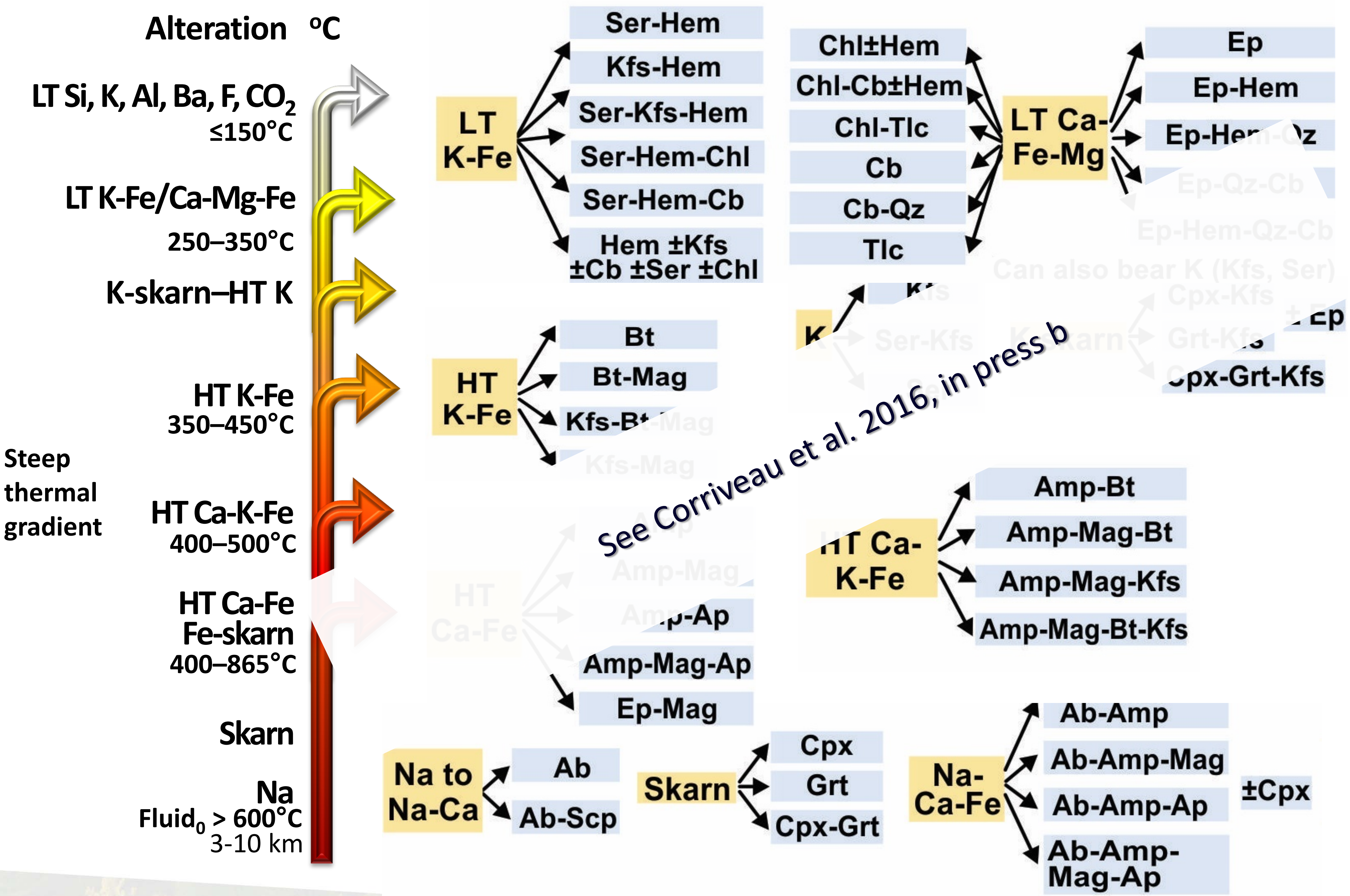
+ Overprints

[1]: Canadian deposits
References in Annex 2

Additional potential critical metals resources (in ppm) based on upper 10% contents in available Olympic Dam (AU) and Great Bear (CA) datasets
(BHP-Olympic Dam, unpublished data; Corriveau et al. 2015; Corriveau et al. in press a)

Al_2O_3	17-35 wt %	**Sc**	14–325	**Ta**	3–30	**V**	500–2k
Sb	100–910	**Sn**	68–256	**Te**	5–26	**Y**	137–710

Framework tool #2c: MIAC system evolution and mineral assemblages in metasomatites



+ Mineral assemblages of phyllic, argillic, advanced argillic, sericitic alteration and sillicification
+ Veins systems and associated breccias

+ dissolution (leaching) of host-rock cations, metals, volatiles, etc. in minerals unstable at each facies and their transfer to the main fluid plume for subsequent precipitation

+ isovolumetric* mineral assemblage precipitation, pseudomorphism of host textures, texture destruction or volume change

* Isovolumetric as in Punis (2021, p. 14)

See Corriveau et al. 2010, 2016, in press a–e; Ehrig et al. 2012; Putnis 2021

Framework tool #2: Summary

The array of MIAC deposit types stems from extreme redistribution, recycling and addition of metals in the upper crust induced by the ascent of voluminous, highly reactive, high-temperature, saline to hypersaline fluid plumes and associated fluid-rock reactions and metasomatic physicochemical transformation of host rocks. During ascent, consecutive alteration facies form, each defined by a specific suite of mineral assemblages and precipitating distinctive metal associations that form distinct deposit types.

Early albitite corridors can later host albitite-hosted U, Au-Co-U deposits. Early skarn can precipitate W. High-temperature Ca-Fe alteration (amphibole to magnetite dominant) can precipitate iron skarn, iron oxide-apatite (IOA), IOA-REE (high HREE to LREE contents) and metasomatic Fe-rich Ni deposits. Iron-rich Au-Co-Bi deposits or Ni mineralization in some Ni deposits are cogenetic with the high-temperature Ca-K-Fe alteration facies (amphibole to magnetite to biotite-dominant assemblages with arsenides, sulpharsenides and iron sulphides). Magnetite- to hematite-group IOCG (or locally iron-sulphide copper-gold) deposits form at the K-Fe alteration facies with mineral assemblages precipitating Cu-sulphides.

A wide variety of other deposit types form at the later stages of the systems through 1) overprints, 2) previously repressed metal and host mineral precipitation due to the physicochemical conditions of the earlier facies, and 3) metal remobilization and reconcentration.

Systems metamorphosed at upper amphibolite and granulite facies preserve metamorphosed IOA and IOCG mineralization among garnet-rich rocks and other metamorphosed MIAC metasomatites commonly mapped as metasedimentary or meta-igneous rocks.

Physicochemical conditions of the evolving fluid plume govern mineral precipitation (hence geological, geochemical and geophysical signatures) and, with the additional control of co-precipitating minerals, govern the mineral chemistry. The main fluid plume can stem from multiple fluid sources. Additionally, elements and isotopes dissolved and captured by the fluid plume through metasomatic coupled dissolution and precipitation processes from sub-surface (<10 km deep) to surface across1000s km^3 continuously changes fluid plume chemistry. Ingress of external fluids (magmatic, basinal, evaporite-derived, etc.) further modifies the main fluid plume as it ascends through the crust. Mantle-to-crust processes are also involved in forming the main fluid plume and disrupting it through tectonic and magmatic activities and ingress of external fluids.

See Special Paper 52 of the Geological Association of Canada in press

Framework tool #3: field-based evidence

Tapping on field-based and core-logging observation and data from the Great Bear and global mining districts

'IOCG in the spot light' Fabris 2019

Canada's remarkable exposure allows for detailed observation and description of (MIAC) mineral systems and results in an alteration model for IOCG deposits that explains many of the variants seen worldwide

Understanding of the breadth of deposits that can be expected in IOCG systems provides **expectation of considerable untapped potential** and underlines a need for a more diverse exploration model and approach

Global systems:

Contributions from BRGM, GSSA, GSQ, GSWA, NGU, USGS, BHP-Olympic Dam, Karlsruhe, Chinese Academy of Sciences, China U. of Geosciences

Canadian systems examples:

Contributions from GSC, OGS, BCGS, MERN-Q, GSNL, NB-GS, NS-GS, NTGS; DEMCo, Red Pine, Fortune Minerals, SOQUEM, NextSource, R. Maxima; St. Mary's, UBC, Brandon, Polytechnique, Laval, UQAC

Available photos:

Field geology, Drill cores, Xenoliths

Slabs, Stained slabs, Thin sections, Microphotographs, SEM, etc.

Field and geochemical datasets:

Update and publish GSC and donated industry datasets

Vocabs:

Create an extensive vocabulary for metasomatic rocks and optimizing it so that terms also applicable to metamorphosed metasomatites have been optimized to ensure coherent vocabularies and field data capture protocols and categories

Field-based caveats to geochemical datasets:

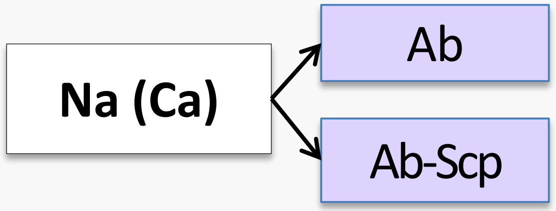
Samples of metasomatites will only be available in corporate datasets if the metasomatites have been identified, mapped, sampled and analyzed. AI on corporate datasets need to take into account the systemic paucity of non mineralized metasomatic rocks analyzed

Framework tool #3a: atlases, short courses, photo collections

Metasomatites are vectors to mineralization! Yet they **remain to be mapped regionally** during most public geoscience mapping program.

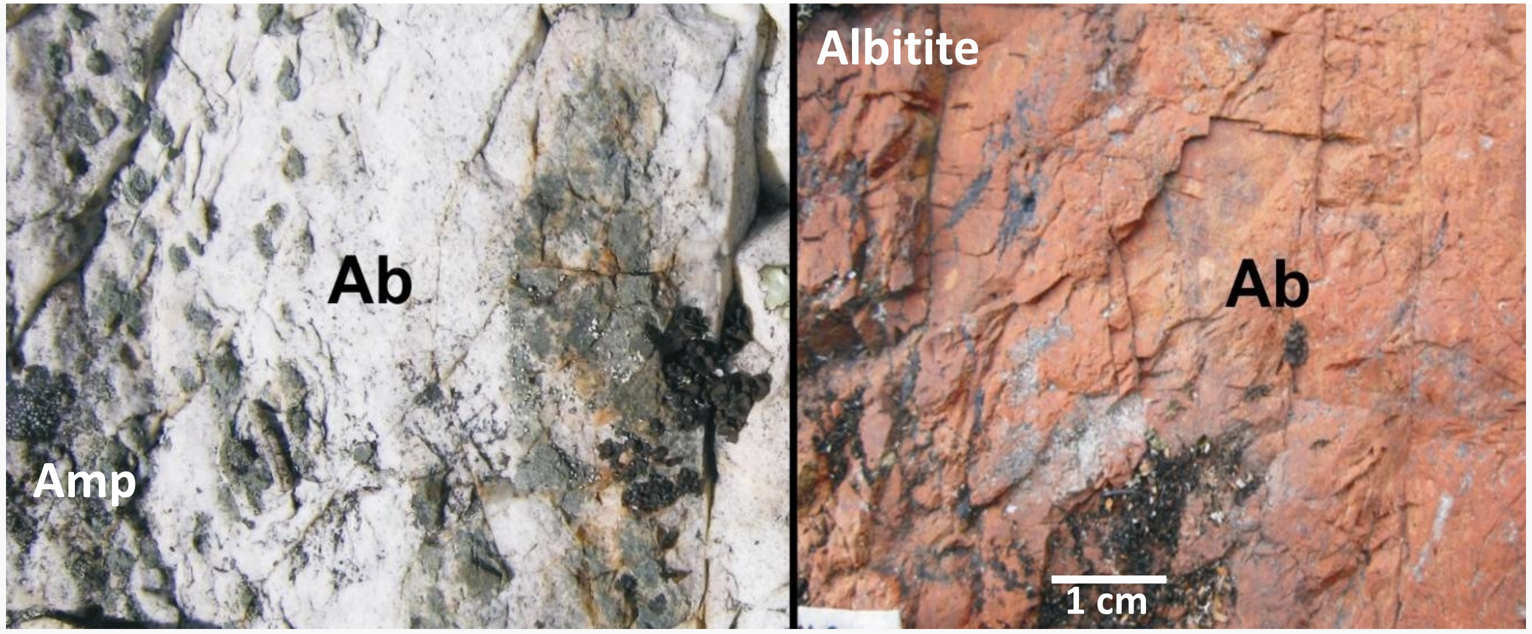
We can only map what we recognize and know about (brain filtering of overwhelming ranges of information on outcrops). Thus **metasomatites need to be…**

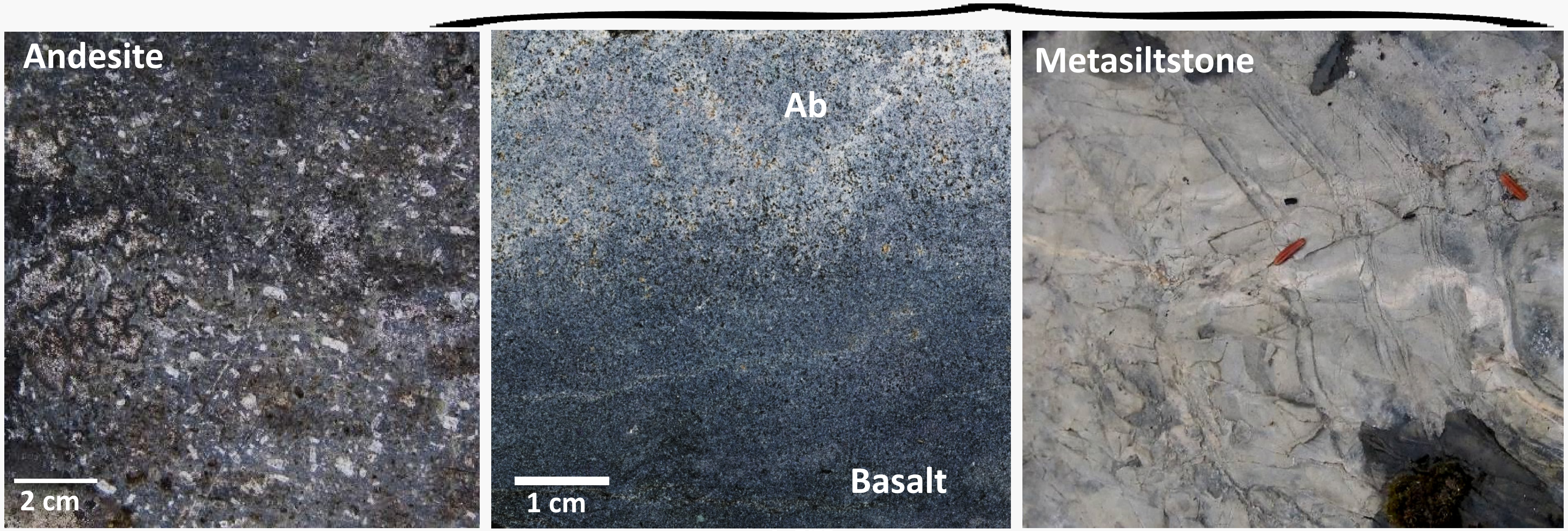
1. Recognized! Atlas in progress.
2. Named! Vocabulary in progress.
3. Visited! Fieldtrip guide book published for an easily accessible system (at granulite facies; Corriveau et al. 2018a).
4. Thought at universities and at short courses and workshops! Short course presentations in progress (Corriveau et al. 2018b).



- Replaces any host rocks
- 8–12 wt% Na_2O
- Km-scale albitite corridor
- Extensive leaching
- Host to later U, Au, Co, etc.

Mineral abbreviations in Annex 1





Framework tool #3b: field-data vocabulary, dictionary, metasomatic rock names

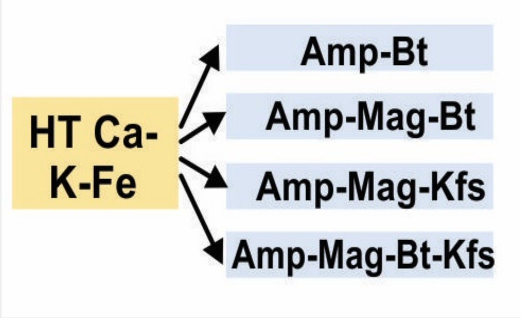
Field data for MIAC systems can only be efficiently recorded if adequate vocabularies (vocabs) for metasomatic / hydrothermal /magmatic-hydrothermal systems are available. Vocabularies are also a key ingredient of machine learning and AI (Ivanic et al. 2021)

1. **Reviews of vocabularies** highlight a need for extensive refinements to existing vocabularies (vocabs) and dictionary to map alteration facies at regional to deposit scale.
   a. GeoSciML – CGI Categories (e.g. Alteration type, Composition, Contact, Simple Lithology)
   b. BRGM, GSSA, Geoscience Australia, GSQ, GSWA

2. **Inclusion of metasomatism in metamorphism vocabs** inhibits:
   a. distinction between metasomatic rocks and orogenic and contact metamorphic rocks
   b. descriptions of metasomatic rocks particularities and relationships to other rock types

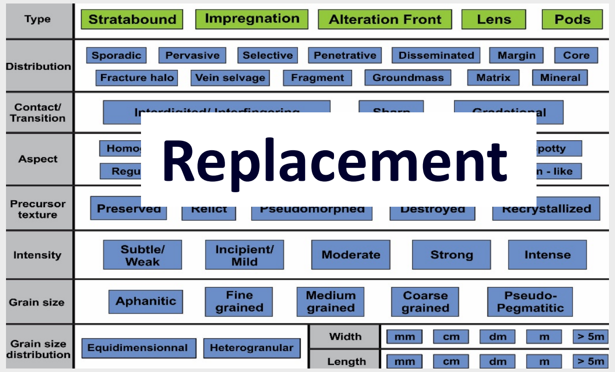
3. Metasomatic rocks are commonly **described as alteration of a protolith** and not as the new rock types they really are. The need their **own set of entries in databases** as those for sedimentary, igneous and contact/orogenic metamorphic rocks

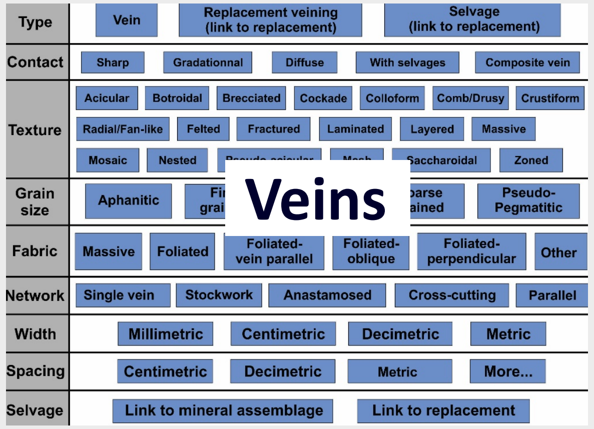
Paragenetic sets of alteration facies

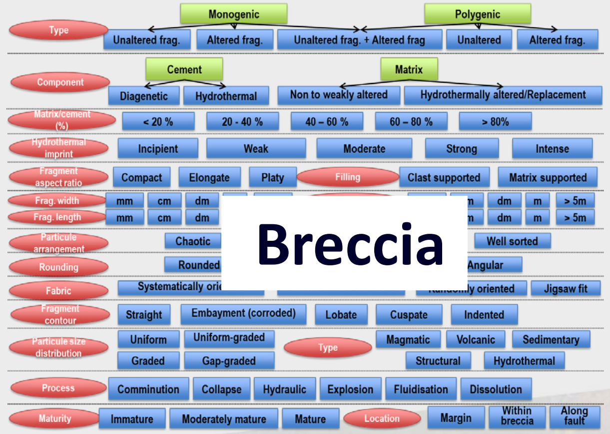


Metasomatites

1. Rock names based on alteration facies (e.g. HT Ca-K-Fe metasomatite
2. Mapped separately from protoliths
3. **Protolith becomes a qualifier**

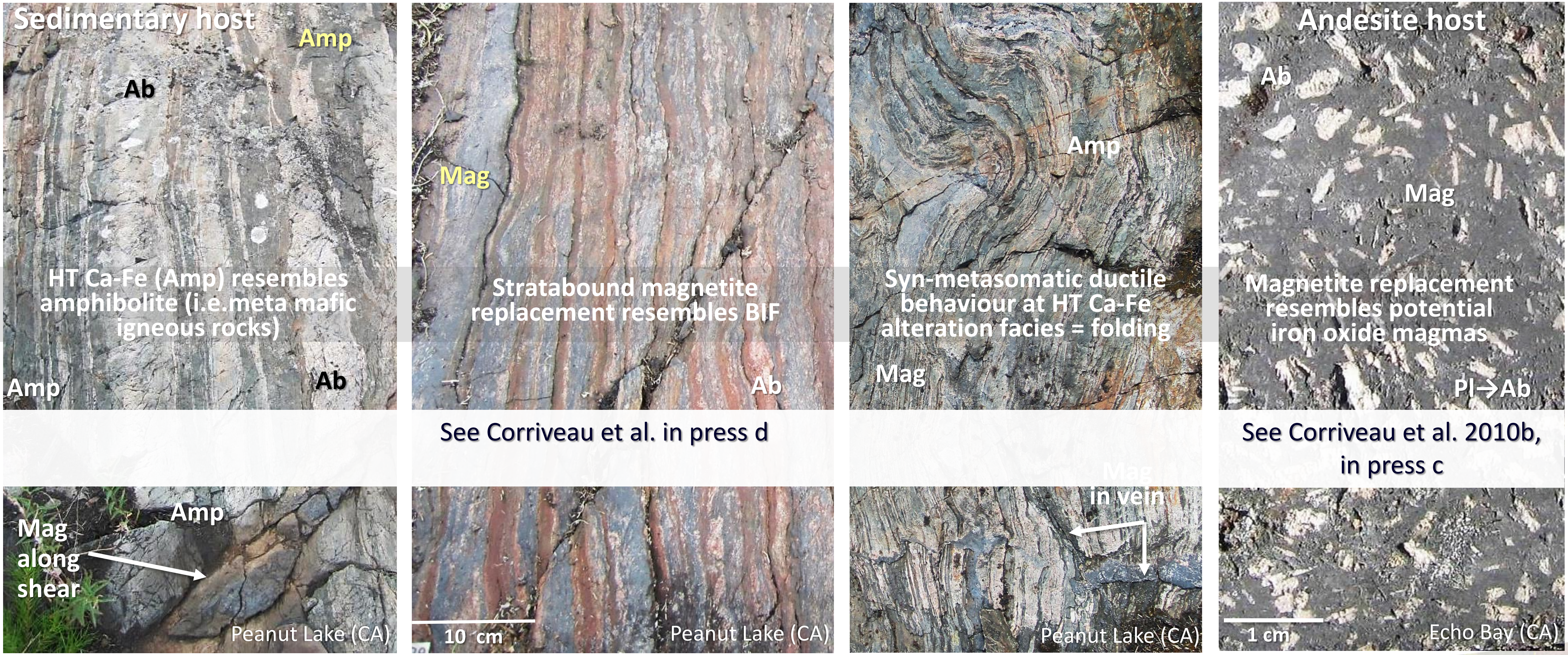






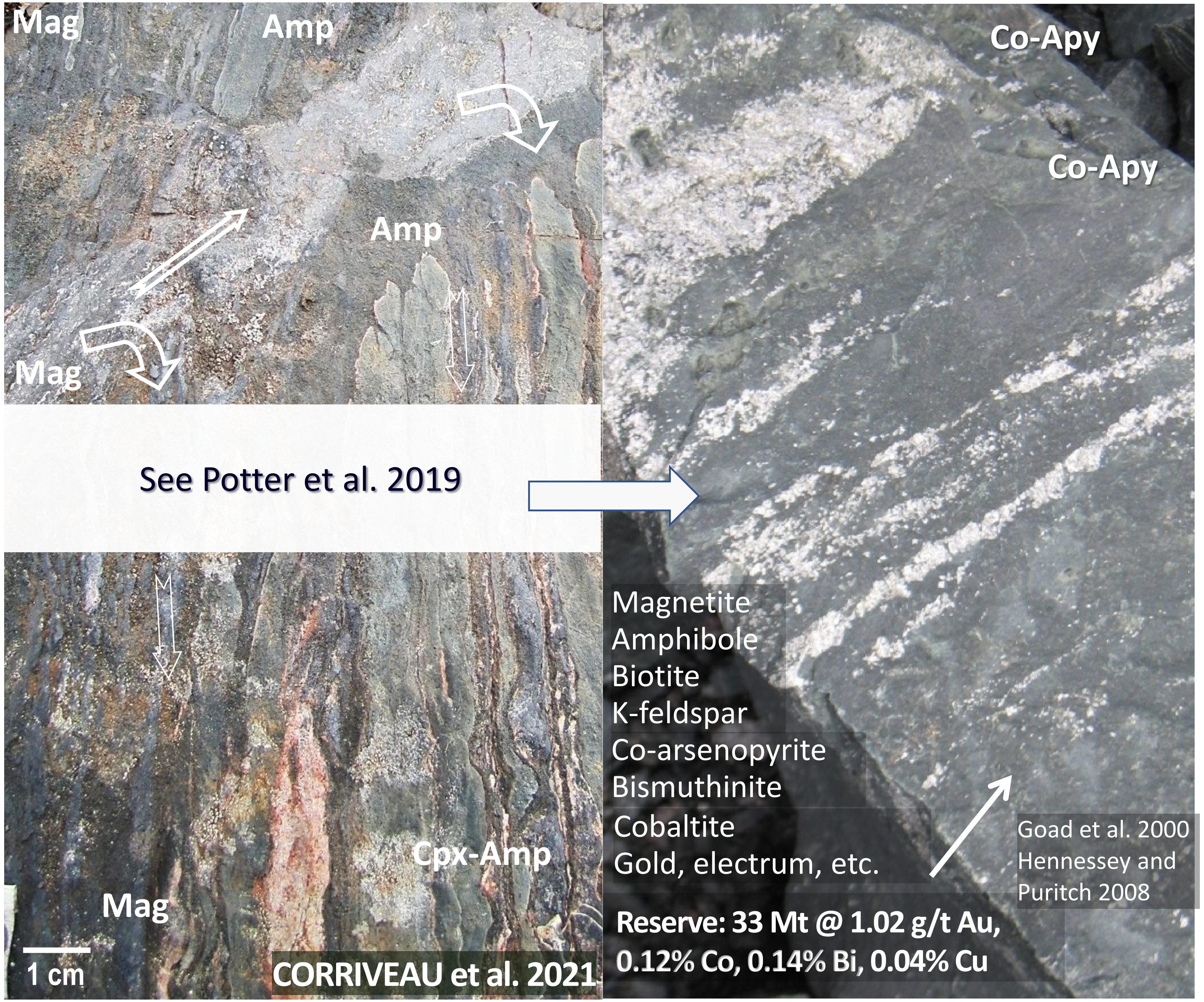
See De Toni 2016;
Corriveau et al. in press c

Framework tool #3c: re-examination of geology descriptions in assessment and government reports/datasets with **local expert knowledge** for appraisal of MIAC affinities of known systems

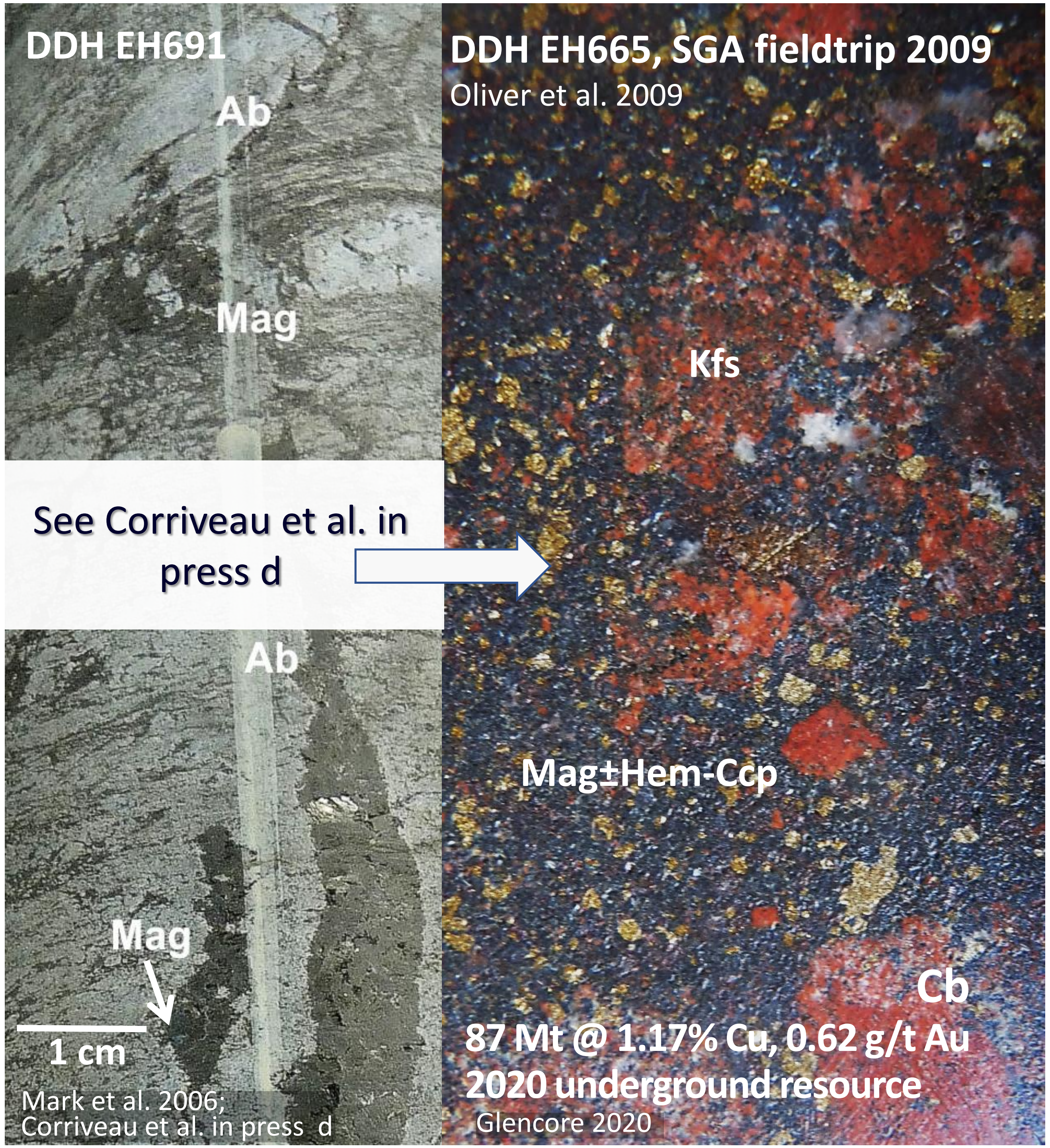


Framework tool #3d: alteration facies as regional vectors to deposits

NICO Au-Co-Bi-Cu at HT Ca-K-Fe



Ernest Henry Cu-Au at HT K-Fe adjacent to albitite



Framework tool #3e: an alteration facies approach to field mapping

MIAC systems develop their deposits through prograde, retrograde, telescoped and cyclical metasomatic paths across diverse host rocks types, leading to alteration zones with highly variable mineral assemblages, contents, textures, and spatial distribution.

Deciphering the evolution of these mineral systems through mapping alteration minerals per se (in addition to veins and breccia) is hampered by the high variability in type of minerals, mineral contents, distribution of minerals and mineral assemblages, textures, structures and other field and microscopic complexities of the systems including the intricate overprints and systematic localized to extensive retrogression of earlier high-temperature assemblages at the microscopic scale.

The great complexity of the metasomatic rocks observed is resolved by applying a metamorphic petrology 'facies' approach to alteration mapping and assessing system evolution at megascopic scale (with additional cobaltinitrite staining of rock slabs or HyLogger mapping). A given alteration facies is defined by the spectrum of mineral assemblages that crystallized under similar physicochemical conditions. Each facies then is characterized by diagnostic bulk compositions. Rather than simply reflecting element enrichment or depletion, each alteration facies is a product of systematic elemental partitioning between fluid and rock, and the stability of the resultant mineral assemblages as the magmatic-hydrothermal systems evolve.

In the Great Bear magmatic zone in northern Canada, well exposed and preserved mineralized systems were mapped from their sub-volcanic roots to their shallowest levels as well as along fault zones. Resemblance of some metasomatites to common sedimentary, volcanic, plutonic or metamorphic rocks were illustrated and metasomatic origin demonstrated by following least to most altered examples. A photographic library of more than 20 000 photos support field interpretations.

A vocabulary, developed to map and log these systems at regional to deposit scale is being refined and will serve to optimize field datasets and databases for their publication. Once completed, the field data-capture vocabulary will be included in the GSC on-site data collection application for geologists of Huot-Vézina and Girard (2021) and shared globally. Such datasets are needed to apply AI and machine learning tools (e.g. Rieuwers and Caté 2019).

See Corriveau et al. 2010, 2016, in press c; Potter et al. 2013; South Australia Geodata Database 2020; Chen and Zhao in press; Daliran et al. in press; Zhao et al. in press

Framework tool #3f: field record of a main fluid plume that evolves through time and space

The study of ore deposit commonly record overprinting relationships within a localized volume of IOAA systems. Identification of distinct mineralization stages within ore deposits is the norm and encompasses the observations of fluids with distinct temperatures and compositions. Examples are numerous where high temperature fluids is observed for early IOA mineralization and overprinting IOCG mineralization is associated with a later fluid that precipitates copper and associated mineralization at diverse lower temperatures ranges. This is observed among other at the Olympic Dam deposit in Australia and at the Candelaria deposit in the Central Andes of Chile (Ehrig et al. 2012, 2017, 2021; del Real et al. 2020).

A common interpretation is that distinct mineralization types in ore deposits form through distinct episodic pulses of fluids from distinct sources rather than fluids having distinct physicochemical conditions (e.g. distinct compositions and temperatures) due to the evolution of a main fluid plume that

1. largely decline in temperatures as time passes and the fluid plume globally ascends toward surface and
2. changes in acidity and other physicochemical conditions including through disruptions of the fluid plume associated fluid ingress during tectonic activities and magma emplacement as well as spatial tectonic disruption of the primary spatial relationships of early facies within system as it forms.

Deposit-scale studies are not at the scales that allow resolving the matter.

Mapping space-time relationships among alteration facies across entire systems (≤15 km wide, ≤ 35 km long, ≤ 10 km deep) and their depth-to-surface and lateral and longitudinal evolution as well as their tectonic and magmatic disruptions allows to determine the consecutive nature of the main alteration facies, their repetition or their telescoping as well as the timing of their varied primary mineralization and the varied remobilization of the primary metal endowments into additional vein or breccia systems.

See Corriveau et al. 2016, in press c; Potter et al. 2013; Montreuil et al. 2016a-c; Chen and Zhao in press

Framework tool #4: geochemistry

Regional MIAC systems generate a regular pattern of consecutive alteration facies through time

Each alteration facies is defined by a specific suite of stable mineral assemblages whose precipitation controls the whole-rock composition of metasomatites

The spatial and temporal relationships amongst the consecutive alteration facies (and their deposit types) reflect the evolution of physicochemical conditions of fluid-rock reactions across the system (e.g. changes in temperature, composition, eH and pH of the fluid plume). Conditions can be influenced by ingress of additional fluids to the main fluid plume and magma emplacement

Mg
K
Fe
Ca
Na

Each alteration facies has its own chemical signature, the range in composition observed for each facies is induced by the variations in mineral contents and type of minerals within the suite of mineral assemblages stable at each facies

Whole-rock cations are proxies for the distinctive minerals of the main alteration facies (because of the regular relationship between mineral composition and bulk chemical composition).

$\frac{Si+Al}{10}$
K
Fe
Ca
Na

Highly visual geochemical tools have been developed based on the key cations to:

1. **document the geochemical footprints of the systems,**
2. **better understand metasomatic and mineralizing processes,**
3. **provide mappable criteria for mineral potential assessments and**
4. **facilitate vectoring to IOCG and affiliated critical metal mineralization**

Framework tool #4a: geochemical barcodes and system evolution applied to deposit studies

Molar proportions from bulk rock geochemical analyses

Barcodes Na Ca Fe K Mg

Metasomatites

1 to 3 dominant cations

Na albitite

Igneous + sedimentary rocks

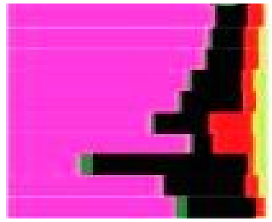
3 to 4 dominant cations

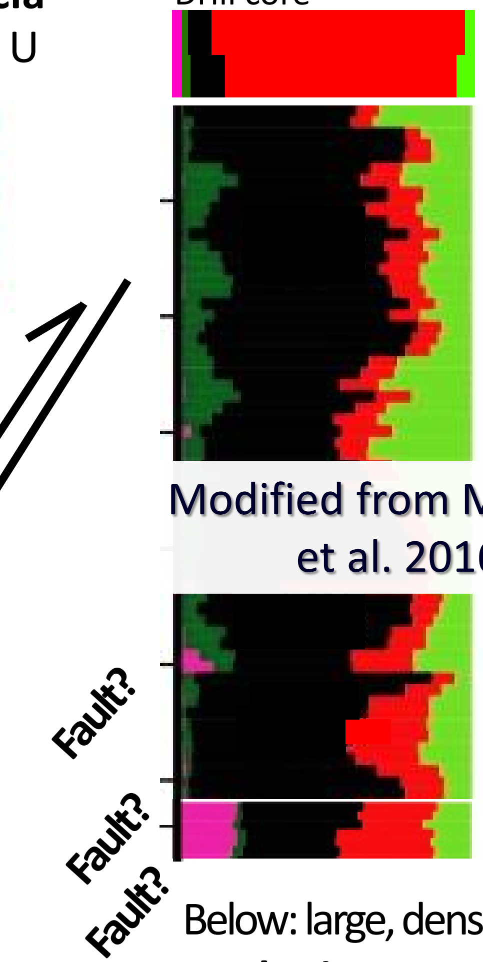
Consecutive alteration facies of MIAC systems

Alteration facies: a record of metal pathways to ore…

Southern Breccia

Albitite-hosted U

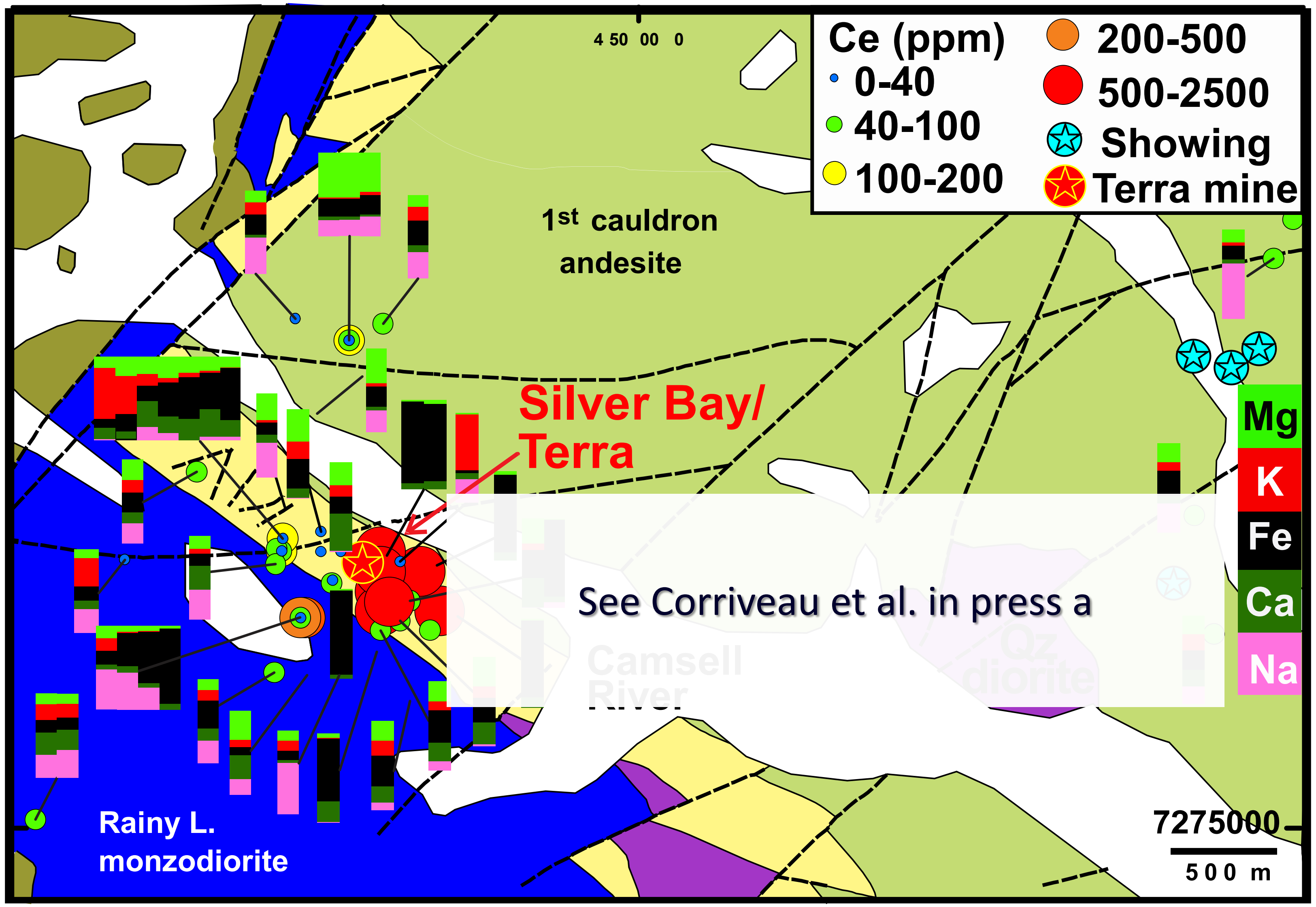




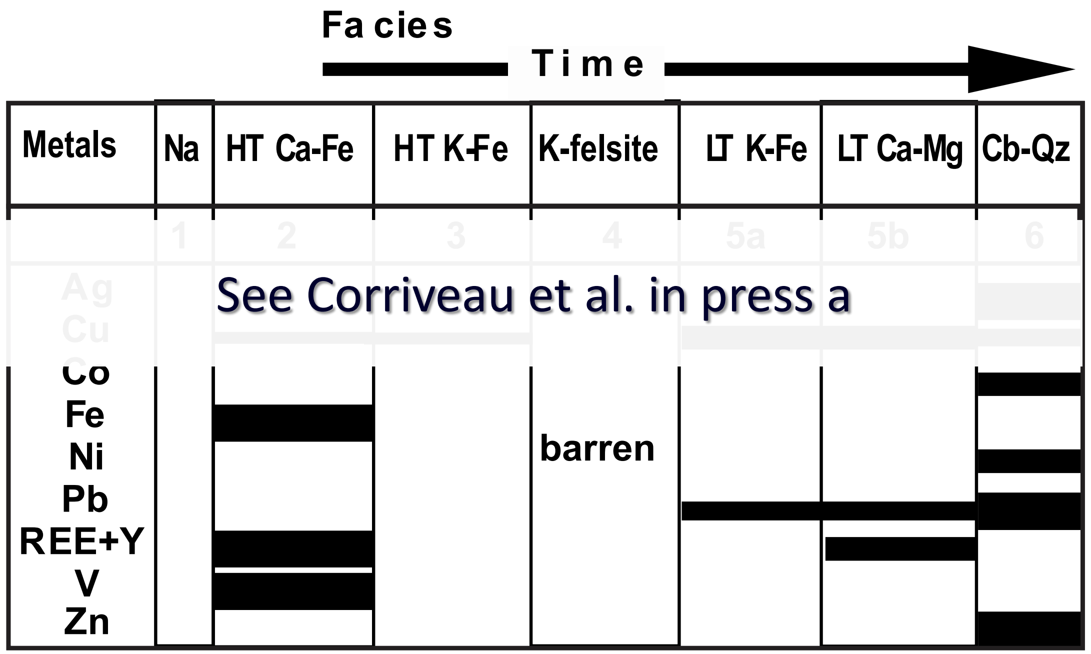
Working hypothesis: faulting has disrupted the system (e.g. HT K-Fe below HT Ca-K-Fe instead of above); this extends mineral potential at depth and laterally

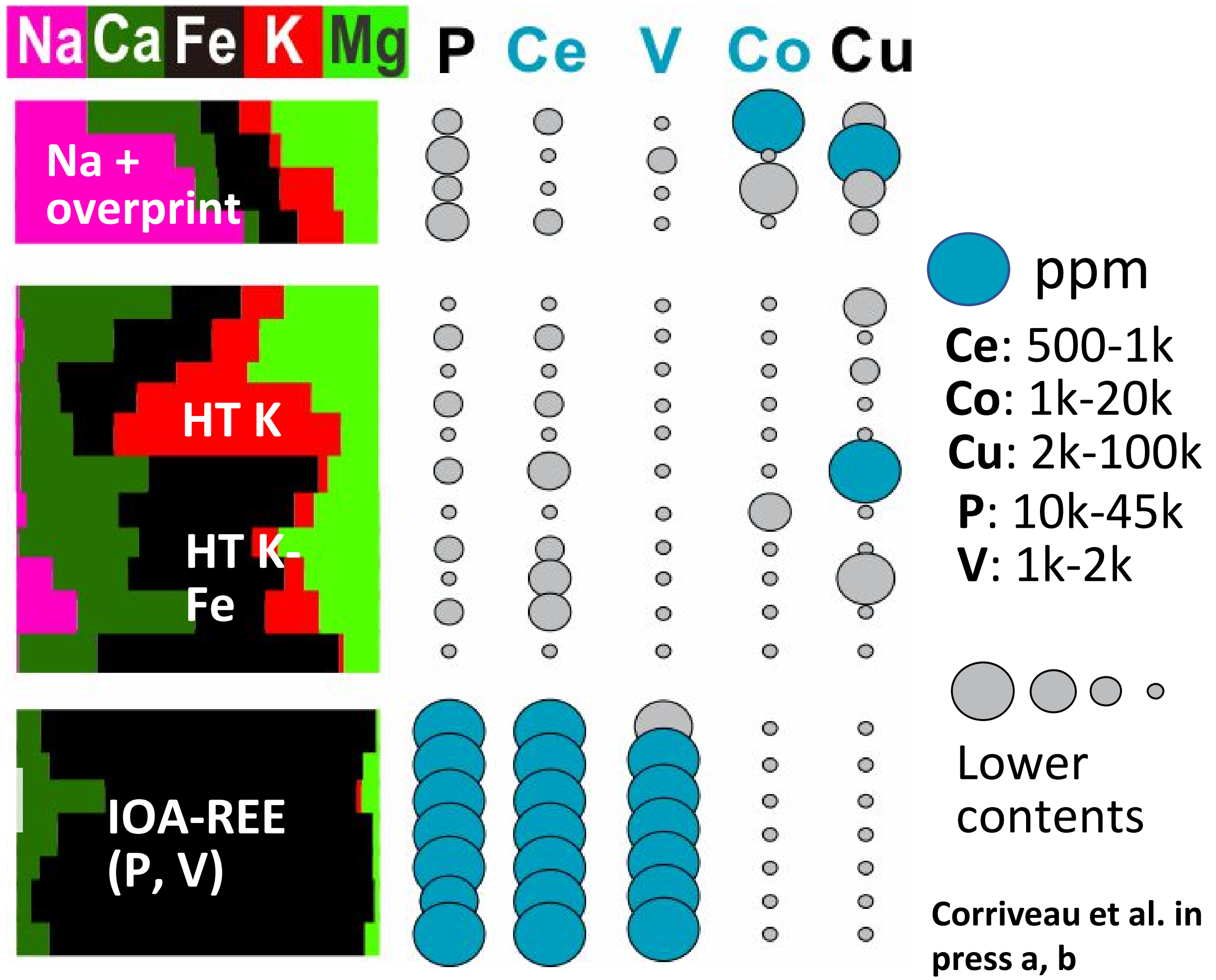
Framework tool #4b: molar barcodes for chemical footprint maps and metal prospectivity at regional scale

Camsell River district (Terra, Norex), GBMZ



See also Bowdidge et al. 2014; Bowdidge and Dunford 2015; Canadian Mining Journal 2016; Beaulieu 2018, 2019

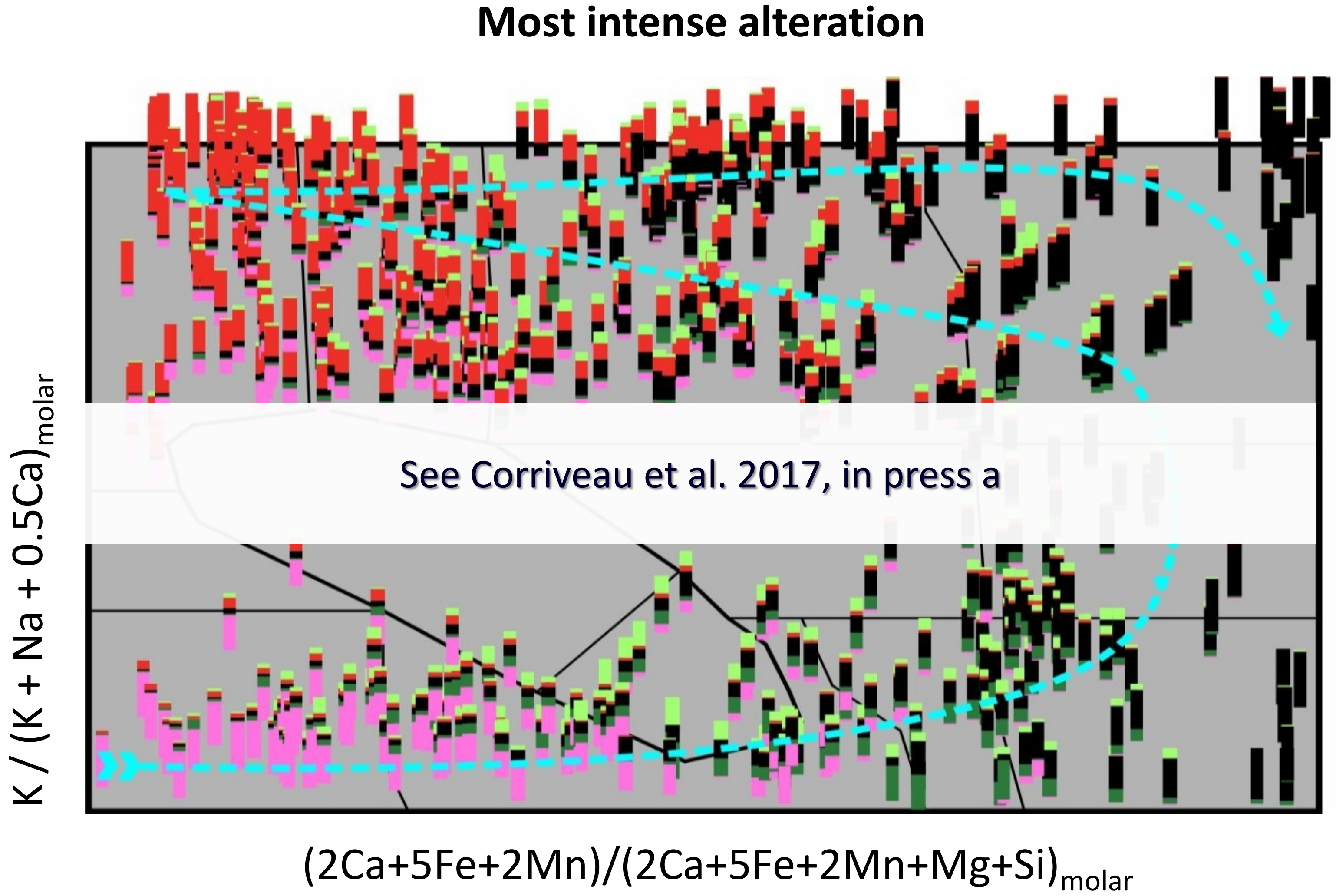




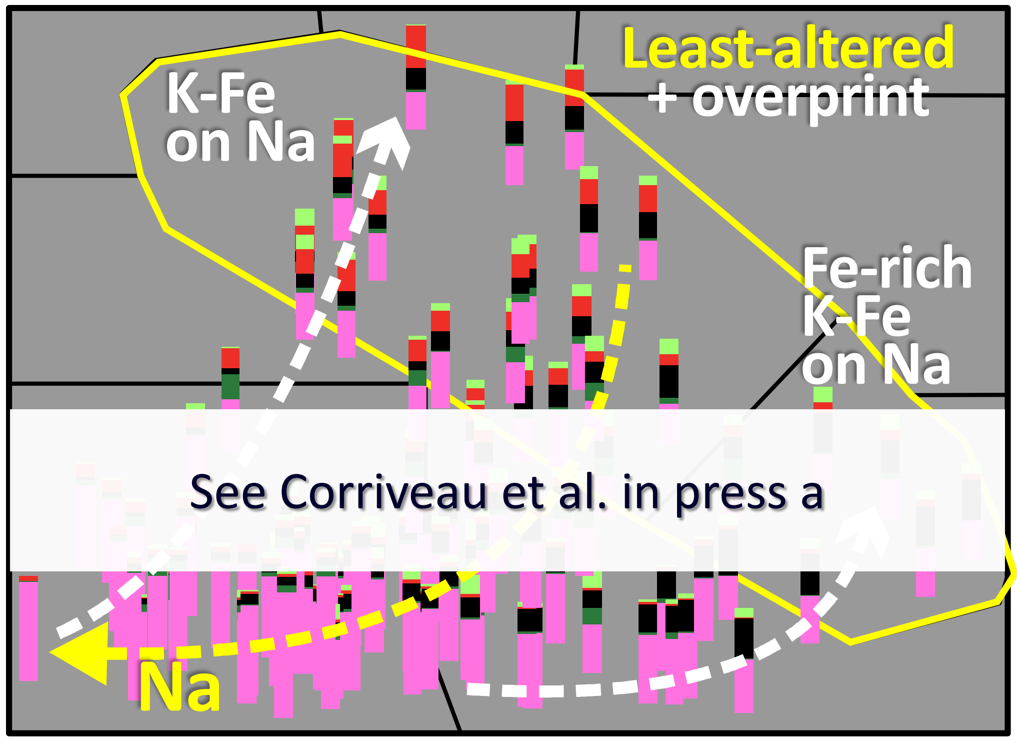
Corriveau et al. in press a, b

Framework tool #4c: alteration indices and AIOCG diagram applied to regional and deposit datasets to document geochemical footprint of alteration facies and mineral systems

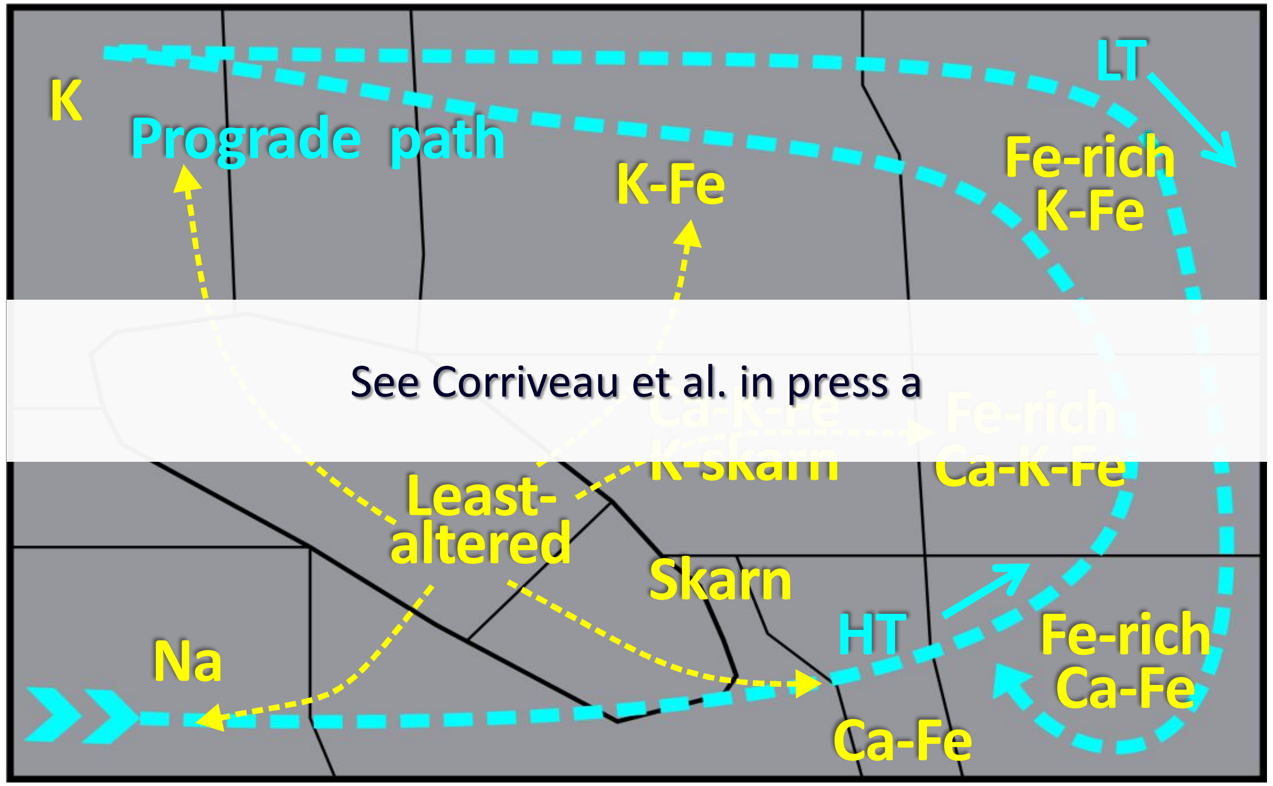
Great Bear MIAC systems footprint



See also Montreuil et al. 2013, 2015; Corriveau et al. 2016, 2018b; Blein et al. in press



Footprint of albitite-hosted U occurrences, Southern Breccia (GBMZ)



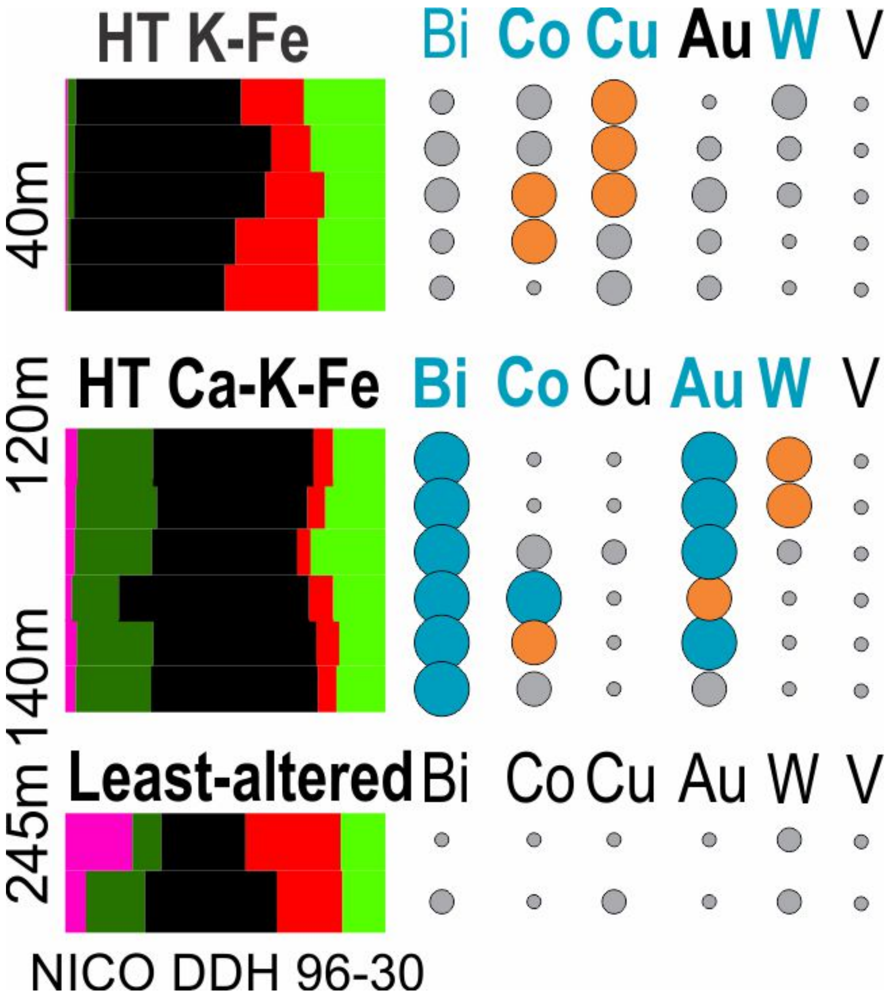
Paths from least altered to most altered samples

Path of most altered samples

CORRIVEAU et al. 2021

Framework tool #4d: metal associations in facies and combination of facies to help prospectivity assessment of systems

NICO Au-Co-Bi-Cu, GBMZ

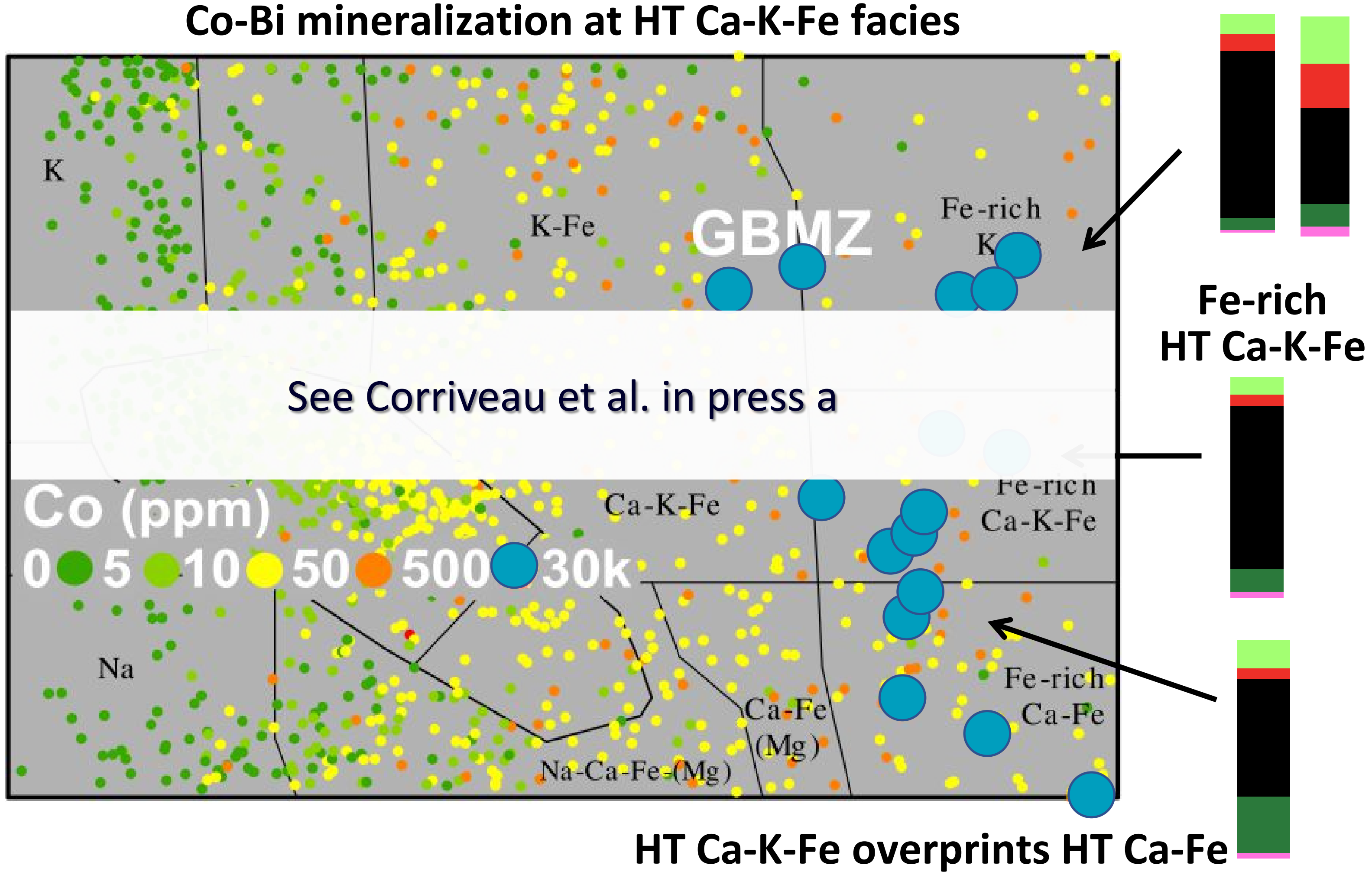


ppm
Au: 5-16
Bi, Co: 1k-20k
Other drill holes have 1-20k Co

ppm
Cu: 500-2k
Co: 500-1k
W: 200-1k

Lower contents

Co-Bi mineralization at HT Ca-K-Fe facies



HT Ca-K-Fe overprinted by HT K-Fe

Fe-rich HT Ca-K-Fe

HT Ca-K-Fe overprints HT Ca-Fe

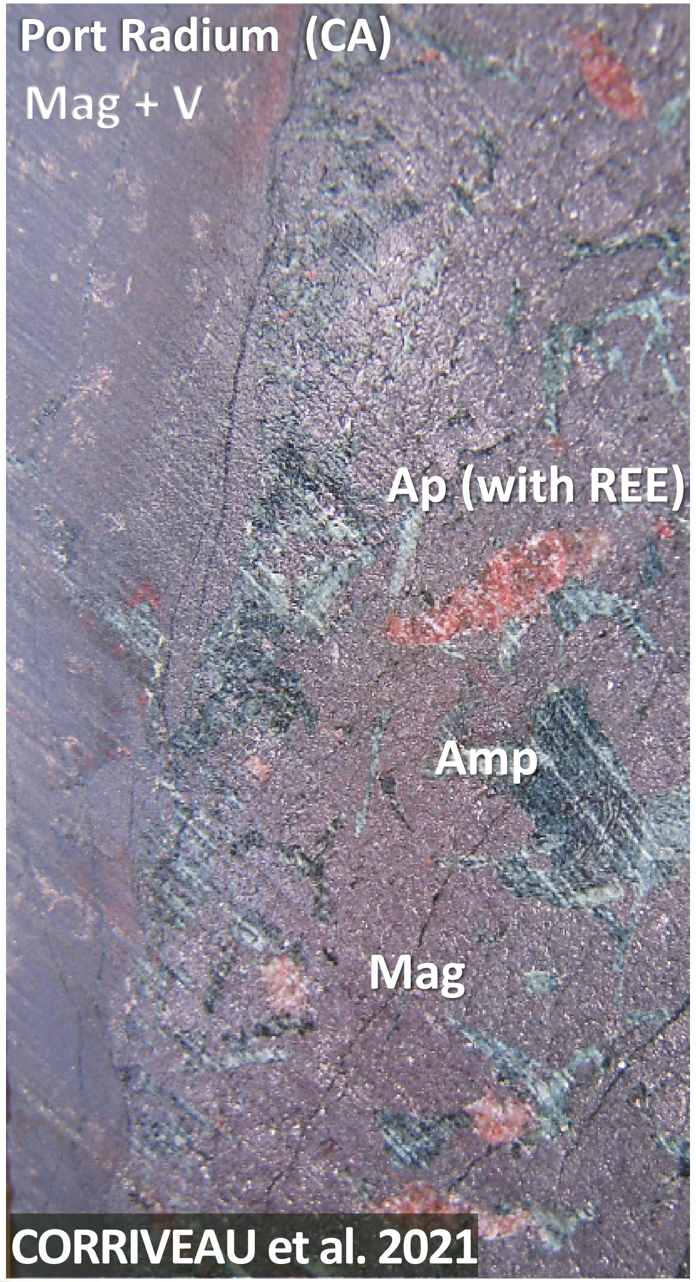
See also Goad et al. 2000; Montreuil et al. 2015, 2016a, b; Blein et al. In press; Corriveau et al. in press a-d; also Fabris, in press for Olympic Cu-Au Province examples

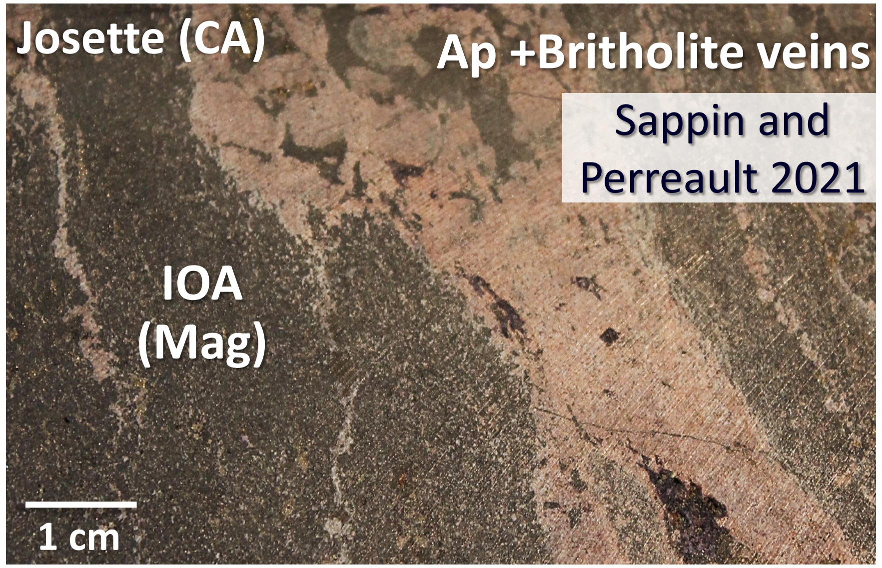
Framework tool #4: summary

1. Na-Ca-Fe-K-Mg molar proportions provide an essential geochemical discriminant for each alteration facies whereas the proportions of (Si + Al)/10 in lieu of Mg best discriminates IOAA systems from those hosting epithermal, porphyry, volcanogenic massive sulphide and sedimentary-exhalative deposits.
2. Reporting molar barcodes of characteristic cations on the AIOCG discriminant diagram of Montreuil et al. (2013) yields a first-order identification of the evolution of systems. They help discriminate least-altered rocks from metasomatites, follow the incremental alteration of a host at a specific alteration facies and assess alteration intensity and probable protoliths, characterize the sequential depth-to-surface development of intense alteration, and identify tectonically telescoped metasomatic paths, potential fault zones, and overprints. Coupled with the distribution of metal contents according to alteration facies in the AIOCG diagram help decipher metal mobility from sources to deposits.
3. Reporting barcodes on maps and along drill cores allows to identify system components and use the MIAC system evolution model to develop exploration strategies at regional to deposit scale.
4. Geochemical footprints of the Great Bear magmatic zone, Romanet Horst, Kwyjibo and Missouri districts, and Central Mineral Belt systems share attributes of systems hosting the Olympic Dam, Acropolis, Punt Hill and varied prospects of the Olympic Copper-Gold Province and Singhbhum Shear Zone.
5. These tools provide novel exploration vectors for IOCG and affiliated deposits, a mean to assess the mineral potential of prospective settings and identify the presence of such mineral systems through the processing of large corporate databases inasmuch as the metasomatites have been identified, sampled and analyzed in the first place.

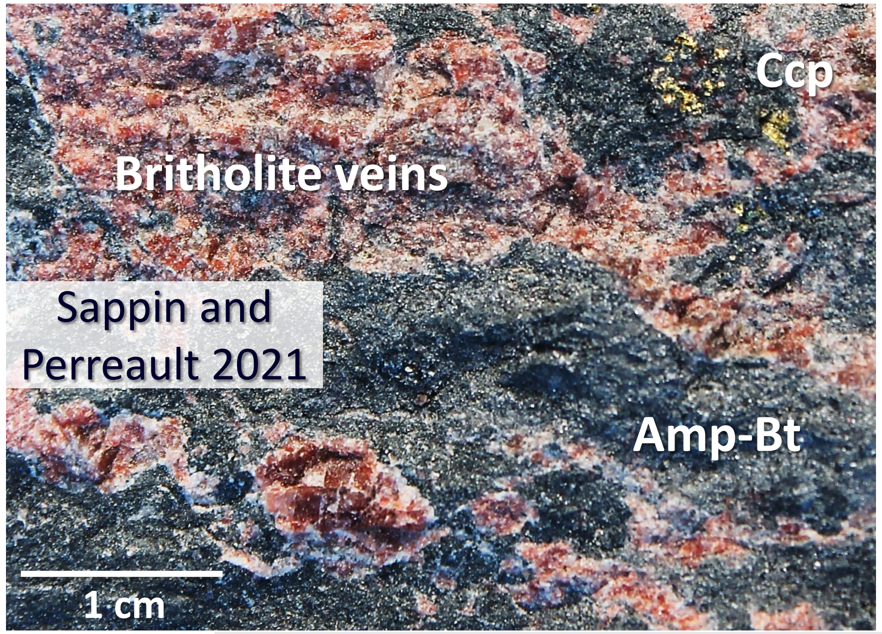
See Montreuil et al. 2013, 2015, 2016a–c; Potter et al. 2019, 2020; Corriveau et al. 2016, in press; Blein et al. in press; Fabris in press

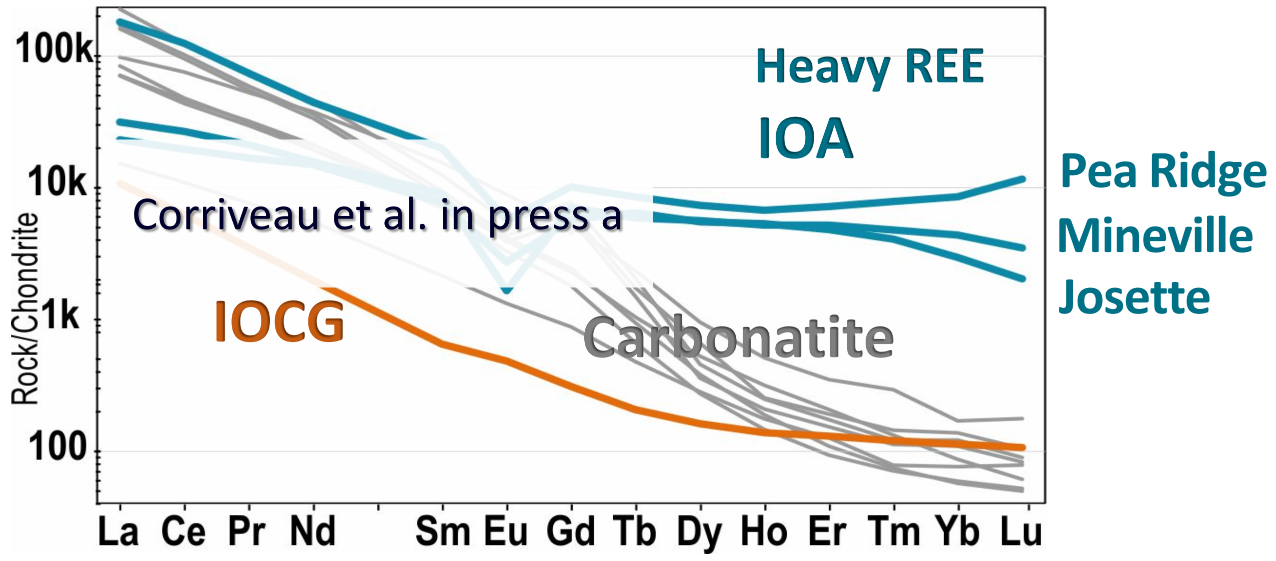
Framework tool #5a: deposit-based evidence supported by regional evolution and field and geochemical footprints (e.g., Josette IOA-REE deposit and GBMZ IOA)

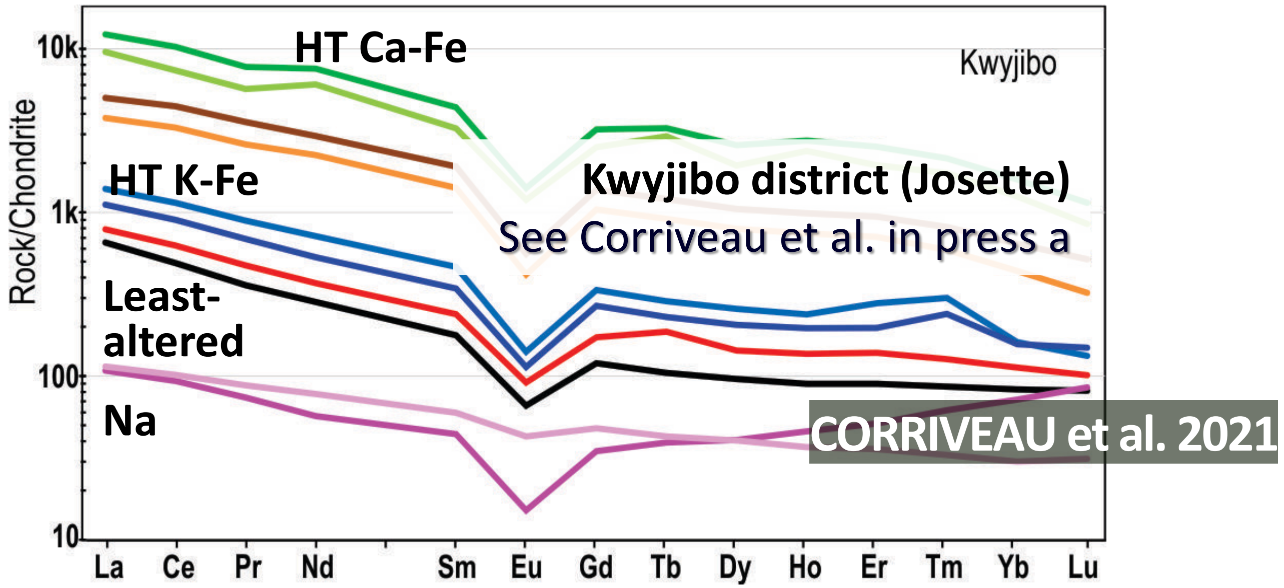




In source REE remobilization = ore





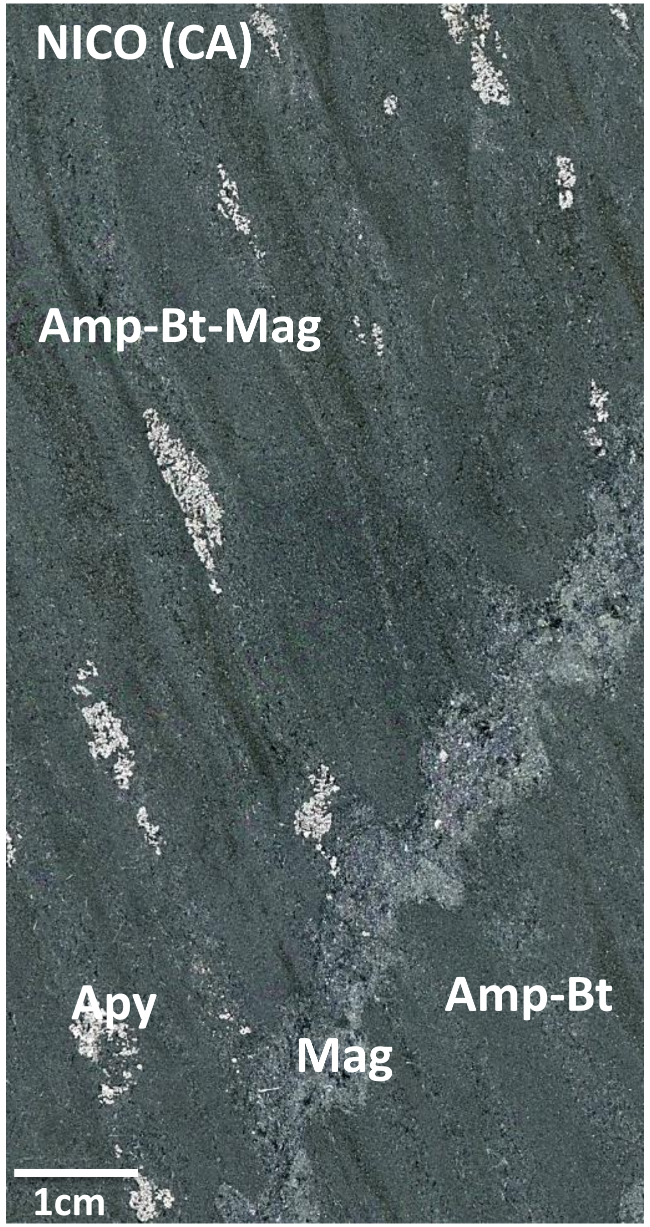


Josette: 6.9 Mt @ 2.72 % REE_2O_3 (= 1.83% LREE, 0.89% HREE)

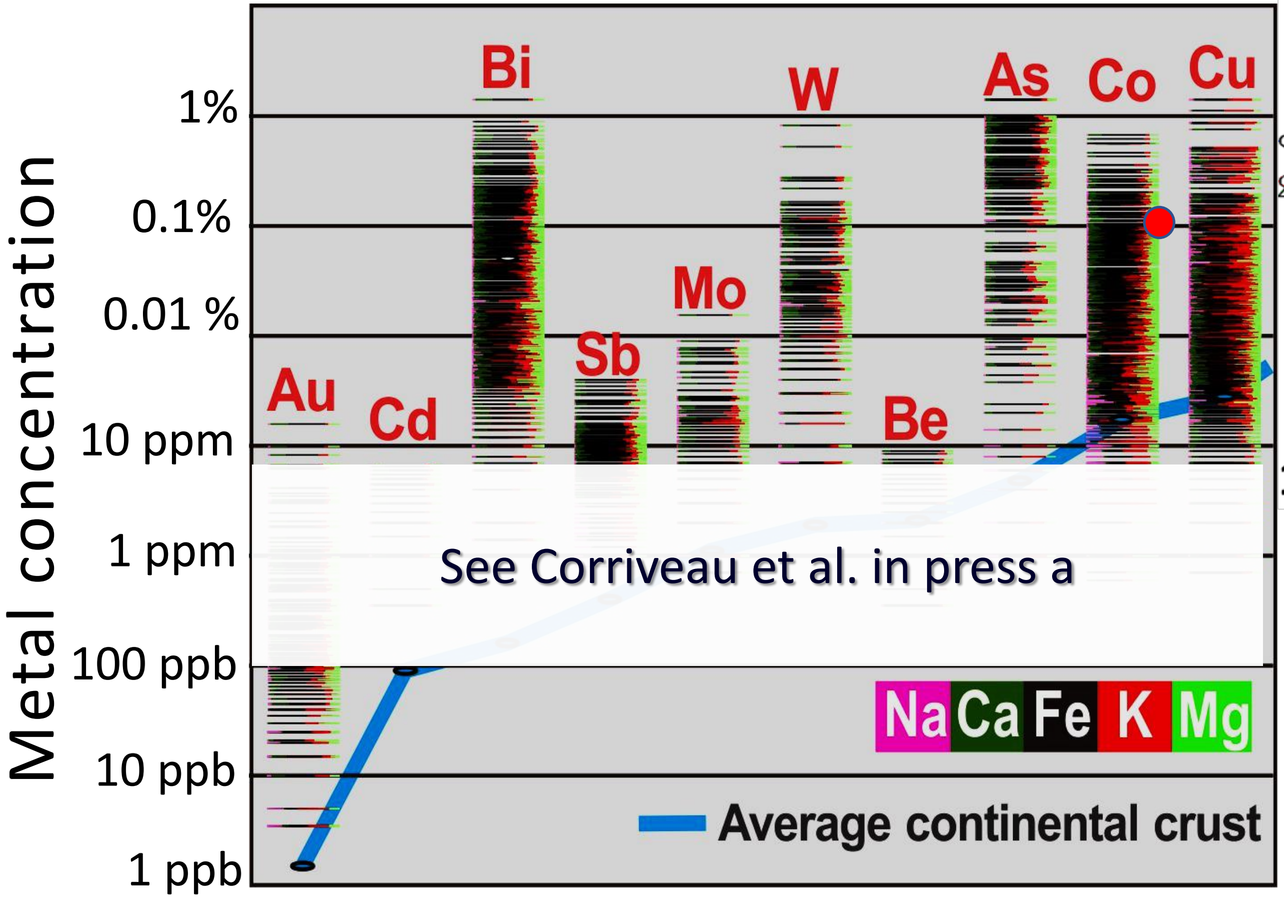
IOA-REE deposits (**Josette, Pea Ridge and Mineville**) are from the **Grenville Province** and its extension into the Granite-rhyolite Province. Time to revisit the '**pinkstone belts**'!

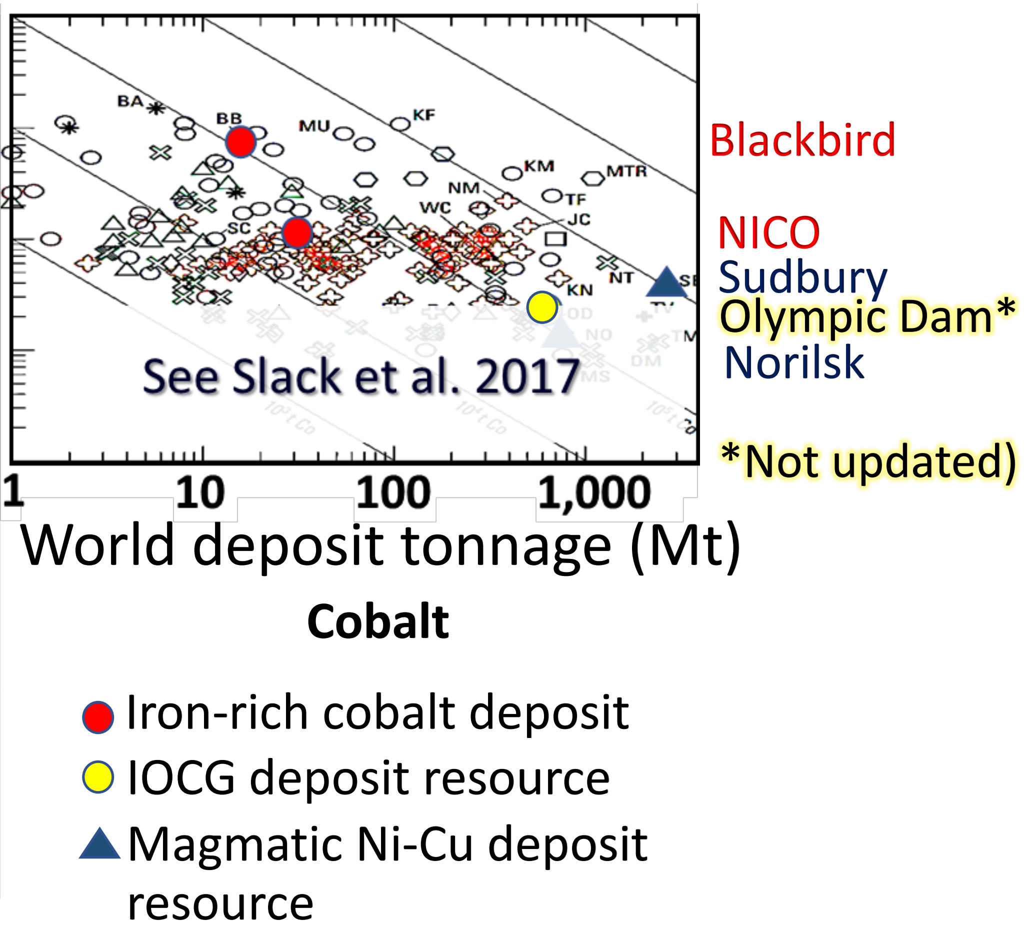
Data: Magrina et al. 2005; Perreault and Artinian 2013; Weng et al. 2013; Corriveau et al. 2015; Day et al. 2016a, b; Taylor et al. 2019

Framework tool #5b: deposit-based evidence supported by regional system evolution (e.g. the NICO Au-Co-Bi-Cu deposit and its W enriched zone)



Au-Co-Bi-Cu ore of the NICO deposit and host MIAC system metal contents (GBMZ)





Goad et al. 2000; Acosta-Góngora et al. 2015a, b, 2018b; Corriveau et al. 2016, in press a-e; Montreuil et al. 2016a, b

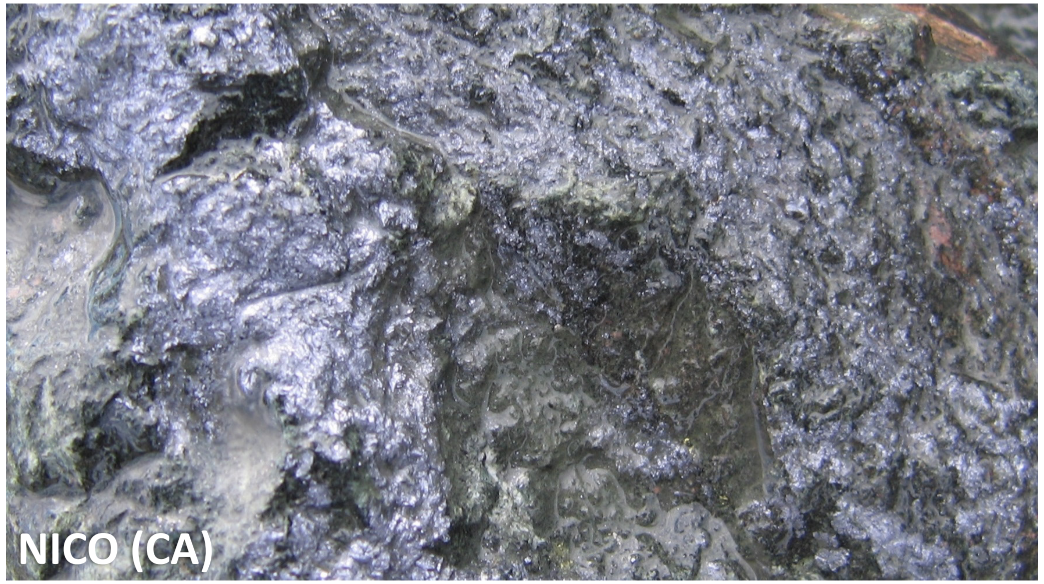
Framework tool #6: a classification of known deposit types within MIAC systems

Mineralization at the LT Ca-Mg-Fe alteration facies
Low iron-oxide to low iron deposits (e.g. iron silicate, iron sulphide, iron carbonate variants)

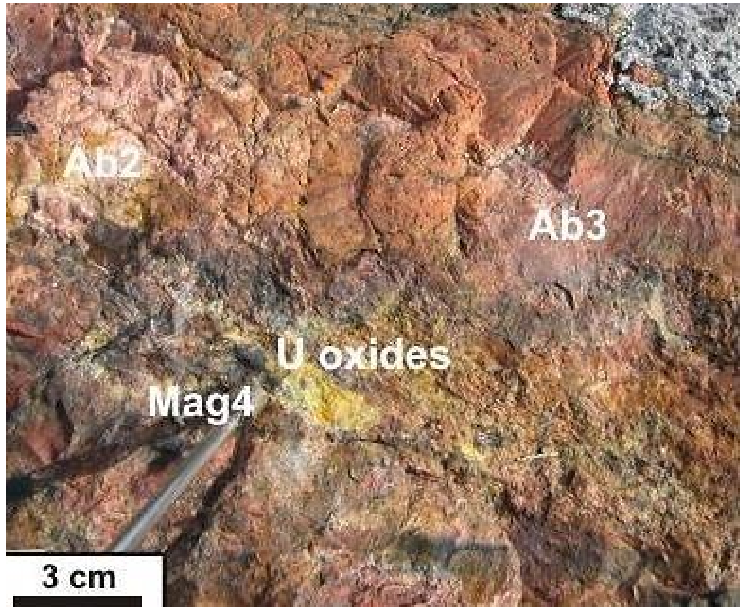
Tectonically active settings
Albitite-hosted U/Au-Co/Cu-Au-Ag-(Co-Zn)

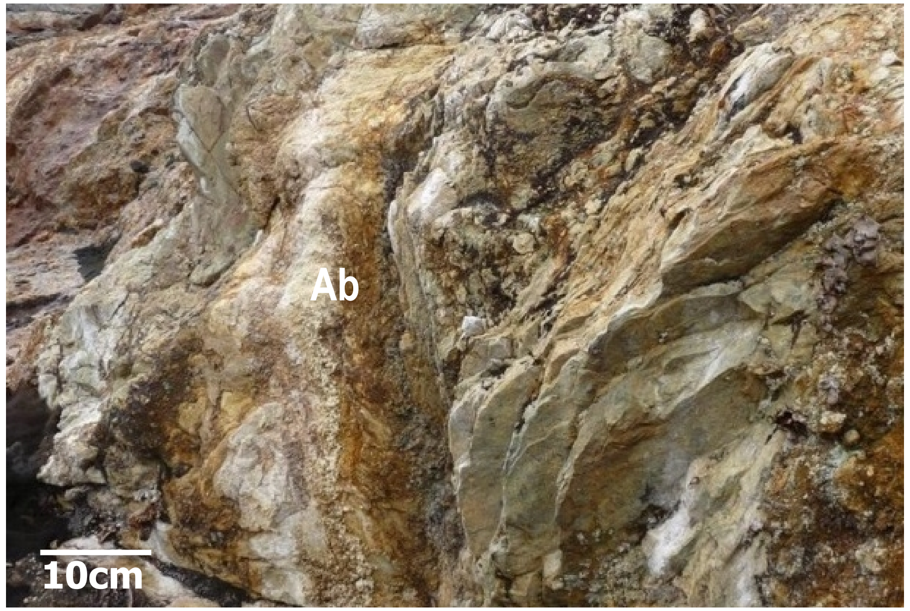
Final stages of system evolution

Epithermal cap, silica flooding
Syn-MIAC vein systems
Remobilized vein/breccia
Deposits with **'leftover', recycled or added metals** (e.g. Merlin Mo-Re, five-element veins)



Vein-type Mo mineralization

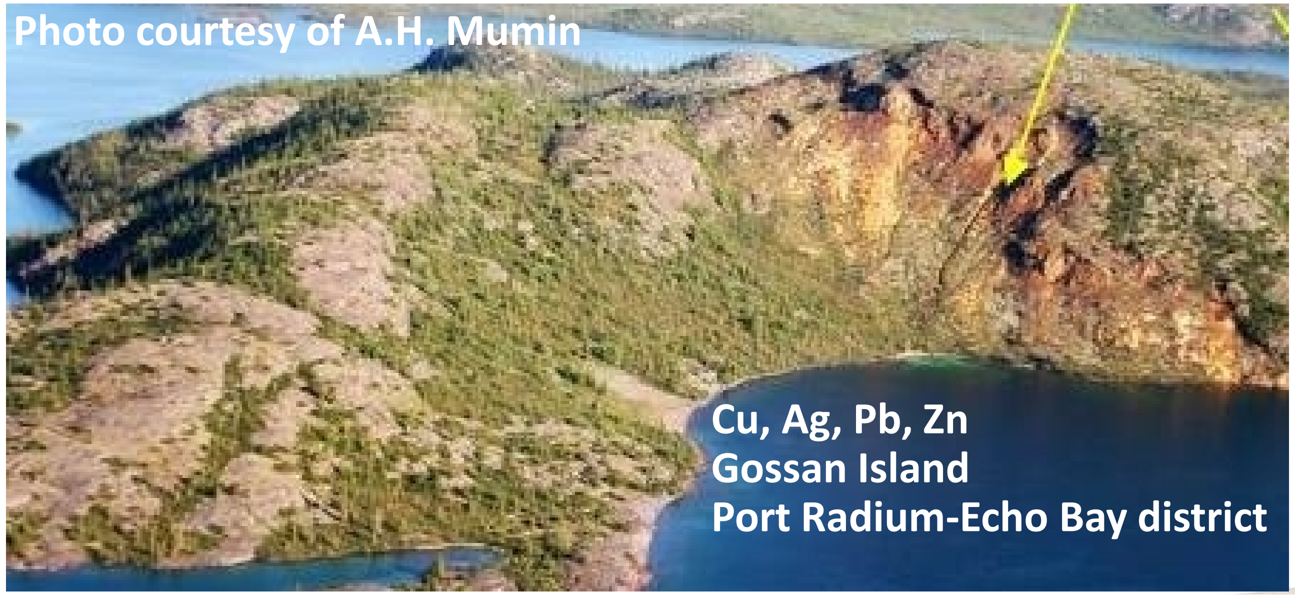




Prospects: Southern Breccia U-Cu-Mo

Delhi Pacific albitite + LT Ca-Mg-Fe + Cu-Au-Ag-(Co-Zn); Taché Co+ pyrrhotite

Epithermal cap, phyllic gossan

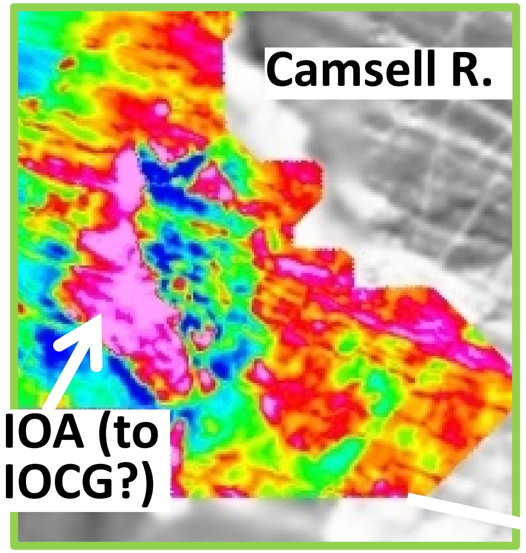


Mumin et al. 2007, 2010; Corriveau et al. 2014, 2016, in press a-e; Montreuil et al. 2014, 2015; Potter et al. 2019, 2020, in press; Hofstra et al. 2021

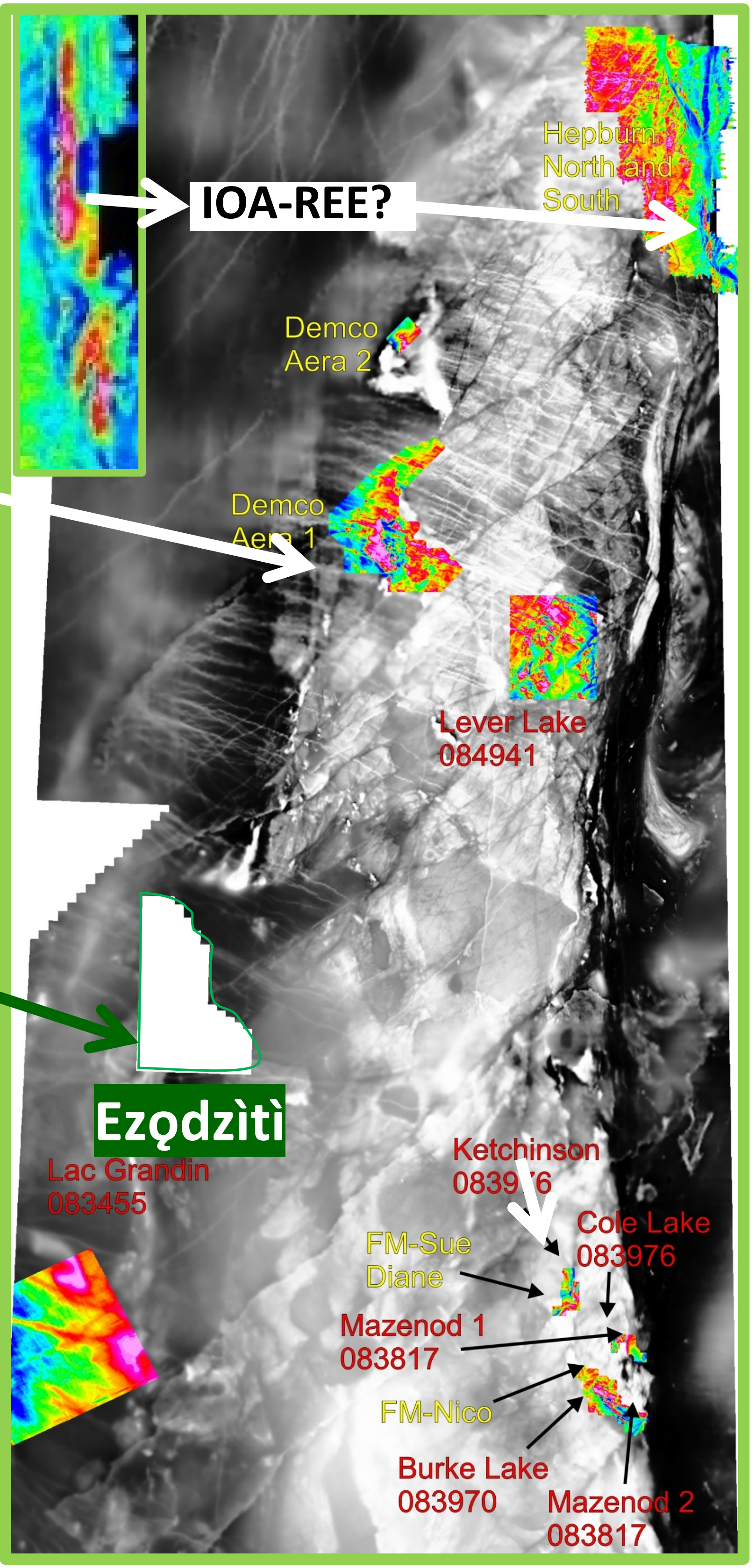
Framework tool #7:

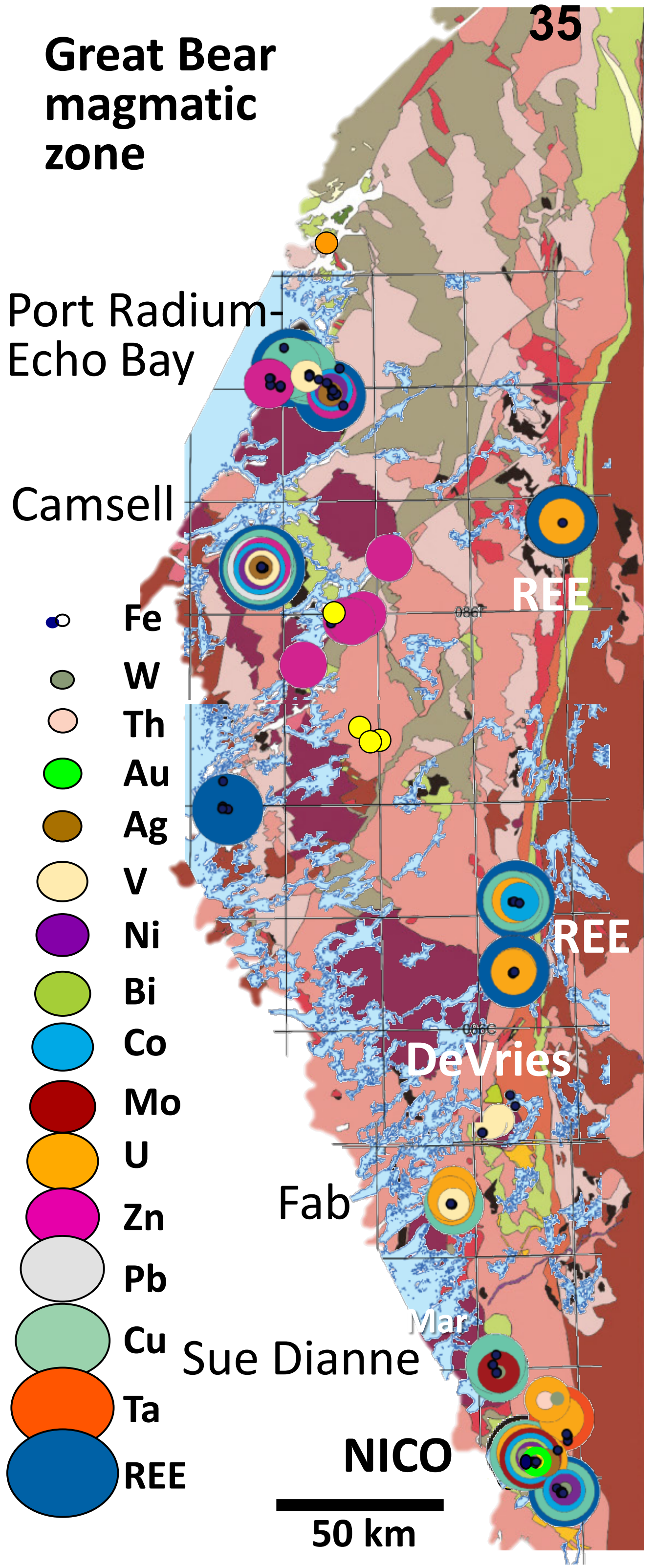
geophysics, from mantle to deposit footprints, rock physical properties, data optimization

See Jober 2009; Jober and Kienlen 2009; Spratt et al. 2009; Hayward and Oneschuck 2011; Lee et al. 2012, 2013; Hayward 2013; Lee and Morris 2013; Hayward and Corriveau 2014; Hayward et al. 2016; Kerswill et al. 2016a, b; Katona and Fabris in press



Data donated by DEMCo; Fortune Minerals proprietary data made accessible for modeling by GSC; Diamond North assessment reports





Bretzlaff and Kerswill 2016; Corriveau et al. 2016; NTGS 2021

Ezǫdzìtì Heritage resource

Framework tool #8:

Respecting sacred and heritage land

when conducting geoscience programs (e.g. Ezǫdzìtì)

Tłıchǫ owned land

Wek'èezhìı resources management area

Mǫwhí Gogha Dè Nııtłèè (Treaty 11)

Tłıchǫ Government 2013

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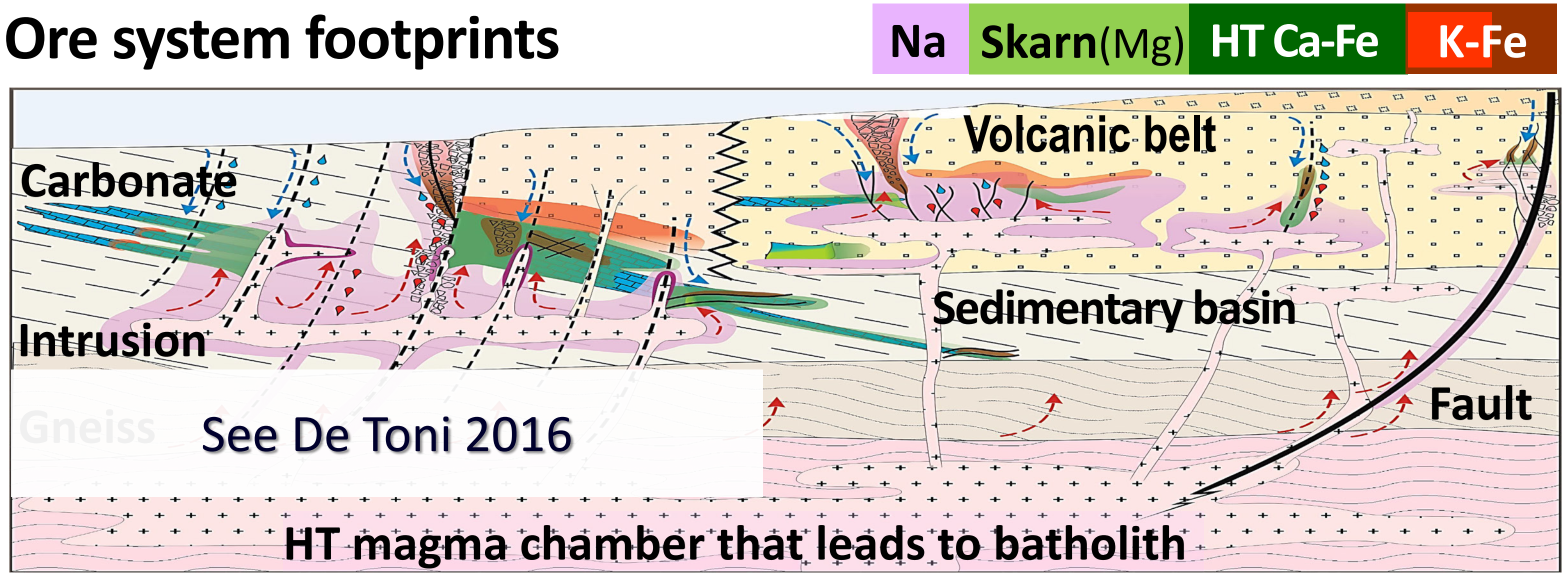
Framework tool #9

Footprints, mineralogy, mineral chemistry, rock physical properties, radiometric data, etc.

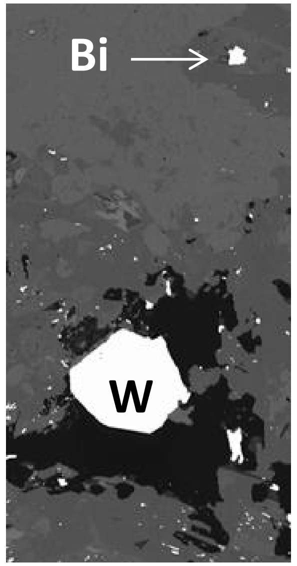
Ore system footprints



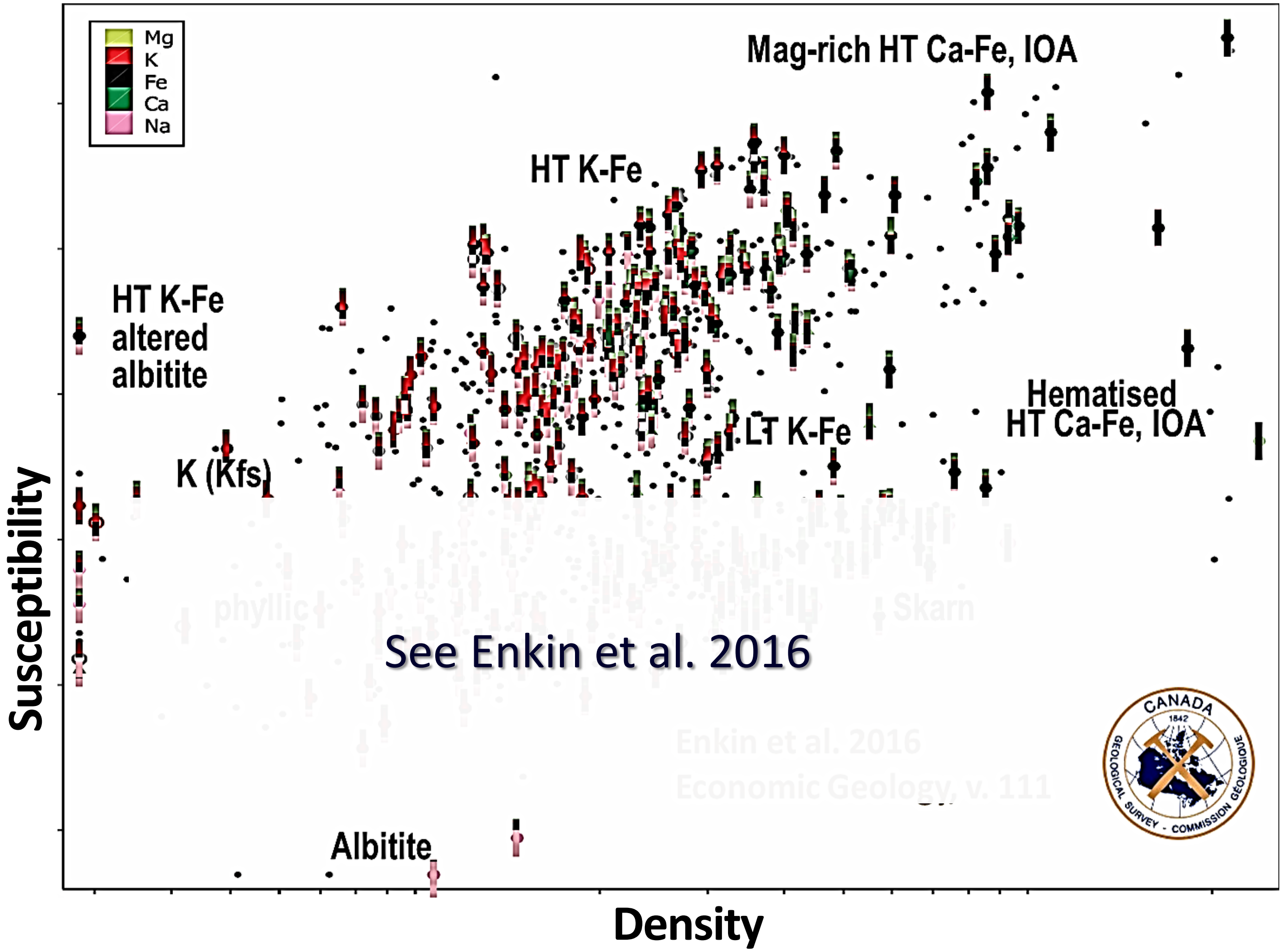
Mineralogy, mineral chemistry, mineral indicators

See McMartin et al. 2011; Lypaczewski et al. 2013; Acosta-Góngora et al. 2014; Sappin et al. 2014; Dare et al. 2014, 2015; De Toni 2016; Percival et al. 2016; Huang et al. 2018, in press; Normandeau et al. 2018; Duffett et al. 2020; Kelly et al. 2020; Potter et al. 2021, in press

See slide 85 and publications to be derived from the December 2021 International Online Workshop on Mineral Chemistry in Systems with IOCG, IOA and affiliated Critical Metal Deposits

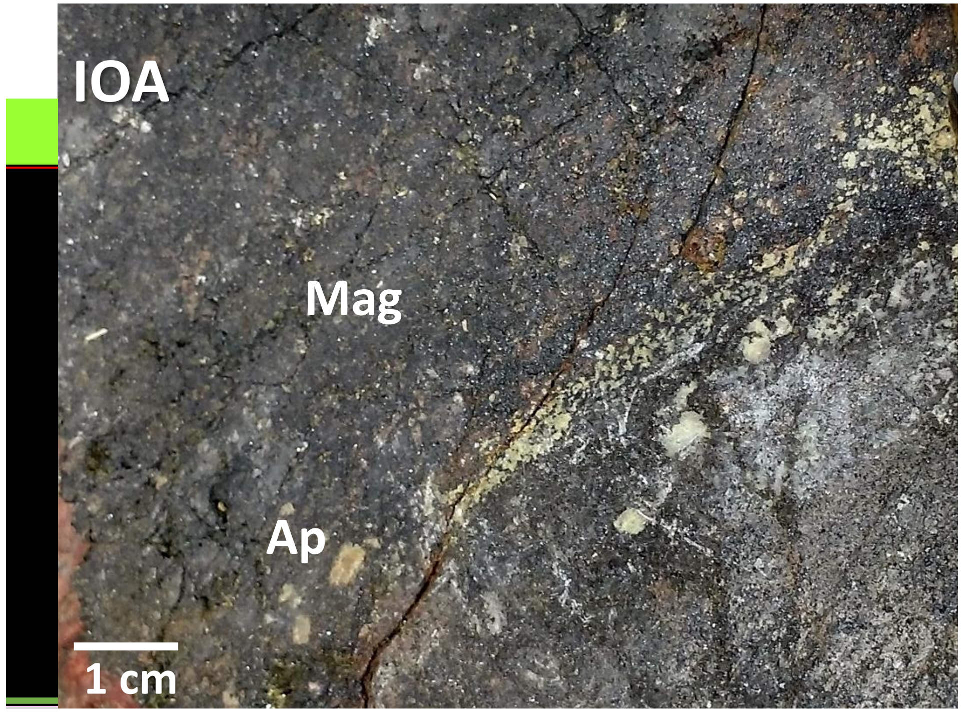


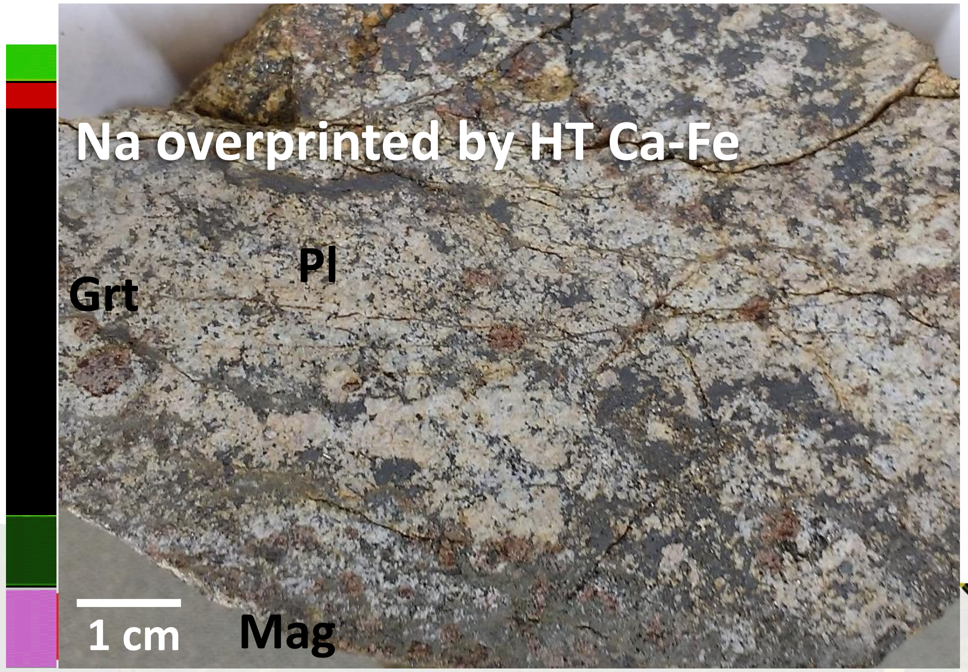
Rock physical properties

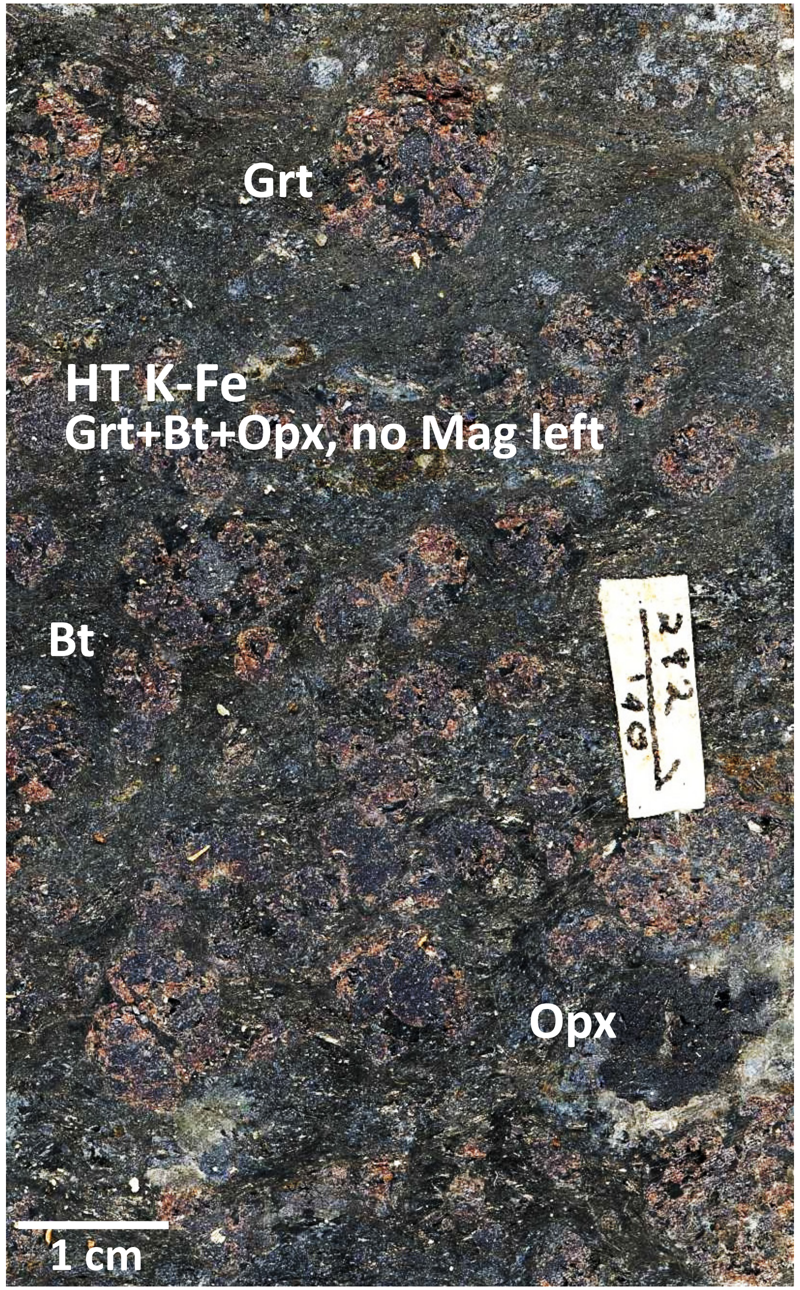


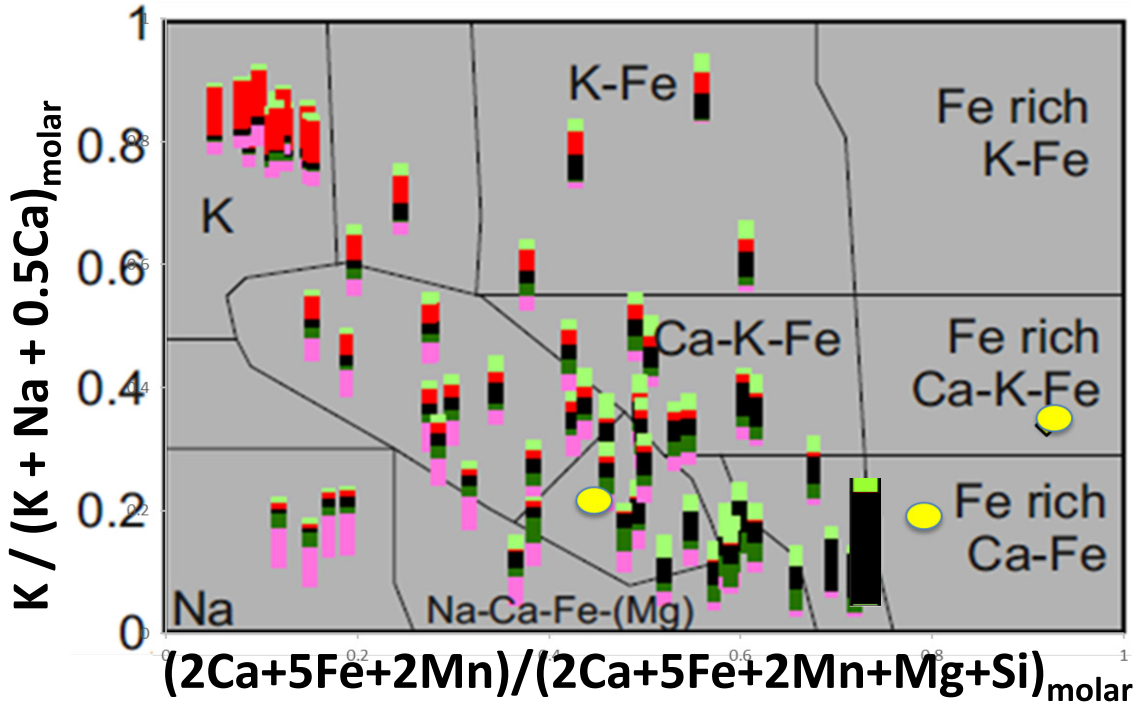
Framework tool #10: case examples of MIAC systems metamorphosed to granulite facies

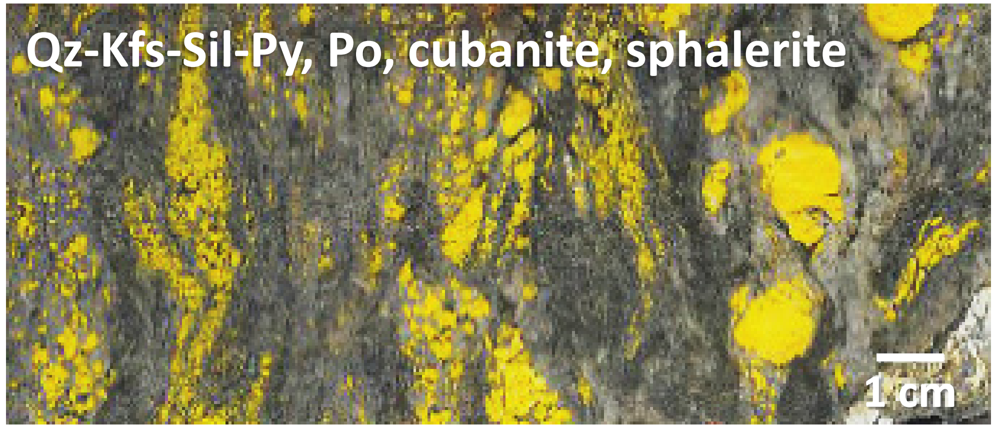
Bondy gneiss complex, SW Grenville Province, CA (see also Johnnies Reward, AU; Collier 2018)







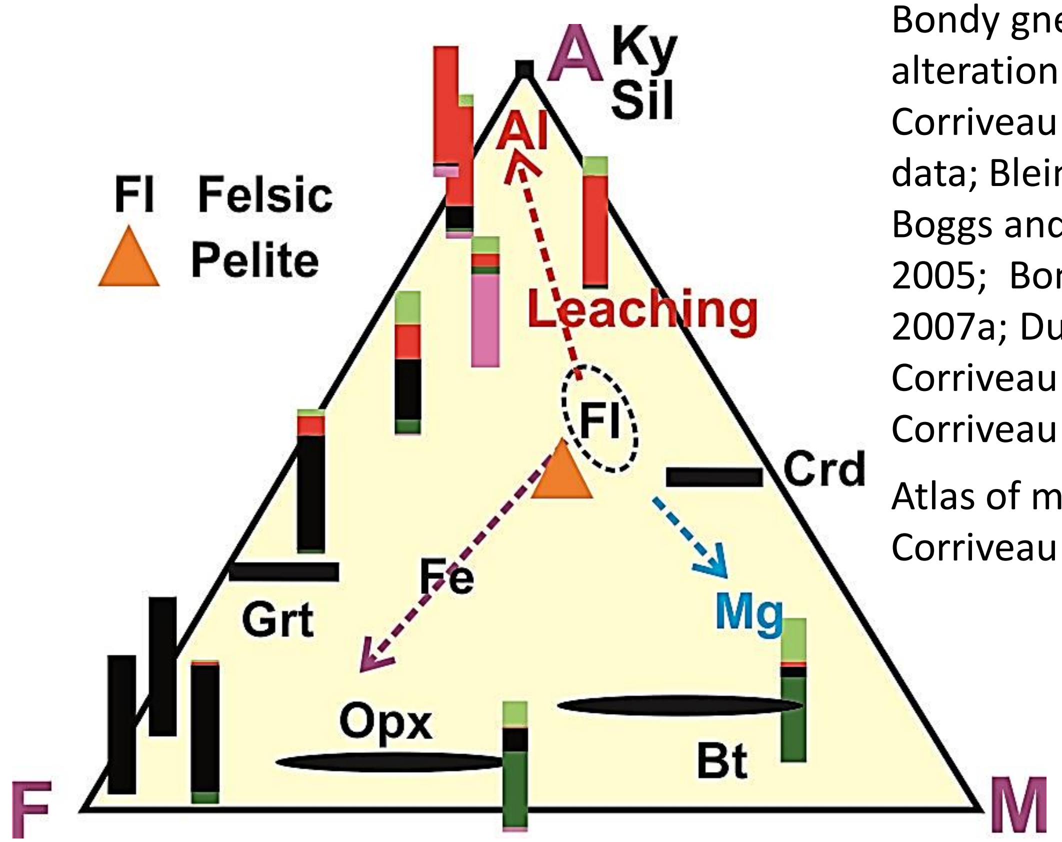




Corriveau et al. 1996b, 1997, 2018a; Blein et al. 2004; Boggs and Corriveau 2004; Dufréchou et al. 2015; Corriveau 2013; Corriveau and Spry 2014; Blein and Corriveau 2017

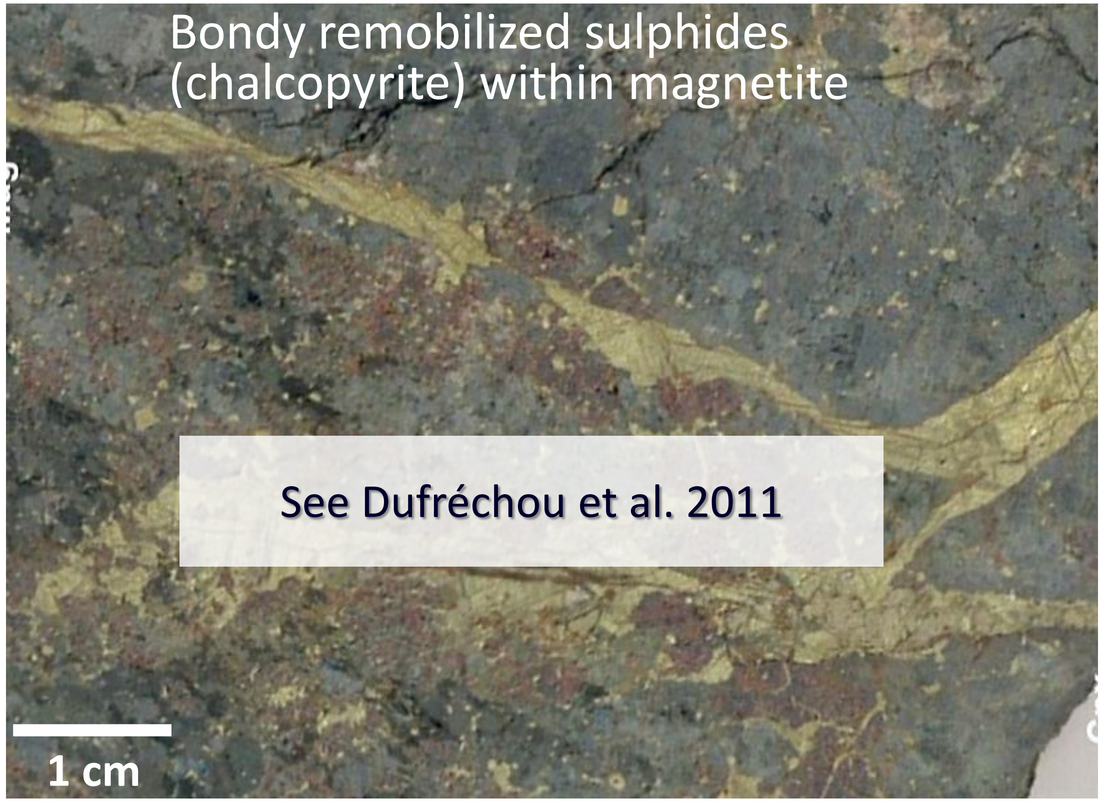
Framework tool #11: metamorphic phase modeling and chemographic diagrams

Chemographic diagrams optimize field interpretations by providing easily visualize contextual frameworks of mineral assemblages and overall contents of alteration facies. They also illustrate how mineral assemblages can be identical to common metasedimentary and meta-igneous rocks in addition to having very diagnostic atypical mineral contents and mineral assemblages (e.g. plagioclase-magnesian orthopyroxene-cordierite-phlogopite-tourmaline-kornerupine; garnet-biotite-chalcopyrite; amphibole-magnetite+chalcopyrite veins; clinopyroxene-garnet-scapolite-bornite-covellite-chalcopyrite; magnetite-apatite; quartz-K-feldspar-sillimanite-pyrite-pyrrhotite-cubanite-sphalerite, etc.)



Bondy gneiss complex and other metamorphosed alteration systems in the Grenville Province: Corriveau et al. 1996b, 1997, 2018a, unpublished data; Blein et al. 2003, 2004, unpublished data; Boggs and Corriveau 2004; Corriveau and Bonnet 2005; Bonnet et al. 2005; Bonnet and Corriveau 2007a; Dufréchou et al. 2011, 2015; Corriveau 2013; Corriveau and Spry 2014; Trapy et al. 2015; Blein and Corriveau 2017; Trapy 2018

Atlas of metamorphosed alteration: Bonnet and Corriveau 2007b



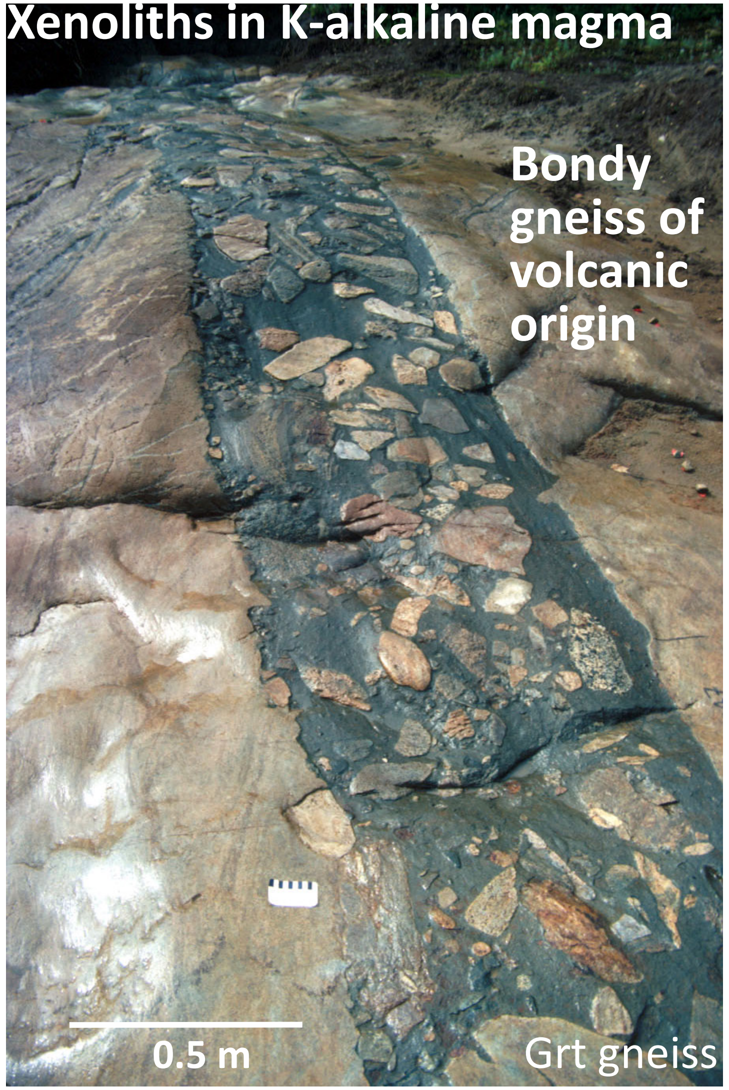
Metamorphic phase modeling provides more robust information of mineral assemblages and mineral contents of alteration facies

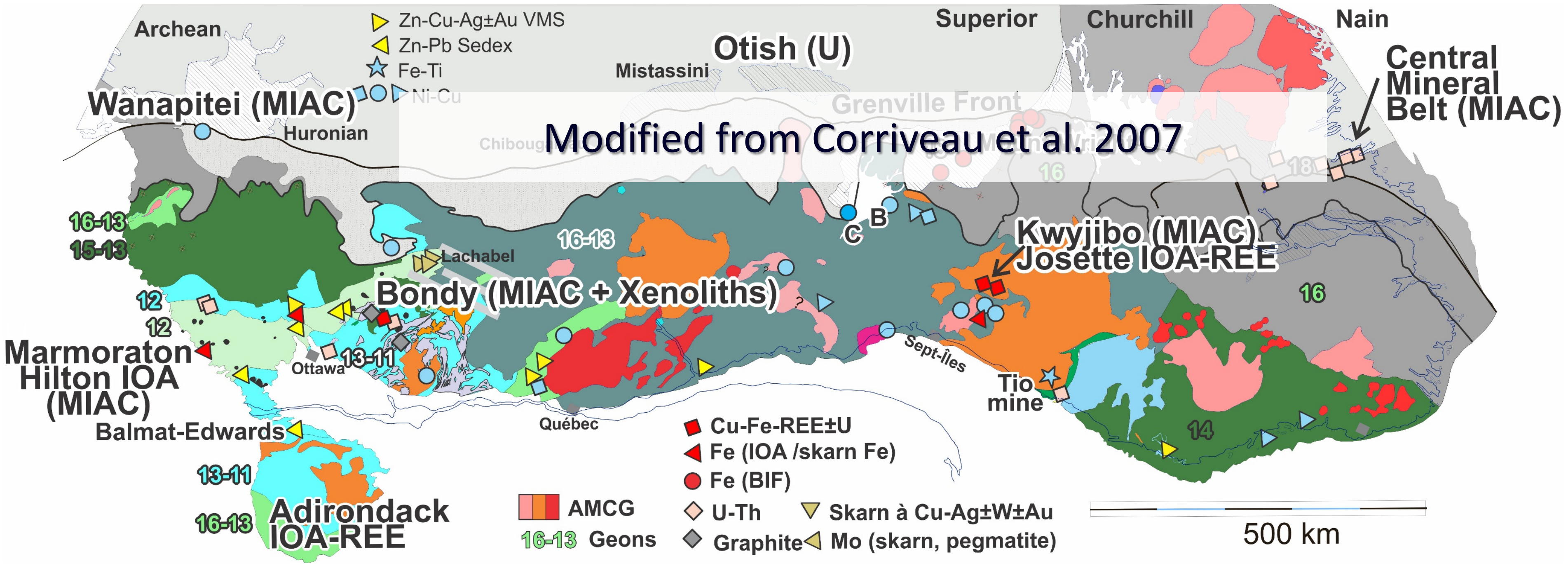
See F. Gervais and D. Regis slides; Corriveau et al. 2018a

Framework tool #12: xenoliths as a record of MIAC-related lithospheric conditions

Unique sampling of rocks across a 'Finger of god'-type magnetotelluric and seismic lithosphere footprint in the SW Grenville Province

From >70 km depth, across the lithospheric MIAC fluid and magma pathway into the Bondy MIAC system after its metamorphism

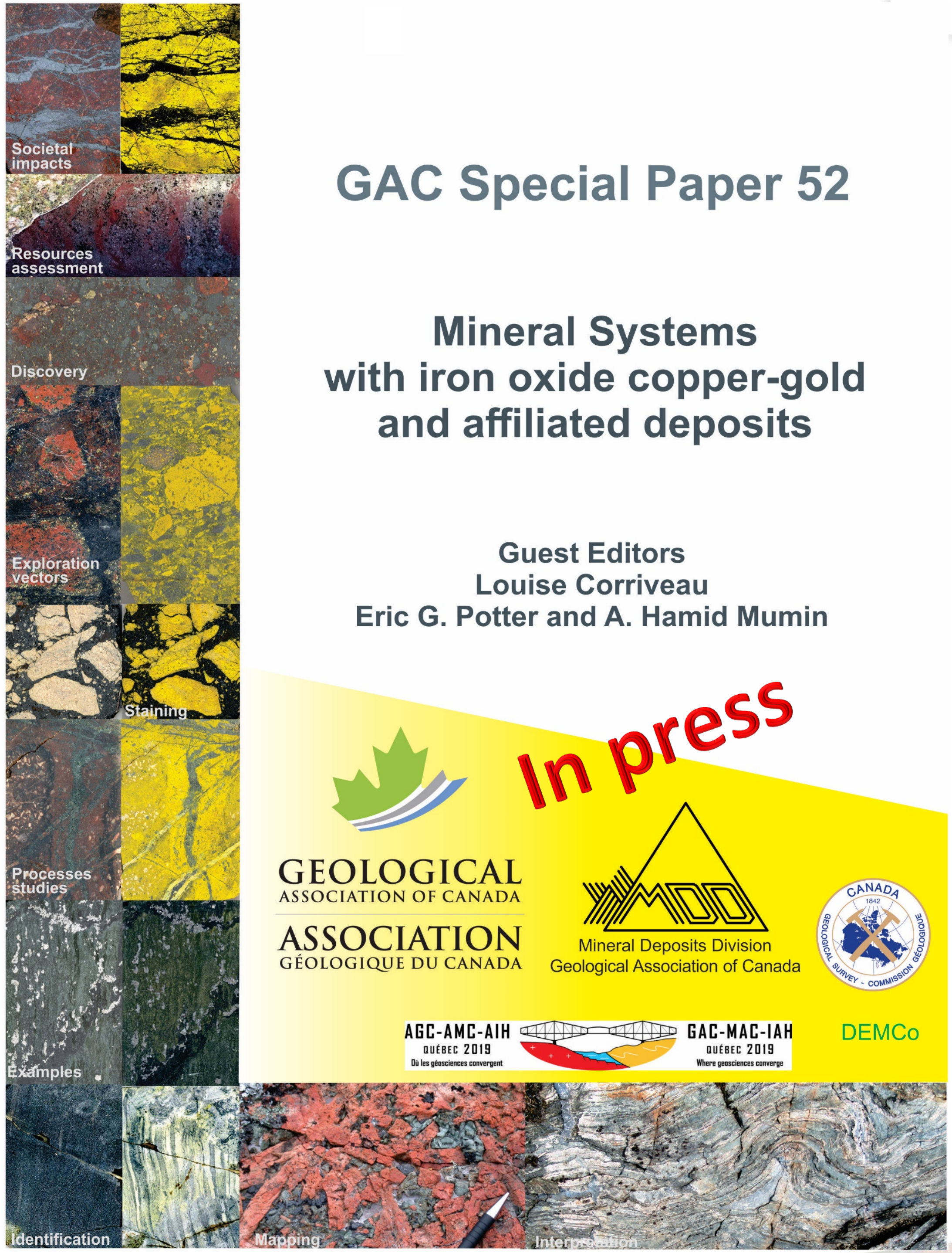




See Corriveau and Gorton 1993; Corriveau et al. 1996a, b; Morin and Corriveau 1996; Corriveau and Morin 2000; Morin et al. 2005; Corriveau 2013

Framework tool #13: synthesis papers in GAC Special Paper 52

1. Corriveau, Mumin, Potter, Introduction and overview
2. Skirrow, Hematite-group IOCG ± U deposits: an update
3. Williams, Magnetite-group IOCGs
4. Corriveau, Montreuil, De Toni, Potter, Percival, Mapping: a facies approach
5. Corriveau, Montreuil, Potter, Ehrig, Clark, Mumin, Williams, Metasomatic footprints of alteration facies
6. Corriveau, Montreuil, Blein, Ehrig, Potter, Fabris, Clark, Geochemical footprints
7. Corriveau, Montreuil, Potter, Blein, De Toni, Metal pathways and ore deposit model
8. Fabris, Geochemical characteristics, Olympic Copper-Gold Province, South Australia
9. Blein, Corriveau, Montreuil, Ehrig, Fabris, Reid, Pal, Geochemical tools for process studies and mineral exploration
10. Katona, Fabris, Targeting for IOCG deposits using gravity and magnetic potential field data in the Gawler craton, Australia
11. Jébrak, Use of breccias in IOCG(U) exploration
12. Potter, Acosta-Góngora, Corriveau, Montreuil, Yang, Uranium enrichment processes.
13. Huang, Beaudoin, De Toni, Corriveau, Makanvi, Boutroy, Fe-oxide fingerprints
14. Chen, Zhao, Andean IOCG deposits
15. Zhao, Chen, Zhao, Zhou, IOA, skarn, and IOCG deposits in China
16. Daliran, Stosch, Williams, Jamali, Dorri, Bafq district, Iran



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Framework tool #14: gathering, compiling, reprocessing and reinterpreting available data

Data from GSC TGI – GEM – SW Grenville xenoliths + provincial and territorial surveys = strategic assets to secure critical metal resources

To do list

- Field datasets + vocabulary
- Geochemical datasets
- Geophysical updates + method testing; MT-seismic surveys (Grenville + GBMZ + Temagami)
- Petrological modelling for metasomatic (non metamorphosed to high-grade metamorphic) systems

Assess MIAC affinities of Canadian prospects + alteration systems

Deposit type classification with Canadian and global examples

Compilation, modelling, publication of donated industry geochemical + geophysical datasets

Exploration framework for critical metals, Mineral potential re-assessment, Decision-making, etc.

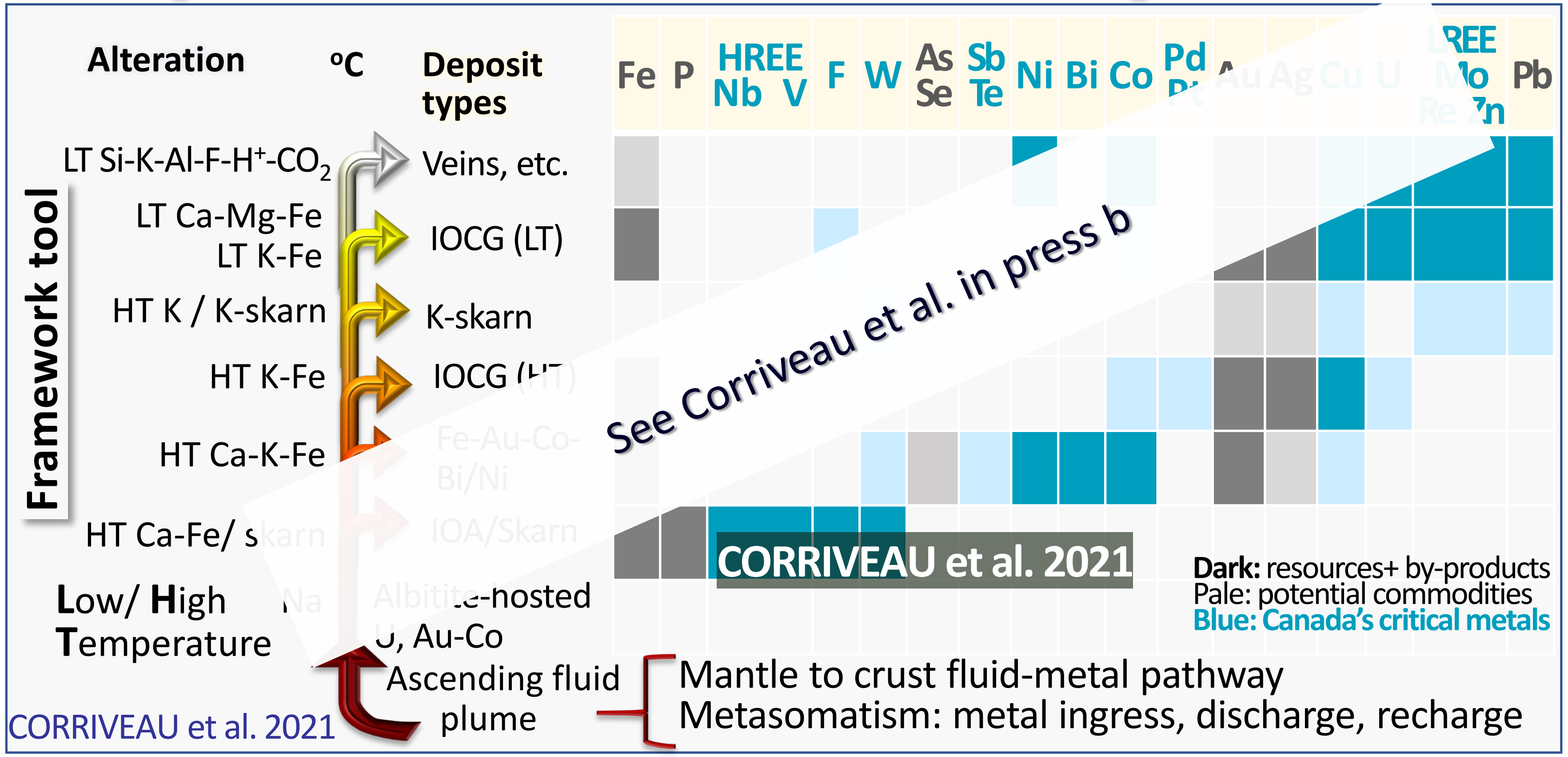
Synthesis of Canadian mineral systems with IOCG and affiliated critical metal deposits anchored on global systems (Australia, US, China, Iran)

Metamorphosed systems with
GSC, BRGM, GSSA, GSQ, GSWA, Polytechnique

Global comparisons and MIAC system research with
GSC, BRGM, GSSA, GSQ, GSWA, NGU, USGS, BHP-Olympic Dam, Karlsruhe U., China Academy of Sciences, China U. of Geosciences and many additional collaborators

Canadian systems framework with
GSC, OGS, BCGS, MERN-Q, GSNL, NB-GS, NS-GS, NTGS
DEMCo, Red Pine, Fortune Minerals, SOQUEM, NextSource, Ressources Maxima, Zonte and other companies
St. Mary's, UBC, Brandon, Polytechnique, Laval, UQAC, etc.

Available data (public + donated by private sector):
Field geology, Drill cores, Mineralogy, Geochemistry, Petrophysics, Geophysics (magnetic, gravity, MT, seismic), Petrological modeling, Xenoliths



Framework tool #15: a table to fill out for prospective settings of interest to collaborators

Canada's MIAC framework is only possible through **provincial and territorial collaborations and consolidation and transfer of knowledge**

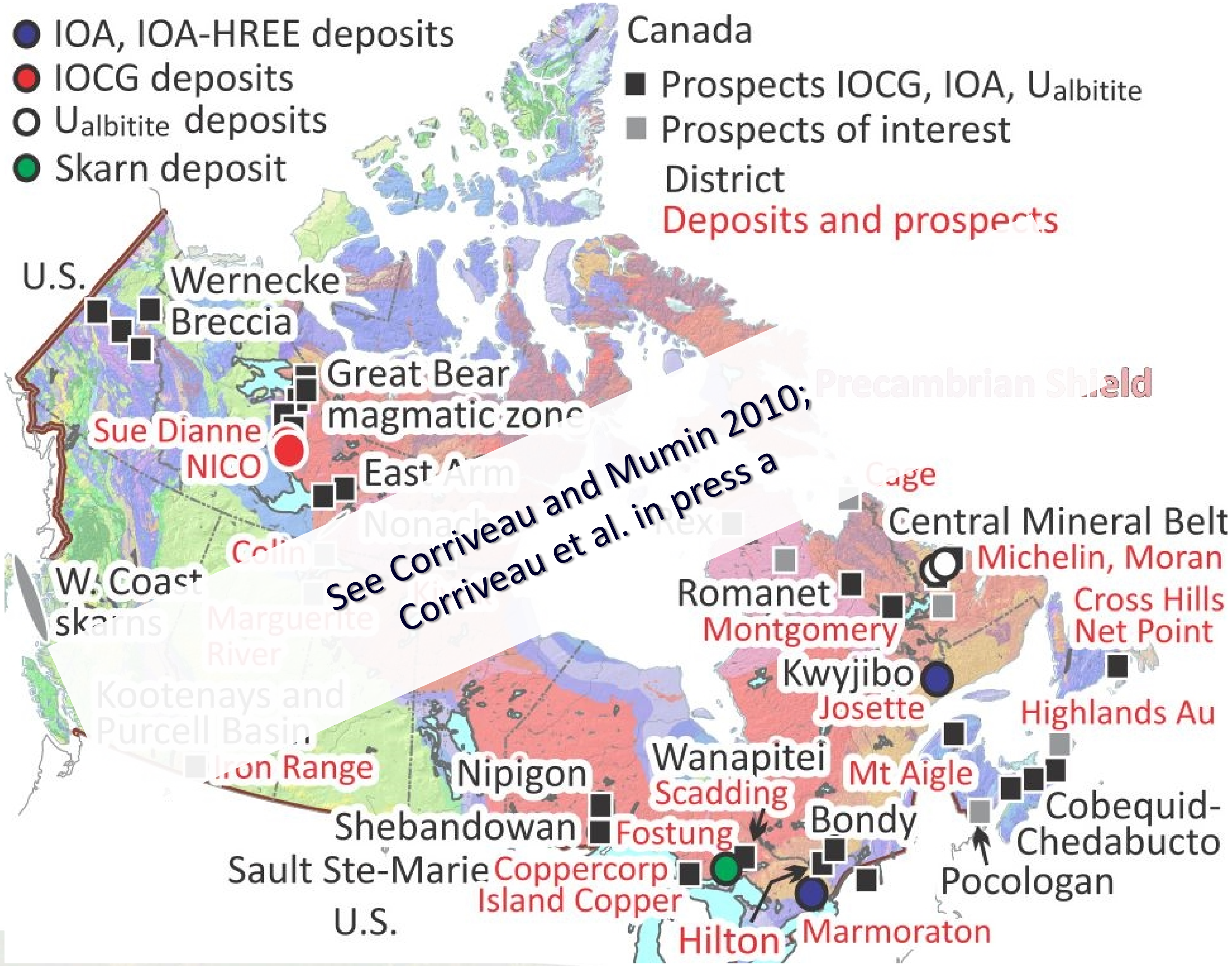
	Facies	Minerals			Element enrichment			Examples
		Major	Accessory to major	Mineralization	Major commodity	Economic potential	Others	Lou system (GBMZ)
Facies 5	LT Ca/Mg/Na /K Si/H^+/ CO_2	Qz, Cb (Dol, Cal), Chl, Ab, Kfs, Ms		Ccp, Brn, Cct, Co-Py, Co-Ars, Gn, Mol, Native Au, Sp, Urn	Au, Co, Cu, Mo, Re, U, Zn			
	LT Ca-Mg-Fe^{2+}	Chl, Mag	Ab, Amp (Mns, Stp), Ank, Dol	Ccp, Native Au, Po, Py, Apy	Au, Cu	Bi, Co, U	Fe, LREE, Na, Ni	
	LT Ca-Mg-Fe^{3+}-(±F)	Act, Adr, Aln, Chl, Ep, Hem, Hst	Ank, Brt, Cal, Fl, Kfs, Ms	Brn, Ccp, Cct, Gn, Py, Sp, LREE minerals, Urn	Ag, Au, Cu, Pb, U, Zn	LREE	Ba, F, Fe, S, K, Mn, Sb, Sn, Sr, Te, W	Chl patch in SBx
	LT Si-Fe-(±Ba)	Hem, Qz	Aln, Ank, Brt, Cal, Fl, Sid	Ccp, Native Au, LREE minerals, Py, Urn	Au, Cu, Fe	LREE, U	Ba, Fe, Si	Only as veins under Facies 6
	LT K-Fe	Chl, Hem, Ms, Sd	Aln, Ank, Brt, Cal, Dol, Ep, Fl, Kfs, Qz	Brn, Ccp, Cct, Hem, Au, LREE min., Py, Urn	Ag, Au, Cu, Fe, U	Co, LREE, Mo, Pb, Re, W, Zn	As, Ba, C, Cd, F, K, Mn, [illegible]	In volcanics above NICO; overprints on HT K-Fe + mineralized veins at NICO
Facies 4	K-skarn	Aln, Cpx (Adr-Grs), Ep, Kfs	Ank, Cal, Dol, Mag	Ccp, Gn, Mol, Py, Sp	None	Cu, Mo, Pb, Zn	K, Th, U	Exobreccia along felsic dykes
	K felsite	Kfs			None	None	Ba, K, Rb, Th	In volcanics above NICO; overprints SBx albitite; breccia along felsic dykes
Facies 3	HT K-Fe (Kfs)	Kfs, Mag	Bt, Cal, Chl	Ccp, Mol, Native Au, Py, [illegible]	Ag, Au, Cu, Fe, U	Mo	Ba, C, F, K, Rb, Mn, P, REE, Sb, Te, Th, V, Zr	Iron oxide breccia with Kfs-altered clasts in volcanics above NICO and in albitite at SBx
	HT K-Fe (Bt)	Bt, Mag	Amp (Gru, Hbl), Grt, Kfs	Brn, [illegible], Po, Py	Ag, Au, Co, Cu, Fe, U	Mo, Pd, Pt	Ba, C, F, K, Rb, Mn, P, REE, Sb, Te, Th, V, Zr	Stratabound Bt-dominant overprint on HT Ca-K-Fe at NICO; Mag-Bt patches in SBx
Facies 2–3	HT Ca-K-Fe	Amp (Act, Hbl), Bt, Kfs, Mag	Ap, Cpx (Aug-Hd), Grt, Sid	Apy, Bism, Co-Apy, Ccp, Co-Loe, Co-Py, Cob, Gers, Lin, Po, Py, Saf, Sch, Sieg, Sku, Urn	Au, Bi, Co, Cu, Ni	Ag, As, Mo, Sb, Se, Te, W	Ba, Ca, K, P, Rb, REE, S, Th, U, Y	Stratabound Bt-Amp-Mag overprints of HT Ca-Fe with Apy stringers and veins at NICO; patches in SBx
Facies 2	HT Ca-Fe	Amp (Act, Cum, Hbl), Mag	Aln, Ap, Cpx (Dp-Hd, Aug), Ep, Qz	Mag, Po, Pn, REE minerals (e.g. Ap, Mnz, Adr, Fl), Sch	Fe, REE	Co, Ni, V, W	Ca, Mg, P, Th, U	Stratabound Amp to Mag in sed.; Amp to Mag veins in HT Ca-K-Fe at NICO recording repetition of facies; patches and veins in SBx
Facies 1–2	Fe-skarn	Cpx (Dp-Hd), Grt (Adr-Grs), Mag	Amp (Hbl, Tr), Qz	Mag, Sch	Fe, W	REE, Co, Ni, V	P, Th, U	
	Skarn	Cpx (Aug, Dp-Hd), Grt (Adr-Grs)	Aln, Amp, Cal, Chl, Dol, Mag, Phl	Sch		W	Fe	Relics in Amp HT Ca-Fe of carbonate unit at NICO
	HT Na-Ca-Fe	Ab, Amp (Act, Hbl), Mag	Ap, Cpx (Aug)		None	Fe, REE, V	Na, Ca, P, Th	Rare
Facies 1	Na, Na-Ca	Ab, Scp (residual Qz)	Amp (Act, Hbl), Cpx (Aug) Mag	None	None	Al	Ga, Na, Nb, Ta, Ti, Zr	Southern Breccia albitite corridor; relics at NICO

See Corriveau et al. in press a, b

CORRIVEAU et al. 2021

TGI-6 global task force on MIAC systems with IOCG and critical metal deposits:

Tools, data, models and case examples are nothing without YOUR CONTRIBUTIONS!



Prospective Settings

- Critical metal resources untapped
- Alteration to map and use as vectors to mineralization
- Prospects to explore

Deposits to discover!

Deposit types to classify!

Geoenvironmental models to establish

MIAC framework to establish together and with comparisons to global mining districts using a shared vocabulary and knowledge base

TGI Ore Systems

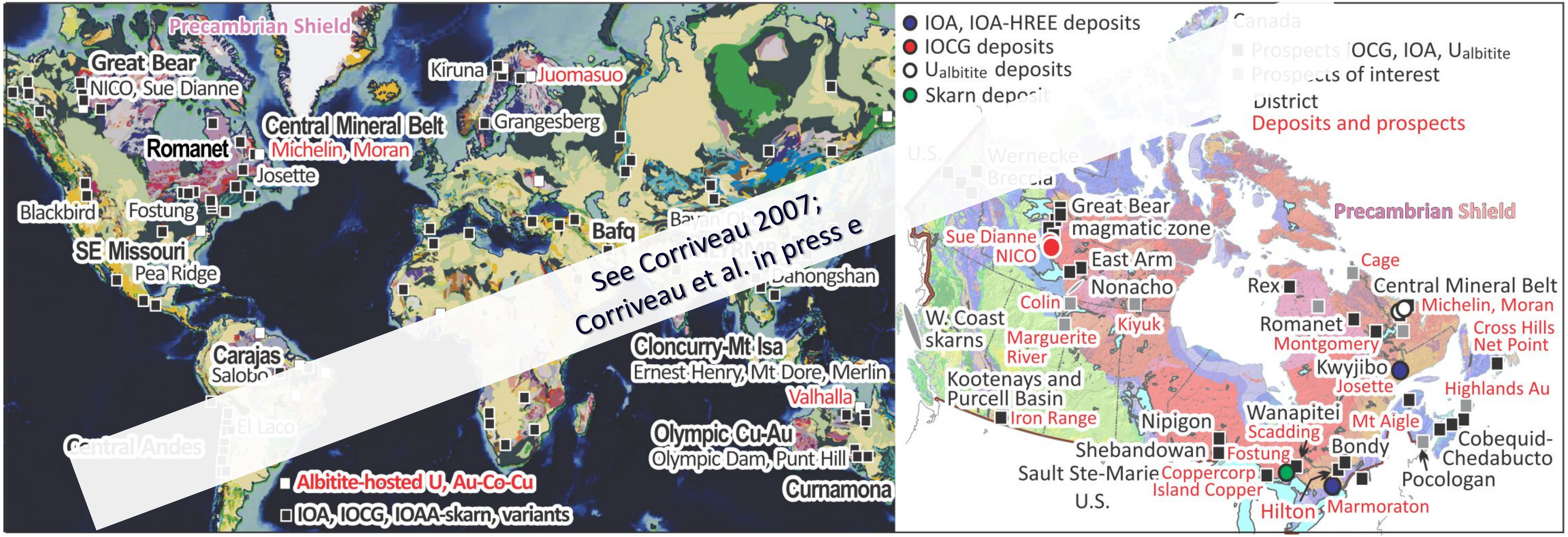
Targeted Geoscience Initiative

GEM

Geomapping for Energy and Minerals (Geo-North)

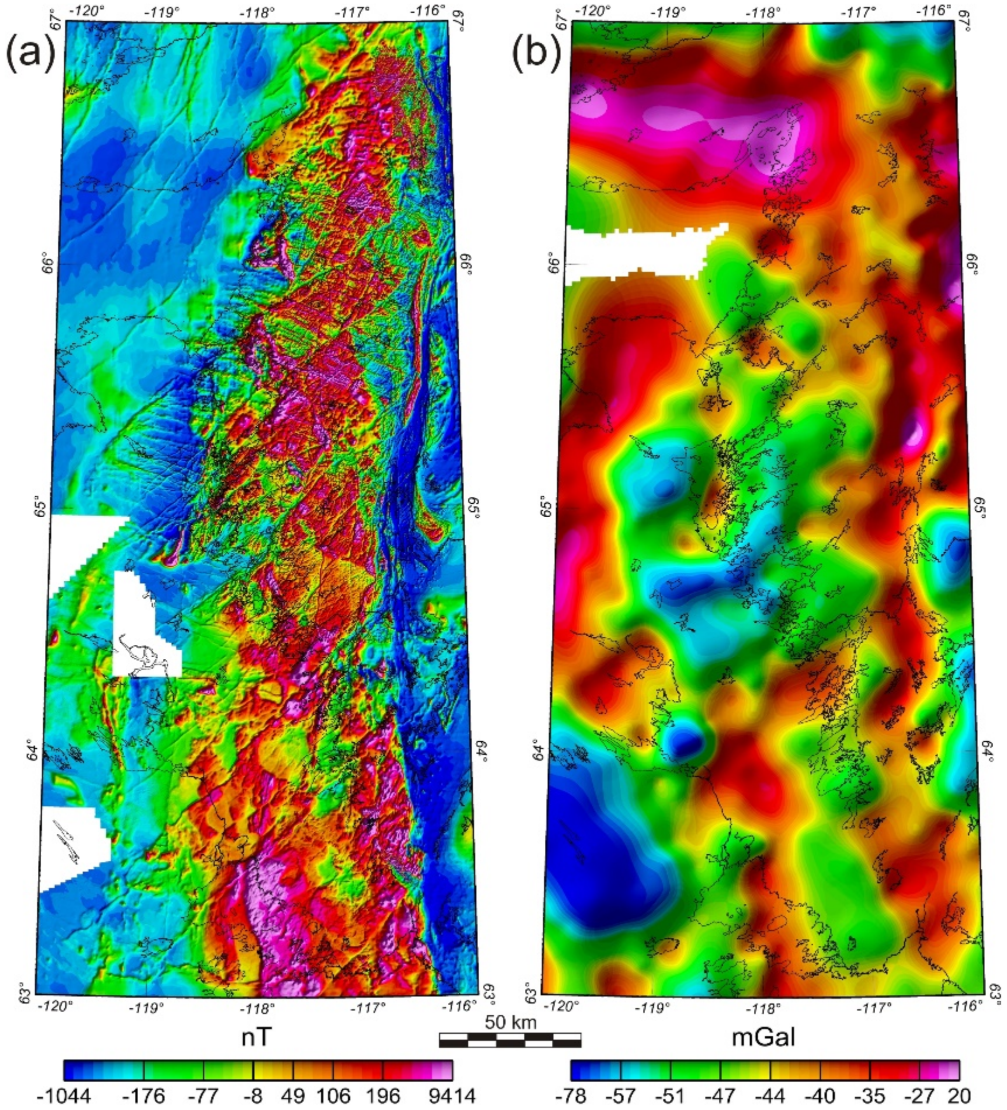
Provincial and territorial survey data, assessment reports, shared or donated industry datasets

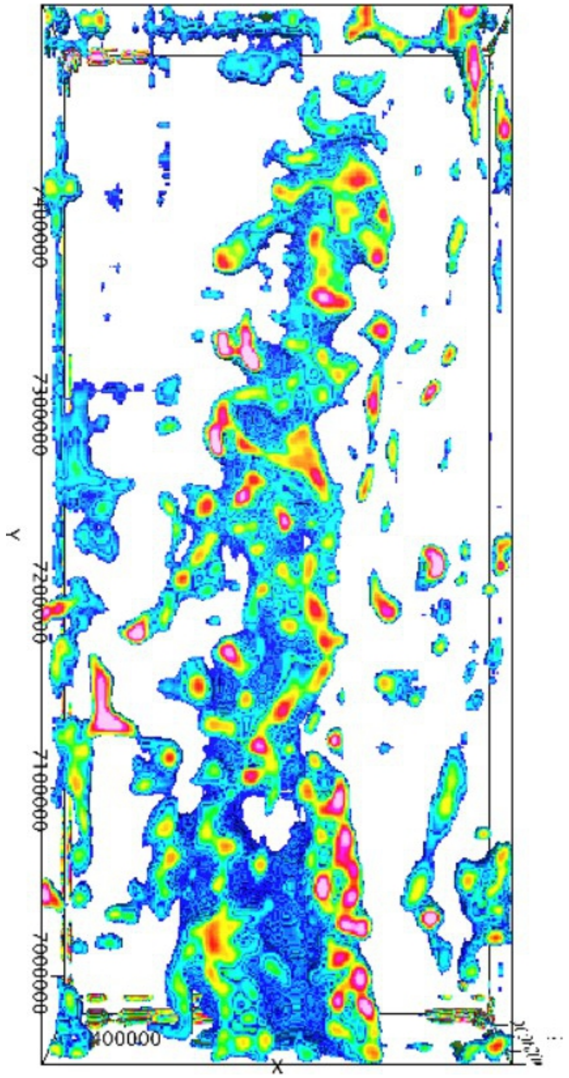
Teammates and their contributions



Nathan Hayward, Vicki Tschirhart, and Randy Enkin, Jim Craven, Louise Corriveau

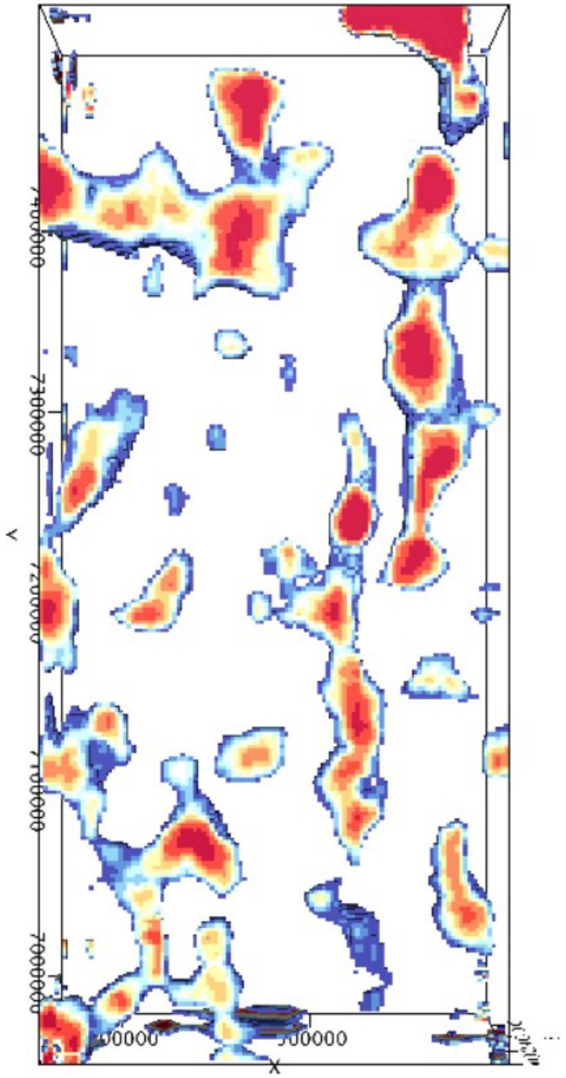
Geological Survey of Canada – GBMZ - Potential Field Modeling





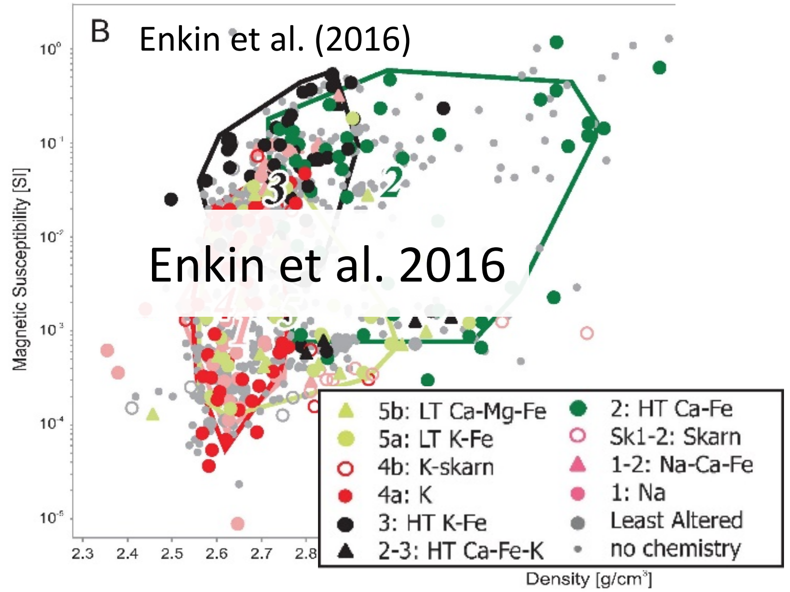
Mag Susceptibility

> 0.02 SI



Density

> 0.03 g/cm3



(1) Two new compilations of shared industry/public aeromagnetic data.

(2) Update to 2011 Open File map 6835

(3) 3-D Gravity and Magnetic Inversions to define zones with greatest physical property variation.

(4) Comparison on Inversion strategies: UBC-GIF vs VOXI.

(5) Calculation of areas with composite density and magnetic susceptibility variations.

See also Craven et al. 2013; Hayward and Oneschuck 2011; Hayward 2013; Hayward et al. 2013, 2016 ; Enkin et al. 2016, 2020

CORRIVEAU et al. 2021

Canada

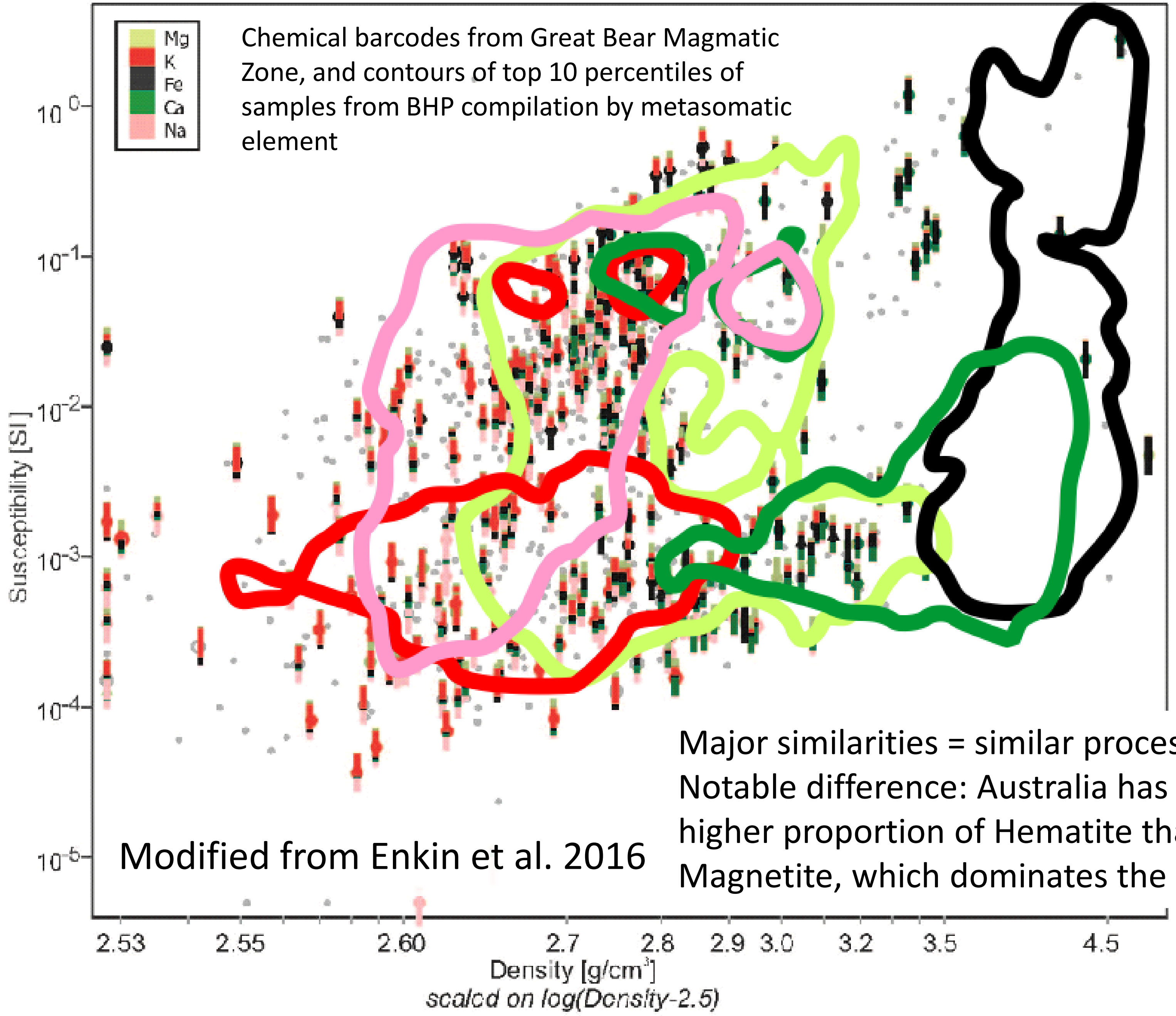
Randy Enkin, Louise Corriveau

Geological Survey of Canada
in collaboration with Kathy Ehrig
BHP-Olympic Dam, AU

Linking MIAC physical properties to chemistry, mineralogy, metasomatism and mineralization

- Compare and contrast the physical properties and chemistry of Australian and Canadian MIAC systems
- Optimize data presentation methods (Chemical Barcodes)
- Determine the role of trace elements in modifying rock physical properties
- Develop geophysical signatures of metasomatism and mineralization
- Apply AI techniques to geophysical/geochemical analysis in MIAC settings

See also Enkin et al. 2016, 2020; Dmitrijeva et al. 2019



Major similarities = similar processes
Notable difference: Australia has a higher proportion of Hematite than Magnetite, which dominates the GBMZ

Jim Craven

GSC Ottawa – Magnetotellurics

On going: work with Martyn Unsworth and Masoud Ansari to reprocess NICO 2009 MT dataset

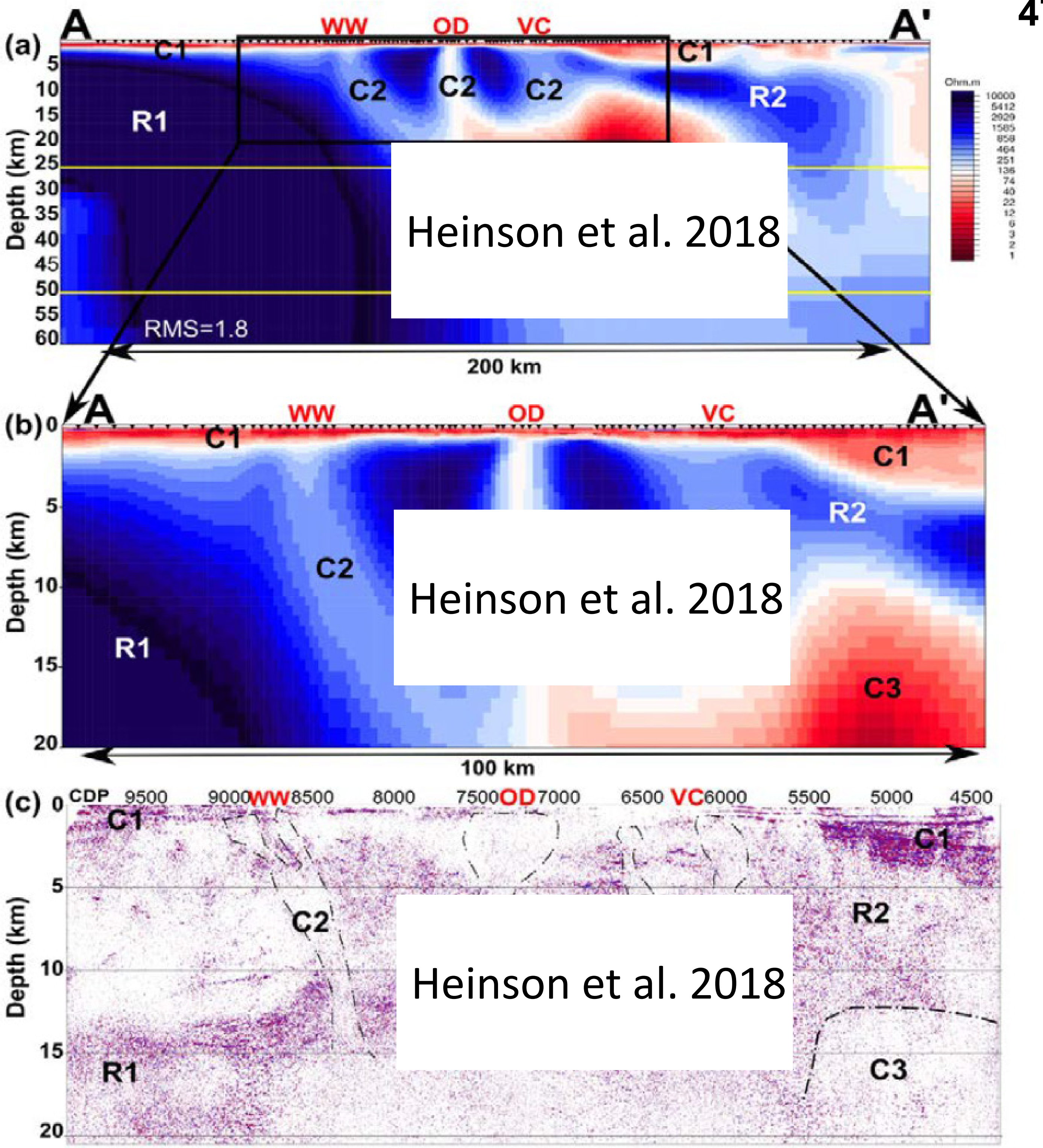
Year 1: Compile EM Data in Great Bear (Nathan)

(Re-)Analyze MT profile near Temagami

Year 3: Low cost MT survey outside Ottawa to leverage legacy data and test the '**Fingers of God**' hypothesis and investigate the role of deep pathways and reservoirs. Xenoliths (Corriveau and Morin, 2000) have sampled this deep pathway and are available to study lithospheric conditions for the generation of MIAC provinces.

Year 4: work with Gilles and Masoud to model MT and reprocess legacy seismic to evaluate the role with a disciplinary deep approach

See also Craven et al. 2013;
Adetunji et al. 2014, 2021;
Hayward et al. 2016;
Wise and Thiel 2020



The '**Fingers of God**' magnetotelluric and seismic footprint of the lithosphere below the supergiant Olympic Dam Cu-Au-U-Ag deposit, South Australia

OD = Olympic Dam deposit

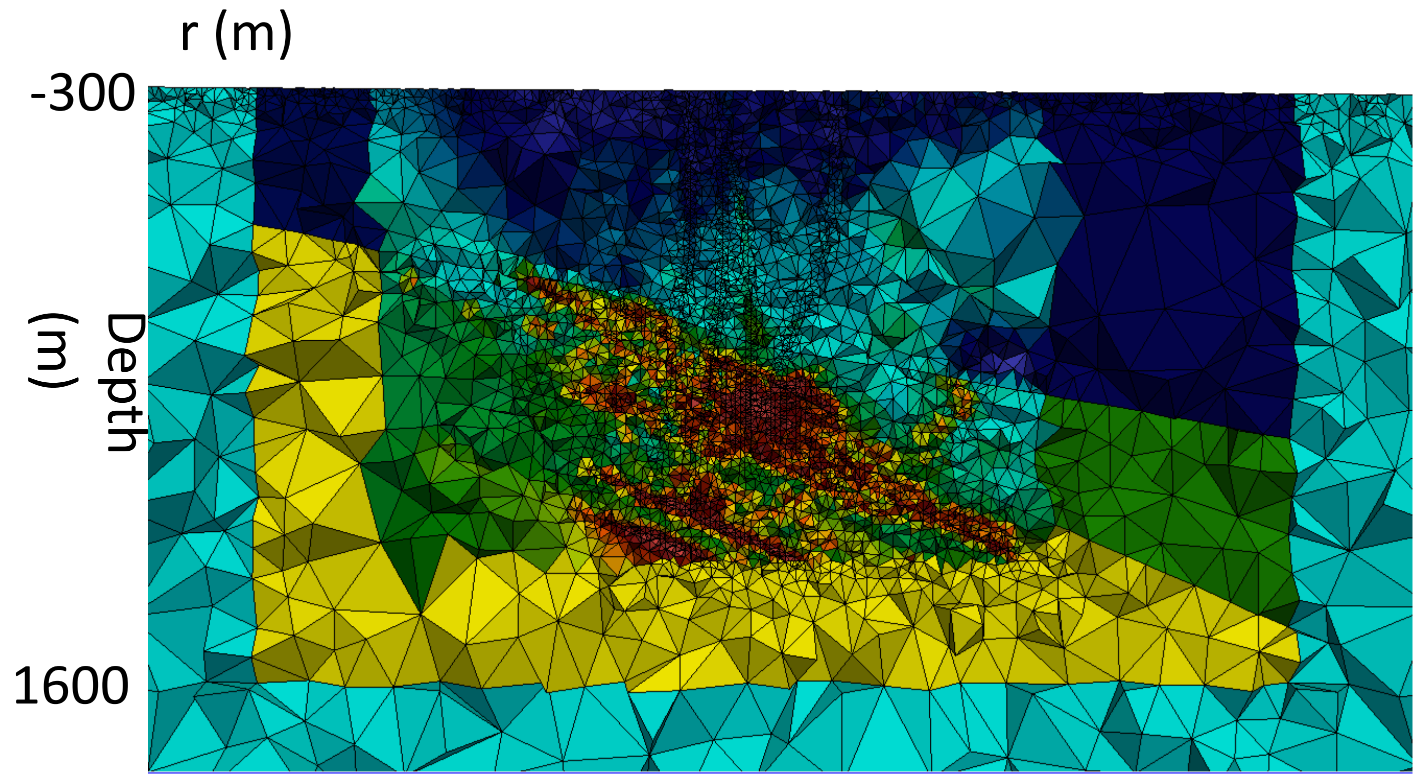
CORRIVEAU et al. 2021

Masoud Ansari
GSC Ottawa

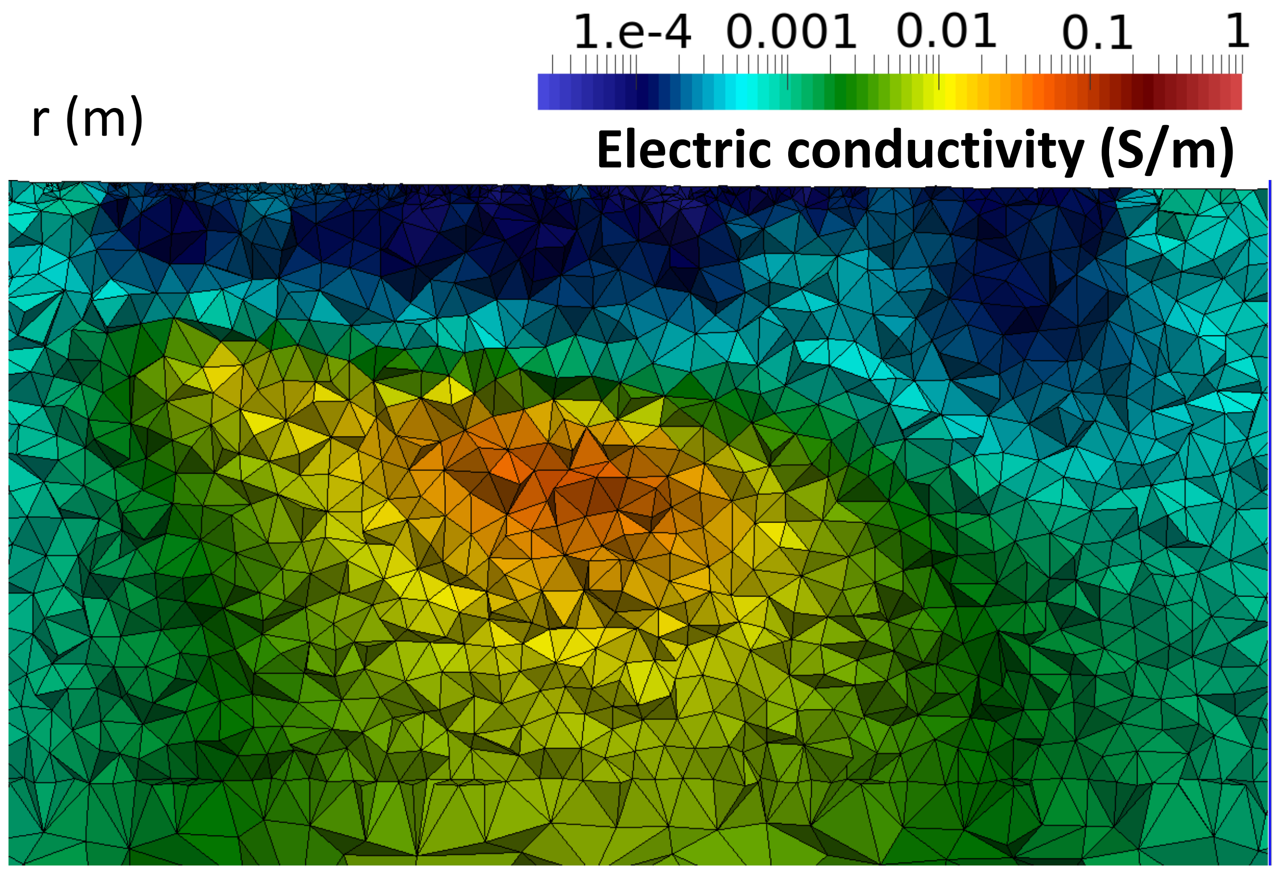
Expertise: Development of numerical modelling and inversion (optimization) algorithms for geophysical electromagnetic (EM) data

Current: working on an inversion methodology and code development for the 3D magnetotelluric (MT) data – The methodology is refined towards imaging complex geology. This is done using finite-element (FE) approximations on unstructured (irregular) meshes.

Goals: Mapping alteration with MT or EM data using these computational tools, and petrophysics; deep crustal modelling and inversion



Geological modelling + wireline log measurements



3D MT inversion

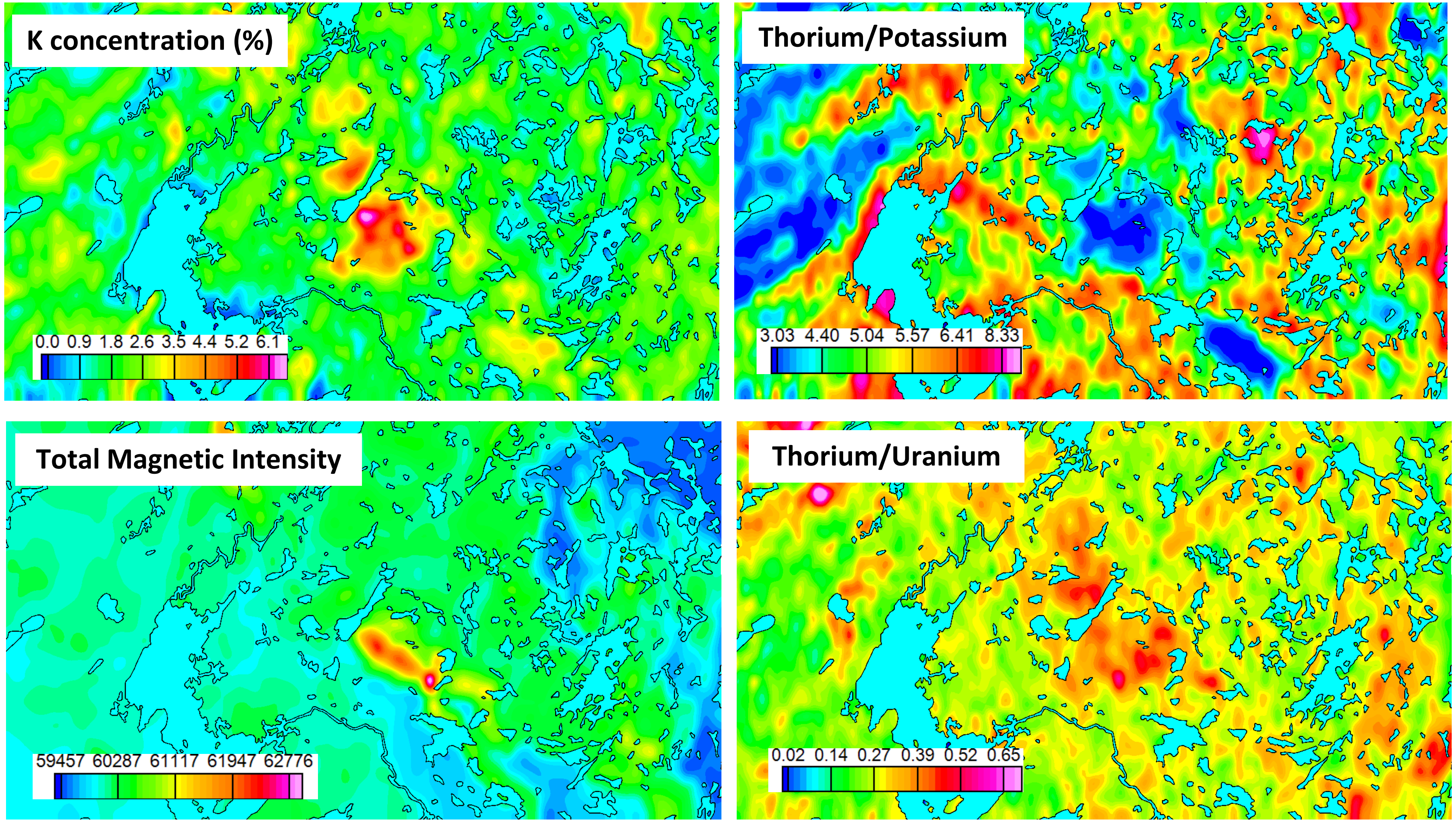
CORRIVEAU et al. 2021

Richard Fortin
Brad Harvey
Mathieu Ouellet
Airborne Geophysics Section
Geological Survey of Canada

Gamma-ray spectrometry for the characterization of MIAC systems in Canadian prospective settings

- ❑Compilation of legacy GEM-TGI in-situ gamma-ray spectrometry and susceptibility measurements for distribution in the GSC's Geophysical Data Repository.
- ❑Develop a data analysis approach for gamma-ray spectrometry in the context of MIAC systems

See also Shives et al. 2000



Gamma ray spectrometric coverage - Lou Lake IOCG system, NT
(Mazenod Lake Airborne geophysical survey, GSC, 1993)

Robin Goad
President & C.E.O.
Fortune Minerals Limited

FORTUNE MINERALS LIMITED

Collaboration with NRCan since Gandhi's days in the Great Bear

NICO Co-Au-Bi-Cu deposit in HT Ca-K-Fe alteration facies of MIAC system

Primary Co, Au co-product, 12% of global Bi reserves, by-product Cu

Received environmental assessment approval and mine permits

Completed a Socio-Economic Agreement with the NWT Government

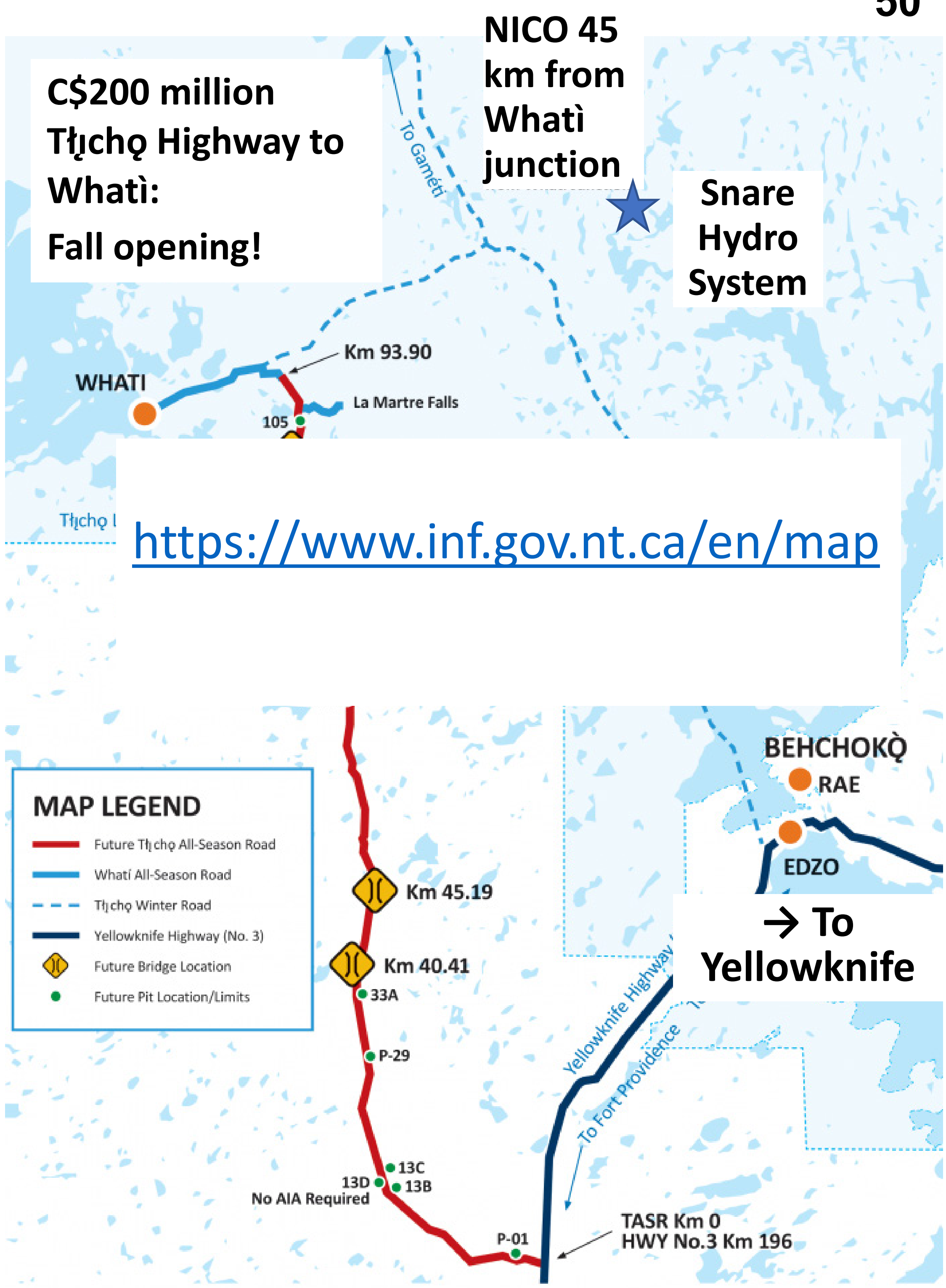
Mine+concentrator (NWT) + Co sulphate, Au, Bi ingots and oxide, and Cu cement hydrometallurgical refinery (AB or SK)

Preferred refinery site permitted + existing facilities

Access Agreement with the Tłįchǫ for road construction to NICO

Follow-up drilling planned on five targets from 2020 geophysical survey

- Coincident magnetic, chargeability and resistivity anomalies E of NICO
- Ralph Zone chargeability high, E of NICO
- Peanut Lake chargeability high anomaly (± coincident with 500m strong magnetic + gravity high with 3 m 1.76 g/t Au+ 0.1 Co; 3 m 1.8 g/t Au; 3 m 1.1 g/t Au + 0.35% Co; 3 m 1.16 g/t Au + 0.06% Co
- Moderate chargeability high 800 m SW of Peanut Lake (i.e. in Southern Breccia albitite corridor; see also Montreuil et al. 2015, 2016a,b; Hayward et al. 2016)
- Magnetic + chargeability anomalies 800 m NE of NICO (cordierite alteration)

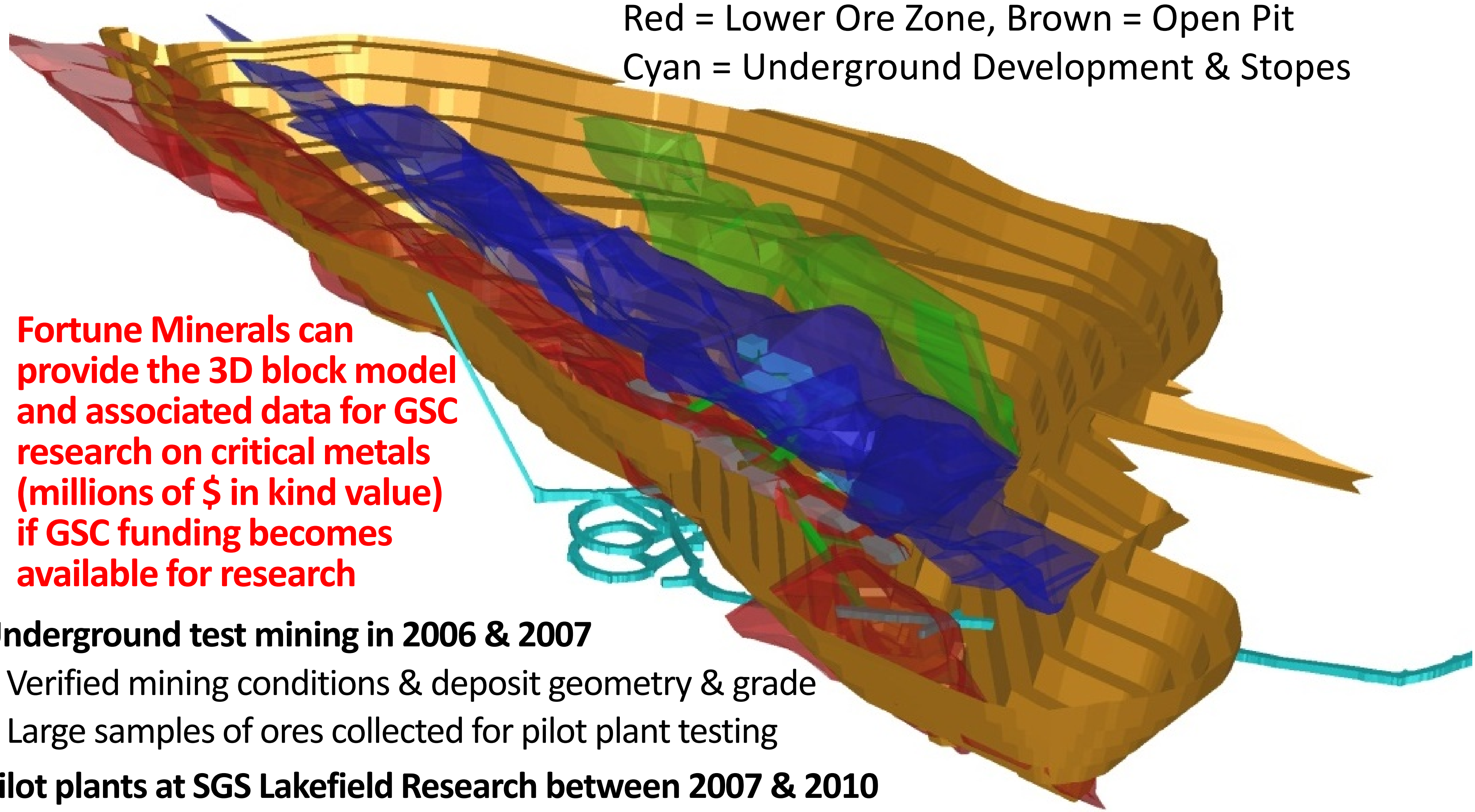


See also Goad et al. 2000; Mumin et al. 2010; Acosta-Góngora et al. 2015a, b, 2018b; Corriveau et al. 2016; Potter et al. 2019, in press

NICO Au-Co-Bi-Cu deposit An update

Open pit optimization & underground workings

Green = Upper Ore Zone, Blue = Middle Ore Zone
Red = Lower Ore Zone, Brown = Open Pit
Cyan = Underground Development & Stopes



NICO Mineral Reserves based on 327 drill holes, surface trenches & underground test mining

- 3 ore lenses up to 1.3 km long, 550 m wide, & 70 m thick with combined mining widths typically > 100 m for low-cost open pit mining
- Ore in ironstone breccia (Fe oxide & silicates) with ~5 sulphides containing economic metals

Fortune Minerals can provide the 3D block model and associated data for GSC research on critical metals (millions of $ in kind value) if GSC funding becomes available for research

See also Goad et al. 2000; Burgess et al 2014

Underground test mining in 2006 & 2007

- Verified mining conditions & deposit geometry & grade
- Large samples of ores collected for pilot plant testing

Pilot plants at SGS Lakefield Research between 2007 & 2010

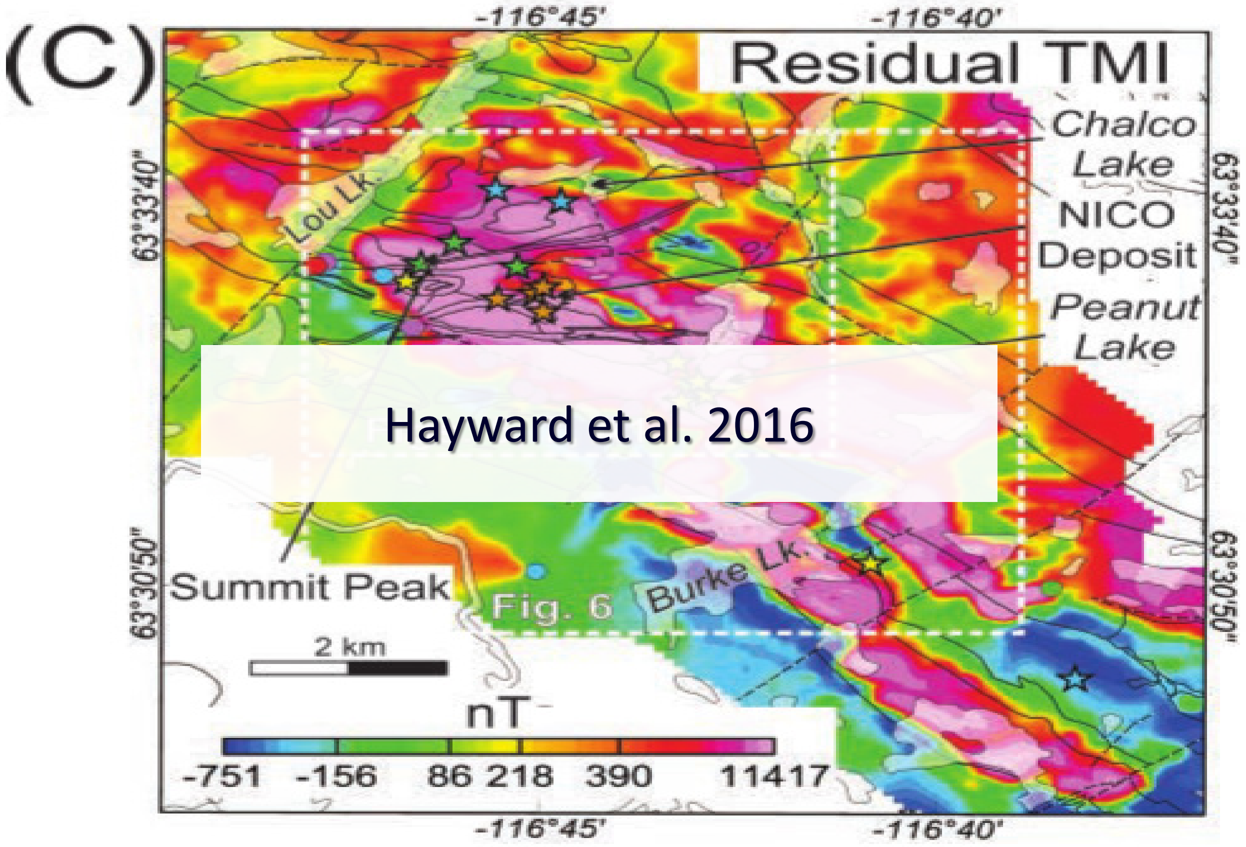
Validated process flow sheets, metallurgical recoveries & produced samples for product testing

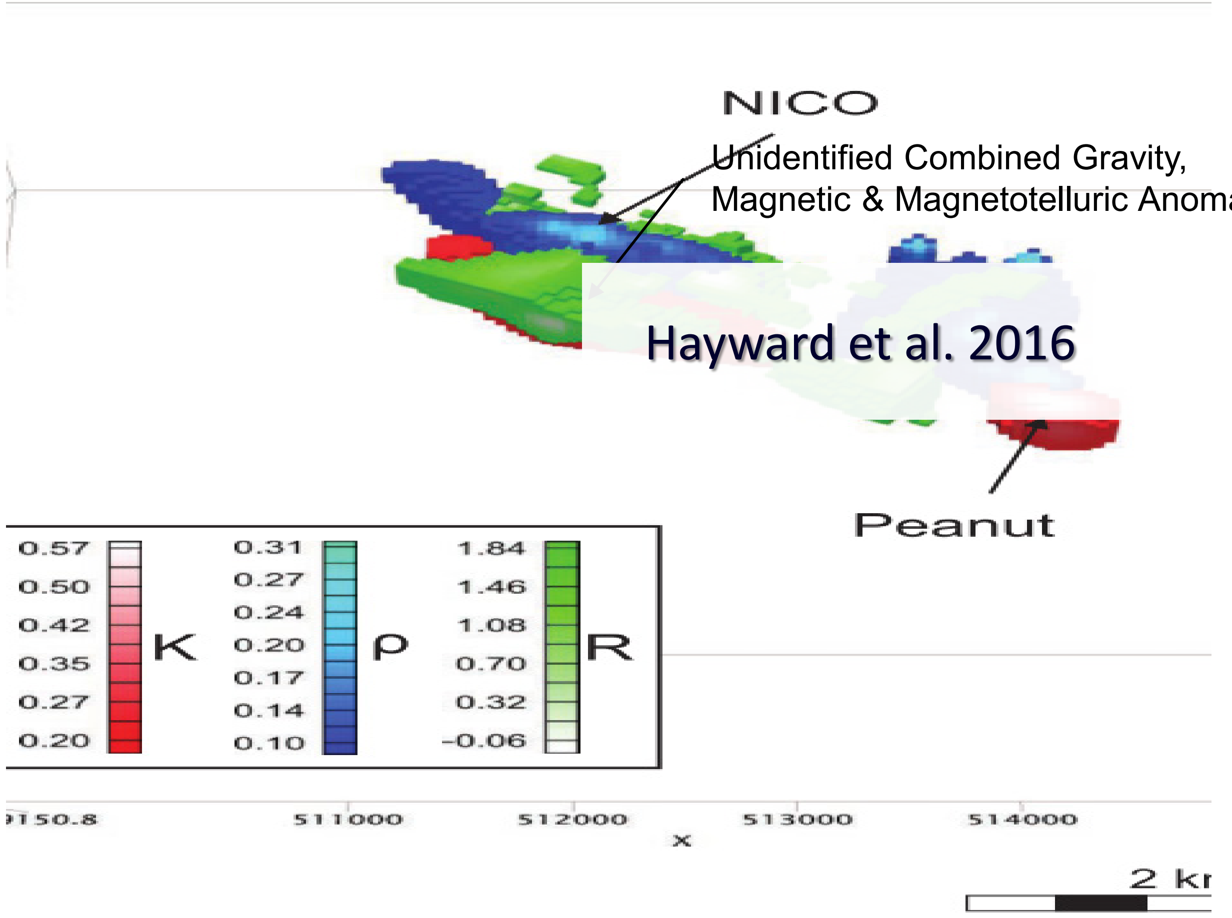
- Crushing, grinding, bulk & secondary flotation
- High pressure acid leach (HPAL) of cobalt concentrate & bismuth leach residue + gold recovery
- Cobalt carbonate precipitation, solvent extraction & ion exchange, electro-winning & cobalt sulphate crystallization
- Ferric chloride leach of bismuth concentrate followed by electro-winning to cathode & smelting
- Environmental characterization of all waste products

CORRIVEAU et al. 2021

Additional resource potential

- Significant potential to identify new resources drill testing surface mineralization & geophysical targets
- Geological Survey of Canada (GSC) identified large coincident magnetotelluric, gravity & magnetic anomalies an order of magnitude larger & stronger than NICO deposit anomaly beneath the known deposit & mantled by copper mineralization that may represent down-faulted extension of deposit
- Copper mineralization identified near Peanut Lake where coincident magnetic, magnetotelluric & gravity anomalies were identified along faulted east strike extension of NICO deposit & remain untested





Source: GSC & its reprocessing of Fortune magnetic & gravity data

CORRIVEAU et al. 2021

Critical minerals project challenges

- **Governments have identified Critical Minerals needed for the transformation to new technologies**
  - Essential uses in manufacturing & defense industries, not easily substituted by other minerals & supply chains threatened by geographic concentration of production & geopolitical risks
  - Cobalt, Bismuth & copper all identified as Critical Minerals
- **Advancements in technologies evolve faster than the resource industry can identify & develop new deposits for supply / demand alignment**
  - Exploration is in decline & only 1 in 1,000 prospects is commercially viable
  - Mineral deposits typically take 15-20 years to develop after a mineral deposit is first identified
  - Critical Minerals market opportunities are not well understood by the investment community & are difficult to attract risk capital
- **Critical Minerals projects cannot be processed in most existing downstream smelters & refineries**
  - Refineries not situated in North America
  - Existing plants not configured to process feed sources from other projects or complex materials
  - Poor metallurgical recoveries using conventional smelting techniques
  - Existing plants cannot recover by-products & / or charge excessive penalties
  - Refineries owned by large companies not focussed on specialty metals that aren't part of their primary business
- **Critical Minerals projects must typically fund their own vertically integrated process facilities**
  - Adds significant capital costs to development projects making them difficult to finance
  - Increases the technical & financial risks
  - Deposits typically do not have the required size or grade to justify the additional investment in a refinery

FORTUNE MINERALS LIMITED

Ontario

Ministry of
Northern Development, Mines
Natural Resources and Forestry

Shirley Peloquin (PhD, PGeo)
Sudbury District Geologist, Resident Geologist Program, Ontario Geological Survey
shirley.peloquin@ontario.ca; 1-705-280-6042

Experience:
- 35 years experience: industry, academia and government
- worked in Ontario, Manitoba, Québec and Newfoundland
- worked on VMS, gold, and nickel deposits

Current Interests:
- Mineral deposits in the Sudbury RGP District (Grenville, Southern & Superior provinces)
- Particularly « uncommon » commodities or mineralization types

IOCG

Area of Interest (Sudbury RGP District):

Historically the « Huronian Gold Belt » (includes Lake Wanapitei area)
- Scadding deposit first proposed as modified IOCG by Schandl & Gorton 2007

Work plans:

Compile Data from OGS (Mineral Deposit Inventory, etc.) and from Assessment Files
- indications of IOCG relationship

Collaborate and consult within the OGS

Request to collaborate with private sector
- property visits (when COVID restrictions lifted)
- possible information access (photographs, samples or analyses)

Discussion and informal collaboration with GSC and other entities to advance knowledge to everyone's mutual benefit, providing non-confidential data for integration into large-scale robust model

Barun Maity
Sault Ste Marie District Geologist, Resident Geologist Program, Ontario Geological Survey
Barun.Maity@ontario.ca
705-257-5931

Experience:

- Ten years of graduate research and analytical experience in Precambrian geology, petrology, lithogeochemistry, isotope geology, mineral chemistry, structure and field mapping.
- Four years of industry experience in iron ore (Zimbabwe) and coal bed methane (India) exploration.

Current Projects:

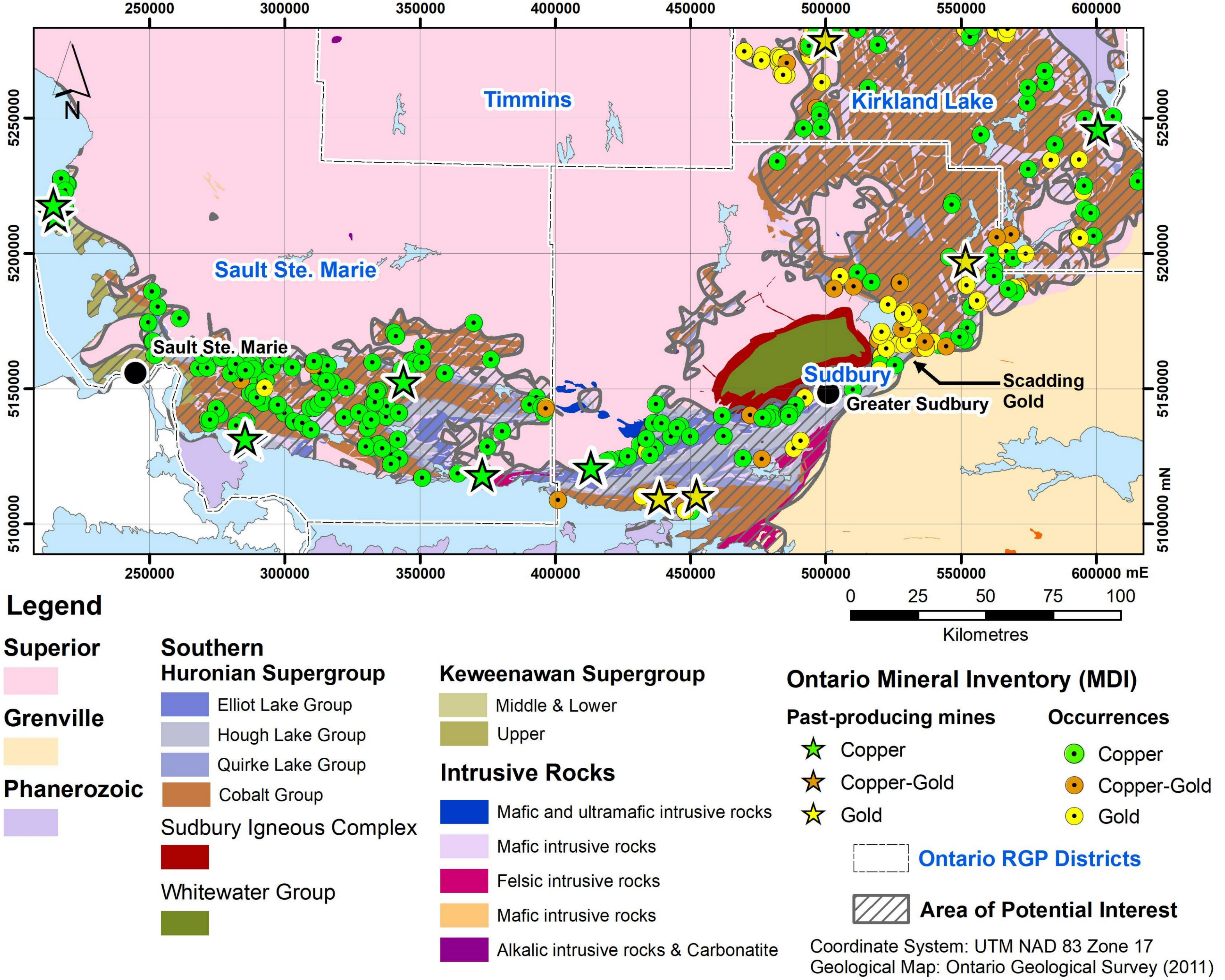
- Delineate mineral deposits systems in SSM.
- Identify occurrences of deposit-scale Critical Minerals in SSM.
- Assist in the discovery of IOCG systems in SSM.
- Collaborate with the geoscientists from the OGS, GSC, industry and academia.

Ontario

Ministry of
Northern Development, Mines

Area of Potential Interest

- Proterozoic in age
  - Huronian Supergroup
- Common alterations recognized include sodium, potassium, iron, calcium and silica (highly variable)
- Copper and copper-iron sulphides, iron oxide, gold
- Uranium in area commonly placer
- Silver-Cobalt (veins)
- Brecciated country rocks



Schandl, E.S. and Gorton, M.P. 2007. The Scadding gold mine, east of the Sudbury Igneous Complex, Ontario: An IOCG-type deposit?; The Canadian Minerologist, v.45, p.1415-1441.

Farrow, D. 2016. Soda metasomatism as a possible iron oxide-copper-gold (IOCG) deposit indicator in the Sudbury District; *in* Ontario Geological Survey, Resident Geologist Program, Recommendations for Exploration 2016–2017, p.65-67.

Ontario

Ministry of
Northern Development, Mines
Natural Resources and Forestry

R. Michael Easton, PhD, PGeo

Geoscience Leader, Proterozoic and Northwest Planning Groups
Earth Resources and Geoscience Mapping Section, Ontario Geological Survey
Email: Mike.easton@ontario.ca

Experience:
- 45 years experience: government and industry
- worked in Ontario, Northwest Territories
- adjunct professor, Carleton University, Ottawa

Interests:
- mapping, geochronology, geochemistry, metamorphic petrology, volcanology

Responsibilities:
- project planning and technical reviews of all ERMGS projects in the Proterozoic in Ontario (Grenville & Southern provinces, Midcontinent Rift, carbonatites)

MIAC:
- calcite-apatite-diopside-mica veins in the Ontario Grenville Province, felsic IOA systems?
- iron oxide-phosphate mineralization in mafic phases of the Frontenac intrusive suite

Ontario

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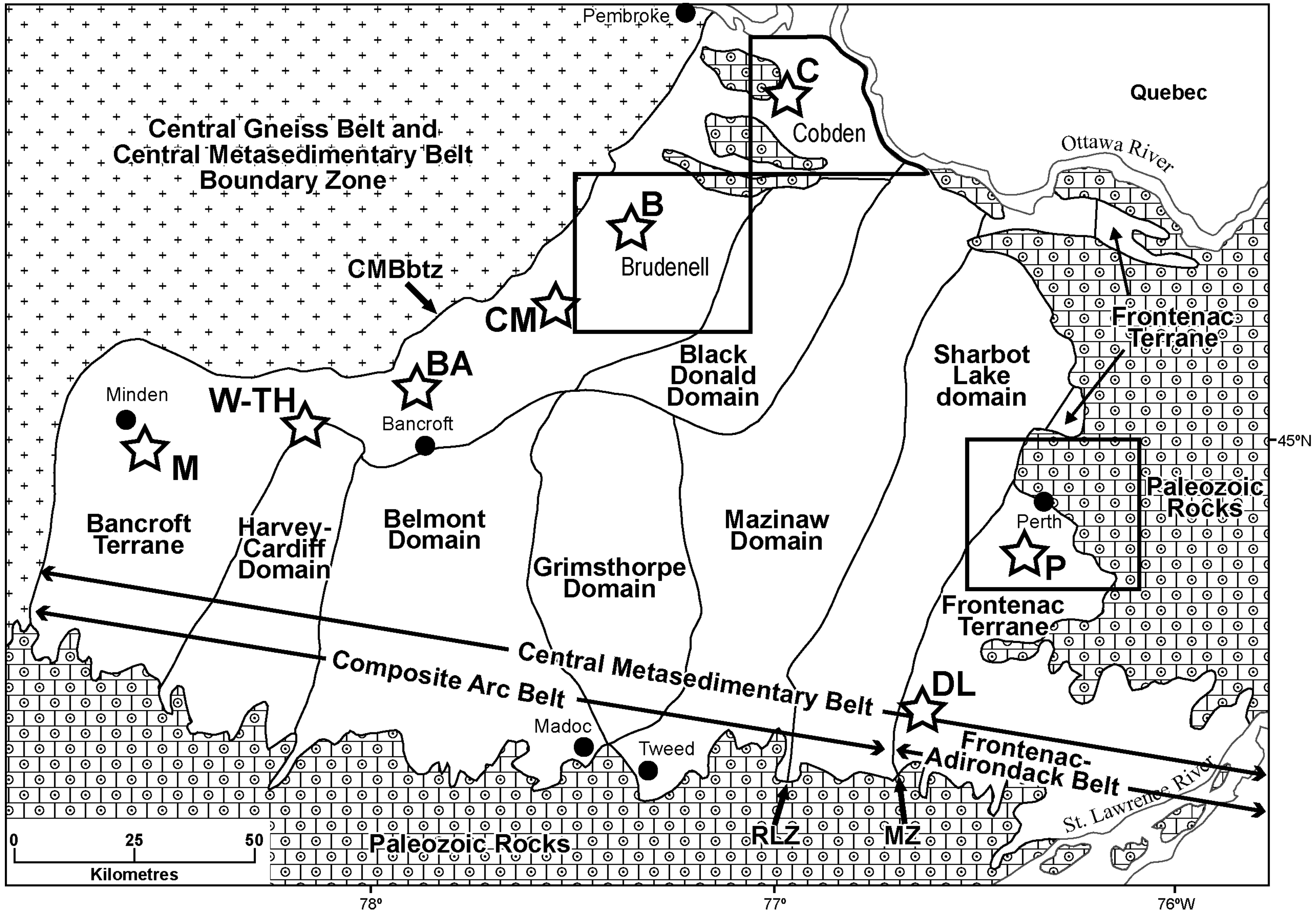
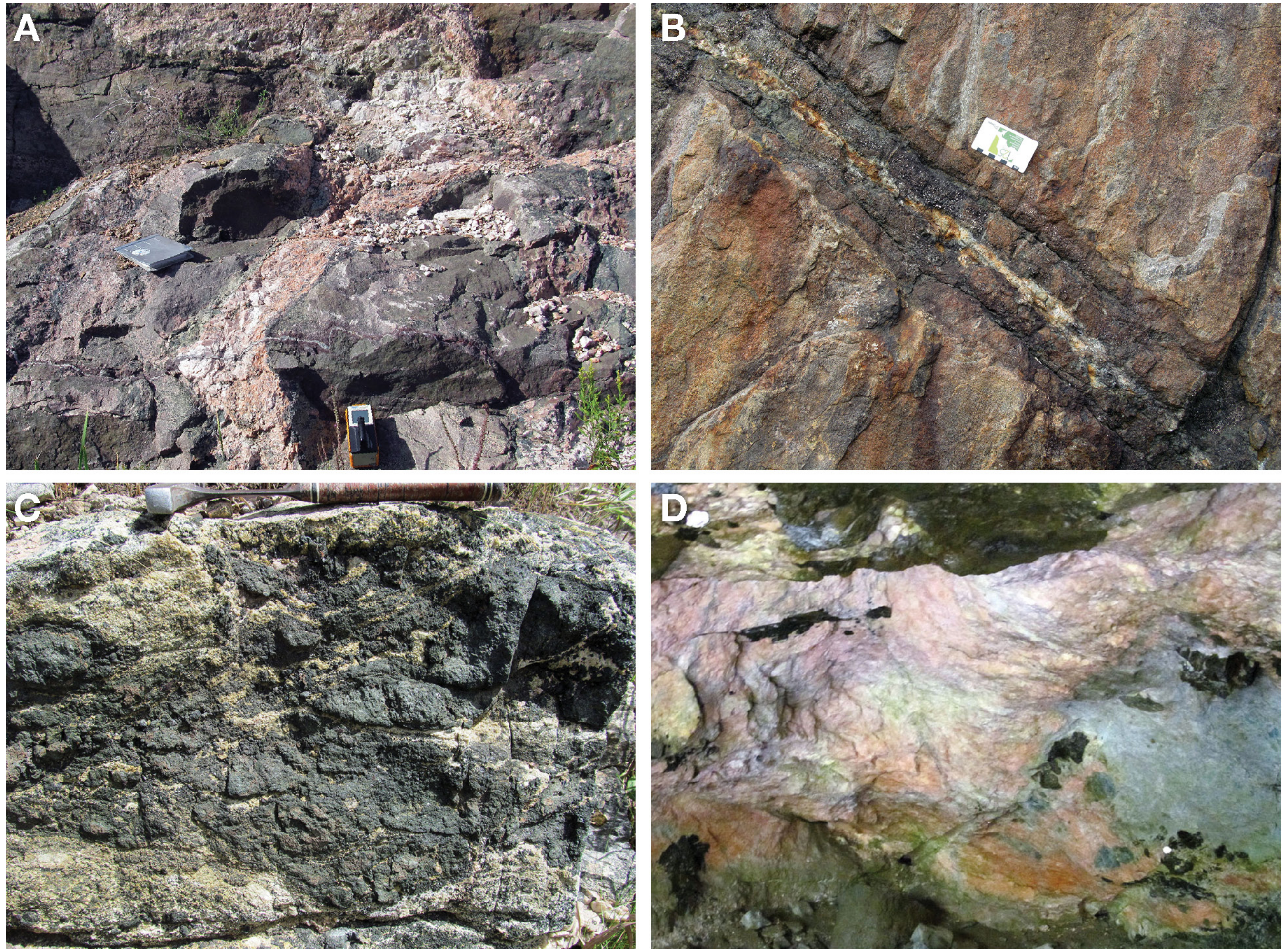
Calcite-apatite vein distribution





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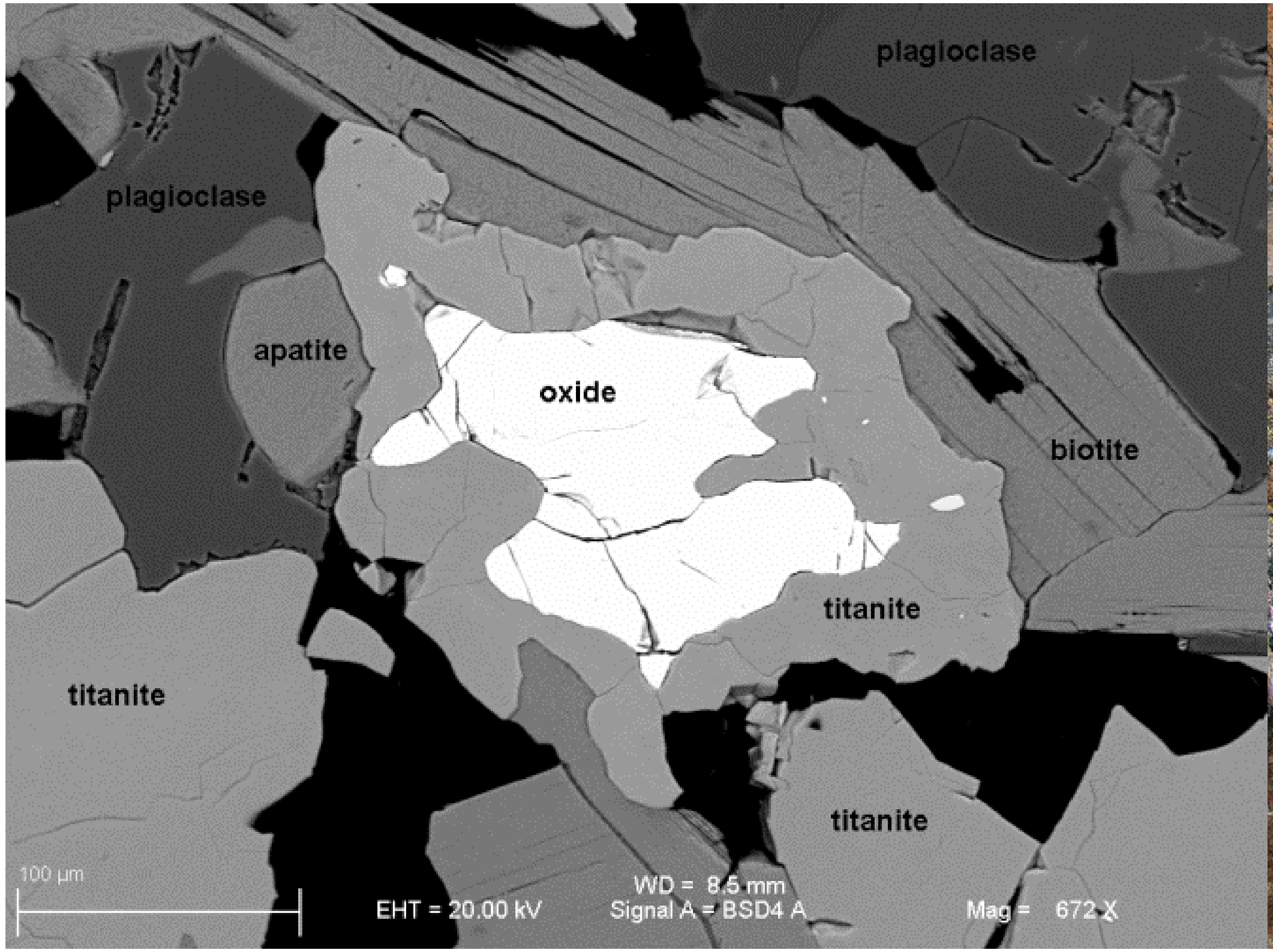
Frontenac suite



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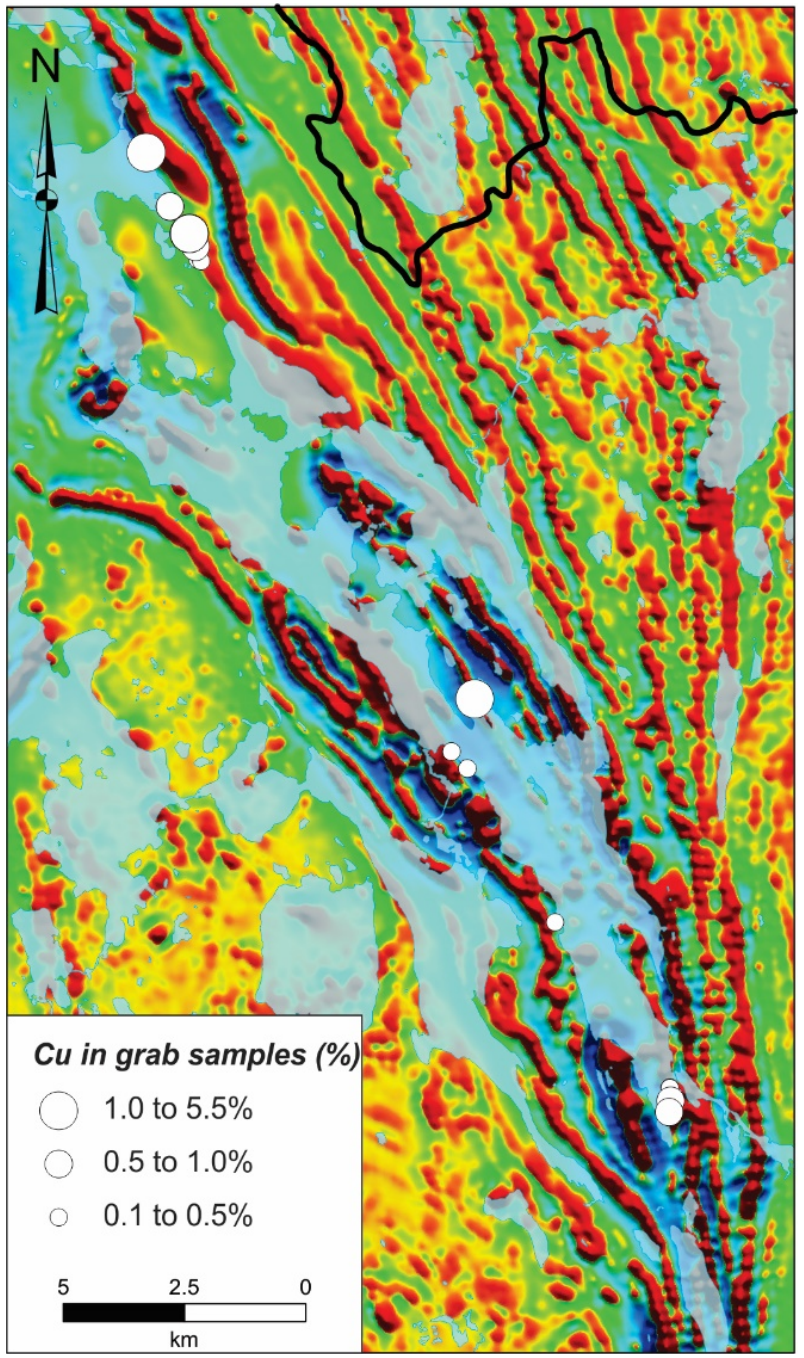
James Conliffe
Project Geologist
Government of Newfoundland and Labrador

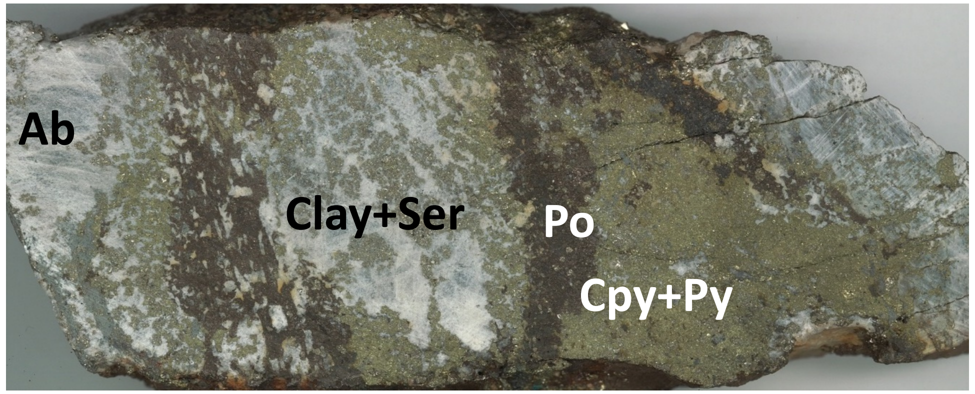
MIAC systems in the Labrador Trough

- MIAC systems and associated polymetallic mineralization have been recognized in the Romanet Horst and Andre Lake areas, Labrador Trough, Canada (Corriveau et al., 2014; Conliffe, 2020)
- Historical data includes drilling from the Labrador section in the 1960s with descriptions of strong biotite-magnetite alteration (HT K-Fe) with up to 0.3% Cu
- 2021-22 Project Objectives
  - Review of historical data from exploration to identify MIAC alteration
  - Regional geochemical sampling and plotting new lithogeochemical data on alteration facies diagrams



2VD magnetic map of Andre Lake area, showing anomalous Cu values in grab samples

Brecciated, albite-altered shale from Montgomery Lake Prospect, Andre Lake area

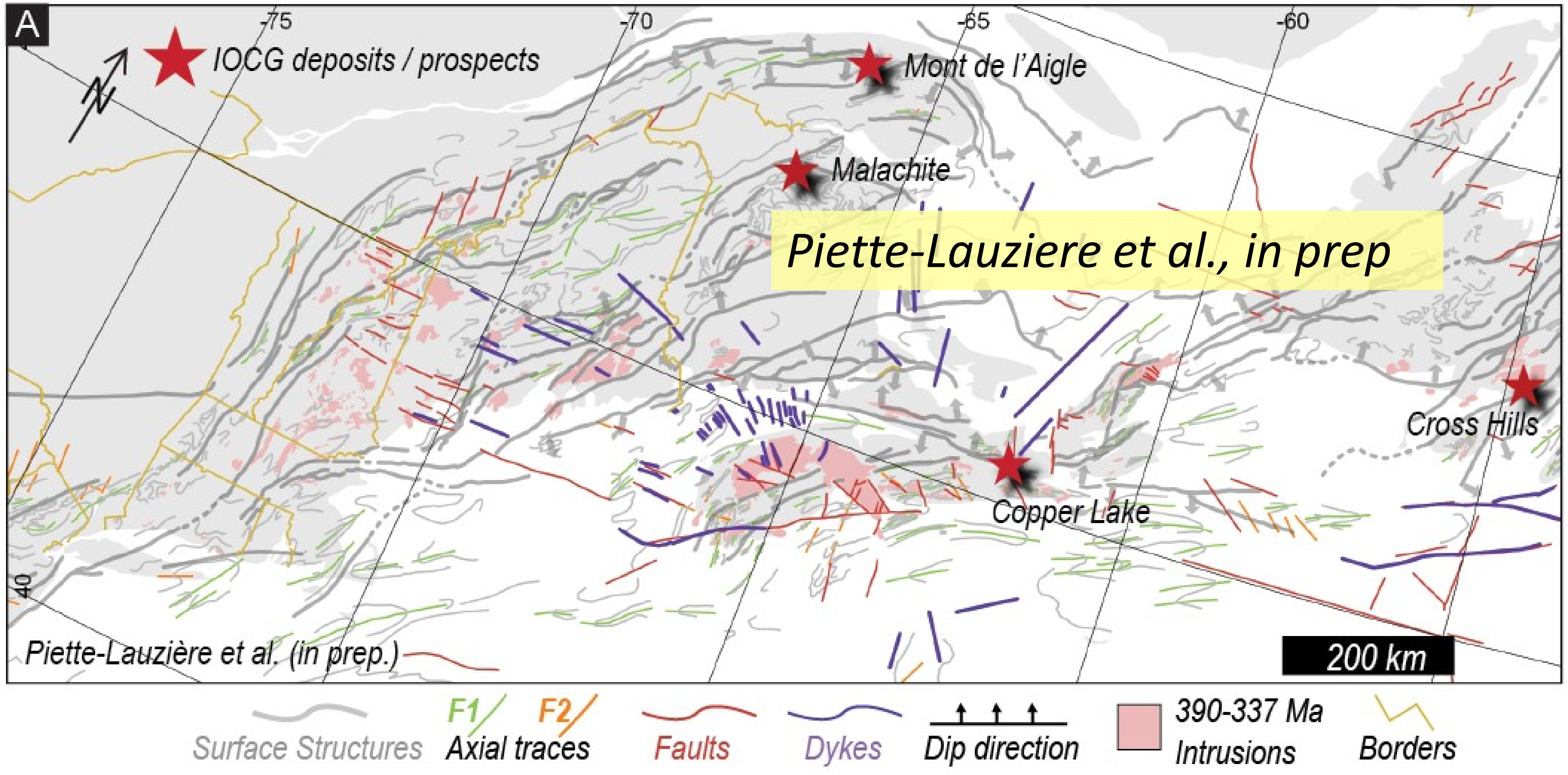


Polymetallic Cu-Ag-Au-(Co-Zn) mineralization from Delhi Pacific – Chibtown Prospects, Romanet Horst

CORRIVEAU et al. 2021

Dawn Kellett and Neil Rogers
Research scientists, Geological Survey of Canada
Appalachian Deep Time TGI-6 sub-activity

An orogen-scale framework to place IOCG and affiliated mineralization into context for MIAC-related TGI-6 research

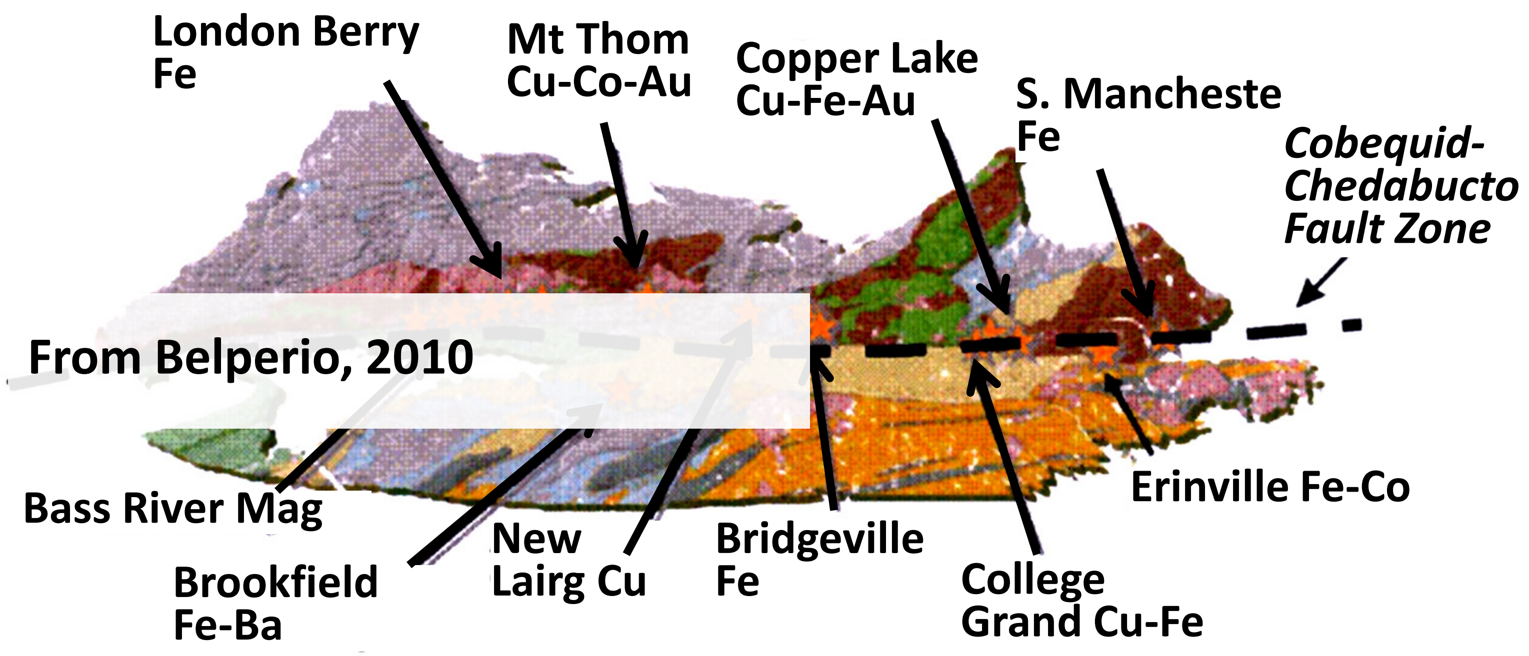


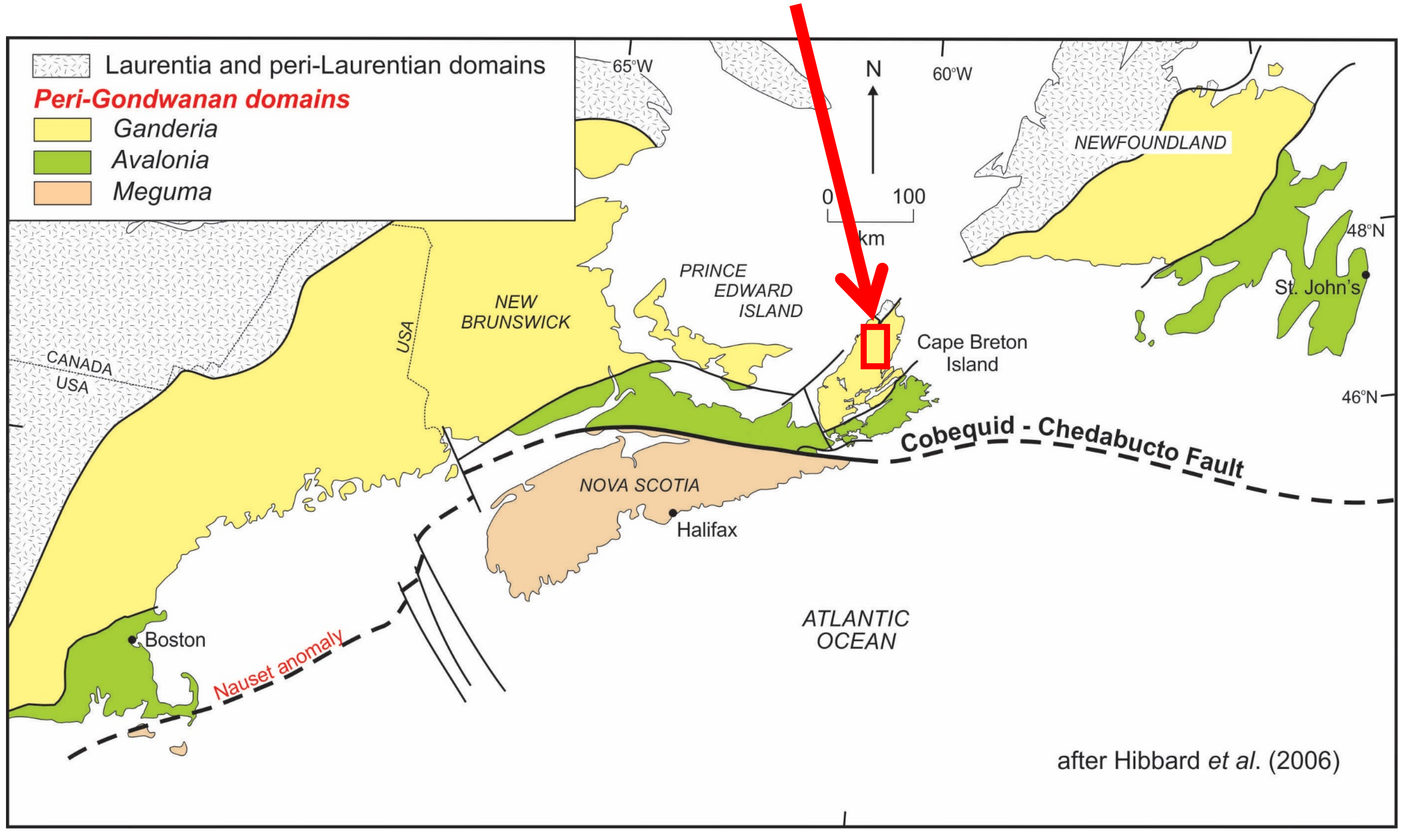
- Multiple generations of overlapping mineralizing events generated during progressive accretionary orogenesis
- Formed spatially and temporally heterogeneous ore systems
- Siluro-Devonian, post-orogenic granitoid-related mineralization in particular contain a wide array of critical minerals, distribution of which is genetically linked with the interactions of earlier orogenic events.
- Critical processes that localize metal enrichment will be targeted by linking multiple (including new) data sources within a tectonostratigraphic plate reconstruction framework.

See Piette-Lauzière et al. 2019, 2020; Kellett et al. 2021

Geoff Baldwin
Nova Scotia Geological Survey

GAC-MAC 2019: Baldwin, G., The Highlands Gold occurrences, eastern Cape Breton Highlands, Nova Scotia: An unrecognized IOCG district?



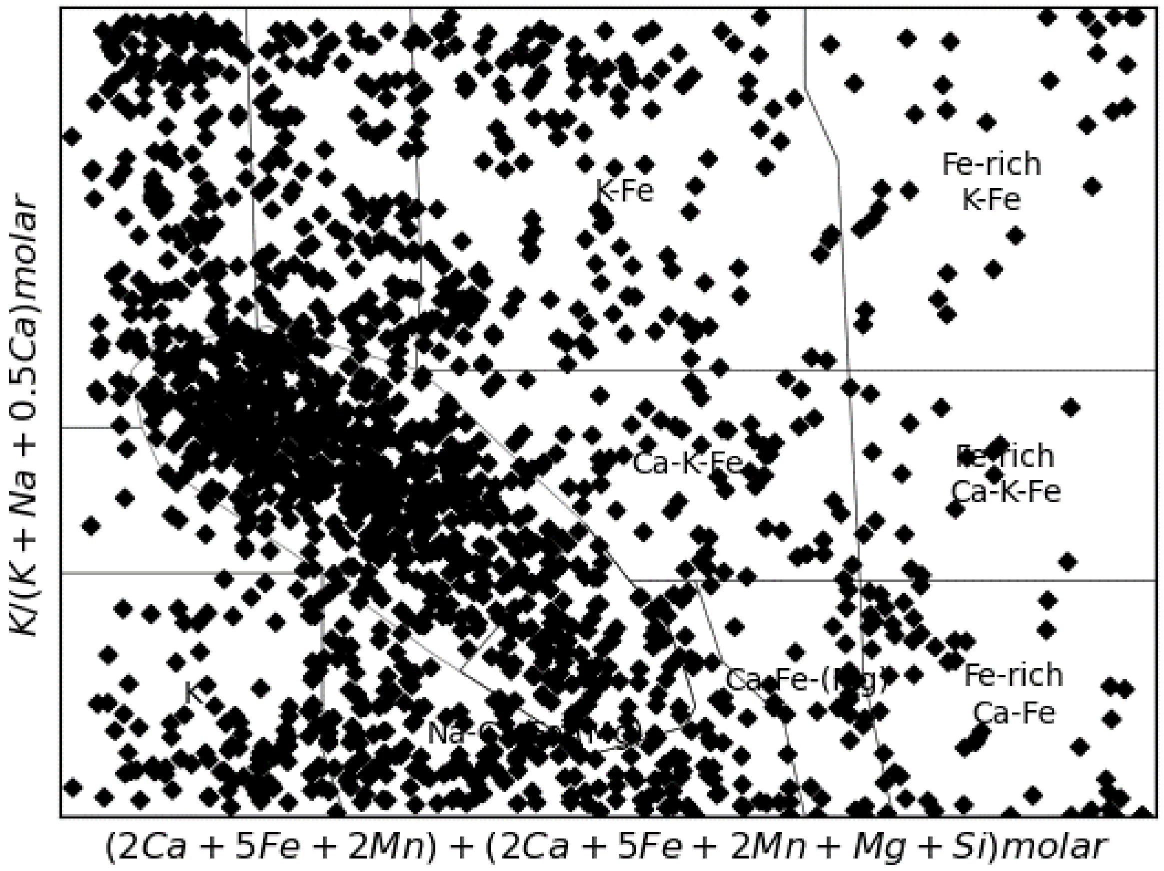


Kevin Neyedley
Nova Scotia Geological Survey

No current project plans related to IOCG/IOA deposits
Available to assist in sample collection or access to samples in our core library

Nicolas Piette-Lauzière

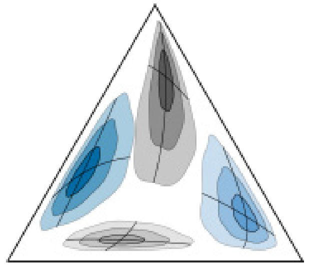
Ph.D. candidate - University of British Columbia
GSC-Québec volunteer



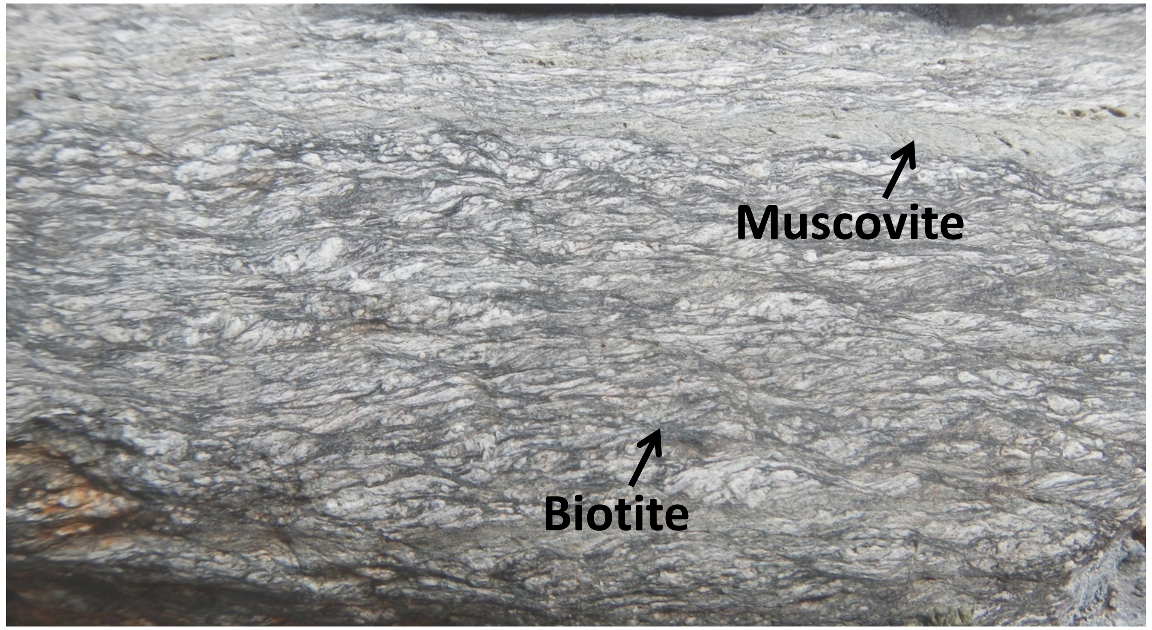
Activities:

-Implementing a routine to plot AIOCG and barcodes in the open source python package Pyrolite

-The AIOCG plot can be used as a classifier (assign alteration type to each analysis) using complementary information from barcodes to discriminate overprints or less intense alteration from samples that have the alteration types of the discriminant diagram field they plot in



pyrolite.readthedocs.io



Research interests:

-Interaction between shear zones and magmatic-hydrothermal systems

-Machine learning applied to mineral prospectivity mapping

See Montreuil et al. 2013; Piette-Lauzière et al. 2019, 2020; Blein et al. In press; Corriveau et al. In press a

Erin Adlakha
Assistant Professor
Saint Mary's University, Halifax

Field of Expertise:

- mineralogy and paragenesis of hydrothermal ore systems (UTUD, W skarn, MIAC)
- crystal chemistry of alteration minerals
- physico-chemical conditions and evolution of mineralizing systems
- mineralogical tools for mineral exploration

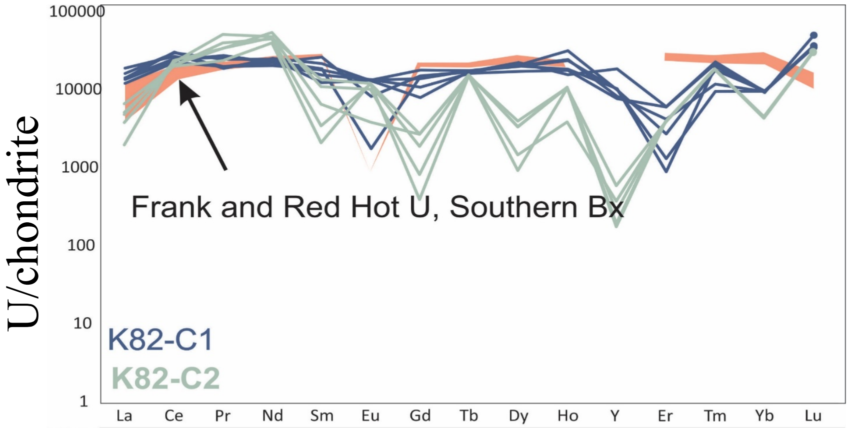
MIAC Research Activities:

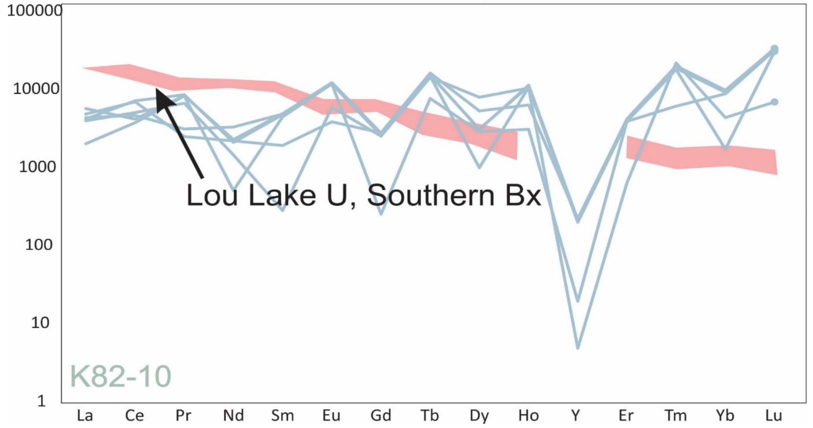
- Paragenesis and mineral chemistry of alkali-alteration zones and polymetallic (Fe-Cu-U-Au-Ag) mineralization of the Nonacho Basin, NWT
- GAC-MAC 2022 Halifax MIAC Workshop
- IOCG deposits of the Cobequid-Chedabucto Fault Zone, Nova Scotia

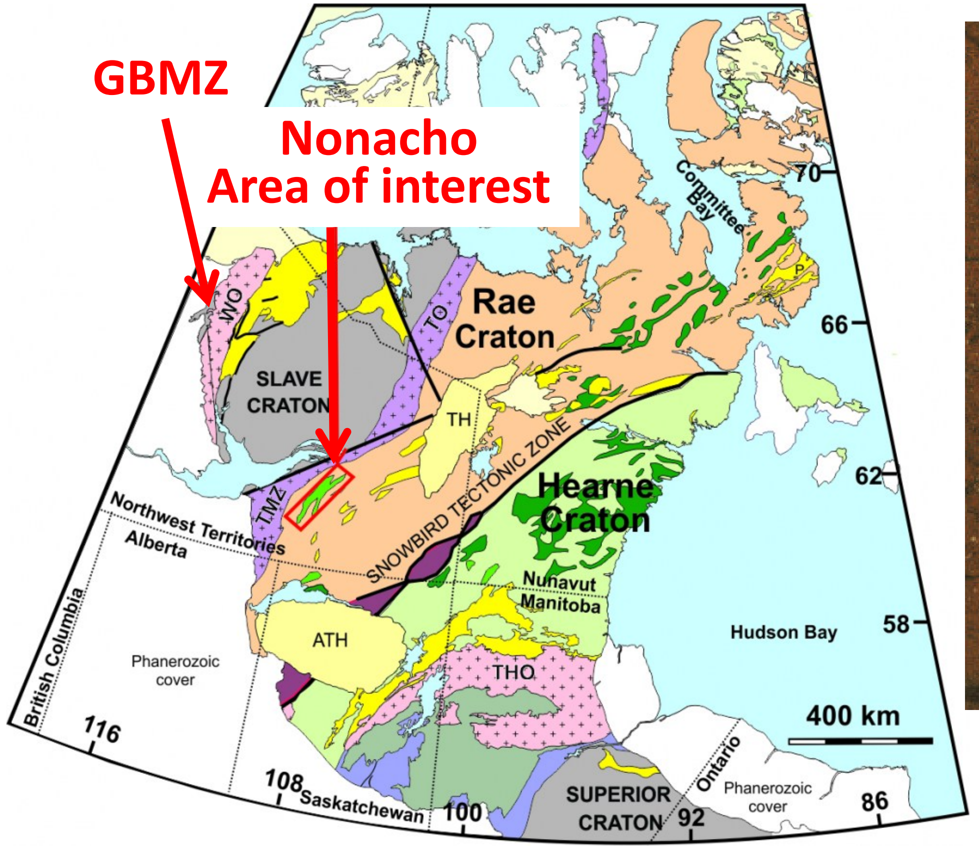
Saint Mary's University SCIENCE

NSERC CRSNG

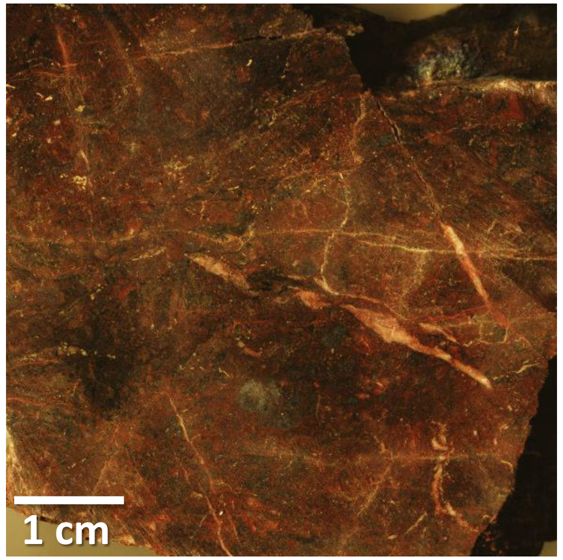
NORTHWEST TERRITORIES GEOLOGICAL SURVEY







Nonacho



5.6 wt% Fe, >1 wt% U, 400 ppm Cu

7 wt% Fe, 834 ppm U

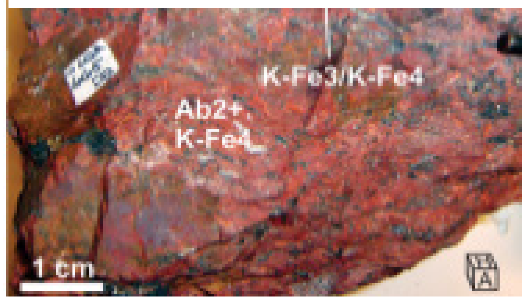
773 ppm Cu

Southern Breccia (GBMZ)

Montreuil et al. 2015

Potter et al. 2019

Potter et al. 2019



See also Adlakha et al. 2019; Potter et al. 2019, 2020, in press

CORRIVEAU et al. 2021

Anne-Aurélie Sappin

Research scientist, Geological Survey of Canada

Expertise

- Research related to Ni-Cu-PGE, Cr, and Fe-Ti-V-(P) orthomagmatic deposits, rare metal deposits
  - *Petrology, geochemistry, mineralogy, geochronology*
  - *Metallogenic and petrogenetic study*

Role in sub-activity

- Link to the magmatic felsic to alkaline mineral systems and their critical mineral resources TGI sub-activity
- Study of the Josette REE deposit (an IOA deposit in the Grenville Province)

See Sappin and Perreault 2021

Photo: M.G. Houlé

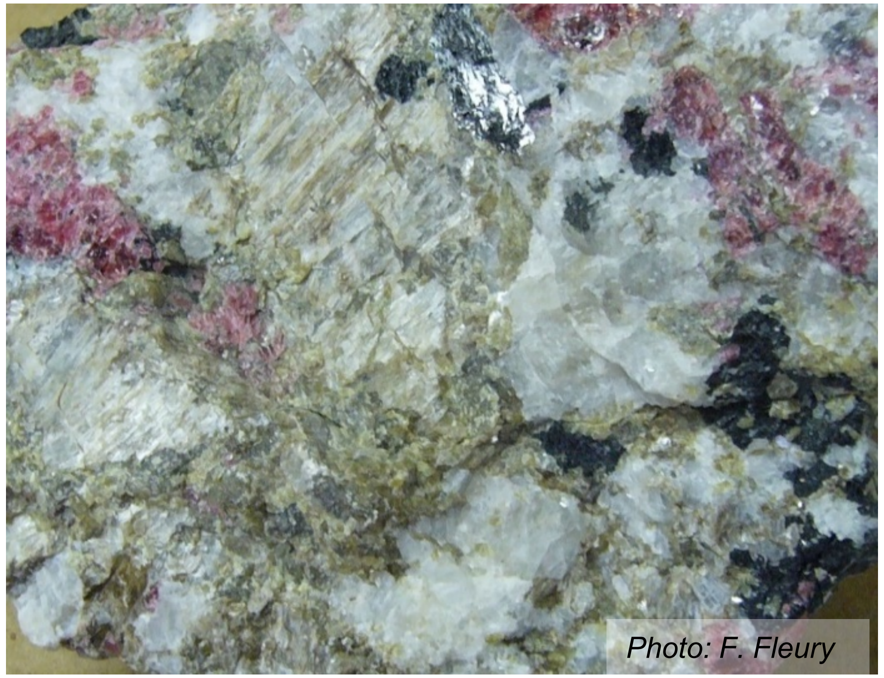
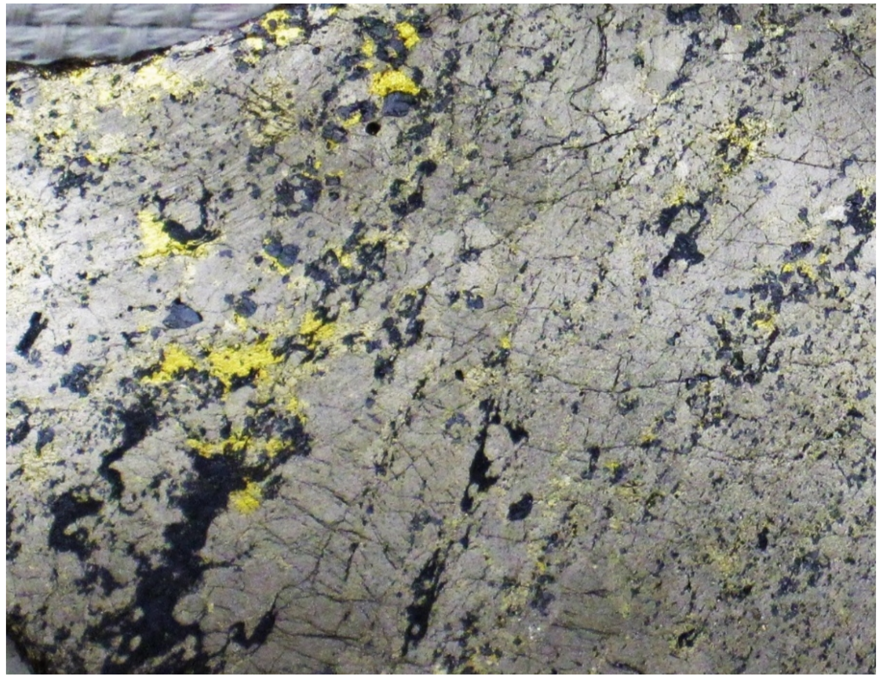


Photo: F. Fleury



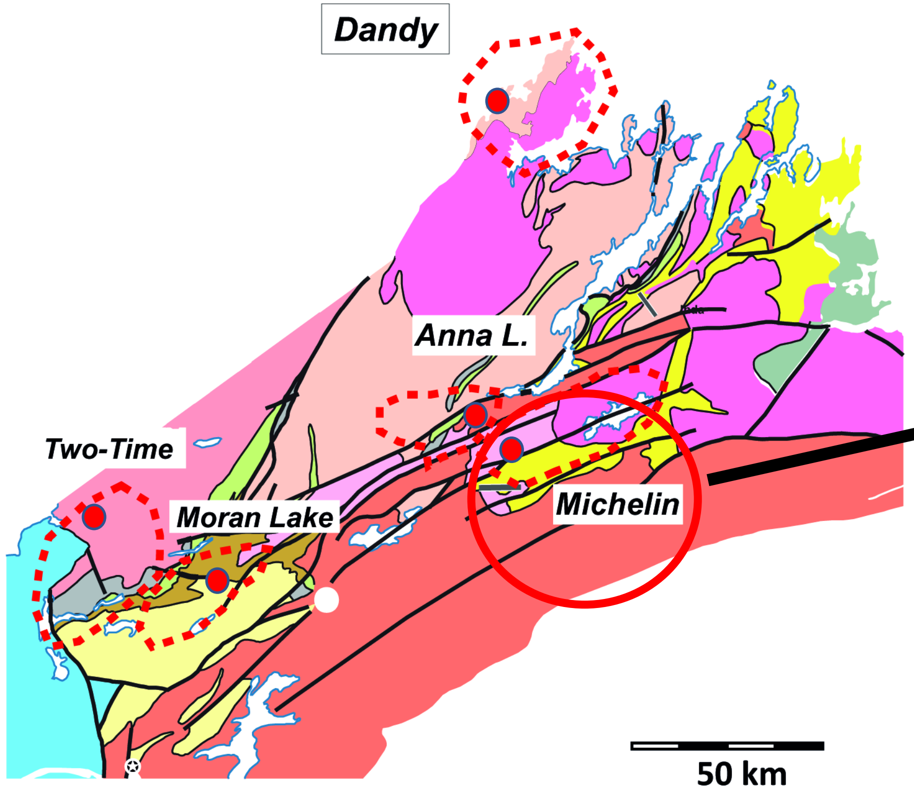
GEOLOGICAL SURVEY OF NORWAY
- NGU -

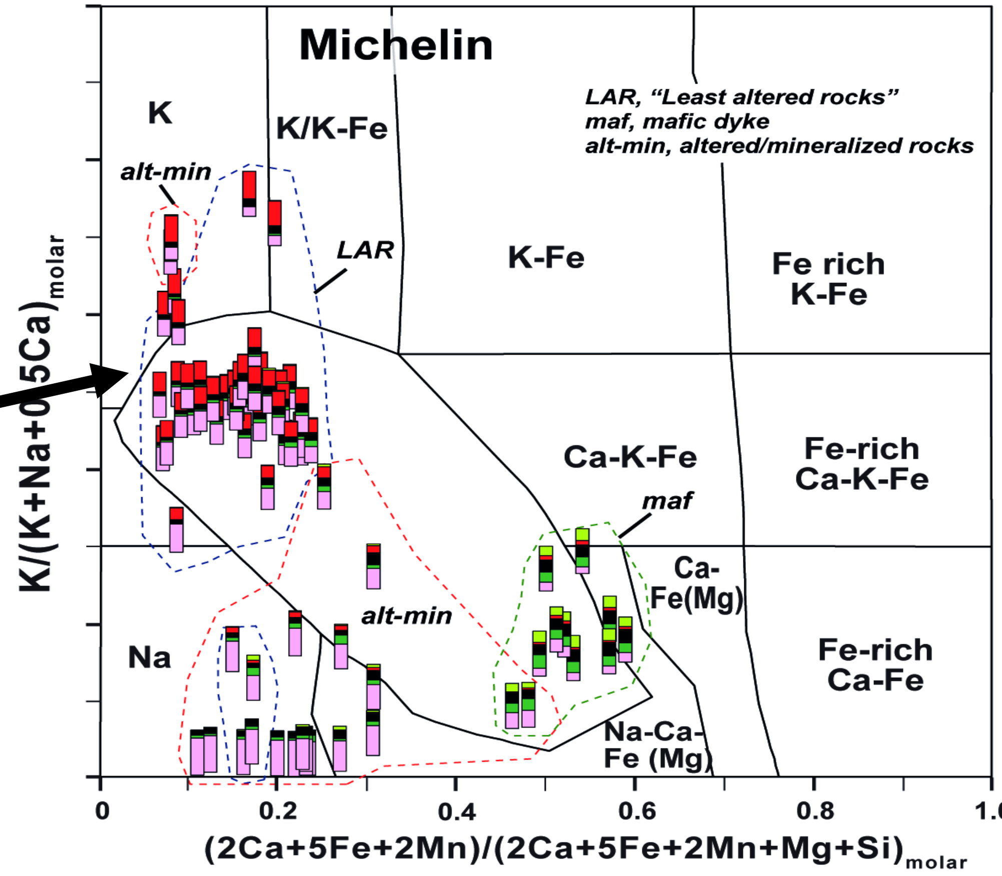
Pedro Acosta-Góngora
Geological Survey of Norway

Central Mineral Belt of Labrador, Canada: alteration type and application of unsupervised learning

Contributions to TGI:

- **Characterization and evaluation of IOAA-related alteration from rocks of the U±base±precious metal-rich Central Mineral Belt in Labrador, Canada (*manuscript submitted*)**
- **Provide guidance on the classification of samples in the IOCG diagram and elaboration of barcodes for other areas of interest.**





See Acosta-Góngora et al. 2018a, 2019; Duffet et al. 2020; Potter et al. 2021

CORRIVEAU et al. 2021

Suzanne Paradis

Geological Survey of Canada, Pacific Division
Mineral Deposits, Research Scientist

IOCG, IOA and related primary critical metal deposits in BC

Involvement in Corriveau's et al. research: Provide geological information on metasomatic iron and alkali-calcic systems with iron oxide-copper-gold (IOCG) deposits in southern BC (example, Iron Range mineralized zones, red star on Fig. 1) and critical metal deposits of BC.

The Iron Range zones is located along the Iron Range fault, a steeply dipping N-striking structure characterized by strong alteration (e.g. albitite, chloritic) and concentrations of iron oxide mineralization (iron oxide ±Cu ±Au). It is the best known IOCG locality in BC; however, others (yellow stars on Fig. 1) with IOCG-like features (i.e. alterations, breccias) exist.

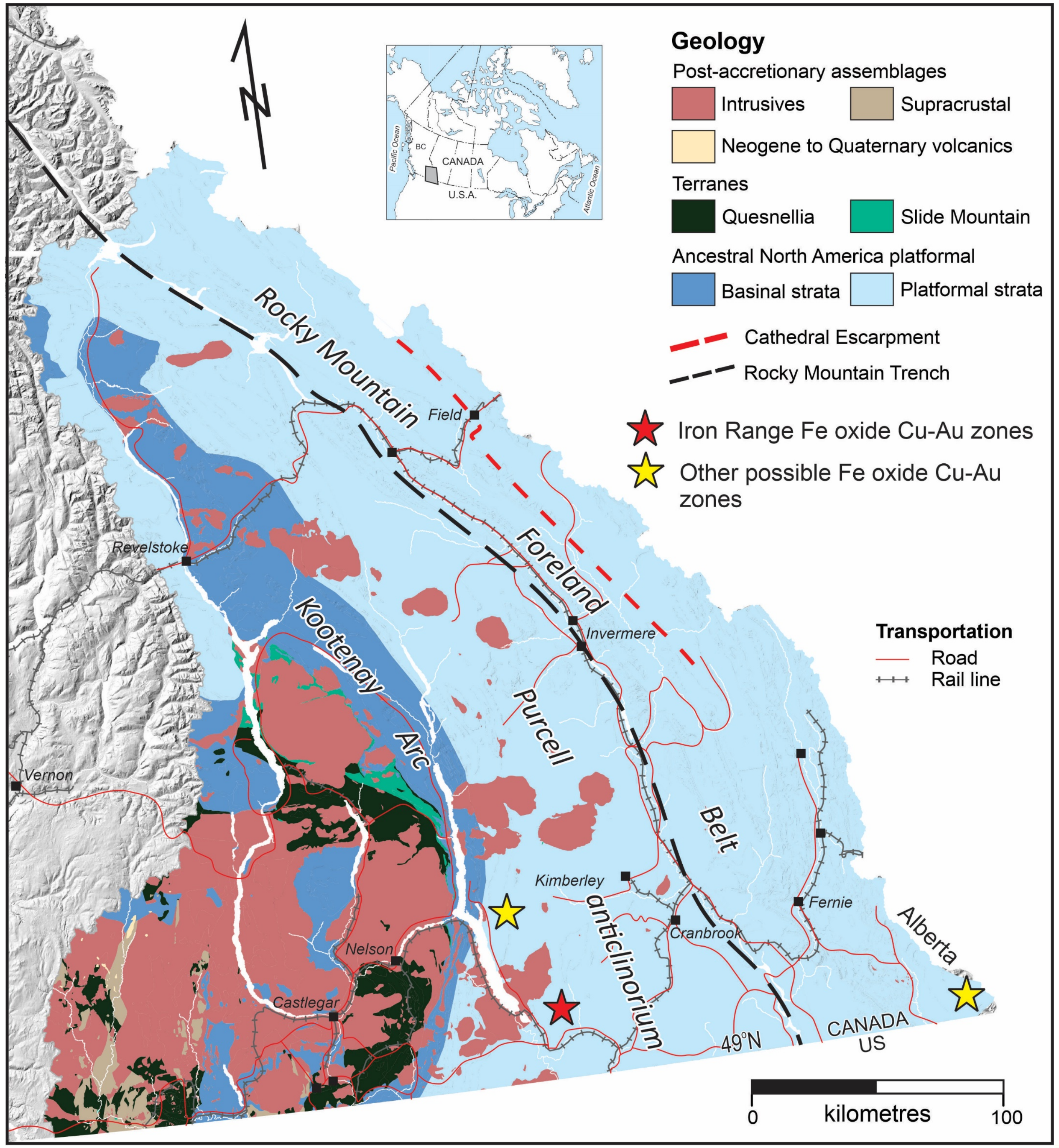


Figure 1. Regional geologic map of southern BC with location of Iron Range mineralized zones in the Purcell Basin. Modified from Katay (2017). Terranes after Cui et al. (2015).

Olivier Blein

Senior geologist, BRGM

Géosciences pour une Terre durable

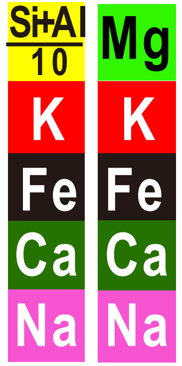
brgm

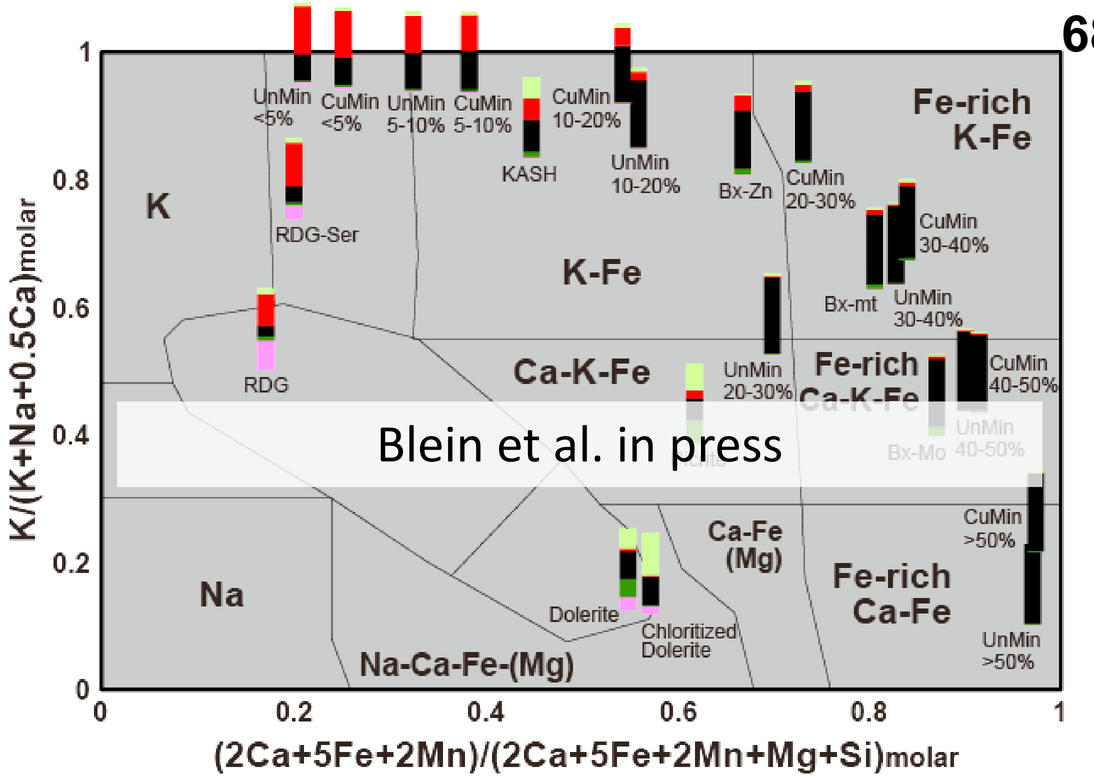
Research interest

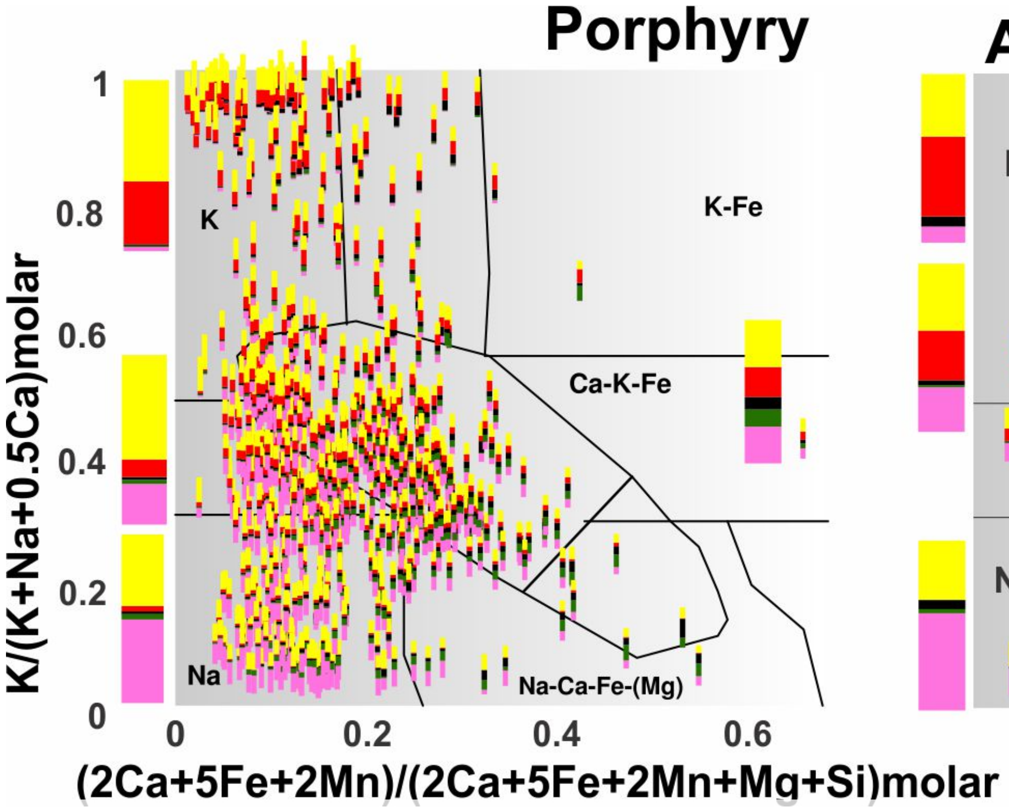
- Geochemical signatures of metasomatic rocks
  - MIAC systems
  - Molar barcodes, e.g. (Si+Al)/10, AIOCG diagram
- Panafrican belts
  - Geological mapping
    - Morocco, Cameroun, Mozambique
  - Cu-Co mineral prospectivity of Panafrican belts
- Mineralization, Craton boundary & Geodynamic setting

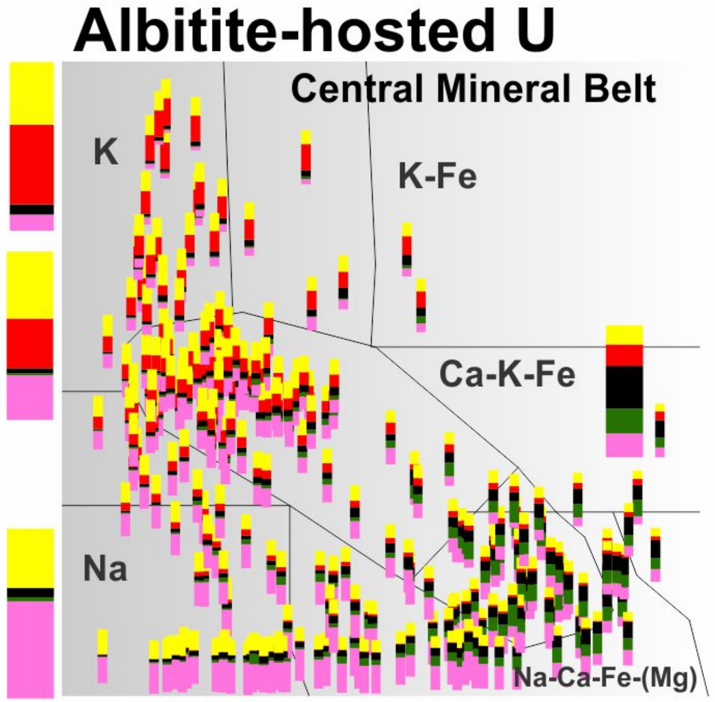
Olympic Dam units

(Ehrig et al. 2012)









See Blein et al. in press; Corriveau et al. in press a

Porphyry datasets: Dilles et al. 2000; Du Bray et al. 2007. CMB datasets : Acosta-Góngora et al. 2018a

Vladimir Lisitsin
Manager, Mineral Systems
Geological Survey of Queensland

Courteney Dhnaram
Senior geoscientist
Geological Survey of Queensland

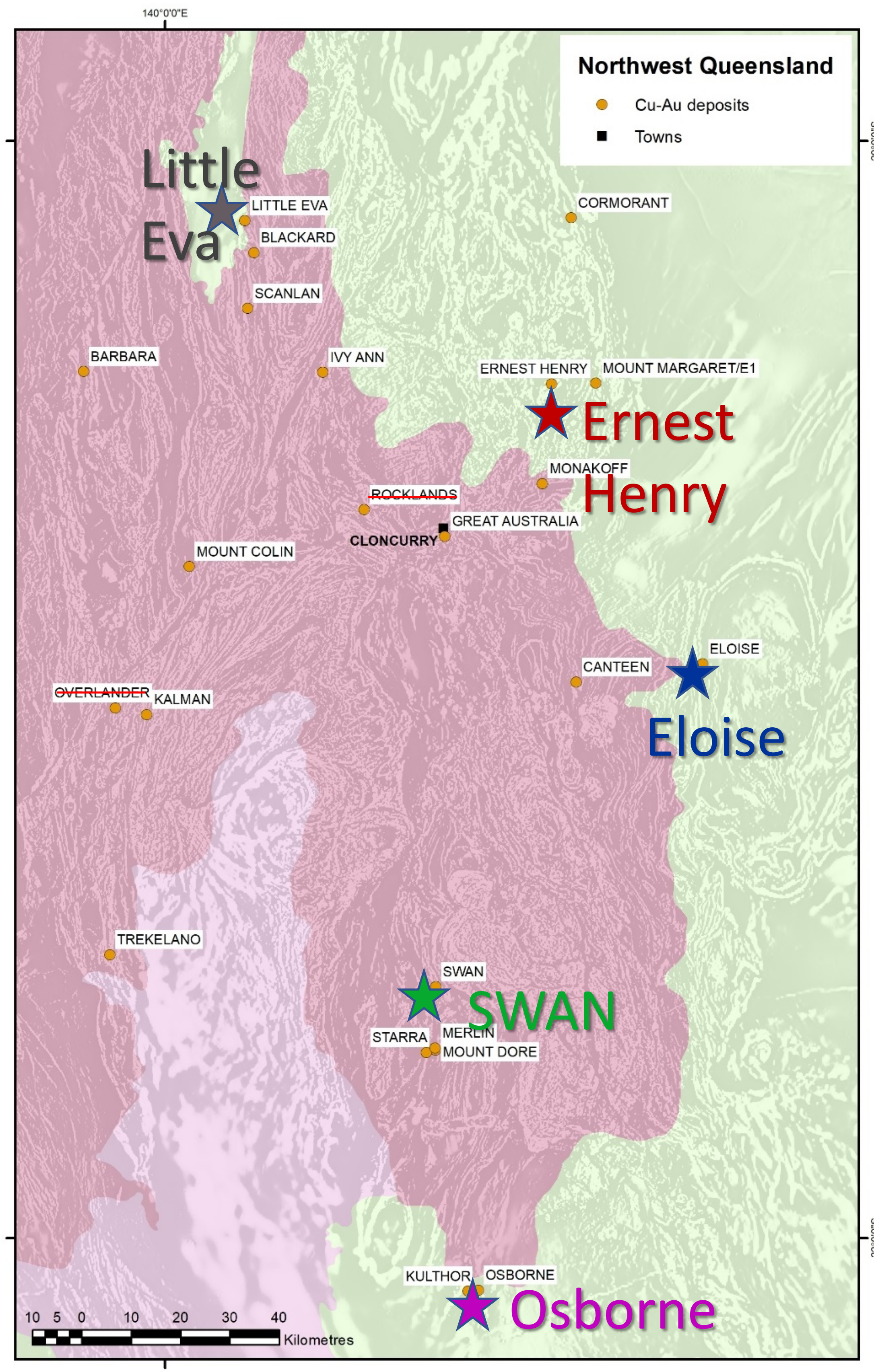
GSQ – Characterising signatures and footprints of IOCG deposits in the Cloncurry district

Geochemistry:

- 22 deposits - 117 drill holes - ~1000 samples (~300 samples with >0.2% Cu)
- 48-67 elements (4-acid digestion ± lithium borate fusion, aqua regia (Te-Se-Hg), Au-Pt-Pd, C-S, F

Mineralogy and petrophysics (Spectral - HyLogger; SEM / TIMA; mag. sus., density…)

Data integration and interpretation – work in progress

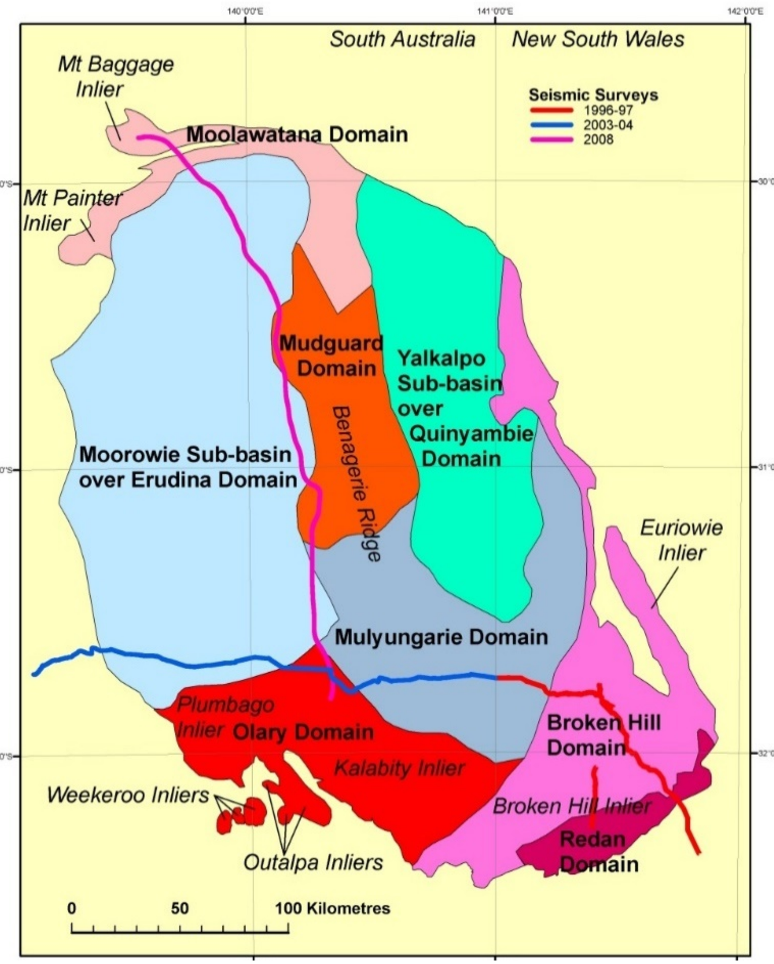


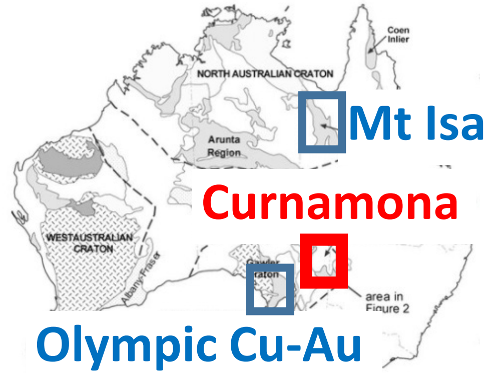
Curnamona Province: IOCG frontier between Olympic Cu-Au Province-Mt Isa

Objective: Improve understanding and assess economic potential for mineralisation associated with metasomatic iron oxide alkali-calcic alteration systems of the Curnamona Province, South Australia

Work planned: Re-log drillholes of the central and northern Curnamona Province, map & catalogue alteration facies, geochemical characterisation, determine timing of alteration & mineralisation. Assess deep earth imaging of Curnamona Province through Curnamona Cube (200 MT+200 seismic sites in a 20 km grid across 300x300 km)
https://sciences.adelaide.edu.au/study/honours/honours-projects/the-curnamona-cube

GSSA Researchers: Claire Wade (geochemistry), Anthony Reid (geochronology), Adrian Fabris (economic geology), Stephen Hore (field mapper), Kate Robertson (magnetotellurics)





Map: Barovich and Hand 2008)

Po-Py in Mag-Bt altered metasedimentary rocks

Layered Ab-rich rock

Sulphide-Kfs-Qz

Mag-Ab breccia

CAL2

Sarah Dare
sdare@uqac.ca

Assistant Professor at UQAC, Quebec
Canada Research Chair in
Geochemistry Applied to Ore Deposits
Directrice of LabMaTer (UQAC)

Chaires de recherche du Canada
Canada Research Chairs
Géochimie appliquée aux gisements métalliques
Geochemistry applied to ore deposits

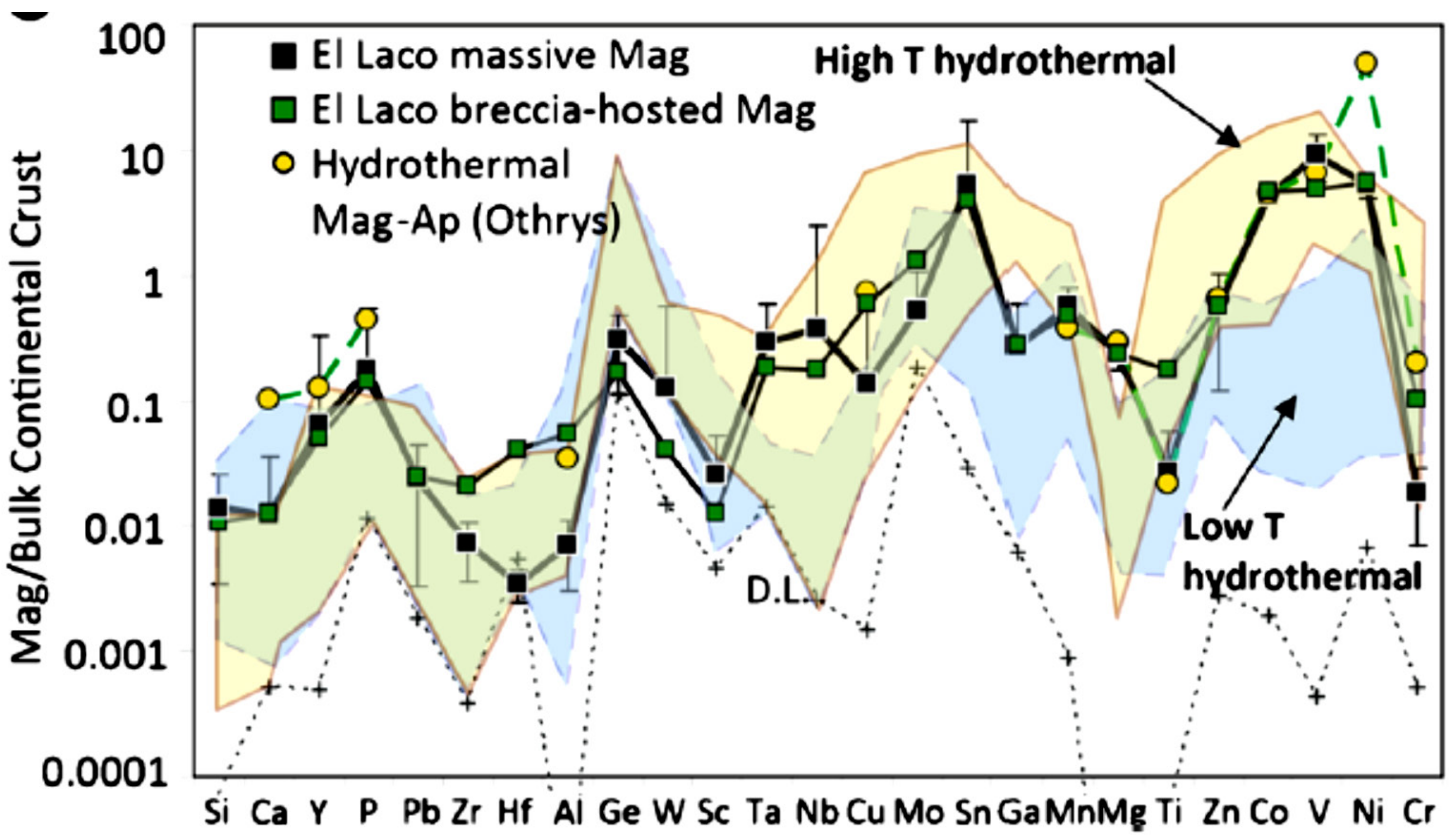
Contribute expertise on magnetite (apatite) chemistry applied to IOA deposits (collaboration/workshops/shortcourses):

Mineral Chemistry	Techniques	Ore deposits
• Chromite, sulfides	• Laser Ablation-ICP-MS	• Ni-Cu-PGE-Cr; (Fe)-Ti-V-P
• **Fe-oxides,** Apatite	• EPMA	• IOA: ex El Laco

Aim to develop mineral chemistry (mgt + ap) as:

Petrogenetic indicators
Trace conditions of formation of magnetite (hydrothermal vs magmatic)
Indicator minerals for exploration

Developed multi-element diagram for magnetite (Dare et al. 2014)



Ex. **Magnetite chemistry** from **El Laco magnetite deposit** best fits a **hydrothermal origin** (*Dare et al. 2015 Mineralium Deposita*).

LabMaTer

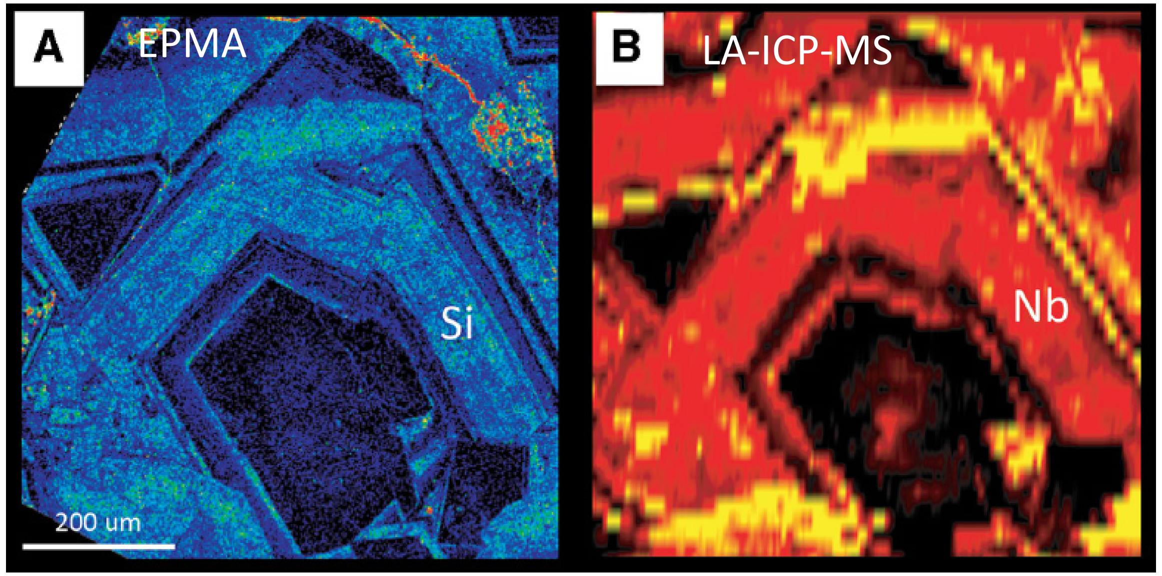
Laser ablation facility specialized in analysis of oxides, sulfides and apatite

Developed own matrix-matched reference materials (BC28, UQAC-FeS1…….)

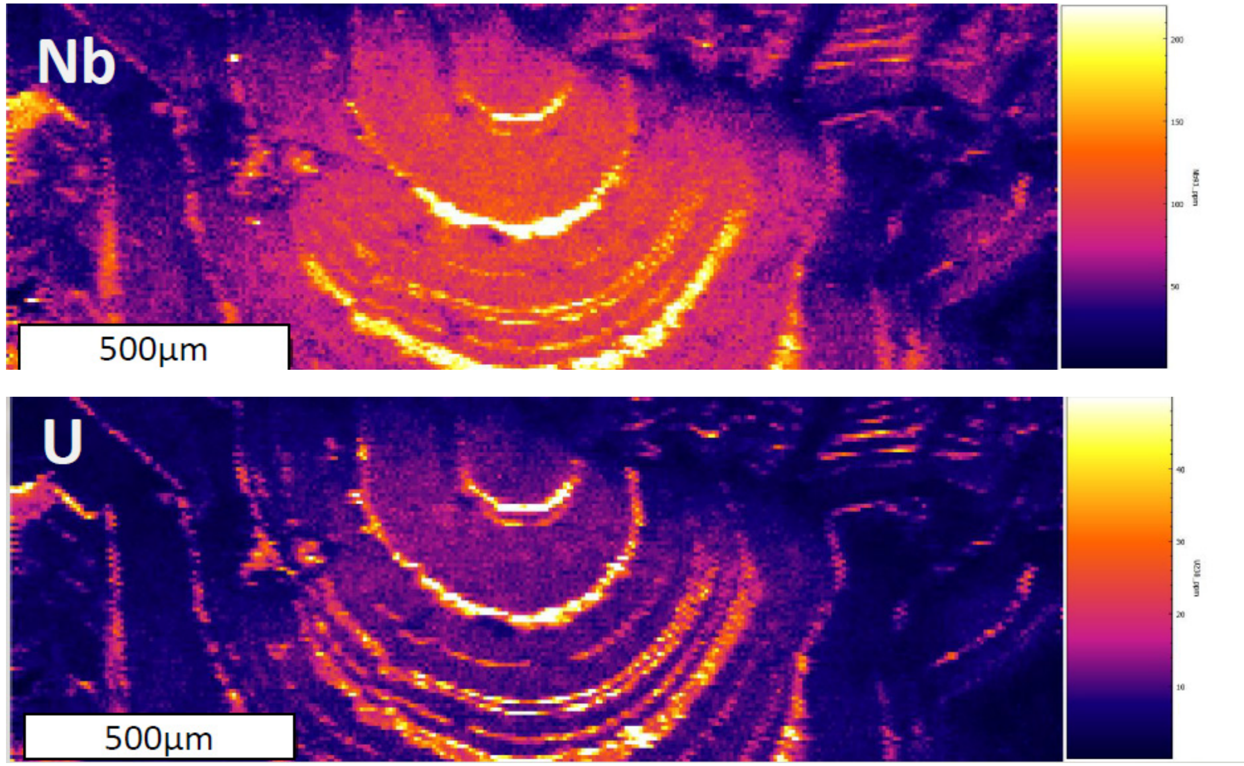
Open to collaboration

http://www.uqac.ca/labmater/index.htm l

LabMaTer
UQAC
Université du Québec à Chicoutimi



Chemical map of zoned magnetite by LA-Quadrupole ICP-MS
19um beam (3 hours)
Ex El Laco (Dare et al. 2015)



Dany Savard

PhD candidate at UQAC
Developing **new Time of Flight ICP-MS technique** for fast, high resolution mapping (7um beam).
All trace elements acquired simultaneously…….discover new elements such as U in magnetite from El Laco!

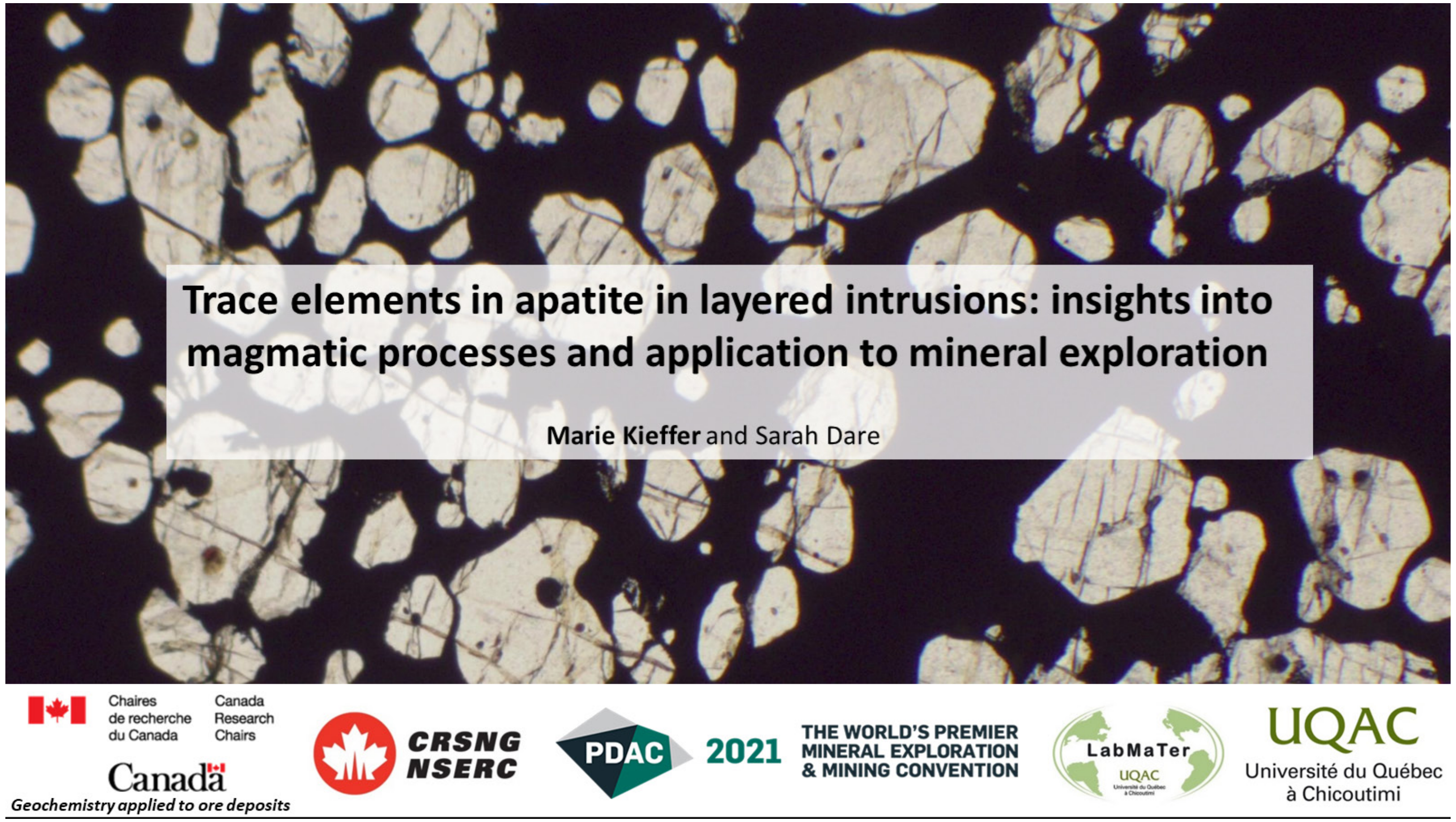
(Savard et al. 2021: Goldschmidt abstract)

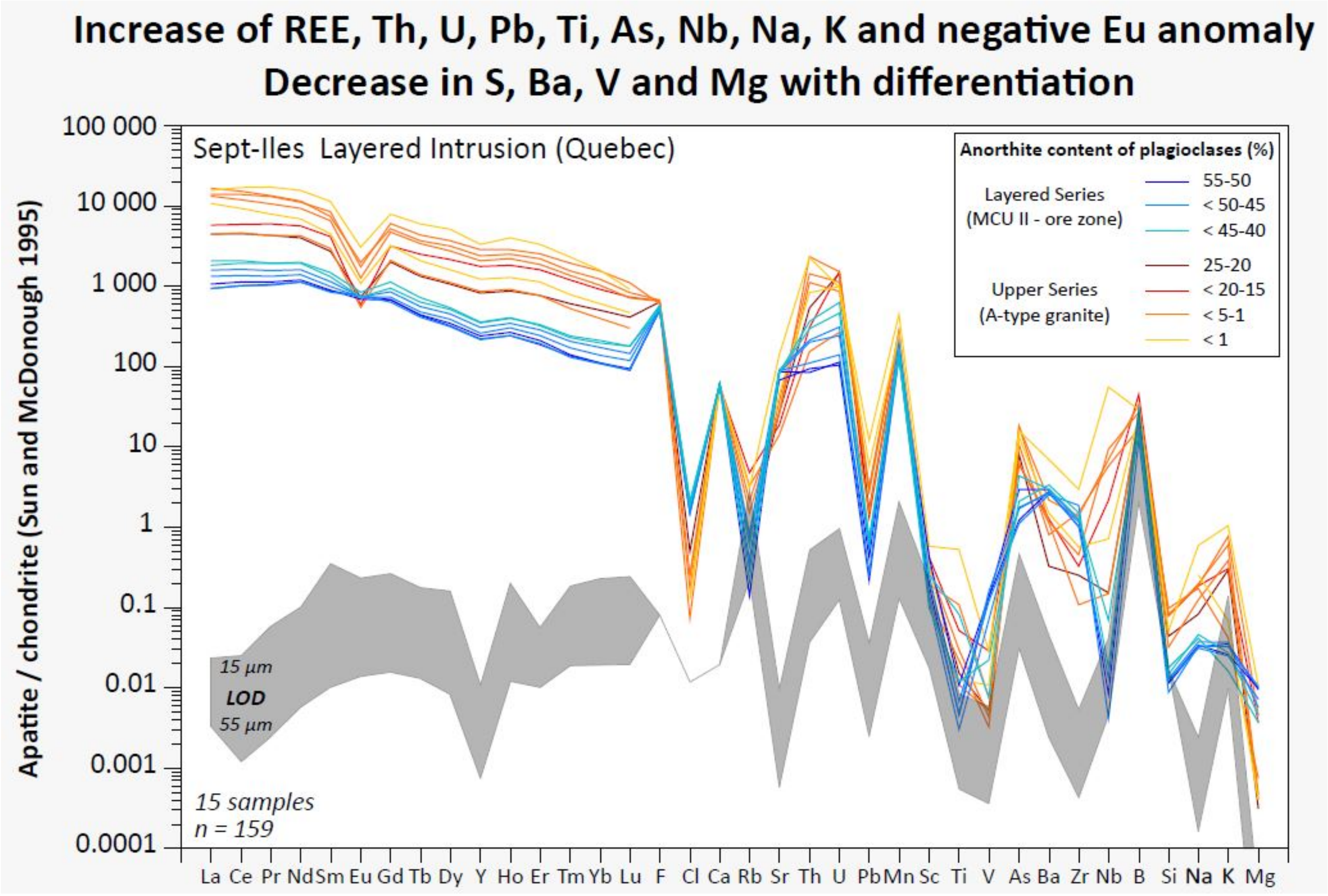
Marie Kieffer
PhD student (2020 -)
UQAC

Aim to distinguish apatite
- of mineralization from host intrusion
- of mafic from felsic magmas
- of magmatic from hydrothermal origin

Implications for IOA deposits

Developing **apatite chemistry** as indicator for petrogenesis and mineral exploration

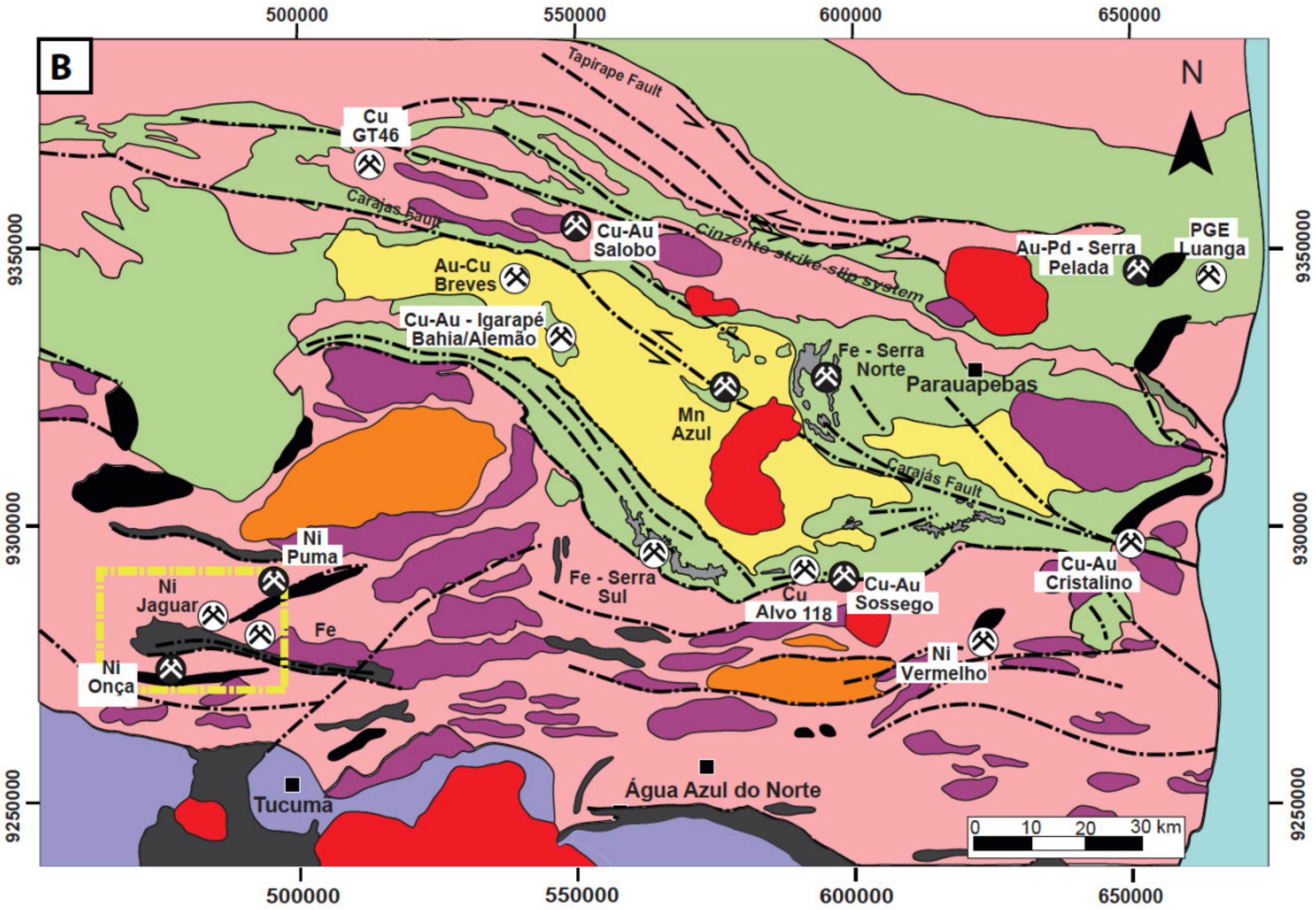




Kieffer and Dare (2021) Goldschmidt abstract

The Jaguar nickel deposit

A potential link between IOA and IOCG deposits within the Carajás Mineral Province?



(Fluidized) brecciated texture

Eduardo Mansur[1,3]
Sarah Dare[1]
Cesar Ferreira Filho[2]
[1]UQAC
[2]Universidade de Brasília
[3]Geological Survey of Norway
etmansur@gmail.com

58.6 Mt at 0.95 wt.% Ni

(Centaurus Metals Ltda, www.centaurus.com.au; February 2021)

CentaurusMetals Limited

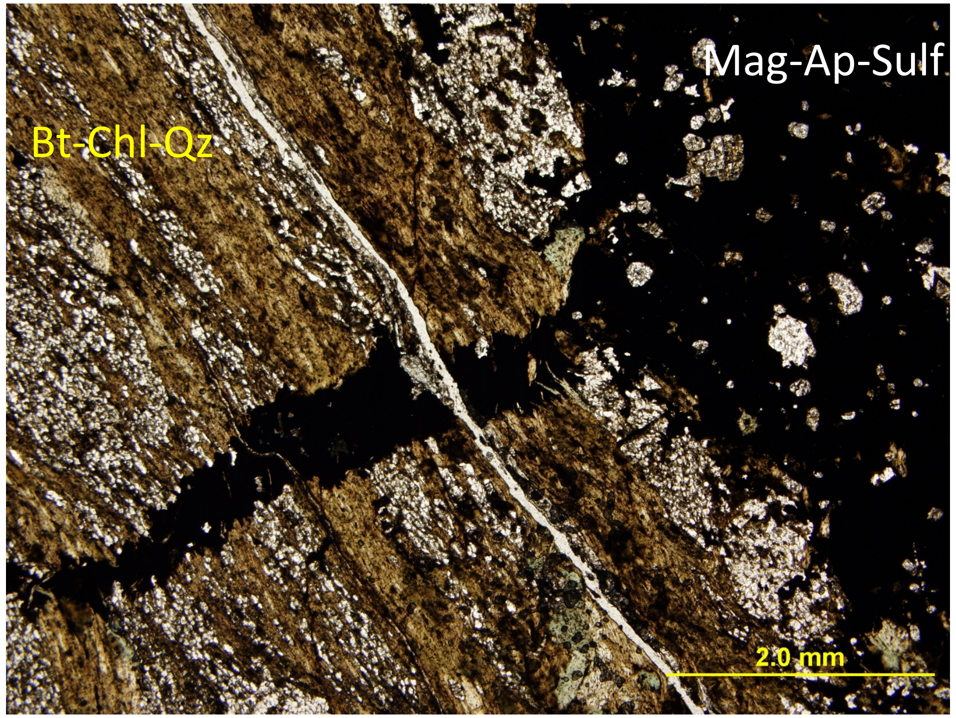
Ni-rich massive sulfides with magnetite and apatite
Unusual magmatic sulphide assemblage?
Or unusual Ni-S-rich IOA?

Apply LA-ICP-MS of sulfides, magnetite and apatite to determine the type of Ni deposit

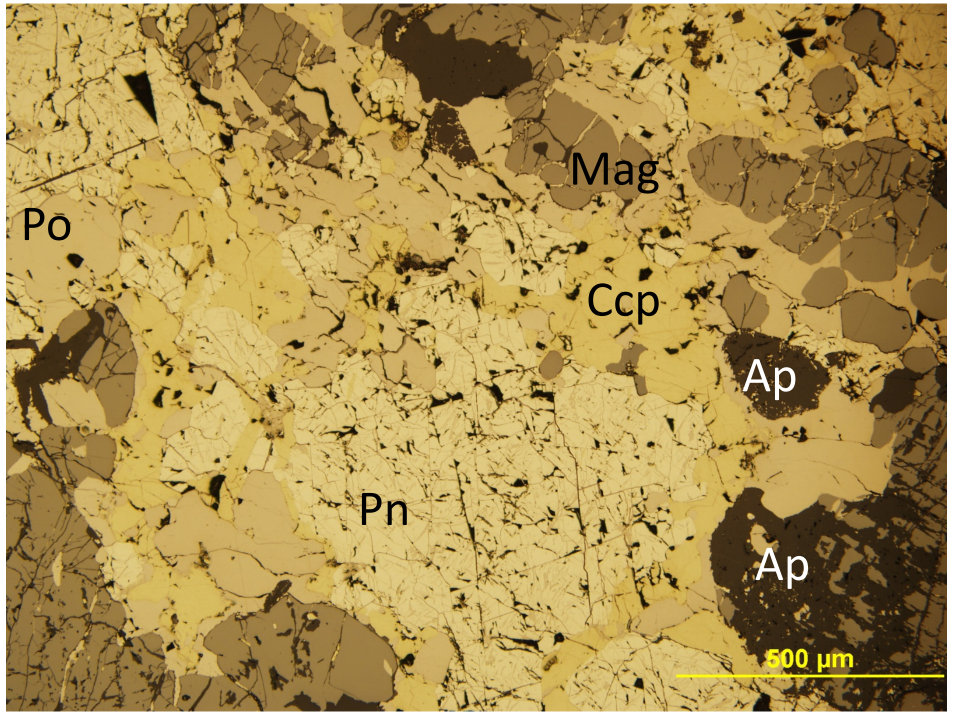
The Jaguar nickel deposit

A potential link between IOA and IOCG deposits within the Carajás Mineral Province?

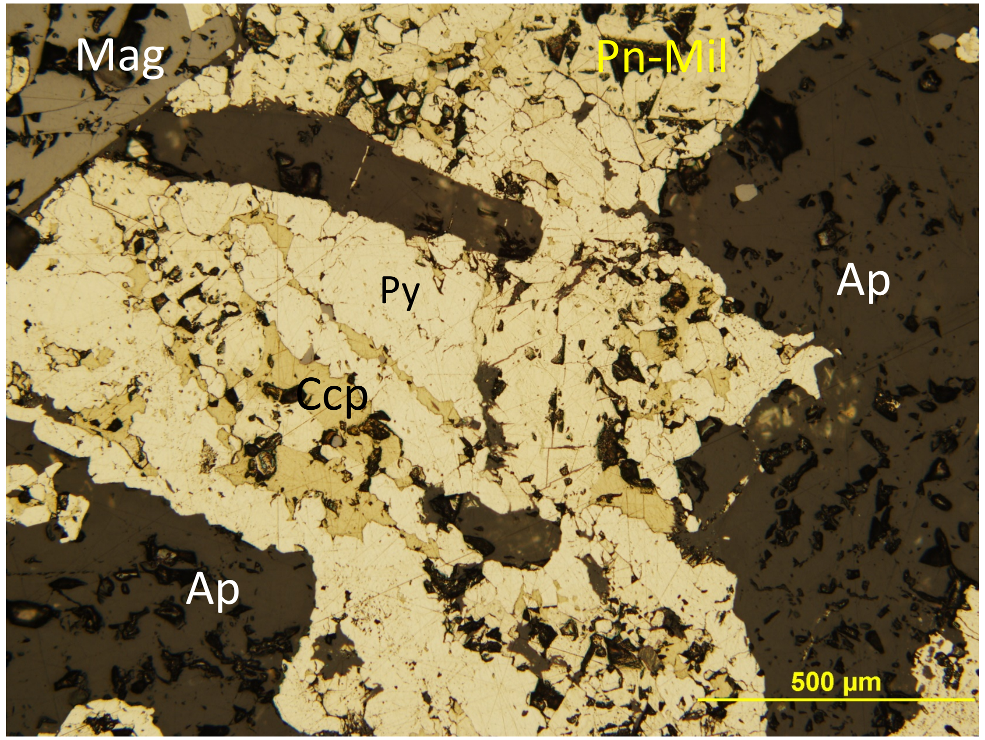
Abundant magnetite and apatite together with sulfides



Mag-Ap-Sulf breccias crosscut the Bt-Chl schists



Less altered sulfide assemblage (Po-Pn-Ccp)



More altered (Pyrite and millerite)

Wide alteration halo
(Bt-Chl±Amp schist)
In surrounding host rocks (felsic subvolcanic rocks/granites)

Alteration continuum in the sulfide assemblage
Po-Pn-Ccp ± Py → Py-Mil-Pn-Ccp

Mineral chemistry indicates hydrothermal origin: **unusually Ni-S-rich IOA**
Mansur et al. 2021: Goldschmidt abstract; Ferreira Filho et al. 2021

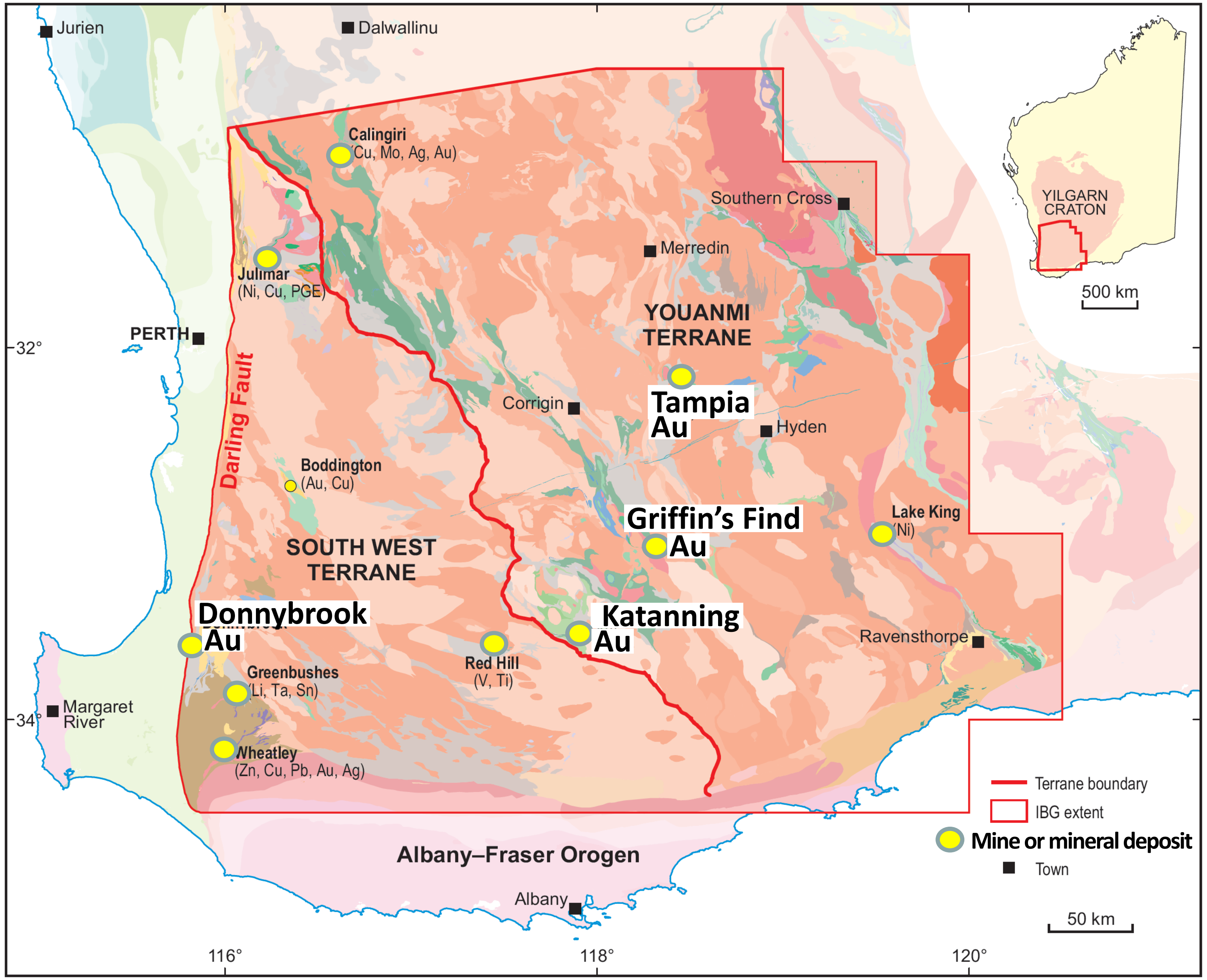
CORRIVEAU et al. 2021

GSWA team

- **Raphael QUENTIN de GROMARD (**structural geologist)
- **Paul DUURING** (mineral systems)
- **Tim IVANIC** (mafic geochemist)
- **David KELSEY and Fawna KORHONEN** (metamorphic petrologists)

Southwest Yilgarn project

- Extends over the redefined terrane boundary between the Meso- to Neoarchean Youanmi Terrane and the Neoarchean South West Terrane
- Neoarchean amphibolite- to granulite-facies tectonomagmatic history with Proterozoic tectonometamorphic overprint
- 2020–21: Completion of the one-year Accelerated Geoscience Program (AGP). Major outcomes include the completion of a new interpreted bedrock geology map, metamorphic history records, alteration maps, isotope maps…
- 2021–24: onset of a 3-year project: “distal footprints of gold mineralization” that examines links between basement rocks, gold mineralization, and cover, using examples of known gold sites: Tampia, Griffin’s Find, Katanning and Donnybrook



Quentin de Gromard et al., 2021, Pre-Mesozoic interpreted bedrock geology of the southwest Yilgarn: Geological Survey of Western Australia, digital data layers

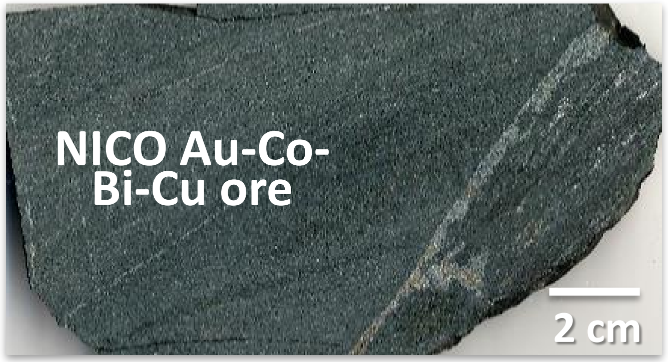
Daniele Regis (GSC, Ottawa)

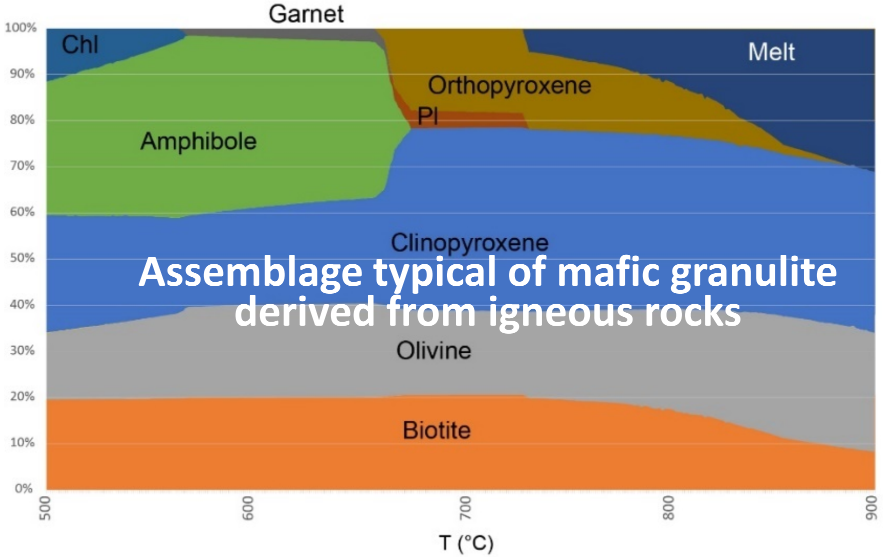
Predictive thermodynamic modelling of IOCG alteration facies at high-grade metamorphic conditions

Main aim: modelling what mineral systems with IOCG and affiliated deposits would look like at amphibolite (melt-absent) and granulite (melt-present) facies conditions to advance exploration, mineral potential assessment and mapping of high-grade metamorphic terranes.

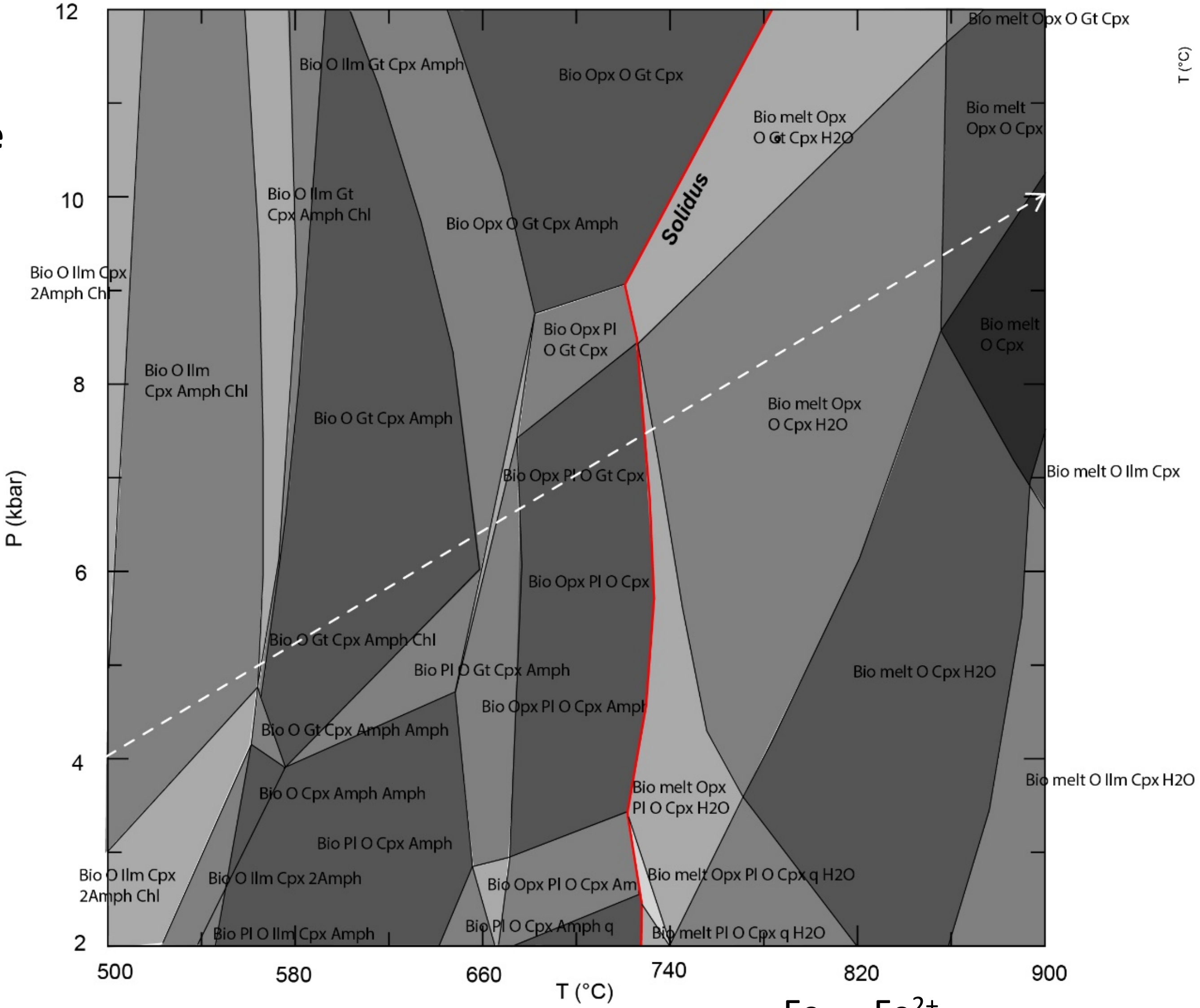
Example: Sample CQA-07-0466A2

Mag-Amp dominant HT Ca-Fe metasomatite
replacing metasedimentary rock

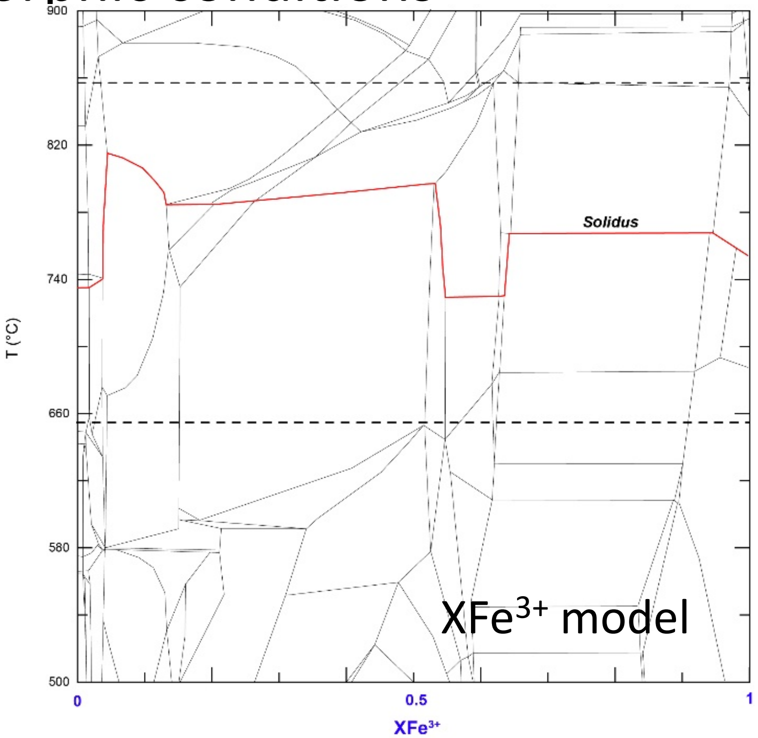


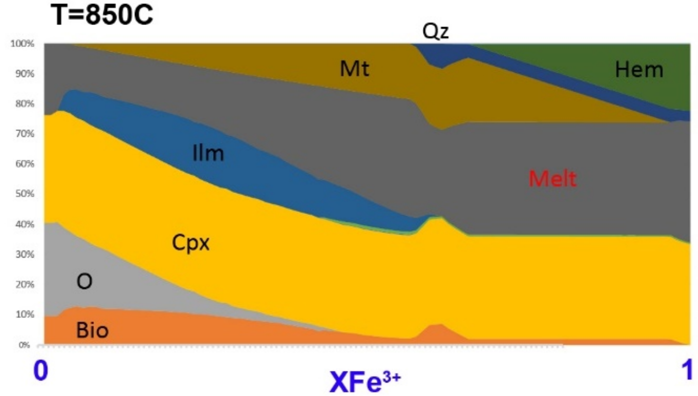


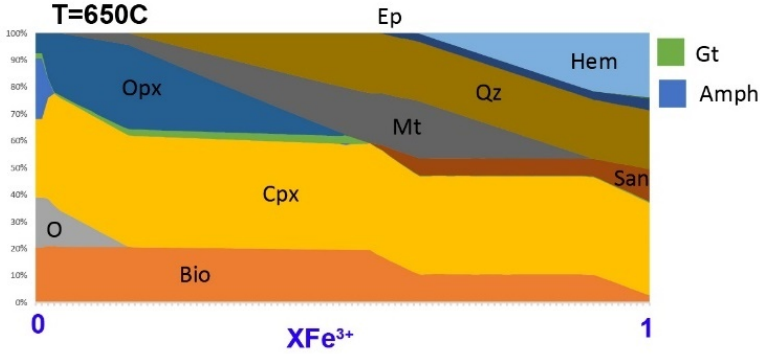
Modal evolution from 500C/4kbar to 900C/10kbar



$Fe_{tot}=Fe^{2+}$



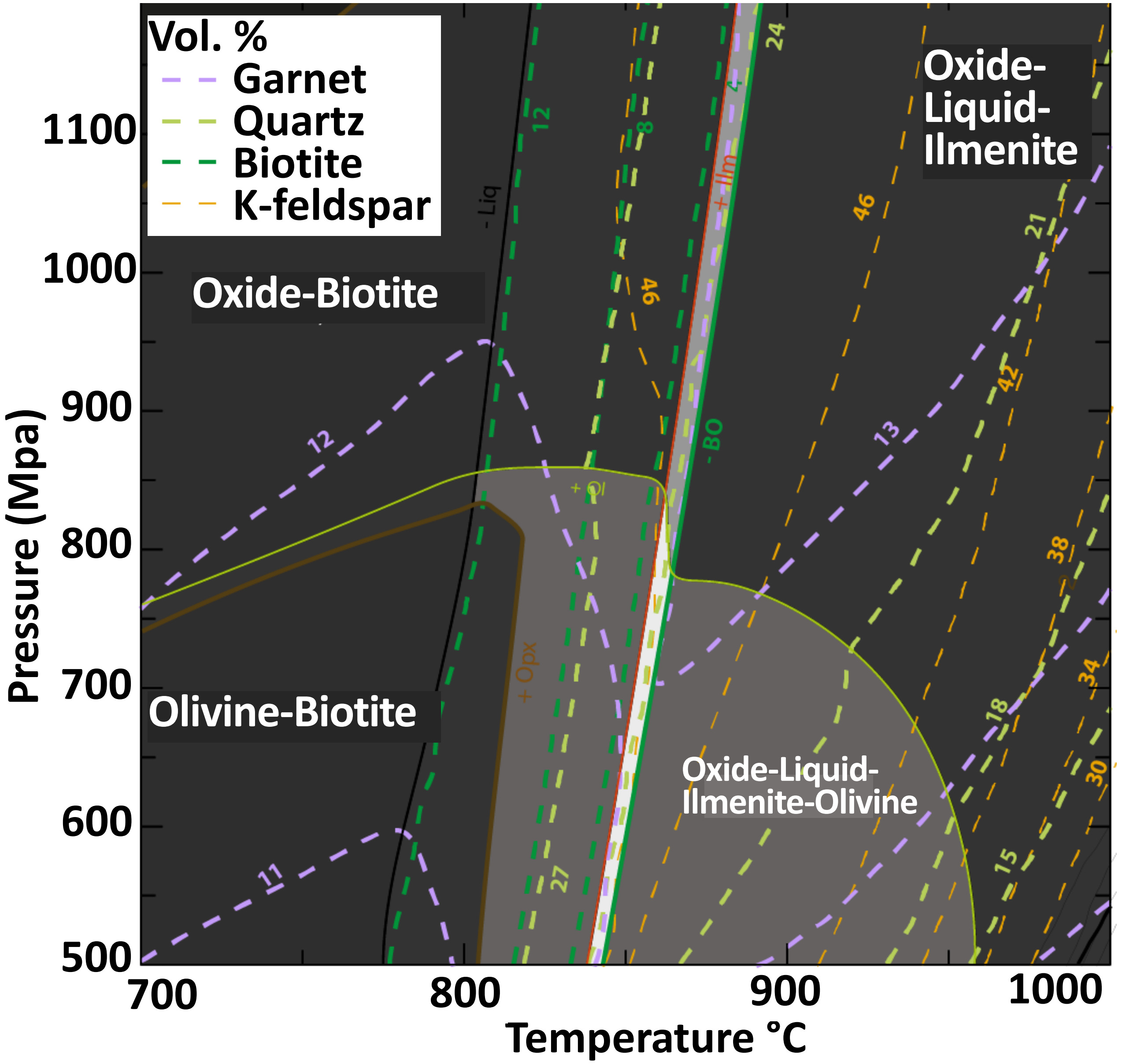


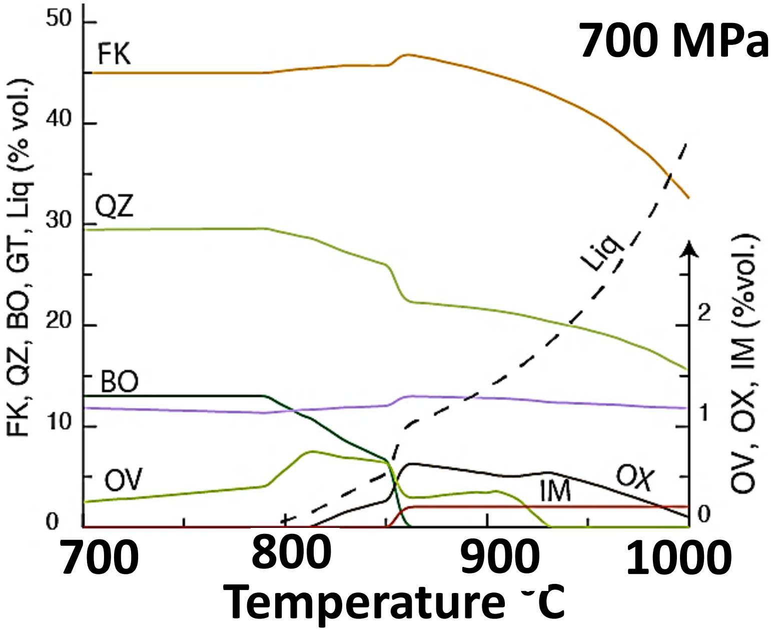


Phase diagram isochemical section for a typical of K-Fe alteration (GBMZ)

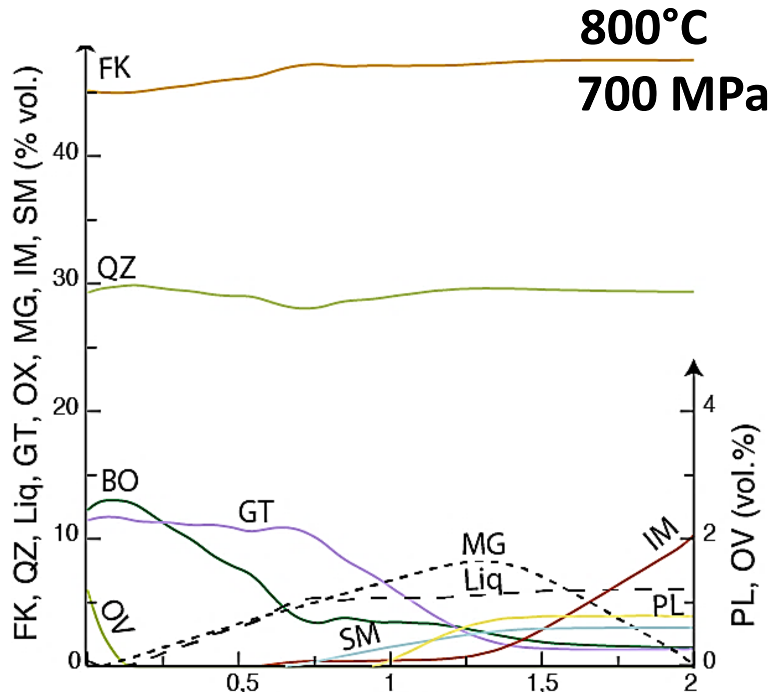
Félix Gervais

Professeur agrégé (associate professor)





Mineral volume isopleths



Increasing oxygen fugacity

Expertise

- Tectonometamorphic evolution of hot orogens
- Petrochronology
- Structural geology

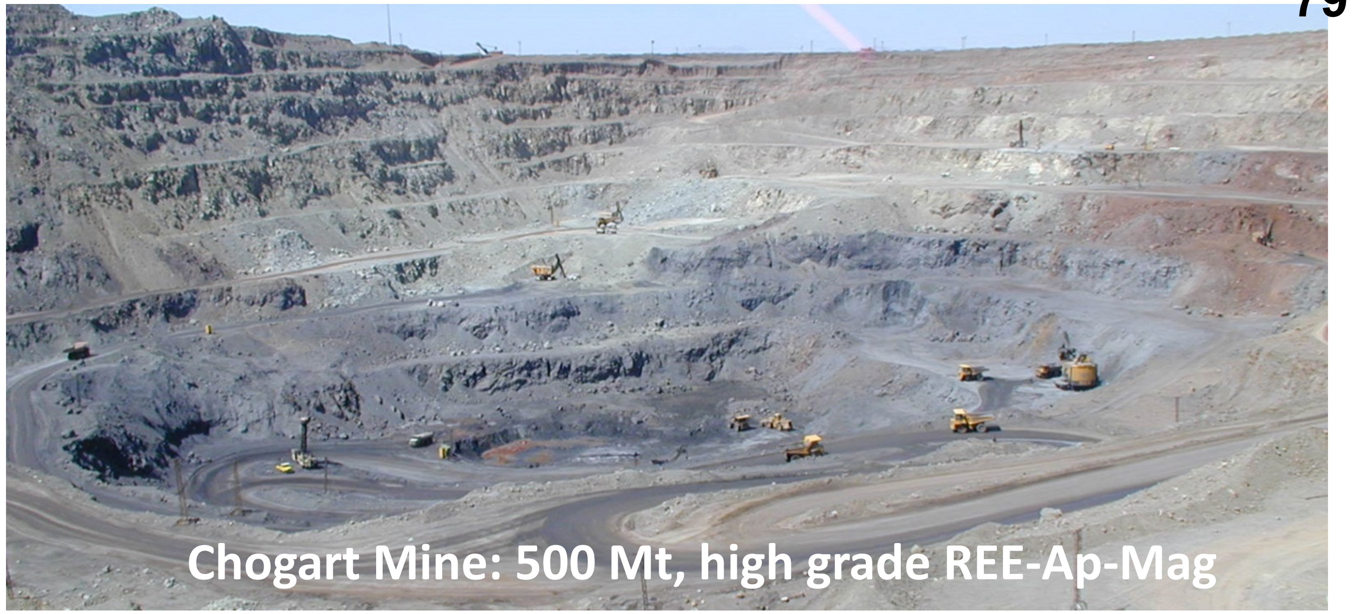
POLYTECHNIQUE MONTRÉAL

Below 800 Mpa, such a rock metamorphosed at the amphibolite to granulite facies would look like a olivine (OV)-bearing granite ± garnet (GT) or magnetite (MG) depending of oxygen fugacity

Trapy et al. 2015; Trapy 2018; Gervais and Trapy 2021

Farahnaz Daliran

Karlsruhe Institute of Technology (KIT)
University of Karlsruhe (TH)



Chogart Mine: 500 Mt, high grade REE-Ap-Mag

Study the Bafq district since 1975

Field geology, tectonomagmatic setting, geochemistry, mineral chemistry, fluid chemistry

IOA-REE, apatitite, U, U-Ni-Co-Bi-Ag-As-Mo-Cu

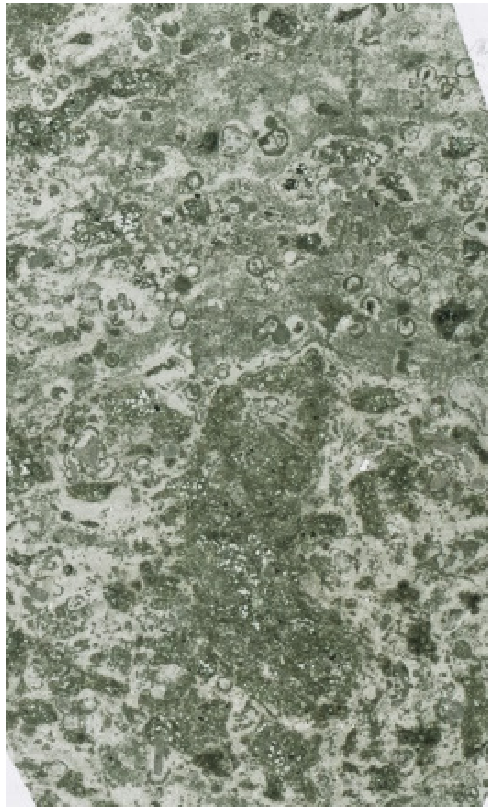
500 Mt to < 20 Mt deposits

High-grade Fe oxide ore (up to 65% Fe)

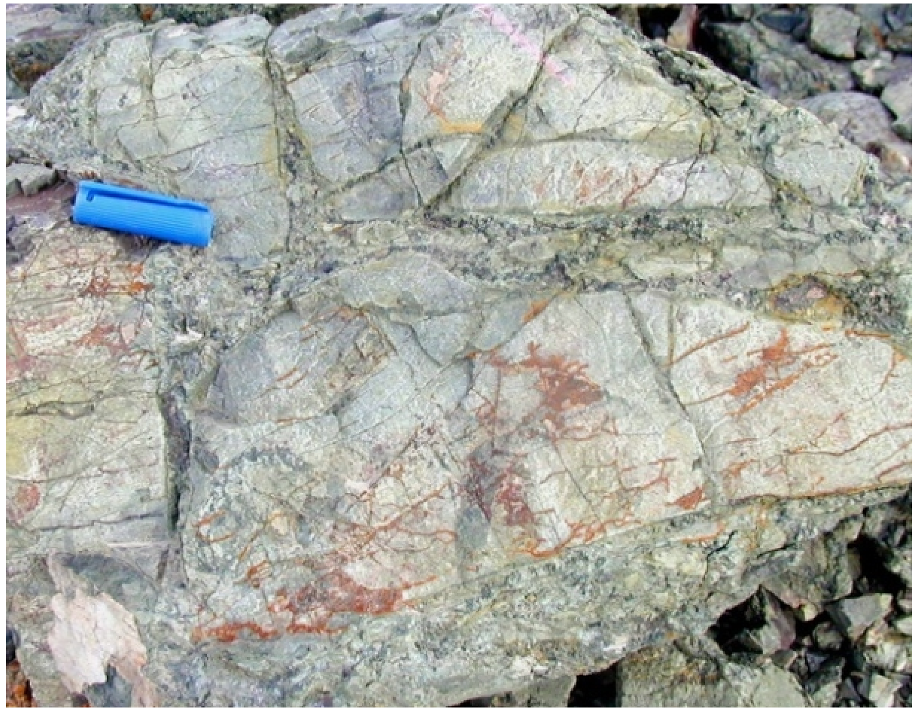
Ti-V-poor (< 1 wt %) magnetite, subordinate hematite

Apatitite: REE-apatite-rich-Cpx-Amp-FeOX-Cb-rocks e.g. Esfordi mine: 20 Mt P, @0.7-2 wt % REE_2O_3

See Daliran et al. 2010, in press



Glass shard replacement!

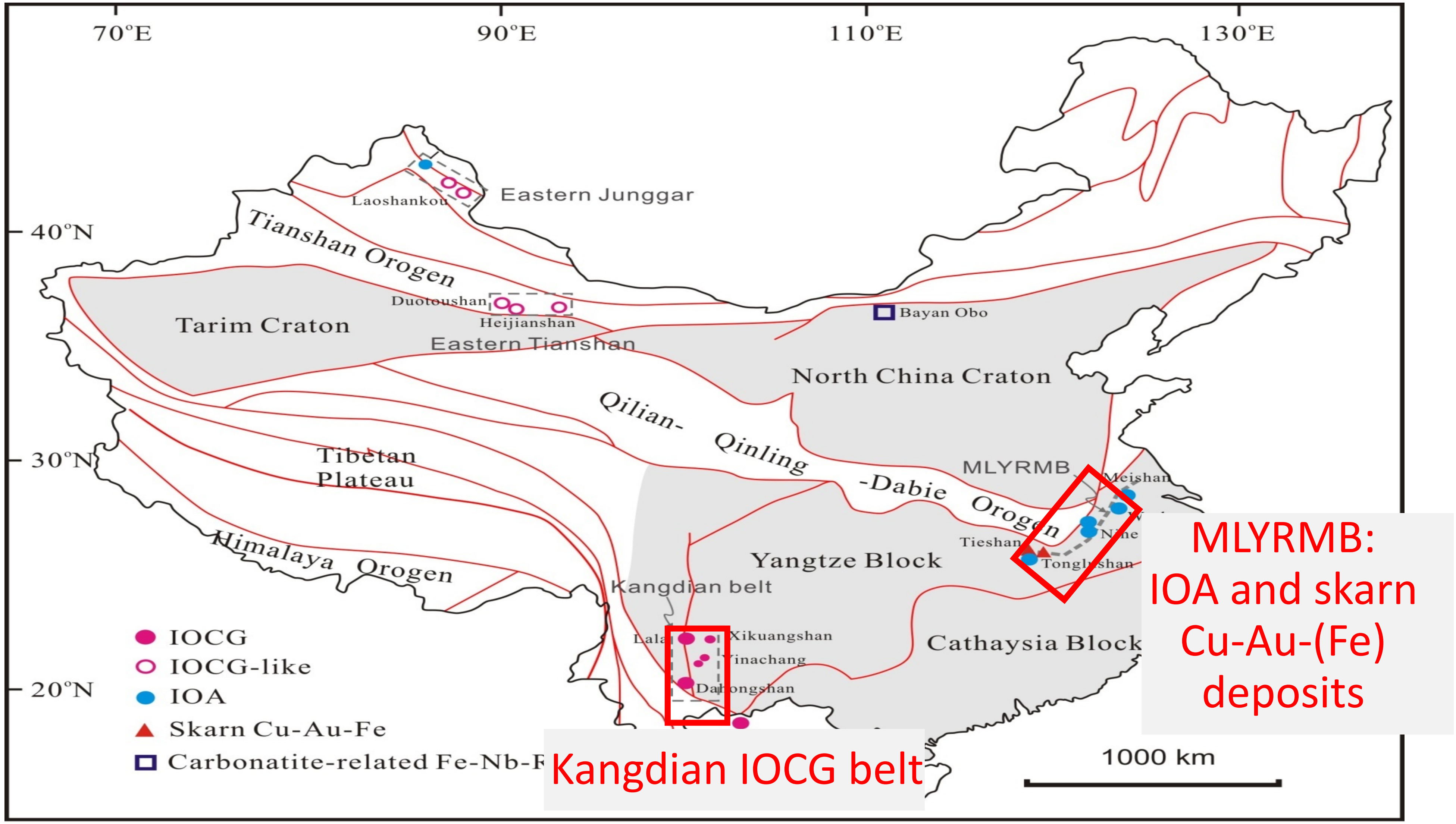


Apatite-magnetite ore
(gas-escape texture?)
Gasestan deposit

Actinolite-filled albitite breccia

Xin-Fu Zhao

Economic Geologist
School of Earth Resources
China University of Geosciences
Wuhan, China
https://scholar.google.com/citations?user=RfXyjIAAAAAJ&hl=zh-CN



Major interests:

1) IOCG deposits
2) IOA deposits
3) Skarn Cu-Au deposit
4) Carbonatite related REE-Nb deposits
5) Lode gold deposits

See Zhao et al. 2017, in press

Xiaowen Huang

State Key Laboratory of Ore Deposit Geochemistry

Institute of Geochemistry

Chinese Academy of Sciences

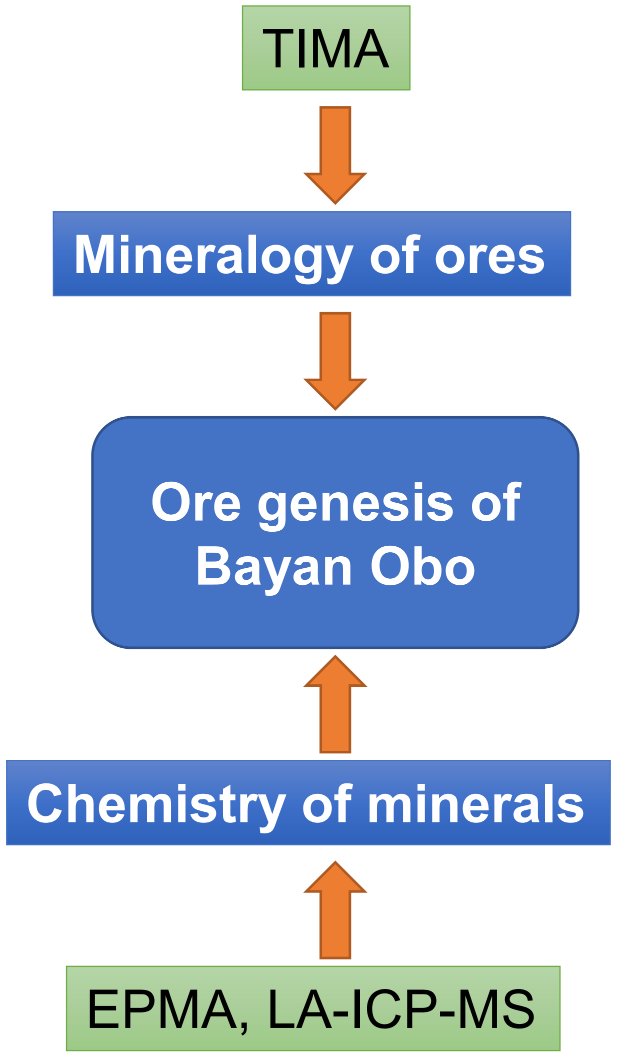
Field of expertise

- Indicator minerals
- Trace element geochemistry of iron oxides from a variety of deposits

Plan on the project for FY21-22

- Understanding the mineralogy of different types of ores from Bayan Obo using automated mineral identification technique such as TIMA
- Constraining the genesis of Bayan Obo ores using chemical composition of minerals such as magnetite, hematite, apatite, fluorite

See Huang et al. 2019, in press



CORRIVEAU et al. 2021

Abdelali Moukhsil

Ph.D. géo

Géologue régional, MERN-Q

Travaux en cours

- Cartographie dans la partie centrale de la Province de Grenville (1:50 000 et 1:125 000)
- Collaborations avec universitaires sur les métaux critiques et stratégiques
  - MSc U-Laval (ETR dans pegmatites granitiques)
  - MSc UQAC (ETR, Nb dans carbonatite)
  - MSc U-Laval (Zn dans des roches métasédimentaires)
  - MSc INRS Québec (Structure d'une faille majeure dans le Grenville central)
- En 2022
  - PhD Polytechnique Montréal (ETR associé au leucogranite dans la région de Manic 5)
  - PhD UQAC (oxydes de Fe-Ti-P±V associées à la Suite anorthositique de Lac-Saint-Jean)

Contributions potentielles pour le projet en 21-22 :

- Répondre aux questions pour la province de Grenville
- Faciliter le lien avec géophysicien du Ministère, etc.

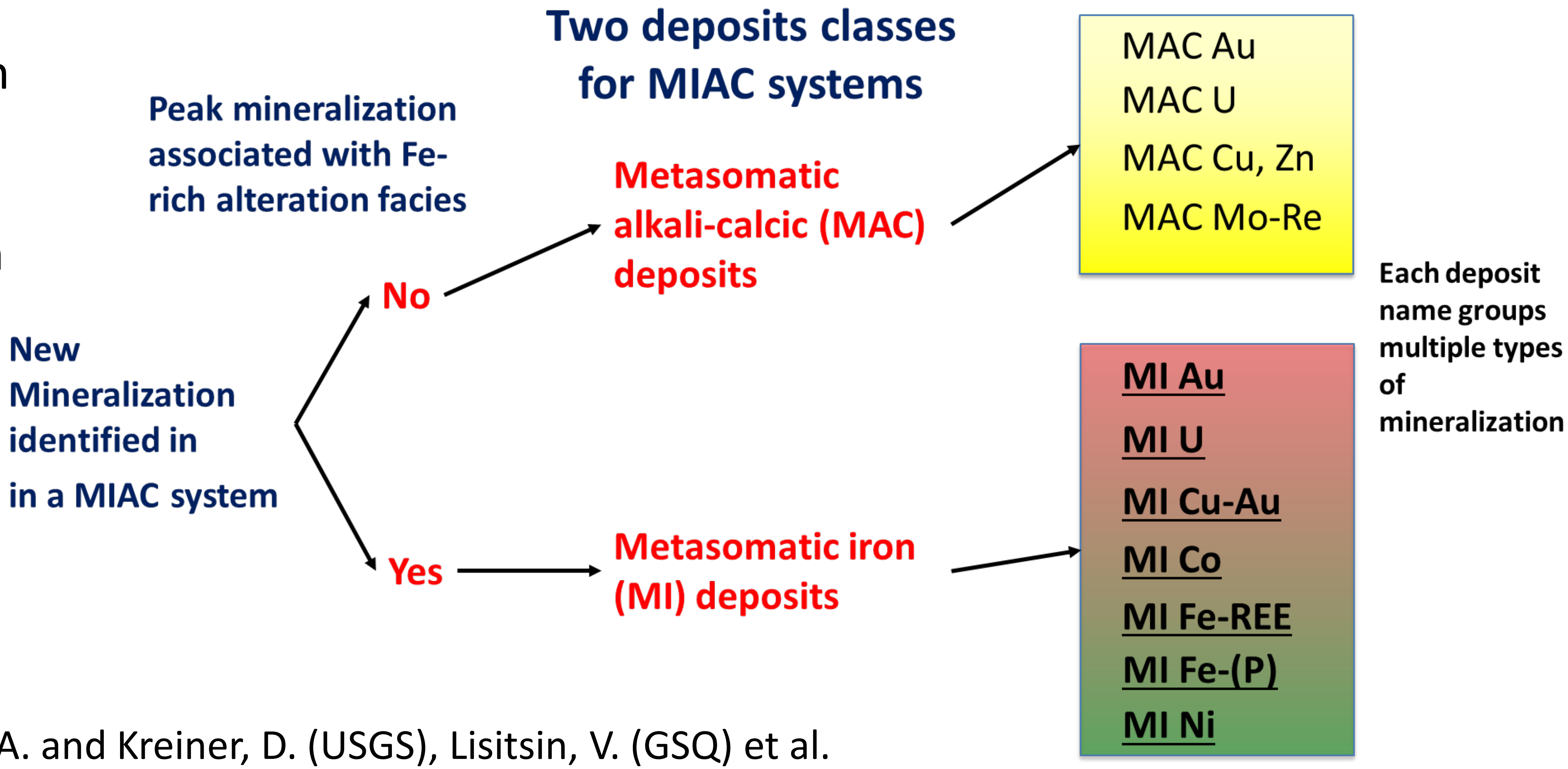
Voir Trapy et al. 2015; Turlin et al. 2019

Jean-Francois Montreuil

Chief geologist
Red Pine and MacDonald Mines exploration

Expertise - Structural geology + alteration and geochemical mapping applied to mineral deposits in 2D and 3D

- **Mineral deposit team leader**
  - Classification of deposit types in MIAC systems
  - Relation between alteration facies and metal enrichments in MIAC systems
- **Long-term**
  - Relation between tectonic setting, magma composition, geological sequence and metal enrichments in MIAC systems



Collaborators – Corriveau, L. (GSC), Hofstra, A. and Kreiner, D. (USGS), Lisitsin, V. (GSQ) et al.

See Montreuil et al. 2015, 2016b, c; MacDonald Mines Exploration Ltd. 2019; Hofstra et al. 2021; Corriveau et al. in press a

CORRIVEAU et al. 2021

Consolidating knowledge on Canadian MIAC systems: a synthesis of themes and contributors

Deposit classification: Montreuil, J.-F. (lead), Corriveau, L., Hofstra, A., Kreiner, D., Lisitsin, V.
Field data capture vocabulary: Corriveau, L. (lead), De Toni, A.-F., Hofstra, A., Lisitsin, V., Montreuil, J.-F., Quentin de Gromard, R., Reid, A.
Short course series + atlas: Corriveau, L. (lead), De Toni, A.-F., Montreuil, J.-F., Percival, J., Potter, E. and the rest of the group
Great Bear framework, geophysic, datasets, etc.: Ansari, M., Aucoin, F., Beaulieu, D., Bowdidge, C., Corriveau, L., Craven, J., De Toni, A., Enkin, R., Fortin, R., Goad, R., Harvey, B., Hayward, N., Jacob, N., Lauzière, K., Létourneau, F., Montreuil, J.-F., Morin, A., Mumin, H., Percival, J., Potter, E. (finalization of products), Regis, D., Tschirhart, V., DEMCo (Dene First Nations company), Fortune Minerals
Central Mineral Belt framework: Acosta-Góngora, P. (lead), Blein, O., Corriveau, L., Potter, E. (finalization of products), Sparkes, G.
Wanapitei-Sault St. Marie framework: Peloquin, S. (lead), Easton, M., Maity, B., Montreuil, J.-F., Corriveau, L.
Appalachian framework : Adlakha, E., Baldwin, G., Kellett, D., Neyedley, K., Park, A., Piette-Lauzière, N.; Corriveau, L., Pilote, J.-L.
SE Cordillera framework: Katay, F., Paradis, S., Simandl, G.; Corriveau, L.
Labrador Trough framework: Conliffe, J. (lead), Corriveau, L., Jacob, N., Montreuil, J.-F., Scherba, C. (data provision)
Grenville Province framework: Belisle, M., Blein, O., De Toni, A., Moukhsil, A., Pelletier, J., Regis, D., Sappin, A.-A.,
Australian district framework and case examples: Dhnaram, C., Ehrig, K., Fabris, A., Lisitsin, V., Reid, A., Robertson, K., Wade, C.
US + Andean, Brazilian settings: Chen, H., Dare, S., Hofstra, A., Kreiner, D., Mansur, E.
Chinese + Iraq settings: Chen, H., Daliran, F., Huang, X.-W., Zhao, X.-F.
Systems metamorphosed to high-grade (modelling, Canadian and Australian case studies): Regis, D. + Quentin de Gromard, R., Blein, O., Corriveau, L., Duuring, P., Fabris, A., Gervais, F., Ivanic, T., Kesley, D., Korhoken, F., Lisitsin, V., Reid, A.,
Rock collections: Jacob, N. (lead), Corriveau, L., Laflamme, C.
Mineral chemistry: Dare, S. (lead), Beaudoin, G., Acosta-Góngora, P., Keiffer, M., Locmelis, M., Mansur, E., Potter, E., Santos, E., Sappin, A.-A., Savard, D.
GACMAC 2022 short course and symposium: Adlakha, E. (lead), Conliffe, J. (lead), Corriveau, L., Piette-Lauzière, N., Park, A.

Consolidating knowledge on Canadian MIAC systems: an international workshop on mineral chemistry

UQAC
UNIVERSITÉ DU QUÉBEC À CHICOUTIMI

International Online Workshop on Mineral Chemistry in Systems with IOCG, IOA and affiliated Critical Metal Deposits

Canada
Natural Resources Canada • Geological Survey of Canada
Ressources naturelles Canada • Commission géologique du Canada

2nd and 3rd December 2021 (8h-11h UTC-5/Toronto)
6th December 2021 (18h – 20h UTC-5/Toronto)

Regional metasomatic iron and alkali-calcic (MIAC) mineral systems generate a wide range of iron-oxide rich to iron poor economic deposit types (IOCG, IOA and affiliated critical metal deposits) with economic resources in many strategic and critical metals. As part of the Geological Survey of Canada-led global research network on critical metals in MIAC systems, this online workshop given by world-leading researchers will outline the textural and compositional variations of minerals (Fe-oxides, apatite, sulfides and fluorite) from a variety of IOCG, IOA and affiliated critical metal deposits. The aim is to better understand and discuss the key processes responsible for the chemical and textural signatures of minerals and their regional- to the mineral-scale variations across the breath of deposit types in these systems. Topics will include coupled dissolution-reprecipitation mechanisms, element partitioning between fluids and minerals, the role of fluid composition and the influence of co-crystallizing minerals.

See https://cerm.uqac.ca/minchem/ for more details of the talks, our speakers and MIAC mineral systems in general.

Organising Committee: Sarah Dare (UQAC), Anne-Aurélie Sappin (GSC), Louise Corriveau (GSC)

Consolidating knowledge on Canadian MIAC systems: an international workshop on mineral chemistry

SESSION 1
2nd December 2021

Dr. Louise Corriveau, GSC **-** Metasomatic iron and alkali-calcic (MIAC) mineral systems framework

Prof. Sarah Dare, UQAC - Introduction to LA-ICP-MS and mineral chemistry for petrogenesis and mineral exploration

Prof. Andrew Putnis, U. Münster **(Keynote) -** Fluid-rock interaction mechanisms and the inevitable consequences for textural evolution, mass transport and mineral precipitation

Prof. Marek Locmelis, Missouri S&T **(Invited) -** The origin of the Pilot Knob IOA cluster in southeast Missouri, USA – Insight from iron oxide mineral chemistry

Dr. Celestine Mercer, USGS **(Invited)** - Trace element geochemistry and cathodoluminescent textures of apatite from the Missouri iron metallogenic province, USA, reveal distinct igneous and magmatic-hydrothermal origins

SESSION 2
3rd December 2021

Prof. Adam Simon, U. of Michigan **(Keynote)** - Compositional variability of apatite, actinolite and magnetite in IOCG and IOA systems

Prof. Xiaowen Huang, Chinese Academy of Sciences **(Invited) -** The links between IOA and IOCG deposits: Constraints from iron oxide textures and composition

Dr. Tobias Schlegel, CSIRO **(Invited) -** Compositional variability of fluorite in IOCG deposits and prospects of the Olympic IOCG province, South Australia – what does it tell us about Cu mineralizing fluids and IOCG deposit formation?

Dr. Eduardo Mansur, NGU **(Invited)** - Jaguar hydrothermal Ni deposit – using mineral chemistry to link IOA and IOCG deposits within the Carajás Mineral Province, Brazil

SESSION 3
6th December 2021

Prof. Cristiana Ciobanu, U. of Adelaide **(Keynote) -** Iron oxides at the nanoscale: Silician magnetite and U-rich hematite from the Olympic Dam IOCG district, South Australia

Dr. Kathy Ehrig, BHP-Olympic Dam **(Keynote) -** Compositional and textural variations of hematite and magnetite variation across the IOCG-IOA spectrum of deposits, Stuart Shelf, South Australia: Discovery to Recovery

Dr. Daniele Regis, GSC **(Invited) -** Predictive thermodynamic modelling of IOCG and affiliated alteration facies at high-grade metamorphic conditions

See Ehrig et al. 2012, 2021; Dare et al. 2014, 2015; Sappin et al. 2014; Corriveau et al. 2016, in press a–e; Ciobanu et al. 2017; Huang et al. 2019, in press; Regis et al. 2019; Mercer et al. 2020; Ferreira Filho et al. 2021; Putnis 2021; Sappin and Pereault 2021; Tunnell et al. 2021

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- Provincial and territorial Canadian geological surveys
- BRGM, Geological Survey of South Australia
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For additional information

Louise Corriveau – Louise.Corriveau@nrcan-rncan.gc.ca, Natural Resources Canada, Geological Survey of Canada

Eric Potter – Eric.Potter@rcan-rncan.gc.ca, Natural Resources Canada, Geological Survey of Canada

Annex 1: Acronyms and abbreviations

IOCG: iron oxide copper-gold deposits; **IOA**: iron oxide±apatite deposits; **Grp**: group; $\mathbf{U}_{\mathbf{albitite}}$: albitite-hosted uranium deposits
IOAA: iron oxide alkali-calcic alteration systems; **MIAC**: metasomatic iron alkali-calcic mineral systems
HT: high temperature; **LT**: low(er) temperature; **REE:** rare-earth elements and Y; **H/LREE**: heavy/light REE; **PGE**: platinum-group elements

GBMZ: Great Bear magmatic zone; **MLYRMB**: Middle-Lower Yangtze River metallogenic belt

SEM: Scanning electron microscope; **Mt**: million tons; **DDH**: Diamond drill hole; **k**: 1000

BCGS: British Columbia Geological Survey; **BRGM**: Bureau de la Recherche géologique et minière; **DEMCo**: Denendeh Exploration and Mining Company; **GEM**: Geomapping for Energy and Minerals program; **GSC**: Geological Survey of Canada; **GSNL**: Geological Survey of Newfoundland and Labrador; **GSQ**: Geological Survey of Queensland; **GSSA**: Geological Survey of South Australia; **GSWA**: Geological Survey of Western Australia; **MERN-Q**: Ministère de l'Énergie et des Ressources, Québec; **NBGS**: New-Brunswick Geological Survey, **NGU**: Norway Geological Survey; **NSGS**: Nova-Scotia Geological Survey; **OGS**: Ontario Geological Survey; **TGI**: Targeted Geoscience Initiative program; **U.**: University; **UQAC**: Université du Québec à Chicoutimi; **USGS**: United State Geological Survey

Minerals — Ab: albite, **Act**: actinote, Adr: andradite, Aln: alanite, **Amp**: amphibole, Ank: ankerite, **Ap**: apatite, **Apy**: arsenopyrite, **Ars**: arsenide, **Aug**: augite, **Bism**: bismuthinite, **Bn**: bornite, **Brt**: barite, **Bt**: biotite, **Cal**: calcite, **Cb**: carbonate, **Ccp**: chalcopyrite, **Cct**: chalcocite, **Chl**: chlorite, **Cob**: cobaltite, **Cpx**: clinopyroxene, **Cum**: cummingtonite, **Dol**: dolomite, **Dp**: iopside, **Ep**: epidote, **Fl**: fluorite, **Gers**: gersdorffite; **Gn**: galena, **Grs**: grossular, **Grt**: garnet, **Gru**: grunerite, **Hbl**: hornblende, **Hd**: heddenbergite, **Hem**: hematite, **Hst**: hastingsite, **Kfs**: K-feldspar, Lin: linnaeite, Loe: loellingite, **Mag**: magnetite, **Mil**: millerite, **Mns**: minnesotaite, **Mnz**: monazite, **Mol**: molybdenite, **Ms**: muscovite, **Phl**: phlogopite, **Pl**: plagioclase, **Pn**: pentlandite, **Po**: pyrrhotite, **Py**: pyrite, **Qz**: quartz, **Saf**: safflorite, **Sch**: scheelite; **Scp**: scapolite, **Sd**: siderite, **Ser**: white mica (sericite), **Sieg**: siegenite; **Sil**: sillimanite, **Sku**: skutterudite; **Sp**: sphalerite, **Stp**: stilpnomelane, **Sul**: sulphides, **Syn**: synchysite, **Tr**: tremolite, **Ttn**: titanite, Urn: uraninite (Whitney and Evans 2010)

Annex 2: References for location, deposit types and resources of deposits

(in alphabetical order)

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