ANNUAL **REPORT**

2022-23

MERC

Mineral Exploration Research Centre
at the HARQUAIL School of Earth Sciences

IN THIS REPORT

MERC

Metal Earth

WATCH NOW!
Metal Earth - Benefits to Canada

About us

Laurentian University's Mineral Exploration Research Centre (MERC) in Sudbury, Ontario, Canada, conducts and promotes global, collaborative, lab- and field-based research on mineral deposits, exploration, and targeting.

MERC hosts internationally recognized projects and researchers from academia, industry and government. Together, faculty members, research scientists, and graduate students focus on mineral deposits, Precambrian geology, and exploration methodology and targeting. MERC also leads the Metal Earth project, one of the world's largest public geoscience projects.

We promote an integrated approach to undergraduate and graduate studies through applied research, education, and HQP training that is designed to:

- solve mineral exploration and mining challenges
- fill knowledge gaps and promote the advancement of geological and exploration education
- supply the sector with a qualified workforce.

As part of Laurentian University's Harquail School of Earth Sciences, MERC is a recognized source of research and geologic expertise. MERC plays a critical role in the training and development of highly qualified personnel for key positions in the mining and minerals industry, academia, and government.

LaurentianUniversity
UniversitéLaurentienne
HARQUAIL School of Earth Sciences École des sciences de la Terre
Canada's Mining University

WATCH NOW!
Metal Earth - Building Research Capacity

Metal Earth:
$104M, the largest university-led geoscience research project in the world

Message from TAMMY **EGER**

Vice-President, Research, Laurentian University

As Laurentian University's Vice-President, Research, I am proud to share this Annual Report, which features remarkable research outcomes, publications, projects, and collaborationsthat place Laurentian University, the Mineral Exploration Research Centre (MERC) and the Harquail School of Earth Sciences (HES) as global leaders in geoscience research.

Through Laurentian University, with funding from the Canada First Research Excellence Fund, MERC leads the Metal Earth project, the largest university-led publicly funded geoscience research project in the world. It's also the largest research project ever led by Laurentian University and is a testament to Laurentian's expertise in geoscience research and teaching through MERC and HES.

In December 2023, Research Infosource released its annual ranking of Canada's Top 50 Research Universities. Among primarily undergraduate universities, Laurentian ranked 1st in research income growth and 2nd in three other categories: research income, faculty research intensity, and graduate student research intensity.

These rankings are something to celebrate, and like the pages of this annual report, they reflect the dedication, effort, partnerships, and positive relationships with academic, government, and industry supporters and collaborators.

Laurentian's leadership and expertise in geoscience was again on the national stage in May 2023, as Sudbury hosted the Annual Meeting of the Geological Association of Canada, Mineralogical Association of Canada, and the Society for Geology Applied to Mineral Deposits (GAC-MAC-SGA Sudbury 2023). More than 700 geologists and students from across the globe participated in three days of scientific presentations and six days of field trips and workshops.
I would like to thank the local organizing committee (comprised mostly of faculty from the Harquail School of Earth Sciences) and all other Laurentian faculty, students, staff, volunteers, and participants for making Laurentian (and Sudbury) shine on the national stage!

Finally, these successes, like the projects in this report, are possible through daily decisions by faculty, staff, students, and collaborators dedicated to research, teaching, projects, and partnerships.
I look forward to supporting their future efforts and celebrating their next achievements.

Thank you, merci, miigwetch

WATCH NOW!
About Metal Earth (2021)

Message from ROSS **SHERLOCK**

MERC and Metal Earth Director

I'm pleased to present this annual report, which provides a snapshot of our 2022-23 Mineral Exploration Research Centre (MERC) and Metal Earth projects.

The following pages highlight the progress and research results of hundreds of researchers, students, faculty members, and staff who have contributed to MERC and Metal Earth projects. The report also features data releases and key peer-reviewed publications made available during and after the end of the official reporting period (March 31, 2023).

MERC and Metal Earth continue to deliver scientific breakthroughs, publish high-impact open-access journal articles, partner with industry, government, and academic institutions on geoscience projects, prepare public data releases, organize global events, and host international collaborations. None of this would be possible without our dedicated team and support from government, industry, and academic partners. We thank them for their contributions at every level.

Canada's Metal Earth project, the largest university-led geoscience project in the world, is now in its eighth year. Since its inception, the project has advanced from massive field data collection across more than a dozen transects to data analysis and research synthesis.

Milestones are marked through peer-reviewed publications, published theses, new geological maps, the adoption of novel lab techniques and algorithms, and the sheer numbers of young and emerging geoscience researchers and professionals who have successfully advanced their careers through their experience with Metal Earth.

Most importantly, the project and its people are changing our understanding of the fundamental processes that result in differential metal endowment, answering key questions that improve mineral exploration targeting and success. Laurentian University leads Metal Earth with research groups at partner universities, and the project's primary funding comes from the Canada First Research Excellence Fund (CFREF).

As the mineral resource industry and government continue to invest in exploration to meet increasing global demand, MERC focuses on developing partnerships, projects, and research that advances geoscience. It's inspiring work, and I am pleased to share it with you as we look forward to 2024.

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eldorado gold

Evolution Mining

IAMGOLD

KINROSS

Tier 2 Members

Agnico Eagle

Equinox Gold

Exiro

GFG Resources

Glencore - Sudbury Integrated Nickel Operations

Gold Fields

International Explorers and Prospectors (IEP)

KGHM

McEwen Mining

Melkior Resources

Noble Mineral Exploration

SRK Toronto

Transition Metals

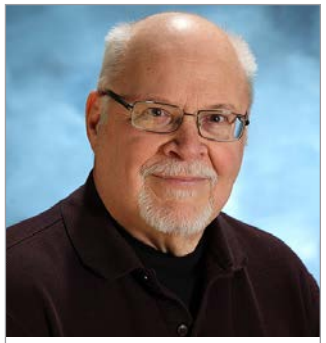
Vale Canada Limited

Wesdome

MERC PEOPLE

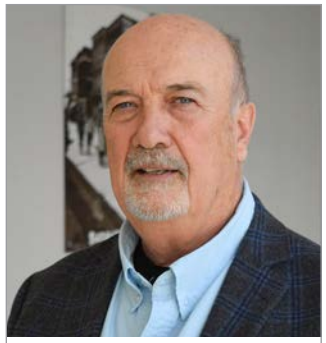
Administration

Ross Sherlock
MERC and Metal Earth Director, Chair in Exploration Targeting



John Ayer
MERC Associate Director, Adjunct Professor

Bruno Lafrance
Metal Earth Associate Director, Professor of Structural Geology



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Founding Director, Metal Earth; Professor Emeritus, Volcanology and Ore Deposits

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Finance and Operations Administrative Manager

Courtney Folz
Project and Board Officer

Lynn Bulloch
Communications Manager

Victoria Kannen
Research Equity, Diversity, and Inclusion (EDI) Advisor for the Office of Research Services and Metal Earth

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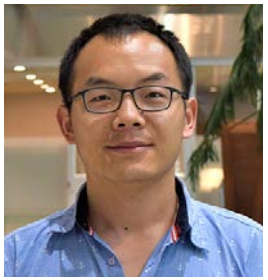
Saeid Cheraghi


Rasmus Haugaard


Taus Jørgensen


Haming Liu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Jeffrey Marsh


Mostafa Naghizadeh


Mohammad Parsadr


Jack Simmons


Jacob Strong


Gyorgyi Tuba


Rajesh Vayavur

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Rebecca Montsion


Kristine Nymoen


Dustin Peters


Adrian Rehm


Eric Roots


Henning Seibel


Jonathan Sutton


Lianna Vice (OGS)

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Nathan Carter


Gabrielle Fouillard


Julian Melo Gomez


Ruth Orlóci-Goodison


Evan Hall


Michael Tamosauskas


Mihir Trivedi

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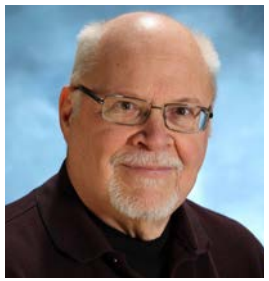
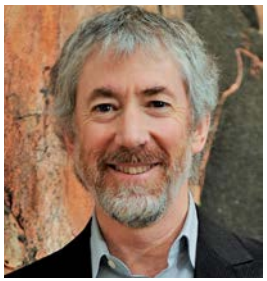

John Ayer


Eric Grunsky


Jeff Harris


François Robert

Technical Staff

Pouran Behnia
Nia Gauthier
Kirk Ross

Canada Nickel, Crawford Deposit

Pedro Jugo

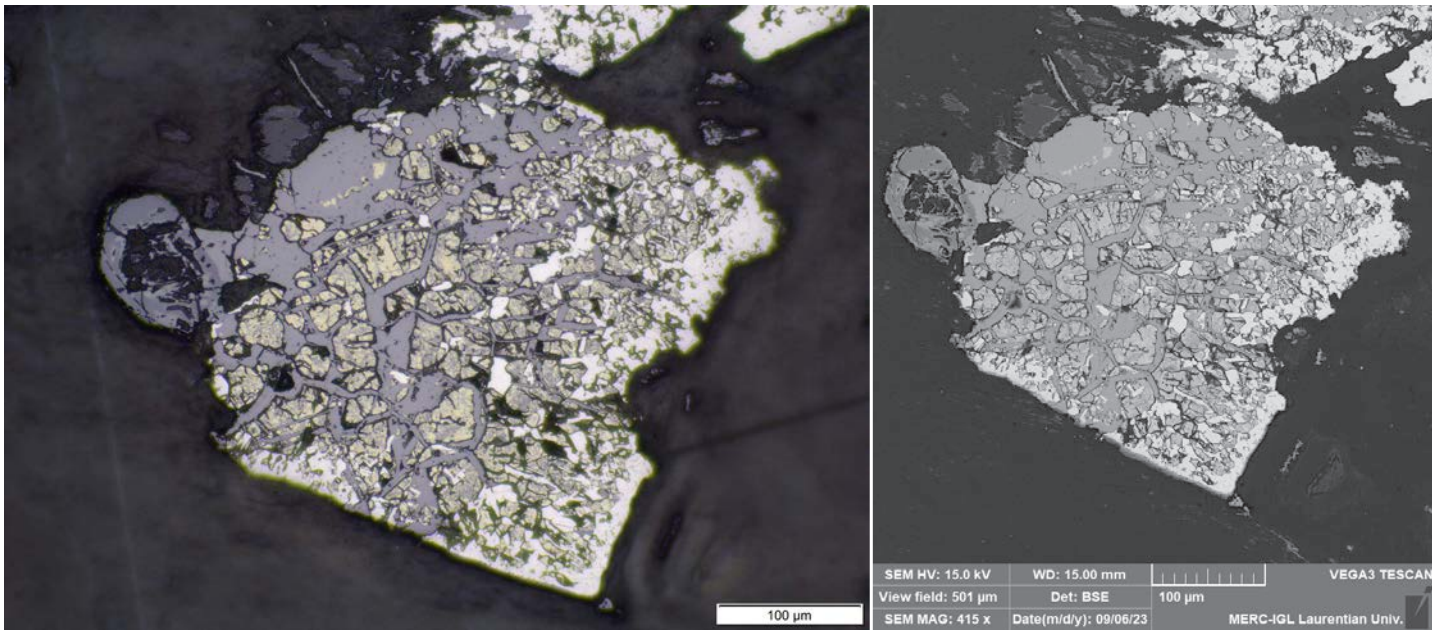
The Crawford Ni-Co-(PGE) deposit is the subject of Nathan Carter's MSc thesis with MERC and the Harquail School of Earth Sciences, in collaboration with the Canada Nickel Company. This project began in May 2022. Collection of the research samples were completed in two field seasons during summer 2022 and 2023.

The 2704 ± 0.88 Ma, Crawford nickel deposit, located 50 km north of the City of Timmins, is part of a mafic-ultramafic intrusion hosted within the metavolcanic rocks of the Deloro Assemblage in the Abitibi greenstone belt. It is recognized as a low-grade, high-tonnage disseminated nickel-bearing body.

The objective of this project is to characterize the serpentinization of olivine and primary magmatic sulfides, determine how it is linked to the Ni mineralization, and extract mineralogical and geochemical parameters that may help locate and evaluate similar deposits in the district and elsewhere.

The intrusion has variable degrees of serpentinization, resulting in complex Ni-rich assemblages, and correspondingly complex textures. These characteristics provide a unique opportunity to reconstruct the mineralogical transformations during the progressive stages of serpentinization that formed the deposit.

Preliminary results show that progressive transformation of primary sulfides (including pentlandite) to secondary sulfides (heazlewoodite and godlevskite) to alloys (awaruite, but also native copper) and secondary magnetite indicate desulfurization during serpentinization and mobilization of Fe, Ni, S, and Cu, which are either lost from the system or stabilized via dissolution-reprecipitation reactions. Pending work includes characterization of the Ni content in olivine and Fe/Ni in pentlandite, which would allow estimation of the Ni content in the dunites prior to serpentinization, link mineral chemistry data with whole rock data, and allow an estimate of the enrichment factor.



Canada Nickel 1 (Reflective Image). Canada Nickel 2 (Back scatter image)

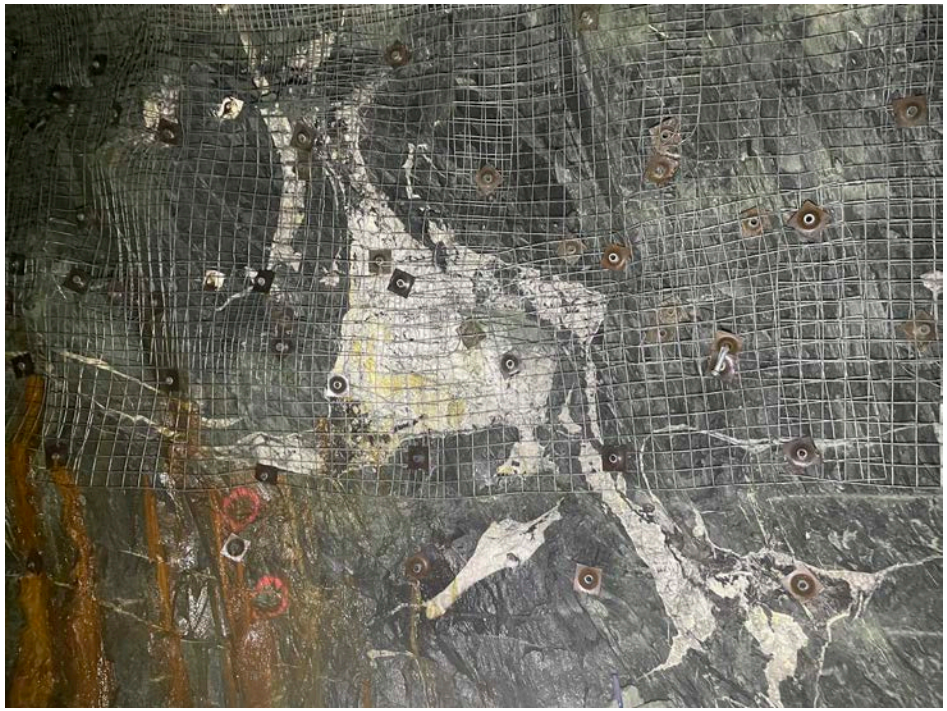
Reflected light image (left) and backscattered light image (right) of an example of the transformations of primary sulfides during serpentinization. Bright areas (bottom edge of the grain, but also cropped top right part of the image) are awaruite; grey areas(top part of the grain and network of veinlets) are secondary magnetite. Bronze colored patches dissected by magnetite veins are residual sulfides.

Eldorado Gold, Ormaque Deposit

Bruno Lafrance, Ross Sherlock

The Ormaque Deposit is a new gold discovery by Eldorado Gold within the renowned Val D'Or, Quebec district in the Archean Abitibi greenstone belt. It has an inferred resource of 2.2 million tonnes grading 11.74g/t for a total of 839,000 ounces of gold. The deposit is situated at the halfway point of an underground ramp that transports ore from the Triangle mine to the mill and is expected to go into production in 2026 with the Lower Triangle deposit.

The deposit is the subject of an MSc project by Shalaila Bhalla in partnership with Eldorado Gold and Mitacs. The Ormaque deposit is hosted by a porphyritic diorite intrusion in contact with volcaniclastic supracrustal rocks of the ca. 2703 Ma Val d'Or Formation. It consists of steeply north-dipping shear zones, which are broadly parallel to the diorite-volcaniclastic contact, and shallowly dipping extensional veins, which form multiple gold mineralized intervals of stacked quartz-carbonate-tourmaline veins surrounded by variably mineralized wall-rock.



Underground blow-out zone at the Ormaque deposit.

The extensional veins are displaced along north-dipping reverse faults and are oriented at an angle of 75° to 85° to the fault zones. The deposit thus differs in geometry from that of the nearby world-class Sigma Mine, where faults are both north- and south-dipping, and the extensional veins are oriented at a lower angle to the fault zones. Determining why the two deposits differ from each other is important because the Val d'Or camp is where the influential fault-valve model for the formation of orogenic gold deposits was originally proposed.

The main objectives of the research project are to characterize the geology of the Ormaque Deposit and explore new models for the formation of the veins and faults at the deposit. The findings from this study will shed new information on the formation of gold deposits in the Val D'Or district and provide new insights into the fault-valve model and formation of orogenic gold deposits worldwide.

MSc student Shalaila Bhalla in the core shack.

VIEW OR DOWNLOAD SHALAILA BHALLA'S POSTER PRESENTED AT PDAC 2023.

Argonaut Gold, Magino Deposit

Bruno Lafrance, Ross Sherlock

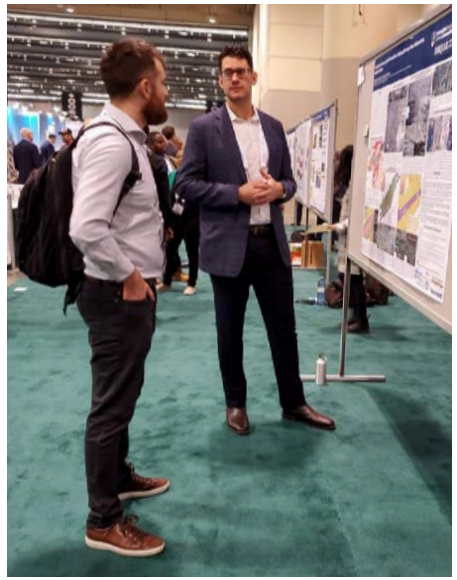
The Magino gold deposit is the subject of Ian Campos' MSc thesis with MERC and the Harquail School of Earth Sciences in collaboration with Argonaut Gold Inc. and Mitacs. Magino is an exciting new project on one of the newest gold mines in northern Ontario. Located northeast of Wawa, the Magino mine poured its first gold in June 2023; commercial production was achieved on November 1, 2023.

Ian Campos and fellow exploration geologists inspecting strongly deformed and folded dykes of the multi-phase Webb Lake Stock intrusion, which intrude the surrounding massive mafic volcanic country rocks.

A need to better understand the geology of the deposit prompted the present project. The Magino deposit is hosted by the Webb Lake stock within the Goudreau deformation zone of the Archean Wawa subprovince.

The main goals of Ian's research are to characterize the styles of gold mineralization at the deposit, resolve the structural controls on mineralization, and propose a model for the formation and subsequent deformation of the mineralized zones and remobilization of gold at Magino. Both intrusion-related and orogenic gold deposits can spatially overlap along major deformation zones, therefore resolving how and when the deposit formed can have important mineral exploration implications. Fieldwork and lab-based analytical work are complete, and Ian defended his thesis in fall 2023.

Significant new findings result from this project. Unlike the nearby Island Gold deposit, Magino originated as an intrusion-related gold deposit, with new gold emplaced or remobilized during the orogenic event that created the Goudreau deformation zone.



MSc student Ian Campos (right) receiving questions about his research at the Student Minerals Colloquium held during the Prospectors and Developers Association Convention in March 2023.

VIEW OR DOWNLOAD IAN CAMPOS' POSTER PRESENTED AT PDAC 2023

Agnico Eagle Mines, Upper Beaver Deposit

Bruno Lafrance, Dan Kontak

An iron-carbonate altered breccia in the damage zone of the fault separating the Blake River and Tisdale Assemblages at Upper Beaver. Photo: Ruth Orloci-Goodison.

The Upper Beaver deposit is being studied as a joint research project between Université Laval and MERC. Agnico Eagle Mines Ltd owns the deposit. The company believes that the deposit has the potential to become a low-cost mine with moderate capital outlays. Mining of the deposit could begin in 2029 with an annual production of 150,000 to 200,000 ounces of gold.

Upper Beaver is an Archean intrusion-related gold-copper deposit located in the Abitibi greenstone belt in Ontario. Mineralization is associated with steeply dipping sericitic ore zones, which are parallel and coeval with the emplacement of steeply-dipping dikes of the Upper Beaver Intrusive Complex. Gold was further introduced during the formation of shallowly-dipping, stratiform, garnet-epidote-amphibole skarnoid ore zones, which are overprinted by the sericitic ore zones.

Three PhD students, two MSc students and one postdoctoral fellow are involved in the project. Of the five students, one PhD student, Jonathan Sutton, and one MSc student, Ruth Orlóci-Goodison, are based at

Laurentian University. Jonathan's research is supervised by Dr. Daniel Kontak (Laurentian University) and Georges Beaudoin (Université Laval).

The main objectives of his research are:

1) to develop a paragenesis for the host rocks, hydrothermal alteration, and mineralization associated with the deposit;

2) to develop a 3D model of the deposit; and

3) to characterize the elemental signature and mineralogy of the various ore zones and determine their significance for the genesis of the deposit.

Ruth's research is supervised by Dr. Bruno Lafrance (Laurentian University). Her project aims to characterize the structural controls on the emplacement and geometry of the Upper Beaver deposit. Ruth's research addresses how alteration, the presence of preexisting planar anisotropies, and the orientation and composition of the ore zones enhanced strain partitioning and the development of structures in the strained ore zones. Ruth presented her research at GAC-MAC-SGA in Sudbury in May 2023 and defended her MSc thesis in November 2023.

MSc student Ruth Orlóci-Goodison with core samples from the Upper Beaver deposit.

Jonathan Sutton is a PhD student and exploration geologist-in-training at Agnico Eagle Mines. He contributed to PDAC's technical program on Archean gold deposits in Canada in March 2023, where he presented the Upper Beaver project.

Blue Star Gold Corp., Ulu Gold Project

Ross Sherlock, Bruno Lafrance

The Ulu Gold Project is the subject of Evan Hall's MSc thesis with MERC and the Harquail School of Earth Sciences, in partnership with Blue Star Gold Corp. and Mitacs.

Located in the relatively underexplored High Lake greenstone belt, ~525 km NNE of Yellowknife in the Kitikmeot region of western Nunavut, the Ulu Gold Project is a significant high-grade gold resource. A need to better understand the geology of the deposit has prompted the present project.

MSc student Evan Hall (second from left) and exploration team at Blue Star Gold Corp.'s Ulu Gold Project, Kitikmeot region, Nunavut, summer 2023.

The deposit is hosted in amphibolite grade mafic volcanics within a major fold structure and has undergone multiple phases of deformation. Yet, the deposit lacks characteristics common to other orogenic gold deposits, such as axial planar cleavage, pervasive carbonate alteration, and is not associated with a dominant belt order structure.

The main goals of Evan's research are to resolve the controls on mineralization by developing a better understanding of the structural controls and the role of lithostratigraphy and chemostratigraphy within the deposit, and to propose a model for the formation of the deposit.

Two seasons of field work have been completed in the deposit area, with samples collected for petrographic characterization of the lithologic units and ore zone, definition of the features controlling mineralization, whole rock geochemistry, alteration assemblage mineral chemistry, and samples for U-Pb dating. Lab-based analytical work is underway, and integration of these results will generate a model that will help guide present and future mineral exploration in this mining camp.

MSc student Evan Hall (left) and fellow exploration geologist inspecting strongly deformed and folded volcanic strata, Ulu Gold Project, Kitikmeot region, Nunavut, summer 2023.

The findings from this study will shed new information on the formation of gold deposits in the High Lake greenstone belt and add to growing literature on the formation of gold deposits hosted in higher-grade metamorphic terranes worldwide.

Sudbury Transect - NSERC CRD

Rasmus Haugaard

Shocked zircons from the gneissic footwall rocks. The gneisses represent the Sudbury crater floor at approximately ~3 km depth. Source: R. Haugaard.

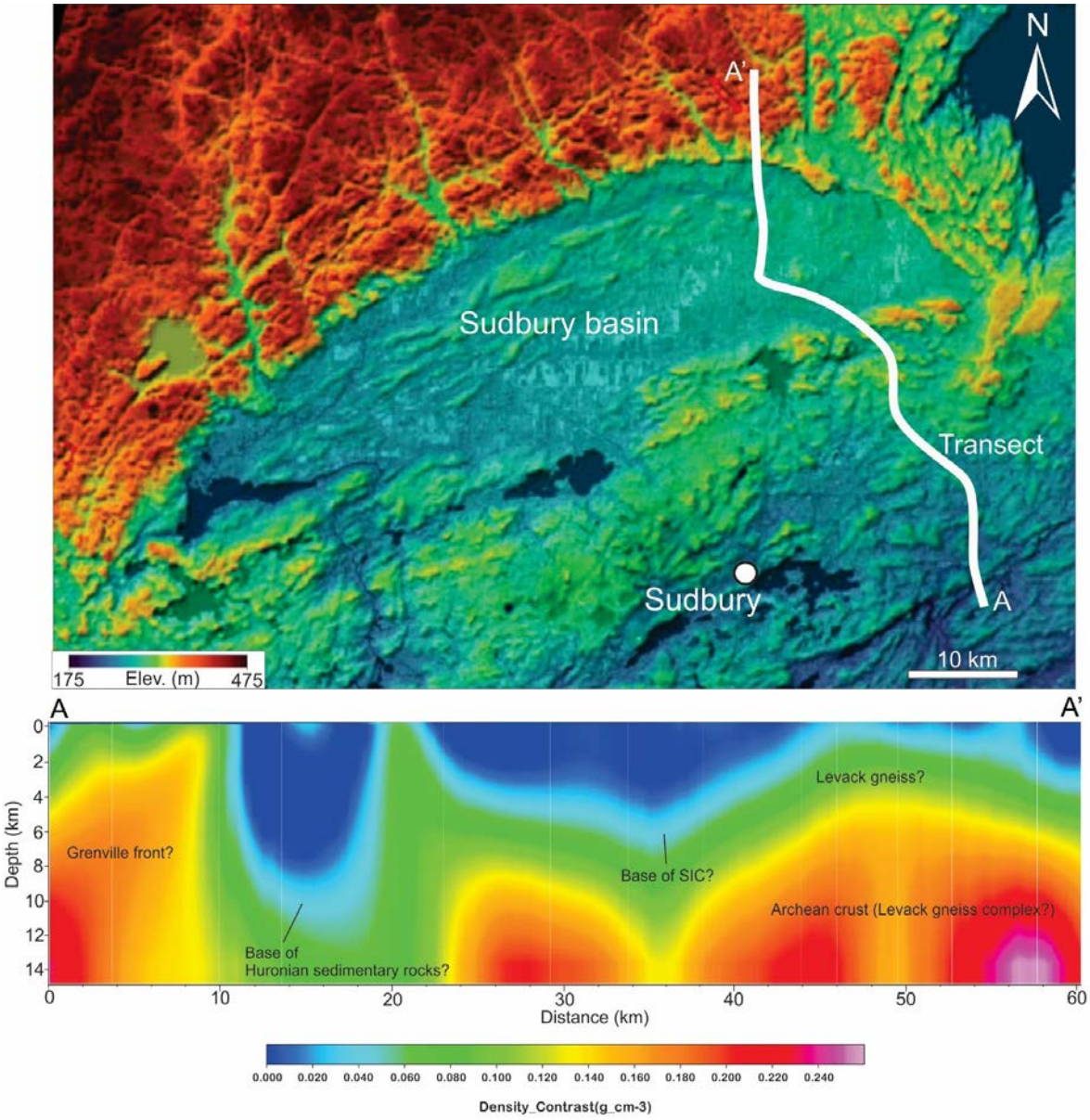
This project is funded through a Collaborative Research and Development Grant (CRD) from the Natural Sciences and Engineering Research Council (NSERC) and industry collaborators Glencore and Vale.

Progress

This project has been generating new geological ideas in the northeast range of the Sudbury Impact Crater (SIC). Geological discussions with Vale and Glencore on new geochronology, stratigraphical constraints and possible new mineralizing structures were carried out.

Geochemical and geochronology constraints have been obtained from the gneissic footwall in >3 km deep drill holes. This, alongside a newly generated higher resolution seismic and MT profile across the northeastern rim of the SIC, has shed light on deeper mineralized structures as well as constraining the deep-rooted geological architecture of one of the largest impact craters on Earth.

At the start of the year, Professor John Spray (Director of the Planetary and Space Science Centre at the University of New Brunswick) joined the project to



help with the overall interpretation of the gneissic footwall rocks underneath the crater.

Three research talks were given in the spring and early summer: one at Willet Green Miller Centre with participants from MERC, Vale, and Glencore; one at an exploration meeting at Vale, and the third at GAC-MAC-SGA 2023, Crustal Architecture and Deep Basement Structures in the North Range of the Sudbury Impact Crater.

Future Work and Anticipated Outcomes

The project is at its final stage, and two manuscripts are being prepared: one focusing on geology (R. Haugaard) and one on geophysics (R. Vayavur). A research meeting with a visit to Glencore in the fall of 2023 is also planned.

Highlights

- This is the first time that the contact between the northern rim of the Sudbury crater and the footwall/contact gneiss has been imaged by deep geophysics, which is a scientific breakthrough.

Top image: A digital elevation model (DEM) of the Sudbury basin and surrounding surface rocks. The white (A-A') line represents the main CRD transect crossing the eastern part of the basin. Along the transect, important deep geophysical surveys (e.g., seismic, magnetotelluric and gravity) have been undertaken and are currently being interpreted with respect to the crustal geology and related mineralizations. Source of DEM map: https://earthobservatory.nasa.gov/images/148844/sudbury-impact-structure.

Bottom image: An example of the large scale gravity modelled along the white (A-A') transect. The Sudbury basin and the Sudbury Igneous Complex (SIC) represent a distinct crustal feature with an overall low gravity anomaly.

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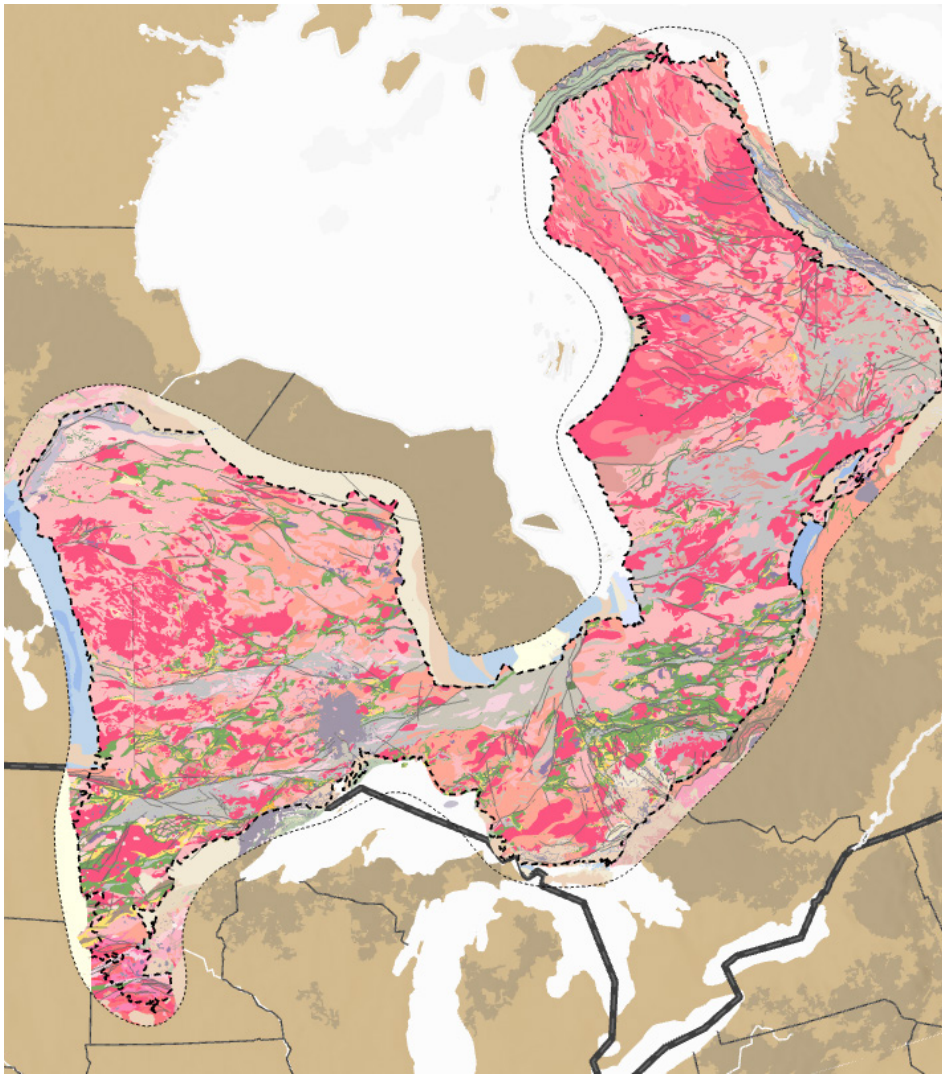
Metal Earth YouTube Playlist

METAL EARTH

Transforming our understanding of Earth's early evolution and processes that result in differential metal endowment



Metal Earth is a Canadian $104 million applied R&D program led by Laurentian University.

The project is transforming our understanding of the genesis of base and precious metal deposits during Earth's evolution. It will make Canada a world leader in metal endowment research and a world-class innovator through open-source delivery of new knowledge and the implementation of new technology.

With funding from the Canada First Research Excellence Fund and additional federal, provincial, and industry partners, this initiative is a strategic consortium of outstanding researchers from academia and allied Canadian and international research centres, government, and industry.

Core goals and objectives

Fundamental Science

- Transform our understanding of Earth's early evolution and processes that govern differential metal endowment.
- Improve the science for targeting and finding new orebodies.

Applied Innovation and Commercialization

- Cement Canada's position as a global leader in mineral exploration research through open-source delivery of new knowledge and the development of transformative technologies targeted at increasing exploration success.
- Improve training of quality young geoscientists for the mineral industry.

Canada

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METAL EARTH

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UNIVERSITY OF TORONTO

SIGNATURE **PUBLICATIONS**

The list below highlights 15 of our signature peer-reviewed journal publications to reflect the breadth and significance of Metal Earth's research progress and outputs in 2022-23.

Adetunji, A. Q., Launay, G., Ferguson, I. J., Simmons, J. M., Ma, C., Ayer, J., & Lafrance, B. (2023). Crustal conductivity footprint of the orogenic gold district in the Red Lake greenstone belt, western Superior craton, Canada. Geology, 51(4), 377-382. https://doi.org/10.1130/g50660.1

Behnia, P., Harris, J., Liu, H., Jørgensen, T. R. C., Naghizadeh, M., & Roots, E. A. (2023). Random forest classification for volcanogenic massive sulfide mineralization in the Rouyn-Noranda Area, Quebec. Ore Geology Reviews, 161. https://doi.org/10.1016/j.oregeorev.2023.105612

Fassbender, M. L., Hannington, M., Stewart, M., Brandl, P. A., Baxter, A. T., & Diekrup, D. (2023). Geochemical Signatures of Felsic Volcanic Rocks in Modern Oceanic Settings and Implications for Archean Greenstone Belts. Economic Geology, 118(2), 319-345. https://doi.org/10.5382/econgeo.4967

Godet, A., Guilmette, C., Marsh, J. H., Rottier, B., Tinkham, D., Siles Malta, I., Rehm, A., Jørgensen, T. R. C., Hamilton, M. A., Ribeiro, D., & Beaudoin, G. (2023). Origin, nature, and evolution of the northern Pontiac subprovince, Canada: Insights from the intrusive record. Precambrian Research, 396. https://doi.org/10.1016/j.precamres.2023.107169

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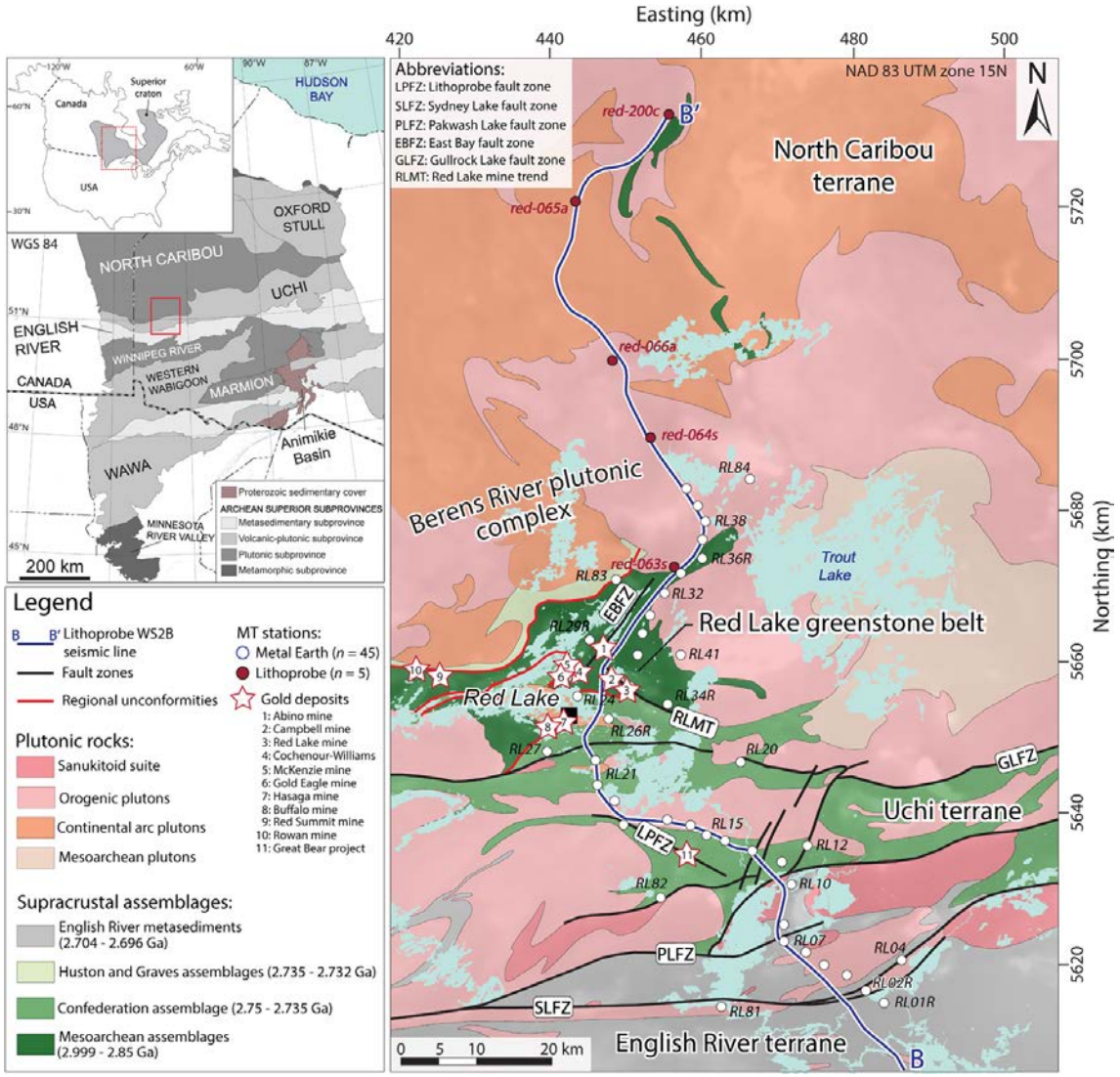
Geophysics in the Metal Earth Project

Lead Researcher: Richard S. Smith, Laurentian University



Progress

Research associate (RA) Saeid Cheraghi focused on the seismic data from the Swayze East area to develop advanced processing methods, including pre-stack depth migration and pre-stack time migration algorithms, as applied to crystalline rock environments. Results were published in Geophysical Prospecting in October 2022.

Saeid is also working on a manuscript to address heterogeneity and scaling behaviour of crystalline rocks with a comparison of examples from the Abitibi and Wabigoon subprovinces.

In another research project, Saeid reprocessed several regional and high-resolution seismic profiles acquired in the Timmins area. The reprocessing improved the imaging results, and they have been utilized to better interpret magnetotellurs (MT) data recently acquired in the Timmins area.

Geological map of study area, western Superior craton, Canada (modified from Sanborn-Barrie et al., 2004), showing magnetotelluric (MT) locations (red and white circles), Lithoprobe WS2B seismic reflection profile (blue line), and Au mineralization (white stars). Coordinate system abbreviations: WGS 84—World Geodetic System 1984; NAD 83—North American Datum of 1983; UTM—Universal Transverse Mercator. Source: Ademola Q. Adetunji et al., Crustal conductivity footprint of the orogenic gold district in the Red Lake greenstone belt, western Superior craton, Canada. Geology. 2023;51(4):377-382. doi:10.1130/G50660.1.

WATCH NOW!
S. Cheraghi: *Interactive seismic attributes interpretation, Metal Earth scientific meetings, March 2023.*

RA Rajesh Vayavur focused on 3-D potential-field inverse modelling of Metal Earth transects. To date, Rajesh has completed 3-D inverse modelling for the Malartic, Chicobi (Malartic sub-transect), Swayze, Matheson, Rouyn-Noranda, Sturgeon, Larder-Lake, Cobalt, Geraldton and Timmins transects. Work is in progress for the remaining transects. Results have been incorporated into the interpretations described elsewhere.

Independent of this work, Rajesh completed 3D-constrained modelling on the Chicobi transect to show the utility of density constraints. This work was included in a petrophysical compilation paper (previous RA work) submitted to Exploration Geophysics and published in November 2023.

Rajesh is also undertaking work to unravel the upper-crustal architecture of the Eastern Sudbury basin by 3D integration of various geological and geophysical datasets. This work is carried out as part of NSERC-CRD grant in collaboration with Vale and Glencore companies. Rajesh observed a good correlation between various geophysical models and geological datasets and identified three shallow conductors in the audio-frequency range MT (AMT) model: one in the north-east range close to the basal-contact of the SIC, the second one in the east-central part corresponds to sediments in the upper parts of the stratigraphy of the Sudbury basin, and the third one in south-east range is also at the basal-contact of the SIC. The broad-band MT (BBMT) model delineated mid to deep crustal conductors that could be a conduit connected to the shallow conductors observed in the AMT model. The potential-field inversions provided geophysical evidence of folding and/or faulting of upper-crustal Archean basement mafic/ultramafic rocks and suggest that the associated deformation might have altered rocks, resulting in weaker magnetic and gravity fields in the East Range of the Sudbury impact structure. High-resolution seismic data support the evidence of deep-seated faulting interpreted from the potential-field inversion models. Rajesh suggests deep-seated faults interpreted from potential-field inversion, and the AMT and BBMT data could act as conduits for hydrothermal fluid flow from deep crustal conductors to shallow conductors. The results are presented at 68th ILSG Annual Meeting and PDAC 2023 conferences. A paper is also in preparation on this topic.

In addition, Rajesh has performed 3D depth-to-basement geometry inverse modelling using gravity data to constrain the topography of the base of the Sudbury impact crater around seismic line 182. The final inverted surface dips southwards from the North Range of the Sudbury basin, as expected, but also identifies an anticline, which is not apparent on the seismic reflection section. The inverted surface complements the seismic reflection section and helps trace the seismic reflector in areas of low signal-to-noise ratio. The results were presented at the GAC-MAC 2023 conference in Sudbury.

Ademola Adetunji has been working on three papers with primarily geophysical content. The paper describing the metallogenic, tectonic, and geological interpretation of the MT results for Red Lake has now been published in Geology. The manuscript describing the Metal Earth MT data interpretation for the Chibougamau transect is in the final stages of geological inputs and will be submitted for publication shortly. An article that describes the large-scale tectonic structures and history associated with the world-class Timmins gold deposits, based on insights from Metal Earth's Timmins broadband MT data, is under preparation and should be published by the next reporting period.

Eric Roots, a PhD student, is working on the inversion of magnetotelluric (MT) data. He is currently working on analyzing and modelling the MT data in the western Superior. The results have been split into two manuscripts (in progress). The first manuscript covers the crust, which exhibits east-west resistivity trends that likely correspond to the tectonic construction of the western Superior. The second manuscript covers anisotropic modelling results of the region to explain an observed disparity in the east-west and north-south conductivities of the region, inferred to relate to channelized metasomatism of the lithospheric mantle and subsequent modification during the Mid-continent Rift event.

Chris Mancuso is a PhD student working on joint inversion of geophysical data in the Western Wabigoon province. He has developed a novel approach to ray tracing that will mitigate extreme

VIEW OR DOWNLOAD
Smith, R.S. et al in The Leading Edge. Geophysical transects in the Abitibi greenstone belt of Canada from the mineral-exploration-oriented Metal Earth project. 2023.

WATCH NOW!
Christopher Mancuso: *The application of ground-penetrating radar surveys for unmarked burials, Harquail School of Earth Sciences seminar series, November 2022.*

heterogenies and velocity inversions typical of highly tectonized mining belts. As part of the proof of concept of this approach, he has developed a complex synthetic velocity model to serve as a more appropriate benchmark for land-based reflection seismic modelling.

Although Hossein Joideri Akbari Fam finished his thesis last year, two of his publications were revised and came out in 2023, so have been included in this report.

Fabiano Della Justina successfully completed and defended his PhD thesis at the end of 2022. Three papers have been prepared from the thesis, with one undergoing revision after review.

The geophysics group has been working with the data integration group of Metal Earth and have coauthored a number of papers that are noted in the Data Analytics portion of this report.

Future Work

The Metal Earth project is embarking on a large-scale MT data acquisition project designed to image the Hope Bay Greenstone belt. Results are expected to help understand similarities and differences between the gold-endowed Hope Bay and Abitibi belts.

Saeid Cheraghi is working on seismic attribute interpretations with the help of machine learning and computer vision. He is investigating an advanced algorithm for better subsurface interpretations.

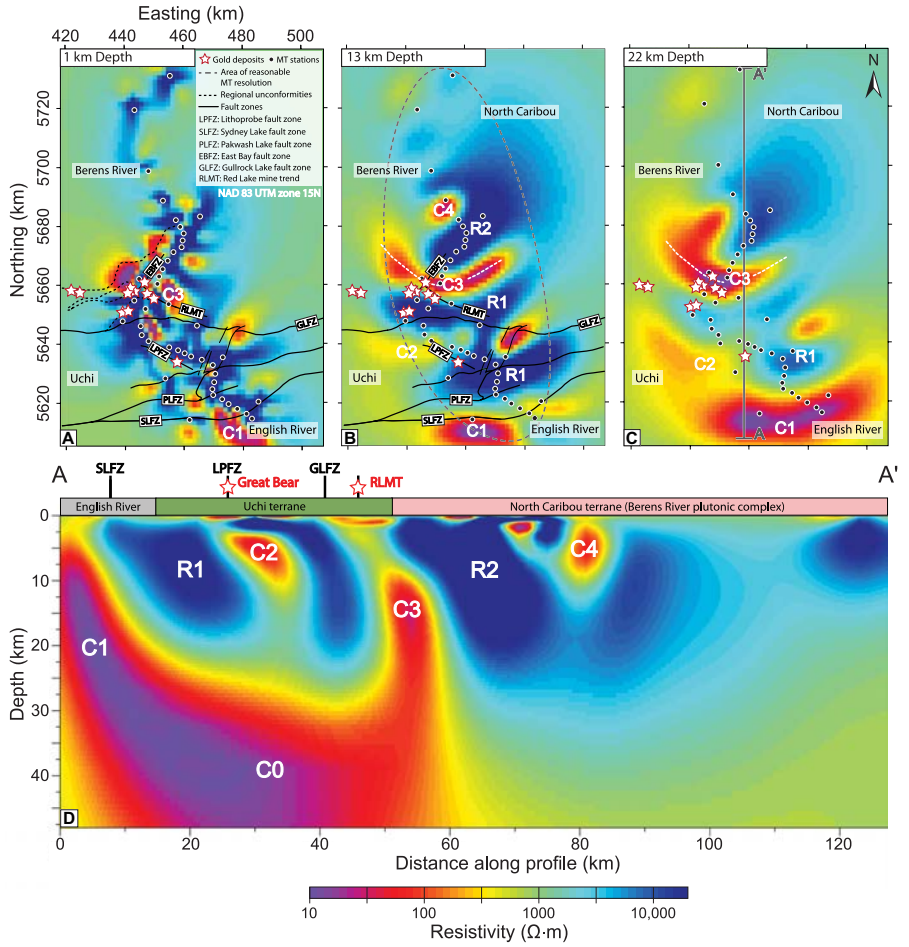
Rajesh will complete his revisions to the Petrophysical paper, which has just been published. He will also complete his Sudbury basin paper for submission to a reputed journal.

Ademola will complete and publish both the Chibougamau and Timmins large-scale MT results.

The latter requires modelling and inverting the extensive AMT data acquired for different companies around Timmins to help with understanding of the deposit scale-structures.

Eric Roots should complete and defend his thesis in December 2023.

Chris Mancuso will use the velocity and density models estimated from travel-time inversion to be fused with regional and transect gravity data to



Top image: (A–C) Resistivity model showing horizontal slices at upper-crustal (A), mid-crustal (B), and lower-crustal (C) depths. MT—magnetotelluric. Bottom image: (D) Cross section extracted from the three-dimensional model along the line A-A′ indicated in panel C. Black dots show the MT locations and white stars show Au deposits. R1–R2 and C0–C4 are resistive and conductive features, respectively. Coordinate system abbreviations: NAD 83—North American Datum of 1983; UTM—Universal Transverse Mercator.

Source: Ademola Q. Adetunji et al., Crustal conductivity footprint of the orogenic gold district in the Red Lake greenstone belt, western Superior craton, Canada, Geology 2023;; 51 (4): 377–382. doi: https://doi.org/10.1130/G50660.1.

WATCH NOW!
F. Della Justina: *The incorporation of geophysical, petrophysical and geological constraints in gravity modeling to resolve structures at depth, Metal Earth scientific meetings, March 2023.*

VIEW OR DOWNLOAD
Fabiano Della Justina's PhD thesis: The incorporation of geophysical, petrophysical and geological constraints in gravity modeling to resolve structures at depth, December 2022.

make joint physical property models of the Western Wabigoon subprovince. He plans to disseminate the ray tracing method and the subsequent joint inversion results in a series of manuscripts and conference presentations in 2024.

Anticipated Outcomes

Saeid's work on machine learning provides a fast and reliable method for interpreting seismic images.

The Sudbury work of Rajesh Vayavur has helped to understand the upper-crustal architecture of the Eastern Sudbury basin. It shows the importance of 3D
integration of various geological and geophysical datasets and 3D-constrained modelling for comprehensive subsurface interpretation.

The conductivity structures imaged by MT data are expected to shed light on the tectonic/geodynamic history and fluid pathways that can be used to construct the source-to-sink history of mineral deposits, or lack of it.

The work of Eric Roots shows that anisotropy is present in the western Superior, which has implications for the geodynamic history of the western Superior province. It could also be used to understand the geodynamic history of other Archaen shields around the world

Implications

Saeid's work on the seismic processing of the Metal Earth data improved the fault imaging down to depths within the deep crust. The fault geometry, e.g., its dip and depth, is a criterion to explain metal endowment in the Abitibi and Wabigoon subprovinces.

The final cross-section and iso-surface models from 3-D potential field inversions are helping transect RAs to refine their interpretation of crustal-scale faults and upper crustal architecture. Rajesh's work on Sudbury has also shown the importance of 3D integration of various geological and geophysical datasets to improve subsurface interpretation.

Fabiano's work ascertained the dip of the Porcupine Destor Fault in the Matheson area, which has implications for exploration targeting in that area.

Highlights

- As a co-author, Hossein Jodeiri Akbari Fam received the Best Paper award from The Leading Edge for "A reality check on full-wave inversion applied to land seismic data for near-surface modelling," published in January 2022.
- Chris Mancuso was awarded the Michael and Patricia Carson Geophysics Scholarship for Indigenous students.
- Another paper, first authored by Hossein titled "3D generalized spherical multifocusing seismic imaging" was nominated by the Geophysics editors and highlighted in "Geophysics Bright Spots" in The Leading Edge, 42, no. 2. doi: https://doi.org/10.1190/tle42020133.1.
- Fabiano Della Justina's thesis outlines a way of quantifying uncertainty in gravity modelling and illustrates the importance of geological constraints in gravity modelling.
- The geophysical results from the Sudbury integration were presented at the 68th ILSG Annual Meeting (2022) and PDAC 2023 conferences. The results were also presented at the 2023 Vale PGEN Meeting and were well received.

VIEW OR DOWNLOAD
Crustal conductivity footprint of the orogenic gold district in the Red Lake greenstone belt, western Superior craton, Canada. Geology 51, 4. 377-382.

VIEW OR DOWNLOAD
Cheraghi, S. et al in Geophysical Prospecting. Reflection seismic imaging across a greenstone belt, Abitibi (Ontario), Canada. 2022.

VIEW OR DOWNLOAD
Esmaeil Eshaghi et al, in Exploration Geophysics. Density and magnetic susceptibility of major rock types within the Abitibi greenstone belt: a compilation with examples of its use in constraining inversion. 2023.

Craton Scale Studies: Isotopic Mapping

Lead Researchers: Phil Thurston, Douglas Tinkham, and Jacob Strong, Laurentian University; David Mole, Geoscience Australia

Post-doctoral fellow Jacob Strong collected samples from remote areas during his summer 2023 field season, at times using his ultralight kayak and/or a float plane to conduct sampling. Image depicts Rieder Lake gneiss complex, Hudson Bay terrane. Photo: Jacob Strong.

WATCH NOW!
Kristine Nymoen - *Integrating whole-rock geochemistry with isotopic mapping and phase equilibria: crustal architecture of the Wawa subprovince, March 2023 Partner Meeting.*

VIEW OR DOWNLOAD
D.R. Mole, B.M. Frieman, P.C. Thurston, J.H. Marsh, T.R.C. Jørgensen, R.A. Stern, L.A.J. Martin, Y.J. Lu, H.L. Gibson, Crustal architecture of the south-east Superior Craton and controls on mineral systems, Ore Geology Reviews, Volume 148, 2022, 105017,ISSN 0169-1368, https://doi.org/10.1016/j.oregeorev.2022.105017.

Progress

Post-doctoral fellow (PDF) Jacob Strong was hired in January 2023. In the summer of 2023, Strong completed Lu-Hf mapping of the North Caribou terrane. He is working on samples from the North Caribou, Hudson Bay, and Winnipeg River terranes. Strong will conduct Hf isotope work on the samples once zircon separation is complete.

PhD candidate Kristine Nymoen is in year three of the Craton-scale mapping project and is continuing work on her thesis, Isotopic mapping of the southern Superior craton in space and time: Implications for large-scale mineral endowment. Phil Thurston, Douglas Tinkham, and David Mole are her supervisors.

Progress made in the PhD study during the reporting timeframe (April 2022-March 2023) includes:

- Fieldwork is complete, including the collection of 50 samples to help fill the remaining gaps spatially and temporally across the Abitibi and Wawa subprovinces of the Superior Province
- Whole rock lithogeochemical and S isotope analysis of sulfide is complete
- Additional trace element, U-Pb geochronology, Hf isotope, and O isotope analyses on zircon are completeted
- Nymoen presented her PhD thesis research at the Prospectors and Developers Association Convention Student Minerals Colloquium in March 2023

Future Work

Future work on the PhD research project includes:

- Complete interpretation of new data and finalize manuscripts
- Further integrate the craton-scale isotopic mapping PhD project results with other Metal Earth research to achieve the stated goals of the Metal Earth program
- Publish a paper on S isotopes in 2023

Anticipated Outcomes

Nymoen's study will enhance our knowledge of the variability of crustal architecture by using zircon geochronology to determine the timing of crustal reworking to generate new felsic crust, using lithogeochemistry to identify geochemical signatures of magmatism and geochemical signature of source rocks, and elucidate the Hf & O isotopic signatures and age variability of source rocks. This allows a better understanding of how crustal architecture may relate to and influence differential crustal endowment in the Wawa-Abitibi region of the Superior Province.

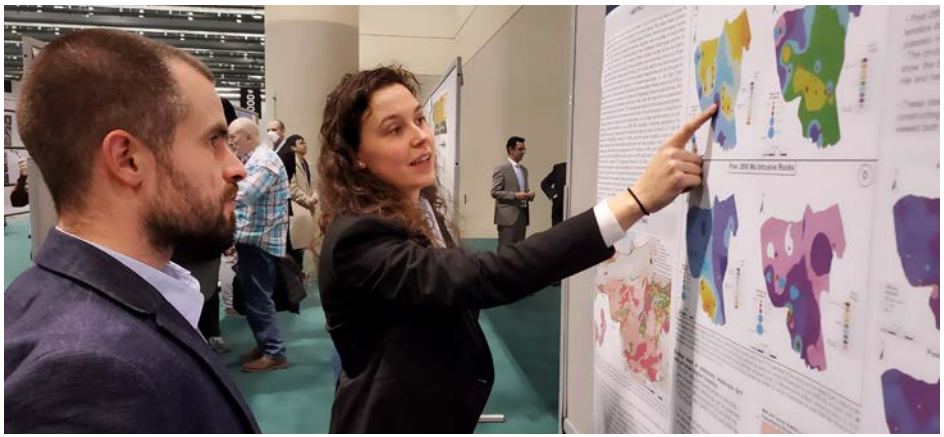
Strong's PDF project will contribute to developing a non-plate tectonic model (i.e., rifting-related model) for the Superior Province.

Implications

Nymoen's PhD project enhances understanding of the variability of crustal architecture throughout the Southeastern portion of the Superior Province. Notably, this project is helping advance our understanding of the variability of crustal architecture in both well-endowed and less-endowed portions of the Superior Province, a stated goal of the Metal Earth program.

(Left) Phil Thurston inspecting dismembered greenstone rafts in leucocratic granitoid, Rasin Lake dome, Winnipeg River terrane. Photo: Jacob Strong.

(Right) Kristine Nymoen on a pre-conference field trip at the 6th Annual International Archean Symposium in Perth, Australia. Nymoen and Phil Thurston were among six Metal Earth researchers to participate.



Marc Fassbender (left) learns about Kristine Nymoen's research as presented at the Student Minerals Colloquium in March 2023.

Highlights

- PhD project tests the architecture of Archean terranes in terms of depth of magma generation and the role of S in Archean magmatism and increases the known spatial extent of older 2.8-2.9 Ga Mesoarchean crust as a source for some Neoarchean TTG crustal growth
- Nymoen passed her comprehensive exam, completed all course requirements, and her first manuscript on the Wawa subprovince is nearly complete, including the initial interpretation of all data
- PDF project tests an accretionary model for Superior Province. At GAC-MAC-SGA 2023, Strong presented the following abstract: Crustal growth and reworking in the Winnipeg River terrane ca. 3.3 -3.25 Ga: Isotope evidence for the survival of an Archean super-craton
- Nymoen has presented her research at a variety of international meetings, conferences, and events in 2023, including the 6th Annual International Archean Symposium in Perth, Australia; the Geological Survey of Norway Winter Conference in Trondheim, Norway, and at GAC-MAC-SGA in Sudbury, and PDAC in Toronto, Canada.

Factors contributing to metal endowment in the western Wabigoon and southern Abitibi subprovinces: A machine learning approach for Precambrian greenstone belts

Lead researcher: Stéphane Perrouty, Laurentian University

Isoclinally folded turbidite sequence in the Manitou-Dinorwic shear zone. Photo: Rebecca Montsion.

Progress

- 3 peer-reviewed publications submitted (two under review)
- 2 conference posters and 3 conference presentations (including 1 invited)
- All feature engineering complete for Dryden and Timmins map areas
- Random forests and sensitivity testing complete for both map areas and all three mineral systems (magmatic, volcanogenic, orogenic)
- Statistical learning complete for whole rock geochemistry database covering western Wabigoon and southern Abitibi
- New classification system defined for Archean igneous rocks
- New igneous rock favourability indices defined for magmatic, volcanogenic, and orogenic deposits in the southern Superior Province
- Dryden map updated with new fieldwork/observations (released as an update on Mendeley Data repository associated with previous peer-reviewed publication)

Future Work

- Edits of submitted papers will progress once feedback is received.

Anticipated Outcomes

Original contributions by Rebecca Montsion (PhD candidate) to this study are as follows:

Datasets

- Regional-scale geological maps for the Timmins and Dryden field areas
- Geospatial database of outcrop lithology observations (N ≈ 17,000) for Dryden
- Geospatial database of structural measurements for Dryden (N ≈ 28,000) and Timmins (N ≈ 8,000)
- Re-processed aeromagnetic grids for the Timmins and Dryden areas
- Compilation of whole-rock geochemistry of metamorphic, igneous, and sedimentary rocks in the southern Abitibi and western Wabigoon subprovinces of the Superior Province in Canada (N ≈ 23,000)
- Table of idealized/average rock properties for Archean rocks including: magnetic susceptibly, total porosity, resistivity, grain density, bulk modulus, shear modulus, compression modulus, cohesion, friction coefficient, and uniaxial compression strength

Methodological development

- Classification diagrams for ultramafic to felsic (including tonalite-trondhjemite -granodiorite and lamprophyre) Archean igneous rocks using statistically and geologically defined element ratios that minimize effect of metasomatism as well as closure and are valid for intrusive and extrusive textures. Diagrams capture igneous melt composition, initial source characteristics, evolution during ascent (assimilation, fractional crystallization).
- Igneous Rock Favorability indices (IRF) for samples with similar geochemical characteristics as samples nearby magmatic, volcanogenic, and orogenic deposits
- Calculation of structural complexity from bedding measurements and auto-detected aeromagnetic lineaments
- Calculation of non-Euclidean distance to geological map units and structures
- Calculation of rheological and chemical contrast maps
- Semi-discrete interpolation of characteristic element ratios characterizing Archean igneous rocks
- Calculation and interpolation of mobile element gain/loss

Knowledge

- Ranking of factors controlling magmatic, volcanogenic, and orogenic prospectivity
- Identification of factors that may have caused contrasting orogenic Au endowment in the Timmins and Dryden areas

Implications

- Scientific results (feature importance comparison from random forests) may indicate fluid sources and/or tectonic environment may control disparate metal endowment in Timmins and Dryden orogenic Au mining camps
- Several regional-scale, multi-disciplinary datasets now available to compare two economically contrasting mining camps
- Several new methodologies comprehensively capture greenstone belt characteristics (for use in statistical and machine learning)

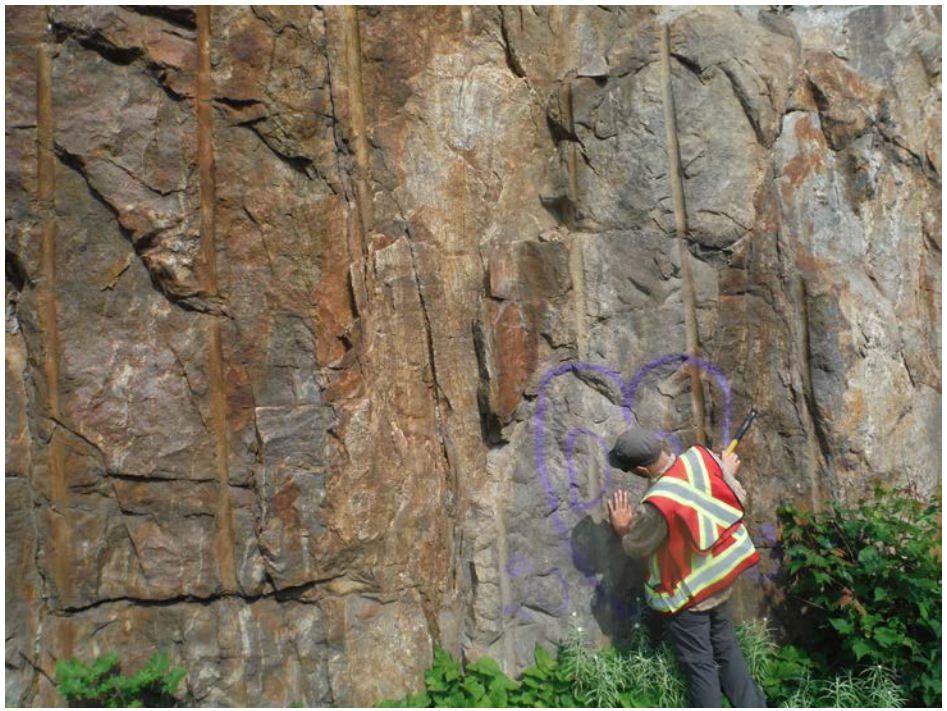
VIEW OR DOWNLOAD
Rebecca Montsion's doctoral thesis: *Factors contributing to metal endowment in the western Wabigoon and southern Abitibi subprovinces: A machine learning approach to Precambrian greenstone belts, August 2023.*

Highlights

Student Rebecca Montsion completed her PhD, graduating in September 2023. She is now a research scientist at the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Perth, Australia.

Gold Fluid Window

Lead Researchers: Carl Guilmette, Université Laval; Doug Tinkham, Laurentian University



Antoine Godet examines migmatitic paragneisses along Route 117 in Quebec, in the Vérendrye Wildlife Reserve, Abitibi (south of Val d'Or), July 2023. Photo: Myriam Côté-Roberge.

VIEW OR DOWNLOAD
Precambrian Research: *Origin, nature, and evolution of the northern Pontiac subprovince, Canada: Insights from the intrusive record, Godet et al., 2023*

Progress

This reporting period constitutes the third year of the Gold Fluid Window Metal Earth thematic project. Our research is primarily performed by four HQPs, including research associate Antoine Godet, post-doctoral fellow Marine Jouvent, and two PhD students, Adrian Rehm and Diogo Ribeiro. This period was dedicated to further data acquisition, fieldwork, and writing of manuscripts.

The third fieldwork campaign of the project was conducted during the summer of 2022 in the Grenville Tectonic Front. More than 70 outcrops were described, and about 40 samples were collected.

Laboratory analyses included collection and interpretation of approximately 30 thin sections, 26 whole-rock analyses, in-situ EPMA analyses of minerals on 35 thin sections, 12 µXRF scanning maps, U-Pb zircon, monazite and titanite dating (LASS-ICP-MS, 7 samples), trace element analyses by LA-ICP-MS (35 samples), and Lu-Hf garnet dating (ID-MC-ICP-MS, 12 samples). Interpretations of initial results were presented at the 2022 GAC-MAC conference, at the Québec Mines 2022 conference, and in Metal Earth scientific review sessions.

Phase equilibria modeling was performed on selected samples from the Pontiac and Quetico subprovinces to quantify P-T-t-X paths and fluid dehydration reactions.

Future Work

- Acquire LASS-ICPMS analyses on datable accessory phases from metasedimentary, metabasite and granitoid samples from the Opinaca and Ashuanipi subprovinces and the Grenville Tectonic Front to constrain the timing of metamorphism and igneous crystallization of selected bodies
- Obtain Lu-Hf isotope ages (ID-MC-ICP-MS) of garnet growth from both transects performed in the Quetico (Geraldton and Thunder Bay) to determine the timing of garnet growth metamorphism, and link those ages

to phase equilibrium calculations to constrain the timing of metamorphic fluid production

- Perform in-situ Lu-Hf garnet analysis (LA-ICP-MS) to constrain the timing of granulite facies metamorphism in the Grenville Tectonic Front
- Pursue the ongoing compilation of geological record in both the Opinaca and the Ashuanipi subprovinces
- Plan and complete the fourth fieldwork campaign that will focus on the Opinaca and Ashuanipi basins (Quebec) in close collaboration with the Ministère des Ressources Naturelles et des Forêts
- Pursue phase equilibria modeling to quantify the P-T-t paths
- Preparation of manuscripts for publication in international peer-reviewed journals (two for Antoine Godet, two for Diogo Ribeiro, two for Adrian Rehm, and one for Marine Jouvent)

Ultramafic rocks, north of the Grand Victoria Lake, Vérendrye Wildlife Reserve, Abitibi, south of Val d'Or, July 2023. Photo: Marine Jouvent.

Anticipated Outcomes

This project will generate a new understanding of the metamorphic and tectono-thermal evolution of the Quetico, Pontiac, Opinaca and Ashuanipi basins, as well as the Grenville Tectonic Front. These areas are considered key lithotectonic domains that record the final stages of the assembly of the Superior Craton, during which most orogenic gold deposits were formed.

The project will provide new high-quality quantitative data that advances our knowledge of the pressure-temperature-time-chemistry-deformation (P-T-t-X-D) history of the belts. This fundamental dataset will contribute to our understanding of craton disaggregation and assembly in the Neoarchean and provide a precise geodynamic framework to understand the role of regional fluid generation and circulation in gold mineralization.

Implications

The project is contributing to the goals of Metal Earth by addressing fundamental knowledge gaps on the potential roles of metamorphism and metamorphic fluid generation on gold endowment in the Superior Province. This project is generating a new understanding of the metamorphic evolution of key lithotectonic domains that record the

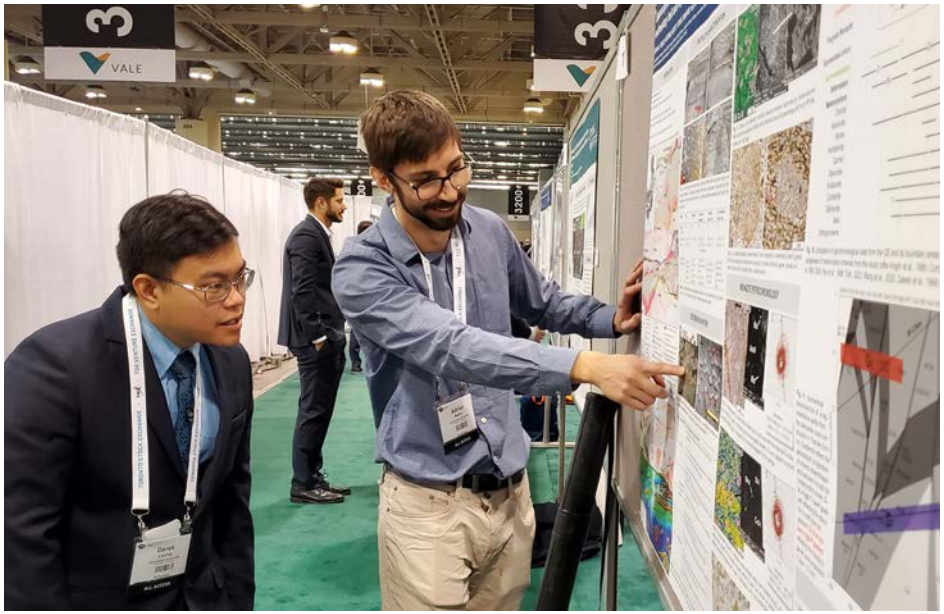
WATCH NOW!
Gold Fluid Window updates presented at Metal Earth scientific meetings in March 2023
Isaac Malta - *Metamorphic and structural evolution of the northern Pontiac subprovince*

WATCH NOW!
Gold Fluid Window updates presented at Metal Earth scientific meetings in March 2023
Adrian Rehm - *Metamorphic constraints on the geodynamic setting of the Quetico metasedimentary belt*

final stages of the assembly of the Superior Craton, a period during which most orogenic gold deposits were formed. The new data will help assess whether the Quetico, Pontiac, Opinaca, and Ashuanipi had similar or differing depositional and tectonometamorphic evolutions and how this may have affected differential endowment in the neighbouring structures and sub-provinces (e.g. Cadillac-Larder Lake Fault Zone in the Abitibi).

Collectively, the results are contributing to the elaboration of models for craton disaggregation and assembly in the Neoarchean, providing a precise geodynamic framework to understand the role of regional fluid generation and circulation in gold mineralization.

Adrian Rehm (right) speaks with Bernard Rottier (left) as Douglas Tinkham (bottom) examines an outcrop during the 2021 field season.



Laurentian University PhD student Derek Leung (left) learns about Adrian Rehm's research at the PDAC-SEG Student Minerals Colloquium, March 2023.

WATCH NOW!
Gold Fluid Window updates presented at Metal Earth scientific meetings in March 2023
Diogo Ribeiro - *Metal and ligand mobility during prograde metamorphism of metasedimentary belts.*

WATCH NOW!
Gold Fluid Window updates presented at Metal Earth scientific meetings in March 2023
Antoine Godet - *Garnet in S-type granite: Lu-Hf dating and trace element distribution.*

Highlights

- Marine Jouvent was recruited as a PDF to quantify the P-T-t-X-D history of the Opinaca and Ashuanipi basins
- Successful fieldwork was conducted in the Grenville Tectonic Front
- Diogo Ribeiro received a grant of $250 from the E4m Center to attend GAC-MAC 2022
- Adrian Rehm received the Queen Elizabeth II Scholarship in Science and Technology, $15K
- Preliminary results were presented at GAC-MAC 2022 in Halifax by Diogo Ribeiro and Adrian Rehm and at the Québec Mines 2022 conference by Antoine Godet and Diogo Ribeiro

Mineral exploration footprints of crustal-scale deformation zones in Neoarchean greenstone belts, Canada

Lead Researcher: Stéphane Perrouty, Laurentian University

Progress

PhD student Théo Lombard started his PhD in January 2022.

Work began with planning the PhD project, a literature review on the formation and footprint of orogenic gold deposits, the Wabigoon sub-province (Dryden area) and the Abitibi sub-province (Val d'Or area); looking at available data (geological, outcrop, geochemistry, geophysics) available on OGSEarth and SIGEOM; and building maps and databases.

A summer fieldwork and sampling campaign was conducted, with 288 samples collected. Following this, Lombard continued with:

- Building a map of the alteration intensity of the Larder Lake-Cadillac Deformation Zone and the Wabigoon Deformation Zone.
- Sample preparation for thin section and whole rock geochemistry analysis coupled with gold ultra-low detection (ALS)

PhD student Théo Lombard overlooking Wabigoon Lake, standing on gabbro.

- Acquisition of hyperspectral data on all the samples (collaboration with Dr. P. Lypaczewski of the College of the North Atlantic) to get mineral chemistry change (major elements) in the function of the alteration for chlorites, amphiboles, white micas, biotites and carbonate minerals (long-, mid-, short-wave infrared imaging). Interpretation of these data will start to constrain the alteration halo.
- Initial mineralogical and geochemistry interpretation
- Preparation for research presentations

Future Work

- Mass balance calculation
- Pyrite WDS maps and quartz CL imaging (EPMA at UWO, London, Ontario)
- Laser ablation on quartz, pyrite, chlorite to get the mineral chemistry and stage of growth for these minerals
- Secondary-ion mass spectrometry (SIMS) to analyze S isotopes (36S, 34S, 33S, 32S) in pyrite to trace the source of the gold and its potential Archean sedimentary origin
- Evaluating/planning potential fieldwork in 2024 for two other deformation zones

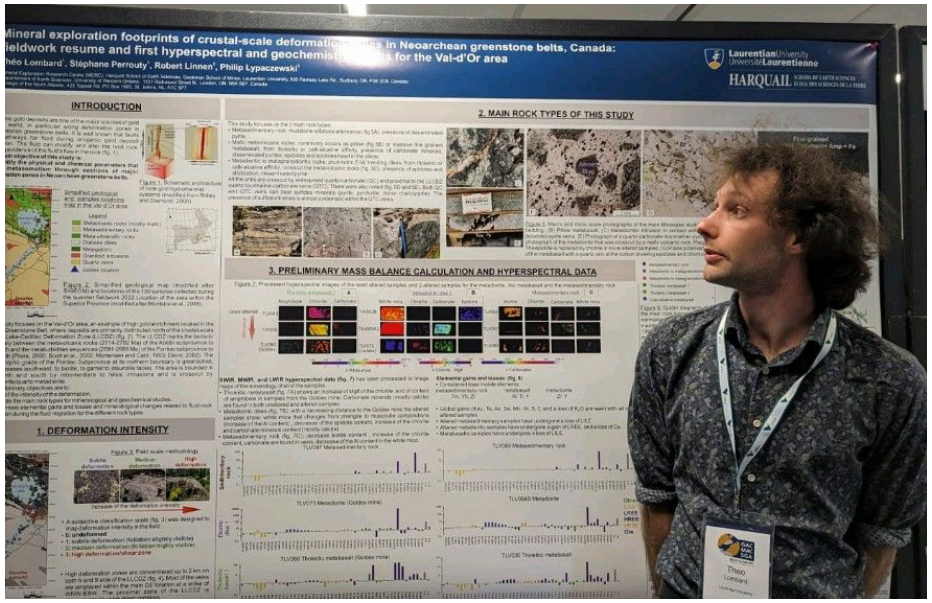
Anticipated Outcomes

The project goal is the identification of physical and chemical parameters showing the metasomatic halo through sections of major deformation zones in Neoarchean greenstone belts.

It aims to understand physical and chemical parameters going through different scale from the whole rock (deformation intensity, mineralogy, and geochemistry) to the mineral chemistry by comparing different sections of deformation zones (endowed or barren) in Archean greenstone belts.

The main objectives are to:

- Define the elemental gains and losses and mineralogical changes related to fluid-rock interaction during the fluid migration (mass balance)
- Define a temperature gradient for the metasomatism (selenium, titaniQ and chlorite geothermometer)
- Identify quartz and pyrite trace element signatures associated with the fluid pathway (CL, WDS and EDS maps)
- Identify key parameters differentiating endowed and barren deformation zones (impact of the deformation intensity, geochemistry, and mineral chemistry)



PhD student Théo Lombard began his project in January 2022 and was honoured with the MDD Keating-Boyle award for best poster in the PhD category at GAC-MAC-SGA in Sudbury, Ontario, May 2023.

VIEW OR DOWNLOAD
Mineral exploration footprints of crustal-scale deformation zones in Neoarchean greenstone belts, Canada: fieldwork resume and first hyperspectral and geochemistry results for the Val-d'Or area.

- Trace the source of sulfur and gold (S isotopes)

Globally, this project will:

- Link the footprint of the deformation zone and gold content
- Provide a better understanding in the process leading to gold endowment
- Provide new exploration tools for targeting enriched deformation zones

Implications

Metal Earth aims to understand the metal endowment process during the Precambrian. Orogenic gold deposits are one of the major sources of gold in the world, usually found along deformation zones in Precambrian greenstone belts. It is well known that faults are pathways for fluid during orogenic gold deposit formation.

By comparing different sections of major deformation zones (some enriched, some barren in gold) instead of focusing on one or more deposits, this project will propose new knowledge on the metasomatism halo on both sides of major deformation zones at a large scale, such as a potential temperature gradient and geochemistry and mineral chemistry changes. This will lead to establishing alteration sequence and intensity along deformation zones in function of the intensity of the alteration.

It will also try to define exploration tools using parameters that influence the gold content to differentiate favourable deformation zones for orogenic gold deposits. Finally, the work on S isotopes will bring new perspectives on the origin of the gold (magmatic vs metamorphic origin).

This project, therefore, fits well into the overall objective of Metal Earth by focusing on the differences in crustal structures between endowed and less-endowed areas and the factors which govern metal enrichment.

PhD student Théo Lombard collecting his first sample of this study.

Highlights

- December 2022: Presentation during the HES Graduate Student Symposium
- Graduate Entrance Scholarship from Laurentian University - Office of Graduate Studies, in recognition of outstanding scholastic achievements
- Won MDD Keating-Boyle Award for best poster, PhD category, at GAC-MAC-SGA, May 2023

WATCH NOW!
Théo Lombard - *Mineral Deposits Division 2023 Keating-Boyle Award Winner (PhD category) - Mineral exploration footprints of crustal-scale deformation zones in Archean greenstone belts.*

Superior Cr-Ni-Cu-PGE Thematic Project

Lead Researcher: Michael Lesher, Laurentian University

Progress

From January to June 2023, PhD student Klaus Kuster focused on completing his PhD thesis proposal and qualifying examination requirements.

Analytical Work

- Petrographic description of polished thin sections
- 166 thin sections from Kuster's 2022 field season were analyzed under binocular microscope; mineralogical and textural features were photographed
- Selection of polished thin sections for mineral chemistry analysis
- Whole-rock geochemical analyses on 246 samples, including standards and blind duplicates, to analyze for major and trace elements
- Preparation of 20-25 extra samples for polished thin sections and geochemistry
- Geochemical compilation of komatiites geochemistry in the Superior Province (MB-ON-QC)
- Compilation is underway and updated as more data become available; a reassessment of compiled sources is also being carried out to look for missed gaps and/or lithologies. So far, more than 12,000 samples are included in the database, and more data will be integrated in 2023. EMPA-SEM & LA-ICPMS mineral analysis is planned for spring/summer.

Writing

Two papers are planned. This first is introductory chapter paper 1: Chr-Ol phase equilibria in ultramafic magmas and the effects of chromite in sulfide solubility, and the second is introductory chapter paper 2: Geochemistry of komatiitic rocks in the Superior Province.

Future Work

July-December 2023

- Review and interpretation (including QA-QC) of geochemistry; a few selected returned pulps will be submitted for PGEs NiS fire assay analysis

PhD student Klaus Kuster presents his research at the Metal Earth scientific meetings in Toronto, March 2, 2023.

- Continue, review, and improve petrographic descriptions
- Submit additional 20-25 samples for whole-rock geochemistry
- EMPA-SEM & LA-ICPMS analysis of selected samples

Kuster will resume and give extra focus to the study of Chr-Ol phase equilibria in ultramafic magmas and the effects of chromite in sulfide solubility using MELTS; aiming to finish models by December 2023.

He aims to finish the geochemical compilation for the Superior Province by the end of the year, including spatial distribution evaluation, QA-QC, PCA and interpretation.

2024

- Follow up petrography and mineral chemistry, if needed
- Interpretation of all analytical data
- Complete geochemical models, write papers, and prepare thesis

Anticipated Outcomes

- Better understanding of the controls on why some mafic-ultramafic magmatic systems contain only Ni-Cu-PGE mineralization (e.g., Abitibi Belt, Ontario-Québec; Yilgarn Block, Western Australia; Cape Smith Belt, New Québec; Thompson Nickel Belt, Manitoba), some contain only Cr mineralization (e.g., Inyala and Railway Block, Zimbabwe; Ipueira-Medrado, Brazil; Kemi, Finland; Sukinda-Nuasahi, India; most parts of the Stillwater Complex, Montana; most parts of the Bushveld Complex, South Africa), and only a few systems (thus far) contain both significant Cr and significant Ni-Cu-PGE (McFaulds Lake and Shebandowan areas, Ontario; Utikomst, South Africa; some parts of the Stillwater and Bushveld Complexes)
- Better understanding of the controls on formation of Cr mineralization in komatiitic magmas and the influence of magma composition (komatiite vs komatiitic basalt vs basalt) and relationship (if any) to particular facies of iron formation

Implications

This work will benefit the mineral industry by developing an exploration model for deposits containing Cr and Ni-Cu-PGE, which will be used immediately in the McFaulds Lake Greenstone Belt (Ring of Fire area) of northern Ontario, but with applications to the rest of the Superior Province and worldwide.

There is a recently discovered and significant difference in the endowment of the critical metals Cr and Ni (and associated Co) in the Superior Province. In terms of Cr, Bird River – Uchi – Oxford-Stull – La Grande – Eastmain [BUOGE] superdomain >> Shebandowan Belt >> Abitibi Belt. In terms of Ni, Abitibi (albeit dispersed) >> Shebandowan (more concentrated) ~ McFaulds Lake part of the BUOGE superdomain >> other parts of the BUOGE superdomain. Understanding the differences between more- and less-mineralized terranes is a fundamental goal of Metal Earth.

WATCH NOW!
Klaus Kuster - *Petrogenesis and Metallogenesis of Cr and Ni-Cu-(PGE) mineralization, presented at the Metal Earth scientific meetings in March 2023*

Highlights

Kuster presented his research at the March 2023 Metal Earth scientific meetings and the PDAC-SEG Student Minerals Colloquium in Toronto. He also prepared an abstract and presentation for GAC-MAC-SGA in May 2023.

Supracrustal architecture of the eastern Michipicoten greenstone belt, Ontario

Lead Researcher: Stéphane Perrouty

PhD student Lianna Vice mapping bedrock on Dog Lake in the eastern Michipicoten greenstone belt during the summer 2022 field season. Photo: Stéphane Perrouty.

Progress

- Summer 2022 field mapping, detailed mapping of Meath Township and targeted locations throughout the greenstone belt in collaboration with the Ontario Geological Survey (OGS)
- Compilation and organization of previous OGS data
- Heavy mineral separation and sample preparation for 17 geochronology samples
- Submission of 2022 geochemistry samples and thin section preparation
- Supervision of a BSc (Hons) thesis project in collaboration with Queen's University

VIEW OR DOWNLOAD

Vice, L.E.D., Perrouty, S., Robichaud, L. 2022. Introduction to a Geochronological and Structural Study of Supracrustal Assemblages in the Northeastern Michipicoten Greenstone Belt. Project NE-22-002. Open File Report 6390, 8-1 – 8-8.

Future Work

- 2023 mapping of Riggs and Glasgow townships with a full OGS field season, additional targeted mapping of key and interesting locations
- Geochronology analyses
- Additional geochemical analyses
- 2024 mapping of strategic locations, Dolson and Echum townships
- Compilation map of the study area, lithological and assemblage
- Better define the regional structural controls on orogenic gold mineralization

Anticipated Outcomes

- Supracrustal assemblage map of the northeastern Michipicoten greenstone belt, comparing it to adjacent greenstone belts
- Identification of meta-turbidite basin with southern contact bounded by a major deformation zone (DZ) (Easey Lake)
- Observation of localized conglomeratic horizons within Easey Lake DZ
- Presence of 2704 Ma F3 rhyolite sliver within the Easey Lake DZ and VMS anomalies within it (upcoming Craig BSc thesis; Queen's University)
- Identification of meta-volcanosedimentary assemblage in Dolson Township bounded by iron formations and gneiss possibly equivalent to Hawk Assemblage

Implications

The Michipicoten greenstone belt is in a strategic location within a moderately endowed, currently producing greenstone belt. The Easey Lake deformation zone is a possible equivalent to the Porcupine Destor deformation zone as defined by the presence of meta-turbidites north of it, polymictic meta-conglomerates within it and several nearby gold occurrences. This project complements the thematic work on the western extent of the Porcupine-Destor deformation zone.

VIEW OR DOWNLOAD

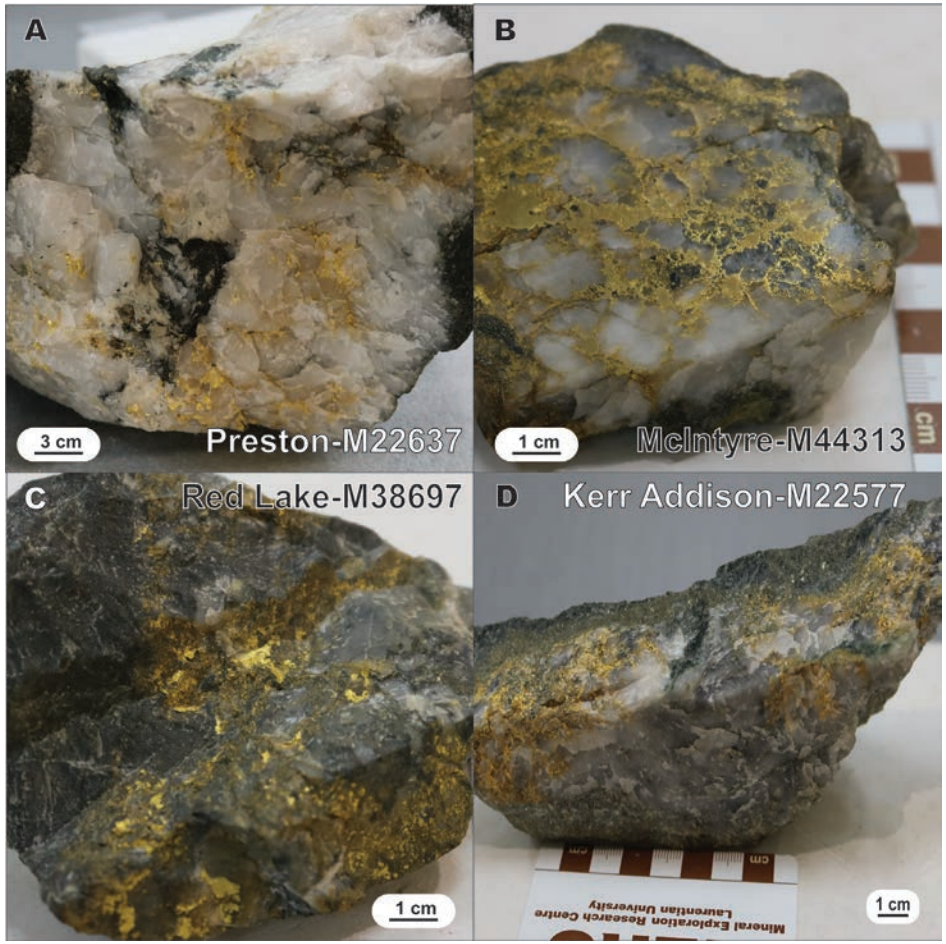
Vice, L.E.D. 2022. Preliminary Geology of Meath Township, Northeastern Michipicoten Greenstone Belt, Northeastern Ontario: Project NE-18-007; in Summary of Field Work and Other Activities, 2022, Ontario Geological Survey, Open File Report 6390, p. 7-1 to 7-10.

Highlights

- Successful summer fieldwork completed in 2022, detailed in Summary of Field Work OGS Open File Report 6390
- Prepared abstract for oral presentation at GAC-MAC-SGA 2023

Gold Fingerprinting

Lead Researchers: Harold Gibson, Laurentian University; Evan Hastie, Ontario Geological Survey



Examples of ultra-high-grade gold in hand samples from Ontario gold deposits feature gold in fractures in quartz veins and the host rock. Source: J. Melo-Gómez.

Progress

- Completion of LA-ICP-MS trace element data processing and compilation for all gold samples collected thus far, including samples from across North America and around the world
- Completion of data interpretation for gold from Ontario's gold deposits as part of Julian Melo-Gómez's MSc thesis at Laurentian University
- Writing of Melo-Gómez's MSc thesis: *Geochemistry of gold from Ontario deposits*

Future Work

- Creation of a database that includes all the SEM, EPMA and LA-ICP-MS data collected
- Partnership with Dr. Robert Chapman and his team to analyze and interpret the data collected from detrital gold grains from the West Coast in the USA and Canada

Anticipated Outcomes

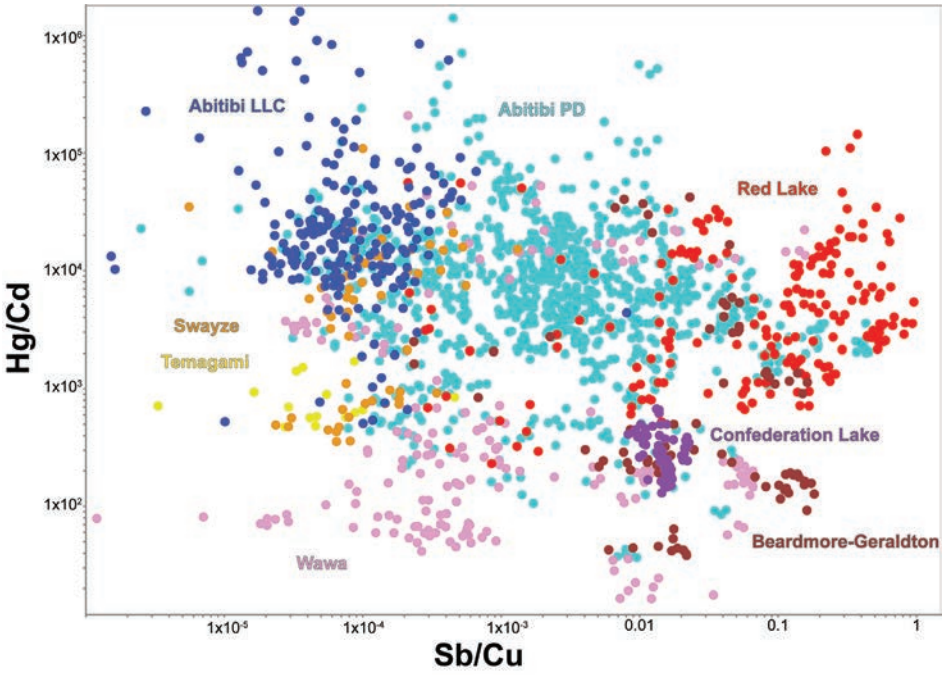
- A robust and reproducible methodology to quantitatively measure the trace element content in gold.
- Data and interpretations to date indicate that deposits within a single metallogenic district in the Superior Craton (e.g., Red Lake, Wawa, Abitibi) tend to have a similar trace element signature in gold.
- A new understanding of the primary and secondary processes controlling the trace element content of gold.

WATCH NOW!
Julian Melo-Gómez - *Trace element content of gold across Ontario's gold deposits, presented at the Metal Earth scientific meetings, Toronto, March 2023.*

Implications

- The project's results show that gold samples from gold deposits within a metallogenic district share a similar trace element composition. This indicates district-scale metal sources and metallogenic processes, which suggests that gold deposits within a district are a product of one ore system. Differences in the trace element composition of gold from different districts in the Superior Province suggest there may be a crustal - mid-crustal – SCLM control on gold geochemistry.
- Trace element signature suggests that deposits associated with the Porcupine-Destor and those with the Larder Lake-Cadillac fault zones evolved differently, producing different elemental concentrations in gold.
- Low-melting point chalcophile elements (LMCE) may be responsible for gold remobilization in some areas, which may explain localized high-grade zones.

VIEW OR DOWNLOAD
Julian Melo Gómez's award-winning poster presented at PDAC 2023;
Using gold to explore for gold: Trace element content of native gold across Ontario/



Biplot of the Sb/Cu and Hg/Cd ratios for all deposits in the Superior Province divided in color according to metallogenic districts. Source: J. Melo-Gómez.

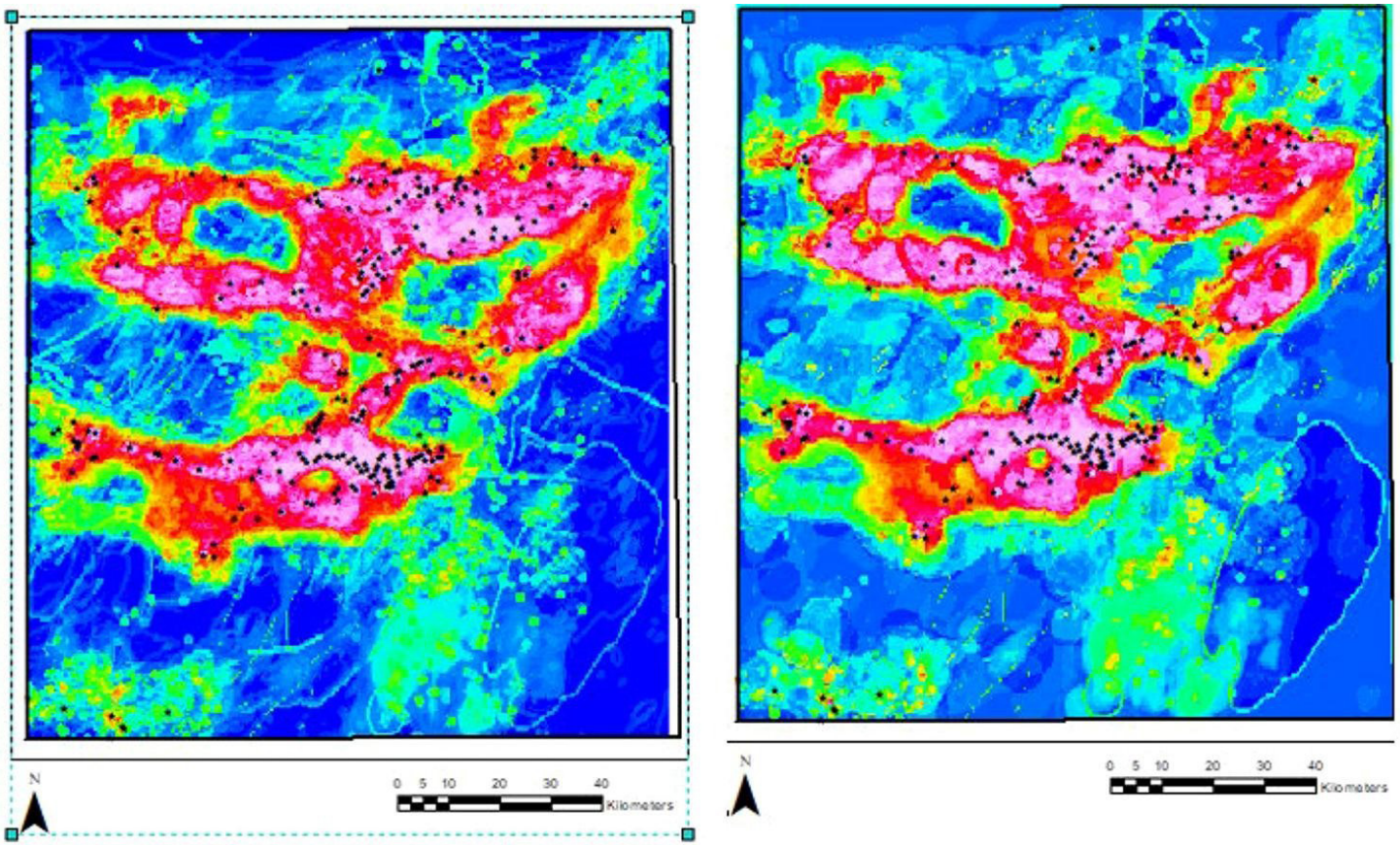
Highlights

- Julian Melo-Gómez's MSc thesis was submitted to Laurentian University's School of Graduate Studies for defence and external review in September 2023
- Melo-Gómez placed third in the MSc category at the PDAC-SEG Student Minerals Colloquium, March 2023
- For industry:
  - Knowing the trace element composition of gold for a single district can better select what elements are directly associated with gold and are most appropriate for exploration vectoring and Au exploration within that district
  - The "gold fingerprint" can be used in placer-paleo placer deposits to differ entiate between sources and epigenetic processes

MSc student Julian Melo-Gómez (left) accepts third place (MSc category) from SEG President Stuart Simmons (right) at the Student Minerals Colloquium Awards Ceremony, Toronto, March 2023.

Data Analytics

Lead researcher: Jeff Harris, Laurentian University



(Left) Mineral prospectivity map (MPM) produced using 35 input predictor variables (maps) and the Random Forest (RF) machine learning algorithm. (Right) Same MPM, but instead, using the best 10 predictor variables calculated by the RF algorithm. Source: Data-driven gold potential maps for the Chibougamau area, Abitibi greenstone belt, Canada. Jeff R. Harris, et al. Data-driven gold potential maps for the Chibougamau area, Abitibi greenstone belt, Canada. Ore Geology Reviews, Volume 150, 2022, 105176, ISSN 0169-1368, https://doi.org/10.1016/j.oregeorev.2022.105176.

Metal Earth's Data Analytics team was formed in year six of the Metal Earth project, led by Jeff Harris, formerly of the Geological Survey of Canada. The team's overall objective is to integrate all the collected legacy data (2D and 3D) to better understand fertile vs non-fertile greenstone belts.

In 2022-23, team members included Jeff Harris, Pouran Behnia, Anne Barr, Eric Grunsky, Mostafa Naghizadeh, Kalpdrum Passi, Mohammad Parsasadr, and MSc student Mihir Trivedi.

WATCH NOW!
Jeff Harris - *A study of faults using the Random Forest machine learning algorithm, presented at the Metal Earth scientific meetings, Toronto, March 2023.*

VIEW OR DOWNLOAD
Liu, Haiming; Harris, Jeff; Sherlock, Ross; Behnia, Pouran; Grunsky, Eric; Naghizadeh, Mostafa; Rubingh, Kate; Tuba, Györgyi; Roots, Eric; Hill, Graham. (2023). Mineral prospectivity mapping using machine learning techniques for gold exploration in the Larder Lake area, Ontario, Canada. Journal of Geochemical Exploration. 253. 107279. 10.1016/j.gexplo.2023.107279.

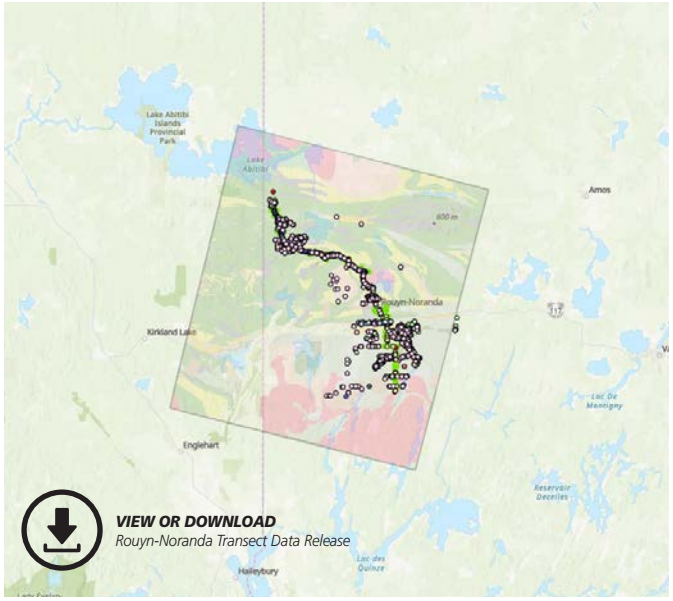
VIEW OR DOWNLOAD
Jeff R. Harris, Mostafa Naghizadeh, P. Behnia, Lucie Mathieu. Data-driven gold potential maps for the Chibougamau area, Abitibi greenstone belt, Canada. Ore Geology Reviews, Volume 150, 2022, 105176, ISSN 0169-1368
https://doi.org/10.1016/j.oregeorev.2022.105176.

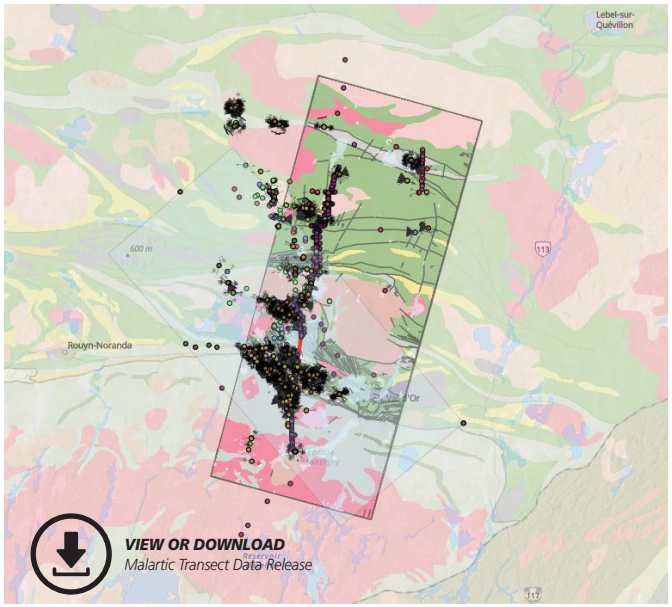
Progress

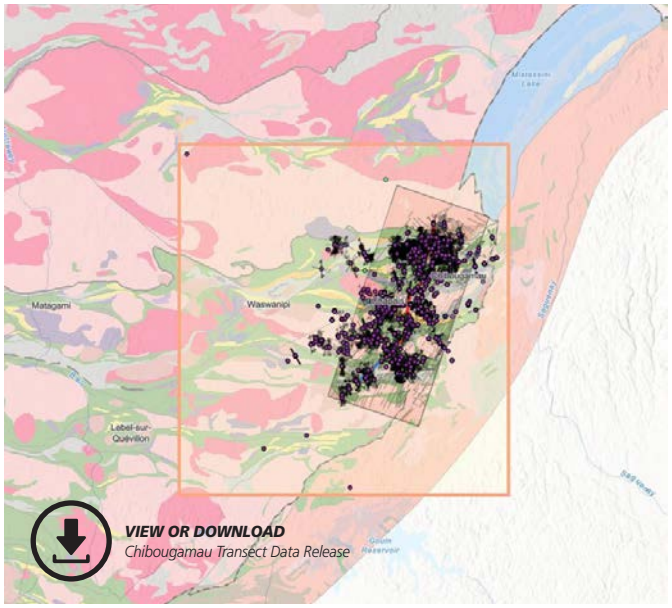
In 2022-23, the team and collaborators worked on manuscripts for peer-reviewed journals, which resulted in the following four publications:

- A study of faults in the Superior province of Ontario and Quebec using the random forest machine learning algorithm: spatial relationship to gold mines, Ore Geology Reviews, March 2023.
- Mineral prospectivity mapping using machine learning techniques for gold exploration in the Larder Lake area, Ontario, Canada. Journal of Geochemical Exploration, August 2023.
- Mineral Prospectivity Mapping for Orogenic Gold Mineralization in the Rainy River Area, Wabigoon Subprovince. Minerals, September 2023.
- Random Forest Classification for Volcanogenic Massive Sulfide Mineralization in the Rouyn-Noranda Area, Quebec. Ore Geology Reviews, October 2023.

Pouran Behnia and Anne Barr organized transect data to make it publicly available. In 2023, data from Chibougamau, Malartic, and Rouyn-Noranda were available for download on the Metal Earth Hub.







VIEW OR DOWNLOAD
Harris, Jeff; Ayer, John; Naghizadeh, Mostafa; Smith, Richard; Snyder, D.; Behnia, Pouran; Parsa, M.; Sherlock, R.; Trivedi, M. (2023). A study of faults in the Superior province of Ontario and Quebec using the random forest machine learning algorithm: Spatial relationship to gold mines. Ore Geology Reviews. 157. 105403. 10.1016/j.oregeorev.2023.105403.

WATCH NOW!
Mohammad Parsasadr: *Overfitting and predictive mineral modelling of mineral deposits (Sturgeon Transect), presented at the Harquail School of Earth Sciences fall 2022 graduate seminar series.*

VIEW OR DOWNLOAD
Behnia, Pouran; Harris, Jeff; Sherlock, Ross; Naghizadeh, Mostafa; Vayavur, Rajesh. (2023). Mineral Prospectivity Mapping for Orogenic Gold Mineralization in the Rainy River Area, Wabigoon Subprovince. Minerals. 13. 1267. 10.3390/min13101267.

MSc student Mihir Trivedi defended his thesis in Computational Sciences in fall 2023: A Comprehensive Analysis of the Geological Features Influencing the Probability of Gold Discovery in the Larder Lake Region Using Advanced Machine Learning Algorithms.

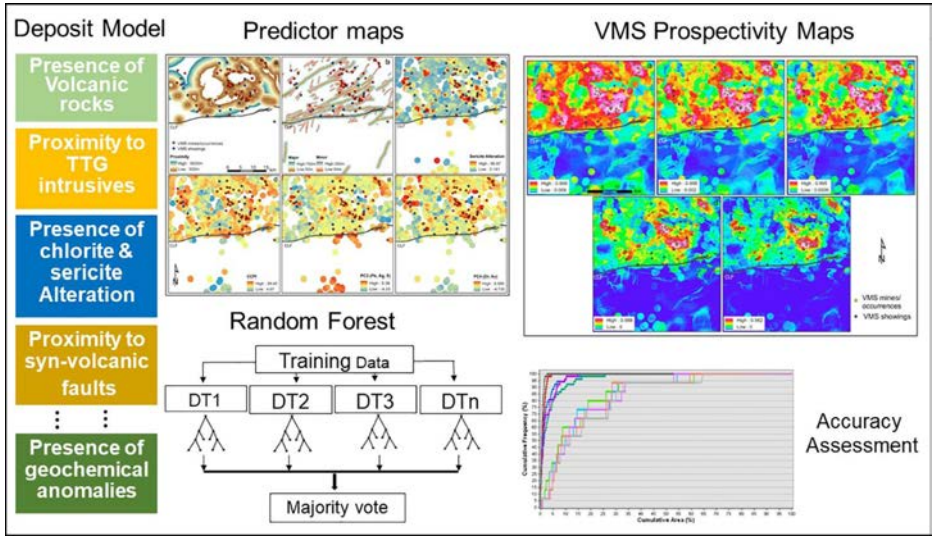
Jeff Harris organized an MPM workshop with six other presenters, delivered at the GAC-MAC-SGA conference in Sudbury, in May 2023. Harris also presented two data analytics papers at the Metal Earth scientific meetings in Toronto in March 2023.

Future Work

- Continue transect data collection, organization, and public release
- Write a data analytics paper on the Geraldton area
- Commercialize mineral prospectivity mapping (MPM) training manual
- Continue to test and apply various algorithms for MPM

Anticipated Outcomes

- Data released publicly for Metal Earth transects will be useful to researchers and industry professionals in Canada and worldwide
- Algorithms and data analytics procedures are and will continue to be made available through published papers, improving understanding of MPM



Graphical abstract: Random forest (RF) classification was applied to 37 predictor maps (vectors to mineralization) producing a Mineral Prospectivity Map (MPM) for volcanogenic massive sulfide (VMS) mineralization in the Noranda District, Abitibi subprovince, which is host to ~ 20 VMS deposits and numerous subeconomic occurrences. Source: Behnia, Pouran; Harris, Jeff; Liu, Haiming; Jørgensen, Taus; Naghizadeh, Mostafa; Roots, Eric. (2023). Random Forest Classification for Volcanogenic Massive Sulfide Mineralization in the Rouyn-Noranda Area, Quebec. Ore Geology Reviews. https://doi.org/10.1016/j.oregeorev.2023.105612

Highlights

- Mihir Trivedi's completed MSc thesis summarizes different machine learning algorithms for producing mineral propspectivity maps. This provides useful data analytics information to industry and researchers. It will be available online in 2024.

Implications

- Published papers from this project deal with the primary question of the fertility of various greenstone belts.
- Publicly available datasets have been released, and additional transect data is being processed, which will help researchers and industry with various applications and projects.

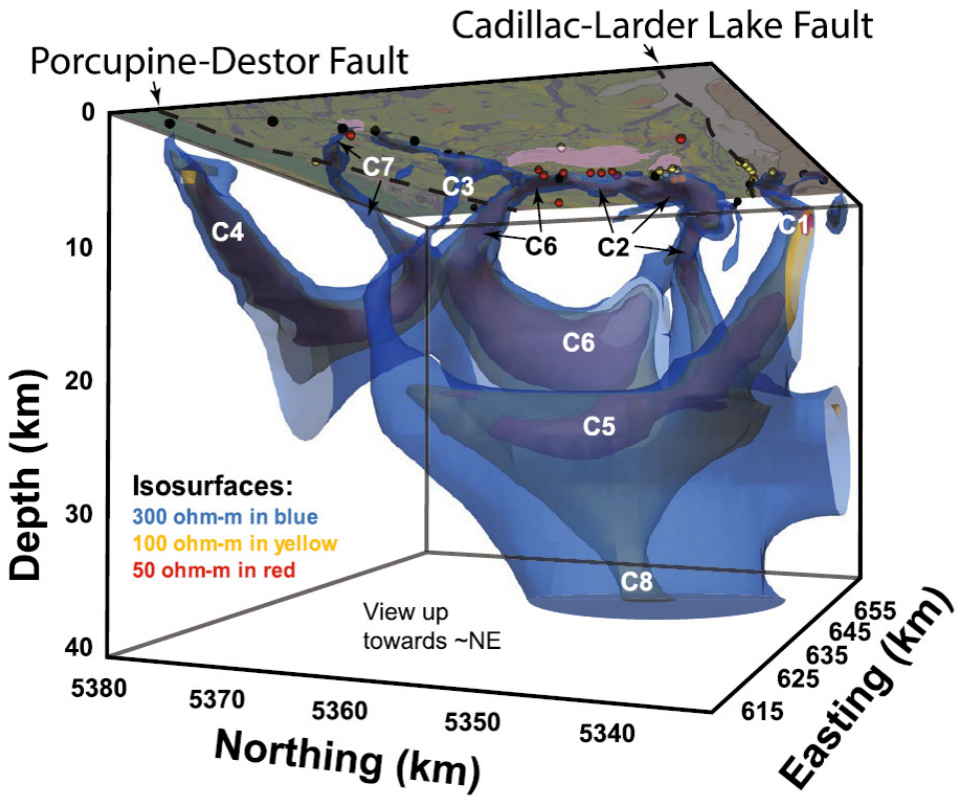
WATCH NOW!
Mihir Trivedi: *Machine Learning for Predictive Modeling of Mineral Deposits, a seminar published online in November 2022 that discusses the application of machine learning for geological prospectivity mapping. The study area for this research is Larder Lake and the Swayze Greenstone belt.*

VIEW OR DOWNLOAD
Behnia, Pouran; Harris, Jeff; Liu, Haiming; Jørgensen, Taus; Naghizadeh, Mostafa; Roots, Eric. (2023). Random Forest Classification for Volcanogenic Massive Sulfide Mineralization in the Rouyn-Noranda Area, Quebec. Ore Geology Reviews. https://doi.org/10.1016/j.oregeorev.2023.105612.

WATCH NOW!
Machine learning for geological mapping and exploration, presented at the Harquail School of Earth Sciences fall 2022 graduate seminar series.

Controls on VMS endowment during the evolution and assembly of Greenstone Belts: Assemblage-level compilation and reconstruction of the Abitibi Greenstone belt

Lead Researcher: Taus Jørgensen, Laurentian University



3D MT model with surface geology of the world-class Noranda VMS district. C1-8 indicate significant low-resistivity features. The two panels on the right are different perspectives of the same 3D model to help visualize the connectivity of many of the low-resistivity features. Red spheres: VMS deposits; Orange spheres: Au-rich VMS deposits; Yellow spheres: Orogenic gold deposits.

Source: Jørgensen et al. (2022): *The implications of crustal architecture and transcrustal upflow zones on the metal endowment of a world-class mineral district.* Scientific Reports. 12. 14710. DOI: https://doi.org/10.1038/s41598-022-18836-y.

Progress

- Refinement of assemblage and lithological compilations for the Abitibi Greenstone Belt across Ontario and Quebec, including the addition of new mapping done by other Metal Earth researchers and a QA/QC process to ensure assemblage boundary lines correspond with historical geochronology data
- Preliminary conversion of compilations to ArcPro GIS

Future Work

- Perform a final quantification of the geological attributes within each assemblage
- Quantitative analyses to investigate the relationship to major structures and VMS deposits, including Au-rich VMS
- Finalize conversion of compilations to an ArcPro GIS environment
- Publish the compilations with a companion paper that utilizes the compilations to interrogate differential VMS endowment in the Abitibi Greenstone Belt

VIEW OR DOWNLOAD
Jørgensen et al. (2022): The implications of crustal architecture and transcrustal upflow zones on the metal endowment of a world-class mineral district. Scientific Reports.
https://doi.org/10.1038/s4158-022-18836-y.

Anticipated Outcomes

This work will improve the VMS model mainly based on deposit- to district-scale research as the current model does not address why geologically similar volcanic centres, assemblages within greenstone belts, or greenstone belts have variable VMS endowment.

The differential base and precious metal endowment of assemblages within the Abitibi greenstone belt and between greenstone belts suggest fundamental differences in assemblage-scale tectonic, magmatic, and crust-mantle processes that impact metal endowment during greenstone belt construction. This research will improve our understanding of these fundamental controls on VMS endowment and provide new insights into Archean tectonics and metallogeny.

Implications

The thematic research will address differential VMS endowment at the assemblage to greenstone belt scales through three integrated and complementary projects that will provide a quantitative comparison, using defined geological attributes, of volcanic assemblages in the well but variably VMS-endowed Abitibi greenstone belt, with comparisons to the less endowed greenstone belts. It builds on and complements Metal Earth's Transect, Craton, and Metal Ocean research.

WATCH NOW!
Controls on VMS *endowment during the evolution and assembly of Greenstone Belts, presented at the Metal Earth scientific meetings, Toronto, March 2023.*

Highlights

Assemblage-level and lithological compilations of the Abitibi greenstone belt in the provinces of Quebec and Ontario will be useful to companies conducting exploration projects. They can also provide a fundamental geological dataset for mineral prospectivity and data analytics researchers.

Petrogenetic Evolution of the Abitibi Greenstone belt

Lead Researcher: Pierre Simon-Ross, Institut national de la recherche scientifique (INRS)

Pierre-Simon Ross (foreground), Enza Magnier (standing back), and Octavio Vite-Sánchez (right) conducting fieldwork as part of VMS project 1b. Photo: Taus Jørgensen.

Progress

Volcanogenic massive sulfide (VMS) deposits are Cu-Zn-Au-Ag (±Pb) deposits that form on the seafloor. Some areas of the Precambrian shield of Canada are more fertile than others for VMS deposits, but we don't completely understand why. The long-term goal of our project, known as Metal Earth VMS subproject 1b, is to compare variably VMS endowed volcanic assemblages within the Abitibi greenstone belt (AGB), focusing on geochemistry and petrogenetic evolution. Combining our results with subproject 1a, which will compile other assemblage-scale attributes, including volumes of volcanic products, area-age relationships, etc., we hope to identify the unique combinations of geological events or conditions that correlate with regional VMS endowment.

During the period April 1, 2022, to March 31, 2023, the following work was completed as part of Octavio Vite-Sánchez's PhD project:

- Study of geochemistry and petrogenesis of the Stoughton-Roquemaure

assemblage, which has the largest area (and presumed volume) of exposed rocks in the AGB but the least amount of VMS mineralization. In the southern portion of the belt, the Stoughton-Roquemaure assemblage contains tholeiitic basalts, komatiites, and rare felsic rocks; evidence for crustal contamination is scarce in the ultramafic to mafic rocks. This is quite different from the VMS-endowed Blake River Assemblage, which has extensive crustal contamination, even in some mafic rocks, and contains no komatiites in the Blake River Group at least. These results were presented at the Metal Earth scientific meeting in Toronto in March 2023.

After much experimentation, the final clustering approach (to separate the rocks from an assemblage into geochemical groups) is as follows:

- isolate the komatiites on the Jensen cation plot
- calculate log-centered ratio transformation using the rest of the data
- perform a principal components analysis, using immobile elements only to focus on protoliths, not hydrothermal alteration, to understand the main patterns and petrological processes
- identify the four most important variables contributing to PC1, PC2 and interpret their petrological significance
- using the untransformed data, build a diagram showing two ratios of immobile elements (Zr/Ti versus Th/Yb) that represent the main petrological processes (magma fractionation and crustal contamination) and sources of geochemical variations
- select geochemical clusters manually on this diagram in ioGAS (with some help from clustering algorithms, such as k-means and hierarchical clustering)
- check that the clusters make sense on extended trace element diagrams ("spidergrams") and on a geology map (geographically consistent units)

This approach, combining multivariate statistical methods and human intuition, works nicely both with the Blake River Group and the Stoughton-Roquemaure assemblage and allows a direct comparison of different assemblages on traditional geochemical diagrams.

Future Work

Papers on the well-endowed Blake River assemblage and poorly-endowed Stoughton-Roquemaure assemblage are being written based on the approach outlined above, and petrological modelling of the main compositions is planned. If time allows, we will look at additional assemblages from the AGB, perhaps the well-endowed Deloro assemblage and a poorly endowed assemblage, for comparison.

Anticipated Outcomes

VMS project 1, including subproject 1b, will produce a better understanding of the constructional history of the Abitibi greenstone belt. We will compare the composition of well-endowed with poorly endowed volcanic assemblages. We will interpret the petrological differences between those, and identify which factors might control both the petrology and the VMS fertility. We hope to identify the unique combinations of geological events or conditions that correlate with regional VMS endowment.

Implications

An overarching goal of Metal Earth is to resolve the processes responsible for differential metal endowment during the evolution and construction of Archean greenstone belts. The VMS thematic projects address differential VMS endowment at the assemblage to greenstone belt scales. This fills a knowledge gap and may result in a step-change in our understanding of the processes responsible for differential VMS endowment. It will also facilitate comparisons with the western Pacific Ocean (e.g., Lau basin).

WATCH NOW!
Octavio Sanchez-Vite: *Geochemistry of the Stoughton-Roquemaure assemblage, Abitibi greenstone belt, presented at the Metal Earth scientific meetings in Toronto, March 2023.*

Highlights

Thanks to additional funding from Metal Earth, a post-doctoral fellow (PDF) will be recruited to continue the work on the remaining volcanic assemblages from the Abitibi over the next two to three years. This PDF will also push the petrogenetic modelling further for all assemblages. Ultimately, there will be a complete synthesis of the geochemistry and petrology of volcanic rocks in the Abitibi and how that relates to VMS fertility over time and space. This will lead to a better understanding of the processes responsible for differential VMS endowment during the evolution of greenstone belts.

The influence of crust-mantle interaction, magma residency, and crust maturity on VMS endowment

Lead Researcher: Stephen J. Piercey, Memorial University

Progress

- Analytical work was undertaken on zircons, including cathode luminescence, SEM-BSE, electron probe microanalysis for major/minor elements, and LA-ICP-MS/MC-ICP-MS for trace elements, U-Pb ages, and Lu-Hf isotope results.
- Results were completed for all David Mole samples from 2017-2018, including results from Chibougamau, Rouyn-Noranda, Larder Lake, Ben Nevis, and Swayze belts.
- Initial interpretation was completed on the U-Pb and Hf isotopic data. Results were presented at the Metal Earth scientific meetings.

Future Work

- Recruit a new PDF and a part-time research assistant
- The new PDF will evaluate results from 2017-2018, including trace element data, and then provide a work plan for further analytical work on zircons from 2018-2019 and 2019-2020 Metal Earth transects, including samples from Chibougamau, Onaman-Tashota, Larder Lake, and Rouyn-Noranda; further evaluation will be done to decipher what other areas need data.
- Data will be acquired on this and other annealed samples from Dr. Jacob Hanley.

Anticipated Outcomes

- This work will enhance our understanding of petrogenetic processes and crustal architecture and how these influence the distribution and origin of volcanogenic massive sulfide deposits (e.g., system-scale controls on deposits and metal endowment of greenstone belts).
- The rocks can act as probes of crustal architecture, crust-mantle interaction, and metal endowment in a given greenstone sequence and VMS-associated or barren units, potentially providing insight into the pre-VMS formation metal enrichment in the magmatic suites and potential fertility for VMS mineralization.
- The results will dovetail with regional studies aimed at using magmatic rocks, the mineral chemistry of included heavy mineral phases (i.e., zircon, monazite, apatite), and the Nd-Hf isotopic compositions of these phases as probes of crustal architecture and crust-mantle interaction, delineating crustal architecture at local scales, and to contribute to more belt- and craton-scale architecture.
- It will use a collection of samples from both well-endowed, less well-endowed, and as a function of varying metal tenor so as to evaluate if magmatic processes and crustal architecture play a role in general endowment and commodity-specific metal fertility.

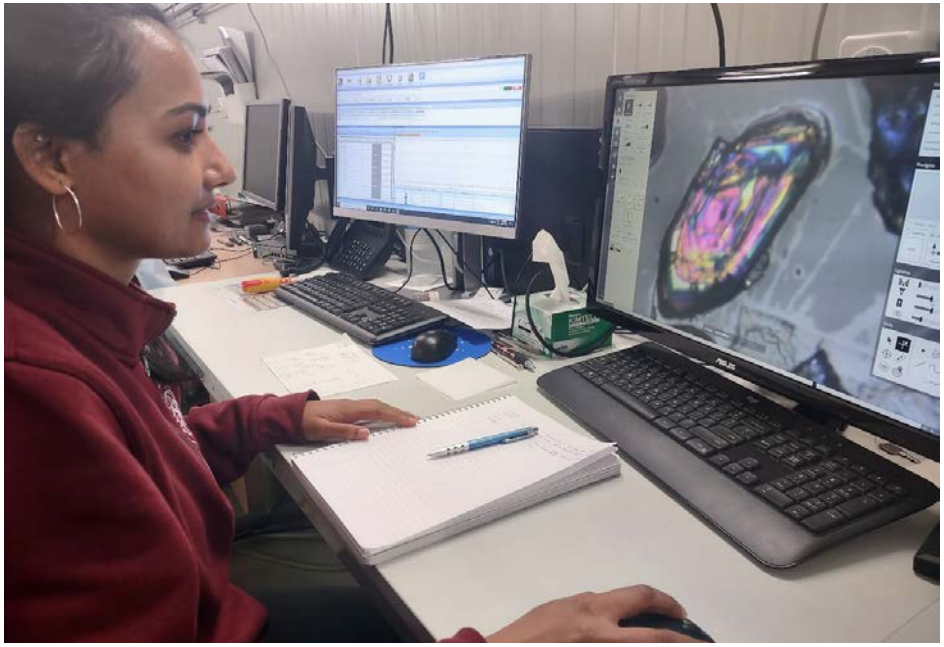
(L-R) C. M. Lesher, S. J. Piercey (holding Derry medal), and D. Gregory pose for a photo to commemorate Piercey being awarded the Duncan R. Derry medal at GAC-MAC-SGA 2023 in Sudbury, Ontario.

Highlights

- The successful recruitment of a new PDF will advance this project, which will increase our understanding of the fertility of belts and exploration targeting and metal endowment of greenstone belts.
- In May 2023, at GAC-MAC-SGA in Sudbury, project lead Stephen J. Piercey was awarded the Duncan R. Derry Medal by the Mineral Deposits Division (MDD). It is awarded annually to an outstanding economic geologist who has significantly contributed to the science of economic geology in Canada.

Volatile and melt chemistry of melt inclusions in accessory minerals in Archean VMS

Lead researcher: Jacob Hanley, Saint Mary's University



PhD student Priyal Daya analyzing zircon grains containing silicate melt inclusions from the Kidd-Creek deposit at the University of Geneva Department of Earth Sciences, September 2022.

Progress

- Completed remaining zircon and associated melt inclusion analysis, related geochronology and zircon host mineral chemistry through analytical sessions at University of Idaho and University of Geneva, including:
  - (i) outstanding samples from the Bousquet Formation to fill in holes in stratigraphic column (Daya Ph.D. thesis)
  - (ii) additional samples from the Swayze area (Buyers B.Sc. thesis) to enable comparison of additional barren intersections of Blake River and Tisdale volcanics
- Manuscript 1 accepted for review in Journal of Petrology (Neyedley et al.); article summarizes geochronology and thermobarometry of the Mooshla Complex, the only syn-volcanic intrusion within the study area scope for gold-rich VMS
- Manuscripts 2, 3, 4 (Daya) and 5 (Buyers) advanced significantly, covering a comparison of melt chemistry within barren and mineralized rocks in 9 study areas within the Abitibi, enabling a critical evaluation of the differences in magma metal endowment in felsic volcanic assemblages associated with contrasting VMS potential and metal grades/tenors

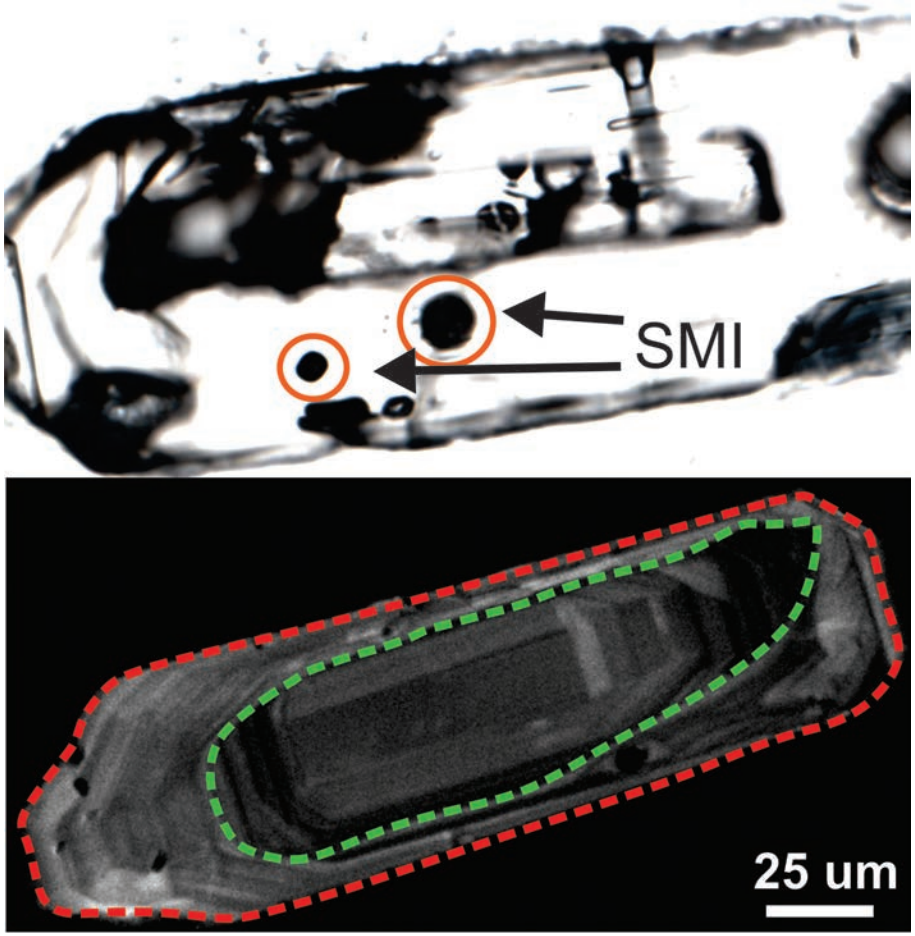
Future Work

- Completion and submission of manuscript 2 in March 2024; 3 in August 2024; and 4/5 in December 2024
- Analytical session planned in February 2023 for Sarah Speight to obtain additional Hf isotope analysis of zircon host grains to melt inclusions from the Bousquet Formation and Kidd Creek stratigraphy at Memorial University (Manuscript 2/3)
- Analytical session scheduled in March 2023 for Priyal Daya to obtain apatite halogen and S analysis in all zircons hosting melt inclusions at the University of Toronto, with the goal of recognizing differences in degassing history in barren and mineralized volcanic domains (Manuscript 4)

- Contribution of key results, including integration with other relevant subprojects under the VMS thematic project

Anticipated Outcomes

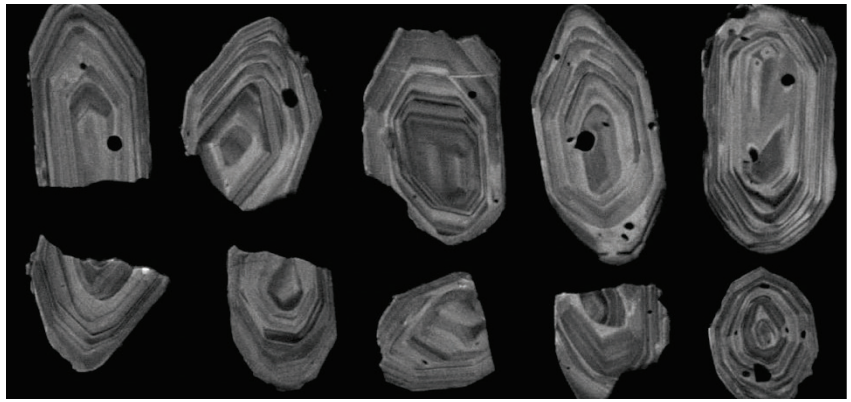
- As per previous reports, a complete trace element/U-Pb geochronology/Hf isotope/apatite halogen chemistry data set for 32 (revised from 28 in 2022) melt inclusion bearing lithologies identifying:
  - (i) Changes in melt chemistry from pre-, syn-, and post-mineralization volcanic assemblages in the Kidd Creek and Doyon-Bousquet-LaRonde camps
  - (ii) Differences in melt chemistry (including metal endowment) across the Abitibi, with a particular focus in 2022-2023 on comparisons of Pacaud, Deloro, Blake River, Tisdale and Kidd-Munro felsic volcanic rocks in several regions across the Abitibi with strongly contrasting VMS endowment
  - (iii) Changes in associated volatile content across these assemblages, to be correlated to melt chemical changes
  - (iv) Details from melt inclusion analysis on the petrochemical classification and origin of volcanic assemblages to reconcile with bulk rock geochemistry
  - (v) Primary metal concentrations and associated mass balance constraints associated with active (degassing) and passive (leaching) models
- Publications (1 in review, 4 in preparation) highlighting the data sets and key interpretation/implications of the items listed above
- Integration of data sets and associated interpretation/outcomes with relevant subprojects under the VMS thematic project (with Sarah Speight and Steve Piercey)



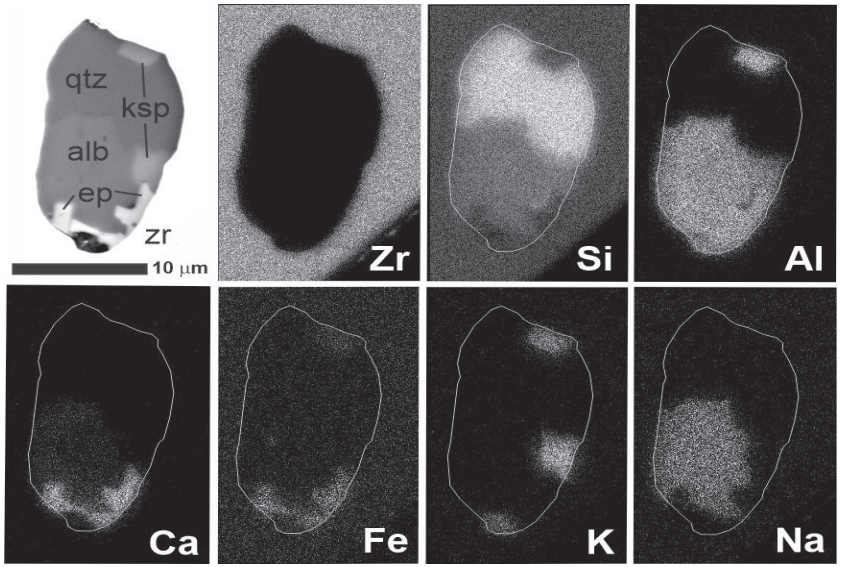
Optical microscope image (top) showing a zircon crystal containing two silicate melt inclusions (SMI) and a cathodoluminescence image (bottom) showing the same zircon with crystalline growth zones visible as light and dark layers. Early layers are contained inside the area outlined by the green dashed line. Younger layers occur in the area between the red and green dashed lines. By correlating the melt inclusions with their positioning in the zoned crystal, chemical analyses of the zircon crystal and its contained melt inclusions can be linked to older and younger geological events in the history of the related VMS deposit and its host rocks. Images from Priyal Daya's PhD thesis research under the Metal Earth VMS Thematic project.

Implications

- Metal Earth intends to transform our understanding of the genesis of base and precious metal deposits during Earth's evolution. The program aims to make Canada a world leader in metal endowment research and world class innovator through open source delivery of new knowledge and the implementation of new technology.
- The research in progress described above within this VMS Thematic Project has implications relevant to the intent and aim described above. The data and interpretation from melt inclusions in Archean VMS will be transformative with respect to contributing to revising current models for VMS systems. The methodology being developed, and application to world class VMS systems in the Abitibi is leading to the first melt inclusion data for Archean-age volcanic rocks globally, and is providing novel constraints on the metal and volatile content on VMS-related magmas of variable metal endowment that other geochemical techniques from bulk rocks cannot provide.



Cathodoluminescence image showing zoned (light and dark layers) crystals of zircon that host silicate melt inclusions. The melt inclusions are the black, often circular objects contained in the layers. The largest zircon (top row, right side) is 100 microns long for scale. Image from Aidan Buyers' BSc thesis research under the Metal Earth VMS Thematic project.



Scanning electron microscope image of an exposed melt inclusion within zircon from the LaRonde VMS deposit (image top left). Accompanying this image are various X-ray maps showing variations in the concentration of various chemical elements within the melt inclusion and zircon host crystal. The chemical composition of the minerals inside the melt inclusion shows that the melt inclusion contains quartz (qtz), feldspar (ksp, alb), and epidote (ep). In particular, the presence of epidote indicates that ore-related magmas were highly oxidized and, therefore capable of potentially carrying elevated concentrations of gold and other metals. Images from Priyal Daya's PhD thesis research under the Metal Earth VMS Thematic project.

Highlights

- 4 manuscripts were advanced for publication in peer-reviewed journals; 1 was resubmitted and accepted for review (Neyedley et al., Journal of Petrology)
- PhD student Neyedley presented two posters at SEG London 2023 and was awarded best poster for topics relevant to gold mineralization (including gold-rich VMS)
- PhD student Daya presented orally at the GAC-MAC 2022 in Halifax in a special session on VMS systems
- BSc Buyers completed a one-year thesis project, successfully defended at Saint Mary's University in April 2023
- PI Hanley presented orally at GAC-MAC-SGA 2023 in Sudbury in a special session on VMS systems and orally at EGU 2023 in Vienna, Austria, in a special session on deep magmatic processes and magma transport

Melt inclusion studies have led to the following breakthroughs in this reporting window:

(i) In fertile VMS assemblages, transitions from tholeiitic to arc affinity can be tracked linking melt inclusion metal chemistry, zircon chemistry and geochronology; importantly, this transition may take less than ~ 1 Ma, and the total magmatic window for volcanic assemblage development inclusive of associated Au-rich VMS deposits may be less than ~2 Ma, comparable to the time scales relevant for the formation of large Cu-Au porphyry deposits

(ii) Metal endowments in VMS-related magmas are similar to those in VMS-barren assemblages, with a few key exceptions. For example, VMS-endowed systems are sulfide-saturated during their history at mid-crustal depth. This may stabilize and store metals during early degassing and ascent of ore-related magmas until they are emplaced or erupted at shallower levels.

(iii) The metal tenor of silicate melt inclusions in felsic volcanics from different assemblages across the Abitibi crustal architecture is distinct. Even analysis of fresh volcanic rocks does not discern these differences. Melt inclusions record pre-eruptive magma metal endowment, whereas bulk rocks do not. Thus, lithogeochemistry will not provide a valuable metric for understanding VMS

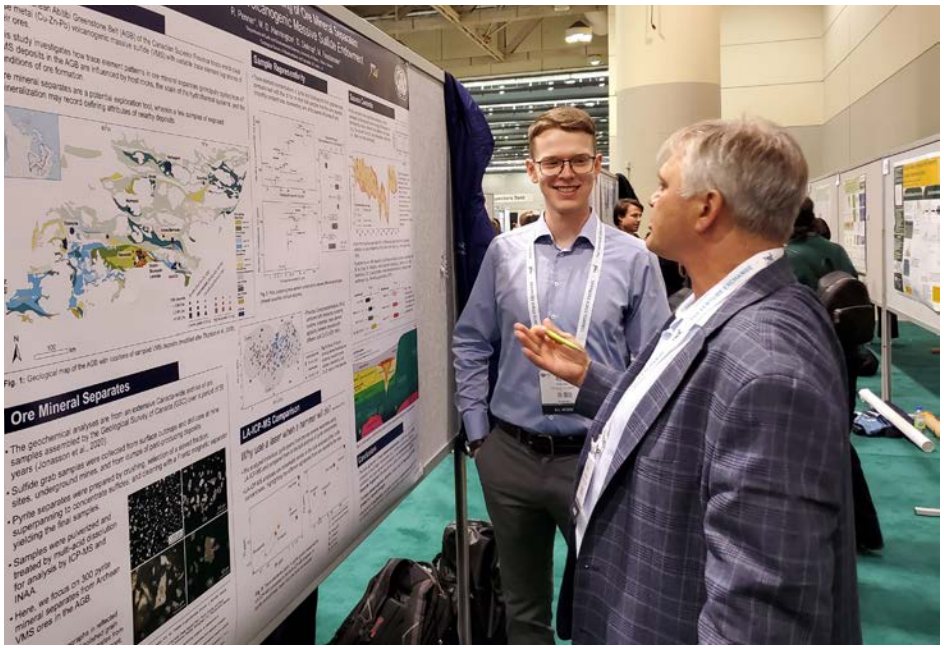
PhD student Kevin Neyedley (far right) receives the best poster award for graduate-level submissions on gold deposits at SEG London 2023 for his partially ME-funded work on melt inclusions in the Mooshla Complex, Doyon-Bousquet-LaRonde district.

WATCH NOW!
Priyal Daya - *Melt inclusions associated with Archean volcanogenic massive sulfide deposits, presented at the Metal Earth scientific meetings, Toronto, March 2023.*

VIEW OR DOWNLOAD
A. Buyers: *Looking for the Blake River in the Swayze: Characterization of Volcanic Rocks in the Swayze Area, Abitibi Greenstone Belt, Ontario. BSc Honours Thesis. Saint Mary's University. April 30, 2023.*

Crust-mantle processes responsible for VMS endowment: Trace metal constraints on the setting and source of metals

Lead Researcher: Mark Hannington and David Diekrup, University of Ottawa



University of Ottawa MSc student Ryley Penner (left) takes questions from Glencore geoscientist Frank Santaguida (right) about his poster, Trace Element Fingerprinting of Ore Mineral Separates: Implications for Volcanogenic Massive Sulfide Endowment, at the PDAC-SEG Student Minerals Colloquium, Toronto, March 2023.

VIEW OR DOWNLOAD
Penner, R. (2023). Trace Element Geochemistry of Volcanogenic Massive Sulfide Deposits in Archean Greenstone Belts: Implications for Metal Endowment and Geodynamic Settings University of Ottawa]. Ottawa. https://ruor.uottawa.ca/handle/10393/45396

Progress

- A focused statistical analysis of the VMS trace element database at the project's core was conducted, including transformation into a machine-learning format and a complete PCA. This work is part of the MSc thesis of R. Penner. The database now contains over 3900 individual analyses from more than 320 Canadian VMS deposits and massive sulfide showings. A large compilation of supporting information was added to the database, including host rock characteristics and mineralogy. A full range of statistical analyses was completed with a focus on pyrite chemistry in Archean VMS and an emphasis on the Abitibi Greenstone Belt (AGB).
- Version 2.0 of the database is a large digital supplement of the MSc thesis. Results from the analysis were presented during the Metal Earth partner meetings and at the PDAC-SEG Student Minerals Colloquium.
- Petrographic work by T. Monecke and his students (L. Patterson, F. Kasprowicz, supervised by K. Pfaff) at Colorado School of Mines (CSM) has focused on a subset of samples from the Matagami and Noranda districts, with emphasis on mineral mass balances and distribution of critical trace elements. A parallel study of 700+ polished sections from 20 additional deposits in the Abitibi greenstone belt (AGB) was also commissioned (I.M. Kjarsgaard). These data are now being used to guide a comprehensive study of critical trace elements in Canadian VMS relative to host rocks, assemblages, and age.

Future Work

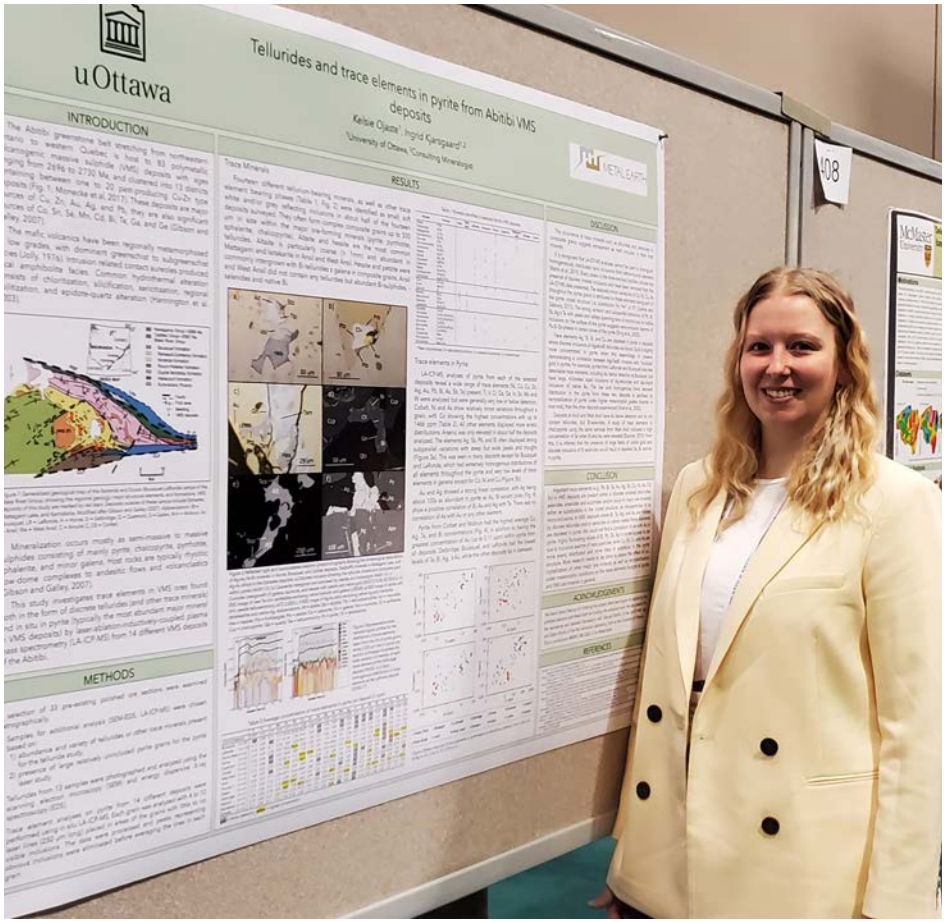
- An initial study of 55 different Archean VMS deposits is being carried out to test the relationship of trace element variations to host rocks, deposit sizes and grades. The analysis includes 258 samples of pyrite from 47 deposits in the AGB, together with 30 samples from 8

deposits in the Western Superior (Sturgeon Lake, Uchi, and Manitouwadge belts), the Benny belt, and 45 samples from 6 deposits in the Slave Province (Hackett River, Hood River, and High Lake belts). The trace element compositions of these samples will be compared to volcanic rock compositions compiled from over 4000 published high-quality analyses of samples from the Superior Province.

- R. Penner is completing his MSc thesis on this topic. Follow-up is being performed on the larger data set by I. Kjarsgaard and D. Diekrup, with BSc Honours student K. Ojaste. F. Kasprowicz and L. Patterson are conducting externally funded MSc thesis projects at CSM on the petrography and trace element geochemistry of samples from the Matagami and Noranda districts. Kjarsgaard, Patterson, and Kasprowicz will establish key mineralogical controls on trace element distribution in Archean VMS using QEMSCAN, EPMA, and LA-ICP-MS.
- A selection of WR samples of unaltered volcanic rocks from the Ontario Geological Survey has been identified for ultratrace analyses of metals with the assistance of T. Gemmell and S. Préfontaine. These analyses will help to gain a better understanding of the possible source rock controls on trace metal distribution in Archean VMS.
- D. Diekrup, now with the Geological Survey of Newfoundland, will continue to be involved in the project.

Anticipated Outcomes

- Subproject 3b is providing a comprehensive trace element and mineralogical database of Archean VMS deposits in Canada.
- Multivariate statistics and machine learning approaches will be aimed at establishing regional time-stratigraphic and spatial control on the distribution of trace elements, with an emphasis on:
  - lithogeochemical controls on trace element geochemistry with links to the sizes and grades of the deposits and their source rocks;
  - key trace element signatures and mineral balances of critical elements in deposits in well-endowed versus poorly endowed assemblages;
  - trace element signatures of the leached volcanic footwall;
  - comparisons of Archean deposits to modern VMS-forming systems.
- An important goal is to identify pathfinder associations that can be applied in exploration.



University of Ottawa BSc student Kelsie Ojaste with her poster, Tellurides and Trace Elements in Pyrite in Abitibi VMS Deposits, at the March 2023 PDAC-SEG Student Minerals Colloquium, Toronto.

WATCH NOW!
Marc Fassbender - *Geochemical Signatures of Mafic & Felsic Volcanic Rocks in Modern Oceanic Settings, presented at the Metal Earth scientific meetings, Toronto, March 2023.*

- The analysis shows the trace element geochemistry of pyrite is a useful fingerprint of the different mineralizing systems, with trace element enrichments and depletions reflecting different source rocks, inferred temperatures of ore formation, and the scales of the hydrothermal systems. District-scale variations in pyrite chemistry mainly reflect host rock and correlate with the bulk tonnage and Cu and Zn grades of the deposits.
- Two peer-reviewed articles by M. Fassbender highlight metal distribution in volcanic host rocks, including different assemblages of the AGB, which overlap with the results of VMS Subproject 3b.

Implications

- The Neoarchean greenstone belts of the Canadian Superior Province host world-class Au and base metal (Cu-Zn-Pb) massive sulfide deposits with distinct geological features, including a wide range of different host rocks and crustal settings. The range of settings is reflected in the trace metal signatures of their ores.
- The goal of subproject 3b is to test the use of trace metal signatures of VMS mineralization as a guide to well-endowed versus poorly endowed greenstone belt assemblages. Systematic trace element behaviour in VMS has already been identified as reflecting greenstone belt crustal composition (e.g., including potential inheritance), which is thought to play a key role in metal endowment in VMS systems.
- These differences highlight the potential application of the trace element signatures of pyrite during exploration for different deposit types in the same region.

VIEW OR DOWNLOAD

Fassbender, M.L., Hannington, M., Stewart, M., Brandl, P., Baxter, A., and Diekrup, D. Geochemical Signatures of Felsic Volcanic Rocks in Modern Oceanic Settings and Implications for Archean Greenstone Belts. (2023). Economic Geology, v. 118 (2), p. 319-245.
https://doi.org/10.5382/econgeo.4967

Highlights

- Publication of the database of trace element geochemistry for subproject 3b in GSC Open File 8727
- Completion of three MSc theses: R. Penner, University of Ottawa; L. Patterson (CSM); and F. Kasprowicz (CSM)
- Results presented at PDAC-SEG Student Minerals Colloquium in 2022 and 2023; Society of Economic Geologists 2023 Conference in London; Geological Society of America Annual Meeting 2022 in Denver.
- Completion of BSc Honours student thesis by K. Ojaste, University of Ottawa

Source to Sink

Lead Researcher: Georges Beaudoin, Université Laval

Outcrop from the Pontiac Group composed of metapelites and metawackes with beds parallel to the main foliation. Isaac Siles-Malta for scale.

WATCH NOW!
Michael Herzog - *Multi-scale controls on orogenic gold precipitation and remobilization in the Malarctic-Val d'Or district, Québec. Presented at the Metal Earth scientific meetings, Toronto, March 2023.*

WATCH NOW!
Isaac S. Malta - *Metamorphic and structural evolution of the northern Pontiac subprovince, presented at the Metal Earth scientific meetings, Toronto, March 2023.*

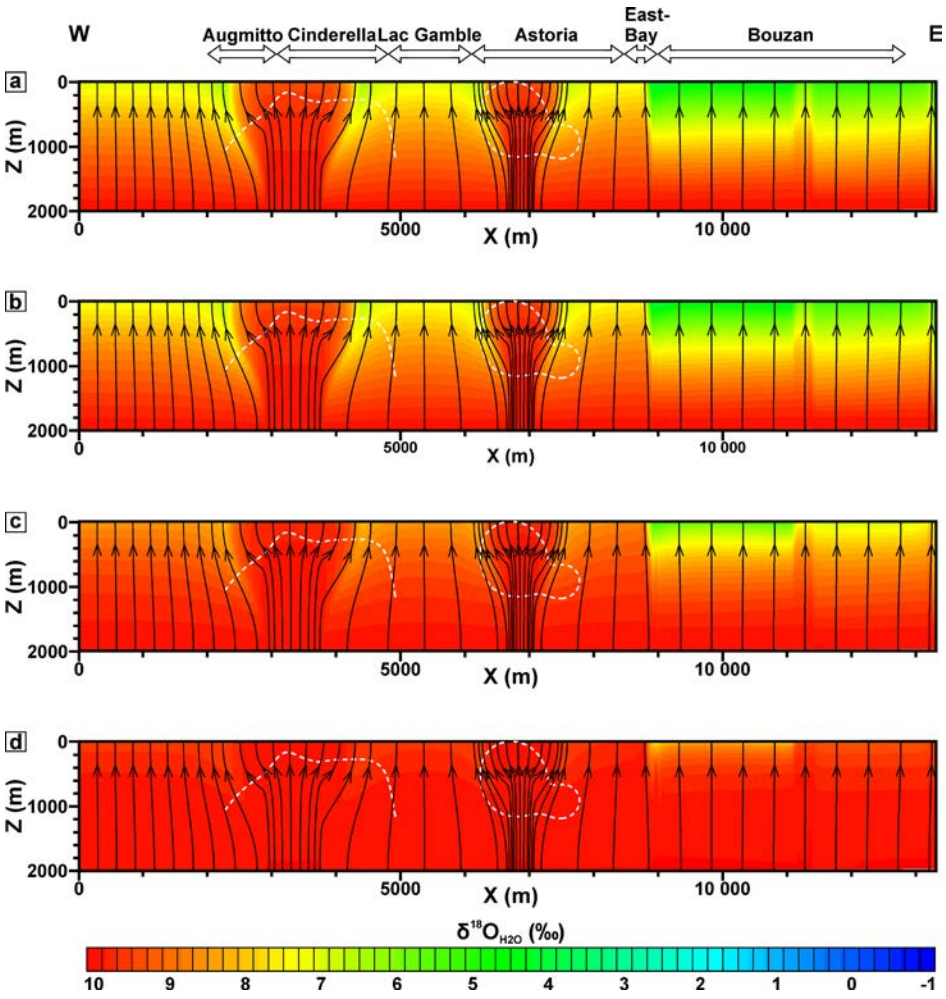
Progress

- G. Raymond's MSc memoir (thesis) *Variation spatiale des conditions de circulation des fluides à l'origine de la minéralisation en or orogénique dans le segment Augmitto-Bouzan (Sous-Province de l'Abitibi, Québec, Canada)* has been accepted.
- A paper on G. Raymond's MSc thesis will be submitted in 2023. Raymond has sampled auriferous veins in the Larder Lake-Kirkland Lake segment to complete the study of fluid sources along the Cadillac-Larder Lake shear zone (CLLSZ). He has completed the data set for H and O isotopes and integrated the results with previous work carried by the team. He is now registered in the PhD program at -ETE.
- B. Quesnel and C. Scheffer left the team in spring 2022. They prepared a draft paper on the fluid sources along the CLLSZ that will be completed in 2023. Quesnel's paper on clumped isotopes has been published. The review paper on stable isotopes in orogenic gold will be published in 2023.
- M. Herzog has submitted a paper on sulphide chemical composition and multiple sulphur isotopes (SIMS collaboration UWA). Another paper on sulphide inclusions and gold transport/deposition documenting nano-particles by TEM (collaboration UWA) will be submitted in 2023. He is expected to defend his PhD thesis: Multi-scale controls on orogenic gold precipitation and remobilization in the Malartic-Val-d'Or district of the Abitibi subprovince (Québec, Canada) in late 2023.
- I. Siles Malta: Phase equilibria modeling was performed on selected key samples from the Pontiac subprovince to quantify P-T-t-X paths and fluid dehydration reactions. A manuscript was written and will be submitted to Journal of Metamorphic Geology.
- Y. Nemati: Mass balance analysis revealed that areas where K+ was gained also displayed an increase in spectral gamma ray counts. Similarly, sections that gained Ca2+ showed a decrease in rock density, which could be attributed to carbonate alteration of komatiites.

We also identified areas likely corresponding to the destruction of magnetite from the komatiite by hydrothermal fluids, resulting in the formation of pyrite and arsenopyrite and precipitation of gold. This hydrothermal alteration corresponds to variations in magnetic, resistivity, density, velocity, and IP responses measured downhole. We also determined that petrophysical data can be used to show the intensity of hydrothermal alterations. These alterations result in the generation of quartz and carbonate veins and destabilization of sulphide minerals, which can be traced using electrical logs, sonic log, and optical televiewers. Additionally, we showed that gamma ray logs can help identify areas with sericite alterations. uXRF data on core samples from the study area demonstrated changes in sulphide minerals on a smaller scale, and results corroborate the results of induced polarization measurements.

Future Work

- B. Quesnel and C. Scheffer remain active collaborators on ongoing projects. They plan on submitting to peer-reviewed journals two scientific articles on
  1) the variation between Sub-provinces of the Superior province of stable isotope composition of vein minerals and fluid(s) that have percolated in orogenic deformation zones and
  2) the variation of stable isotope composition of veins mineral and fluids along the Cadillac-Larder Lake deformation zone.
- G. Raymond will finish writing a paper on his MSc thesis and submit to a journal. M. Herzog will submit his 3rd paper and PhD thesis for evaluation. As for Y. Nemati, given the relations observed in the borehole and from uXRF data, the next step will be to model these behaviours using Finite Element Analysis and eventually attempt to propose an effective medium approximation for rocks that have undergone hydrothermal alterations.
- I. Siles Malta will finalize phase equilibria modelling by including the fluid behaviour in the MnNCKFMASHTO-S system. He will also prepare manuscripts for publication in international peer-reviewed journals, and he will write, submit, and defend his thesis.
- Two post-doctoral fellows will be recruited to date fluid flow along the CLLSZ and to study fluid inclusions in pyrite in orogenic gold deposits of the Superior province.



Simulated δ18OH2O values for the model with high conductivity corridors. The streamlines show the direction of the infiltrating auriferous fluid. Modelling results from G. Raymond's M.Sc. thesis.

VIEW OR DOWNLOAD
Raymond, Guillaume. 2022. MSc Memoire. Université Laval. Variation spatiale des conditions de circulation des fluides à l'origine de la minéralisation en or orogénique dans le segment Augmitto-Bouzan (Sous-Province de l'Abitibi, Québec, Canada)
https://explomin.ggl.ulaval.ca/fileadmin/aem/documents/Documents/Maitrise-Guillaume-Raymond_final.pdf.pdf

VIEW OR DOWNLOAD
Quesnel B., Scheffer C., Beaudoin G. (2023) The Light Stable Isotope (Hydrogen, Boron, Carbon, Nitrogen, Oxygen, Silicon, Sulfur) Composition of Orogenic Gold Deposits In: Huston D, Gutzmer J (eds) Isotopes in Economic Geology, Metallogenesis and Exploration. Springer International Publishing, Cham, pp 283-328. https://link.springer.com/chapter/10.1007/978-3-031-27897-6_10.

Anticipated Outcomes

- Compendium of stable isotope composition of orogenic veins stable isotope composition in the Superior province, comparing gold-endowed and less-endowed domains
- Improved understanding of the sources of auriferous fluids along the CLLSZ.
- Age of gold mineralization events, sources of sulphur and gold precipitation mechanisms in the Val-d'Or area.
- Improved understanding of the petrophysical characteristics of gold-endowed and less-endowed segments of the CLLSZ.

Implications

- The Source to Sink project compares the stable isotope signature of fluid flow along transects cutting across well-mineralized and poorly mineralized segments of major crustal faults and volcanic centers in the Superior province. The project will also identify sources of fluids and sulphur in the province's gold deposits and determine hydrothermal features that explain the metal accumulation of endowed areas versus those that are less endowed.
- Outcomes will lead us to better understand fluid generation during metamorphism of sedimentary rocks (timing and P/T conditions), the sources of volatiles (including sulphur, a critical ligand for gold transport to deposition sites), and the processes involving fluid at the deposit and the timing of hydrothermal fluid pulses in order to better constrain key parameters required to form a deposit.

Université Laval PhD student Isaac Siles Malta presents his research at the Metal Earth scientific meetings, Toronto, March 2023.

Highlights

- The work done in 2022-23 has shown the importance of mineral textures and the scale of these textures on the petrophysical measurements. These findings provide a first step towards the upscaling of this information to 3D geological and geophysical models. The longer-term outcome is to unify the geological and geophysical models.
- Additional highlights include: G. Raymond's thesis was published in 2022. I. Malta was invited to present his research at the Québec Mines convention. G. Beaudoin and I. Malta were invited to share research results at GAC-MAC-SGA in Sudbury in May 2023. G. Beaudoin and M. Herzog will present research results at the SGA in Zurich. M. Herzog presented his results at SEG in Denver.

VIEW OR DOWNLOAD
Herzog, Michael & Laflamme, Crystal & Beaudoin, Georges & Marsh, J. & Guilmette, Carl. (2022). U–Pb vein xenotime geochronology constraints on timing and longevity of orogenic gold mineralization in the Malartic-Val-d'Or Camp, Abitibi Subprovince, Canada. Mineralium Deposita. 58. 10.1007/s00126-022-01131-1.

VIEW OR DOWNLOAD
Quesnel, B., Jautzy, J., Scheffer, C., Raymond, G., Beaudoin, G., Jørgensen, T. R., & Pinet, N. (2022). Clumped isotope geothermometry in Archean mesothermal hydrothermal systems (Augmitto-Bouzan orogenic gold deposit, Abitibi, Québec, Canada): A note of caution and a look forward. Chemical Geology, 121099. https://www.sciencedirect.com/science/article/pii/S000925412200393X?via%3Dihub

VIEW OR DOWNLOAD
Kieffer, Marie; Scheffer, Christophe; Quesnel, Benoit; Bedeaux, Pierre; Beaudoin, Georges ; Mathieu, Lucie; Gaboury, Damien. (2022). Fluid sources and mineralizing processes in greenstone belts: A stable isotope (O, H) comparison between the weakly mineralized Moly-Desgagné–Guercheville system and Val-d'Or orogenic gold deposits, Canada. Canadian Journal of Earth Sciences. 59. 10.1139/cjes-2021-0162. https://cdnsciencepub.com/doi/10.1139/cjes-2021-0162

WATCH NOW!
Yasaman Nemati - *Assessing the geophysical attributes of hydrothermally altered gold deposits. Assessing the geophysical attributes of hydrothermally altered gold deposits using petrophysical logs and geochemical analysis. Presented during the online Metal Earth scientific meeting series, April 2022.*

WATCH NOW!
Benoît Quesnel - *Toward an integrated understanding of the auriferous fluid flow system(s). Presented during the online Metal Earth scientific meeting series, April 2022.*

Borehole Petrophysics

Lead Researcher: Christian Dupuis, Université Laval

Progress

- Using borehole petrophysical data collected from hydrothermally altered orogenic gold deposits, we found that the petrophysical data corroborated with the geochemical data. This is important because earlier studies using machine learning had concluded that this link was impossible to establish. Our results show that it can be done when the analysis is done properly.
- Mass balance analysis revealed that areas where K+ was gained, there was also an increase in spectral gamma ray counts. Similarly, sections that gained Ca2+ showed a decrease in rock density, which could be attributed to carbonate alteration of komatiites.
- We also identified areas likely corresponding to the destruction of magnetite from the komatiite by

WATCH NOW!
Yasaman Nemati - *Assessing the geophysical attributes of hydrothermally altered gold deposits, presented at the Metal Earth scientific meetings, Toronto, April 2022.*

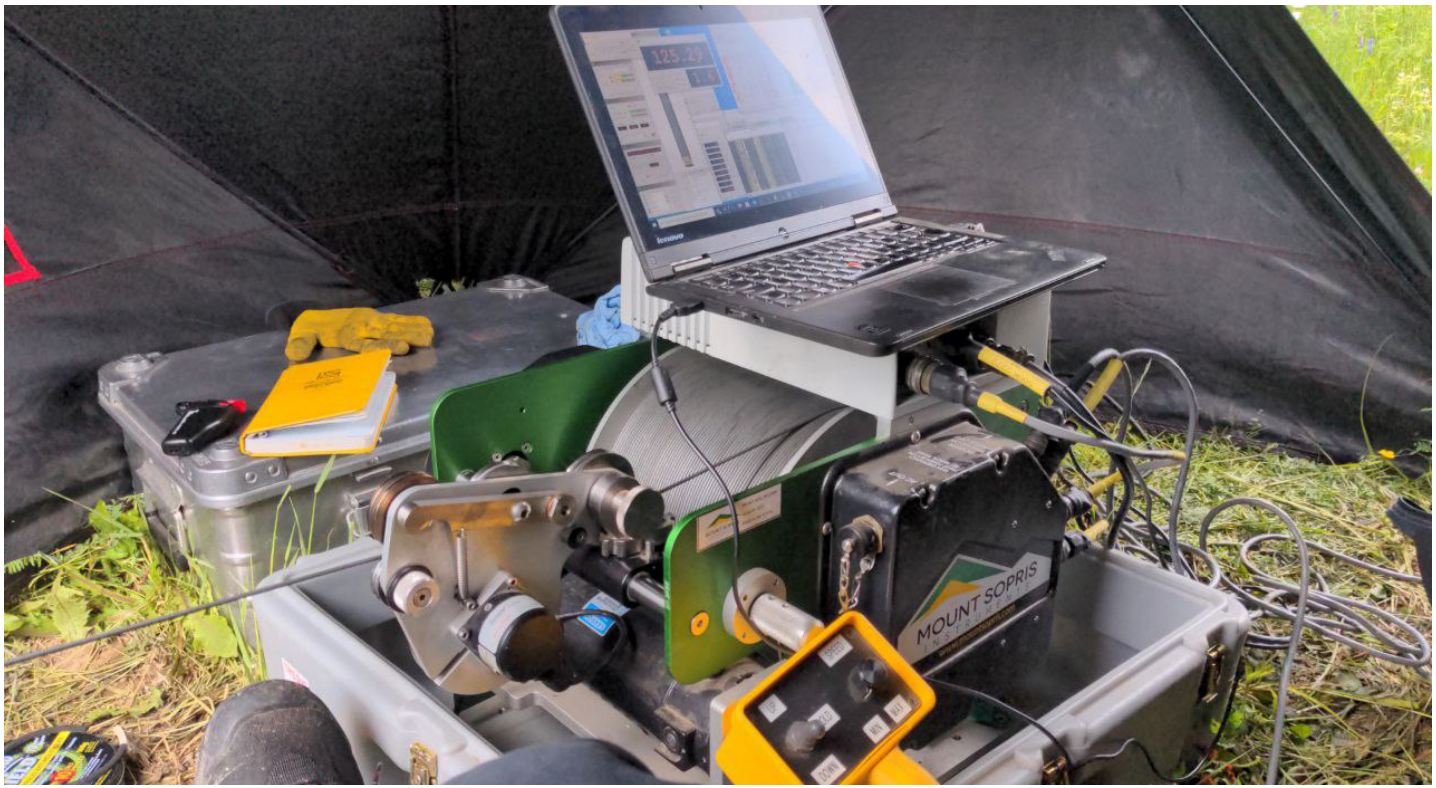
View from the field near Rouyn-Noranda, Quebec. Photo: Christian Dupuis.

hydrothermal fluids, resulting in the formation of pyrite and arsenopyrite and precipitation of gold. This hydrothermal alteration corresponds to variations in magnetic, resistivity, density, velocity, and IP responses measured downhole.

- We also determined that petrophysical data can be used to show the intensity of hydrothermal alterations. These alterations result in the generation of quartz and carbonate veins and the destabilization of sulphide minerals, which can be traced using electrical logs, sonic logs, and optical televiewers.
- Additionally, we showed that gamma ray logs can help identify areas with sericite alterations. uXRF data on core samples from the study area demonstrated changes in sulphide minerals on a smaller scale, corroborating the results of induced polarization measurements.

Future Work

Given the relationships observed in the borehole and uXRF data, the next step will be to model these behaviours using finite element analysis and then attempt to propose an effective medium approximation for rocks that have undergone hydrothermal alterations.



Wireline logging equipment used for borehole data acquisition. Photo: Christian Dupuis.

Anticipated Outcomes

The work done in 2022-23 has shown the importance of mineral textures and the scale of these textures on the petrophysical measurements. These findings provide a first step towards the upscaling of this information to 3D geological and geophysical models. The longer-term outcome is to unify the geological and geophysical models.

Highlights

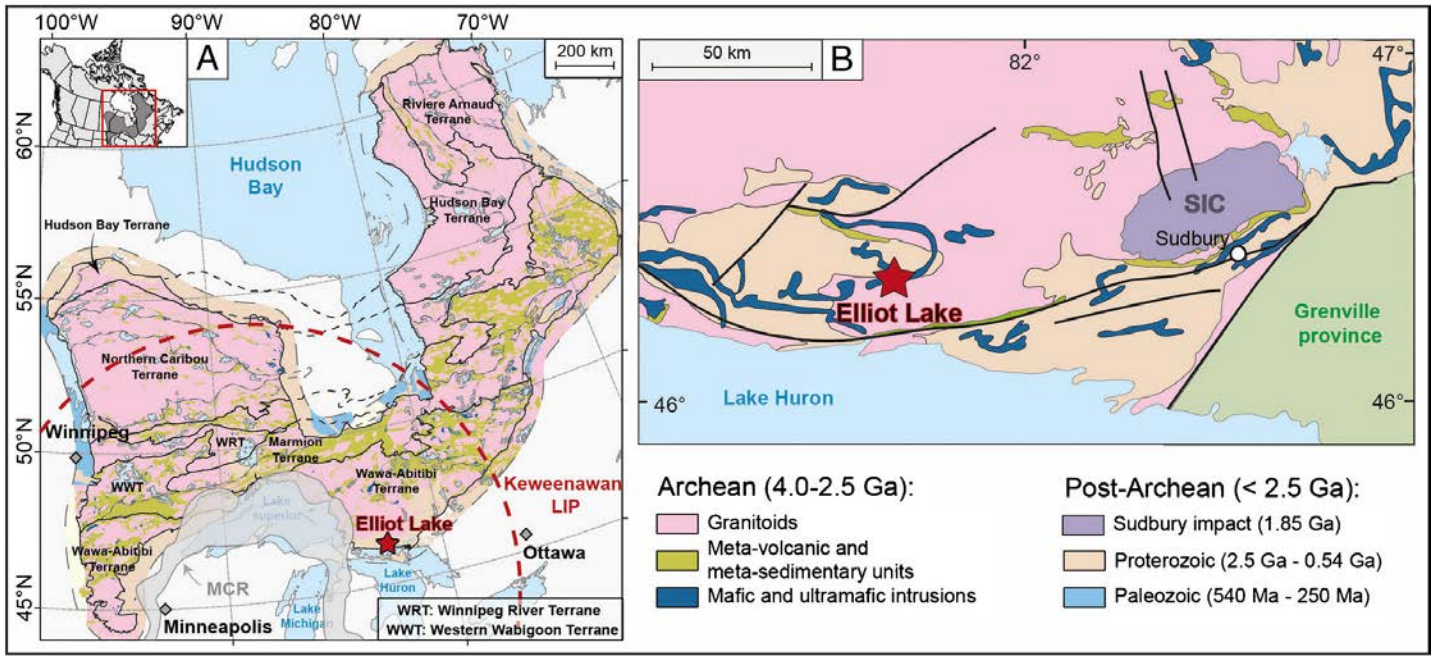
- PhD student Yasaman Nemati was invited to present an oral presentation at PDAC in June 2022. Her presentation, ''Understanding the petrophysical attributes of hydrothermally altered gold deposits using petrophysical logs and mass balance equations," was very well attended, and the audience was engaged. Yasaman also presented her work at a PDAC 2022 poster session, as well as at the Metal Earth scientific meetings at PDAC in March 2023 and the KEGS Symposium. She is preparing a scientific paper titled ''Petrophysical signatures and mineral endowment: The Piché group, Rouyn-Noranda, Québec."

Mantle Group

Lead Researcher: Graham Pearson, University of Alberta

Progress

- Our study of critical metal enrichment in the mantle of the Superior Province is complete. The findings were published as: "Post-Archean Nb-REE-U enrichment in the Superior Craton recorded in metasomatised mantle rocks erupted in the 1.1 Ga Midcontinental Rift event," in Mineralium Deposita, September 2023.
- The U-Pb – bastnaesite and carbonate dating approach has been refined, and the application study to Thor Lake has been completed and is in preparation for publication. This work has led to funding from the Geological Survey of Canada (GSC) for a PhD project dating carbonatites in the Superior Craton and beyond.
- Work has begun on the Slave Craton mapping project. Research associate Chiranjeeb Sarkar has secured an initial batch of samples, which are being processed for zircon and other phases.

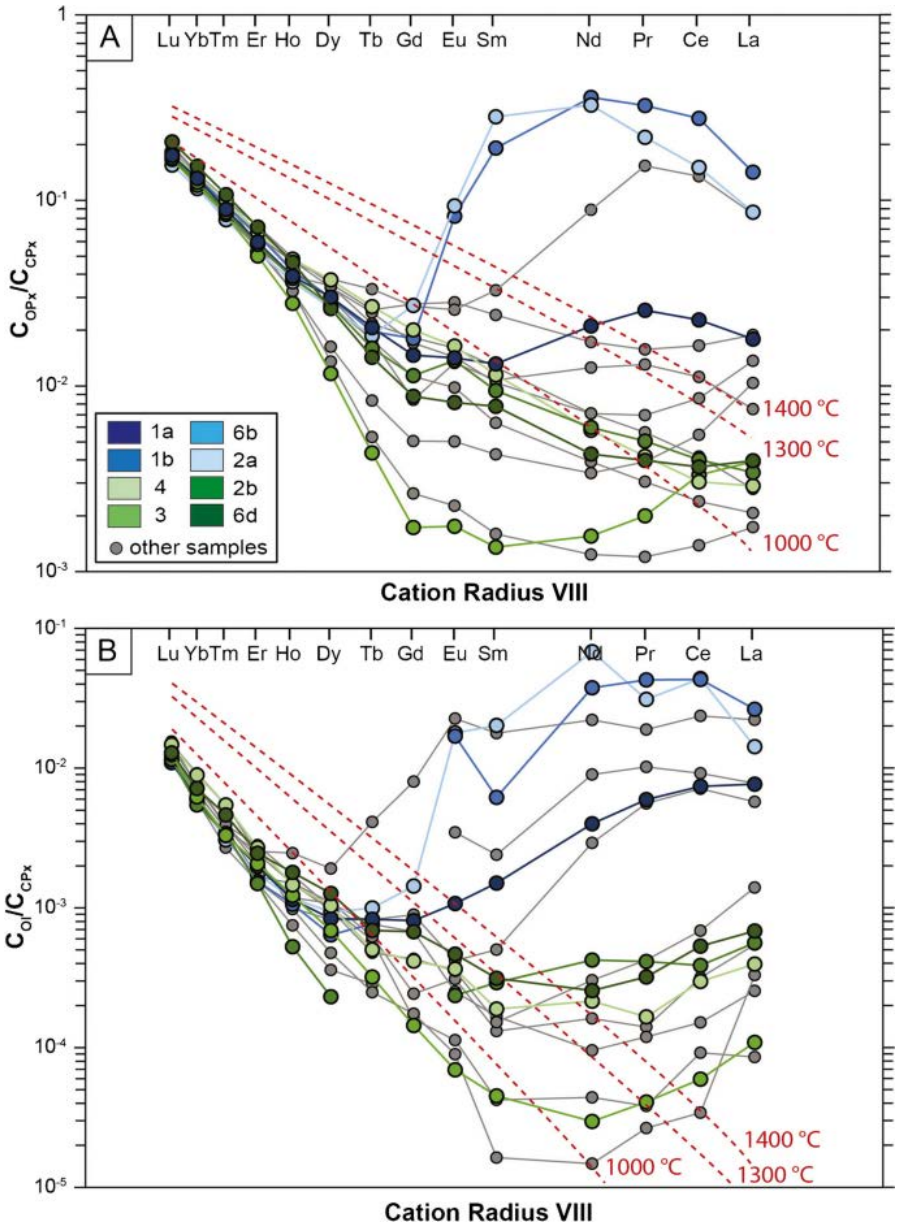


Regional geologic maps of the study area.

Figure 1, A: Main geologic formations and structures from the Superior Craton (East Canada). The map is after Montsion et al. (2018). Our case study is located in the Wawa-Abitibi terrane, in the SE part of the Superior craton. Keweenawan LIP spatial range and MCR are after Wu et al. (2017) and Stein et al. (2018) respectively. MCR=Midcontinent Rift, LIP=large igneous province.

B: local geological map of the Elliot Lake area, north of Lake Huron and west from Sudbury, Ontario, Canada; after Lightfoot (2017). Both gold and uranium paleo placers are disseminated within the Proterozoic sediments surrounding Elliot Lake.

Source: Legros, Hélène, et al. (2023). Post-Archean Nb-REE-U enrichment in the Superior craton recorded in metasomatised mantle rocks erupted in the 1.1 Ga Midcontinental Rift event. Mineralium Deposita. 10.1007/s00126-023-01214-7.



Future Work

- A new PhD student, starting in January 2024, will begin working dating REE-Nb-mineralised carbonatites, aided by Dr. Sarkar.
- Dr. Sarkar will progress with the Slave Craton mapping project, analyzing samples from the first batch of greenstone belts and basement samples from the Bathurst block collected recently by Rasmus Hauguaard. Data compilation will also be initiated.
- We have completed an appraisal of the origin of Knee Lake diamonds from the western Superior Craton with a view to further understanding lithospheric geothermal conditions in Mesoarchean times.

Anticipated Outcomes

- The carbonatite dating project will produce new ages and initial isotope ratios for tracer information to determine whether the age and source regions of "endowed" or "barren" carbonatites are different.
- The Slave mapping project is a long-term, multi-year endeavour to construct an isotopic map of the Slave craton and relate the isotopic "architecture" to known, previously documented lithospheric mantle structure and chemistry.

WATCH NOW!
Hélène Legros - *Nb-REE mineralization in the Superior and Slave cratons: source and geochronology, presented at the Metal Earth scientific meetings, Toronto, March 2023.*

Figure 2. Partition coefficient between Opx and CPx (A) and Ol and CPx (B) for each rare earth element. Dashed lines indicate equilibrium between minerals at specific temperatures (Agranier and Lee 2007). The colour scheme reflects the degree of depletion/metasomatism as illustrated in Fig. 5D. (Figure 3 in this Mantle Group section of the MERC Annual Report). The grey dots represent samples for which whole-rock data could not be acquired.

Source: Legros, Hélène, et al. (2023). Post-Archean Nb-REE-U enrichment in the Superior craton recorded in metasomatised mantle rocks erupted in the 1.1 Ga Midcontinental Rift event.Mineralium Deposita.

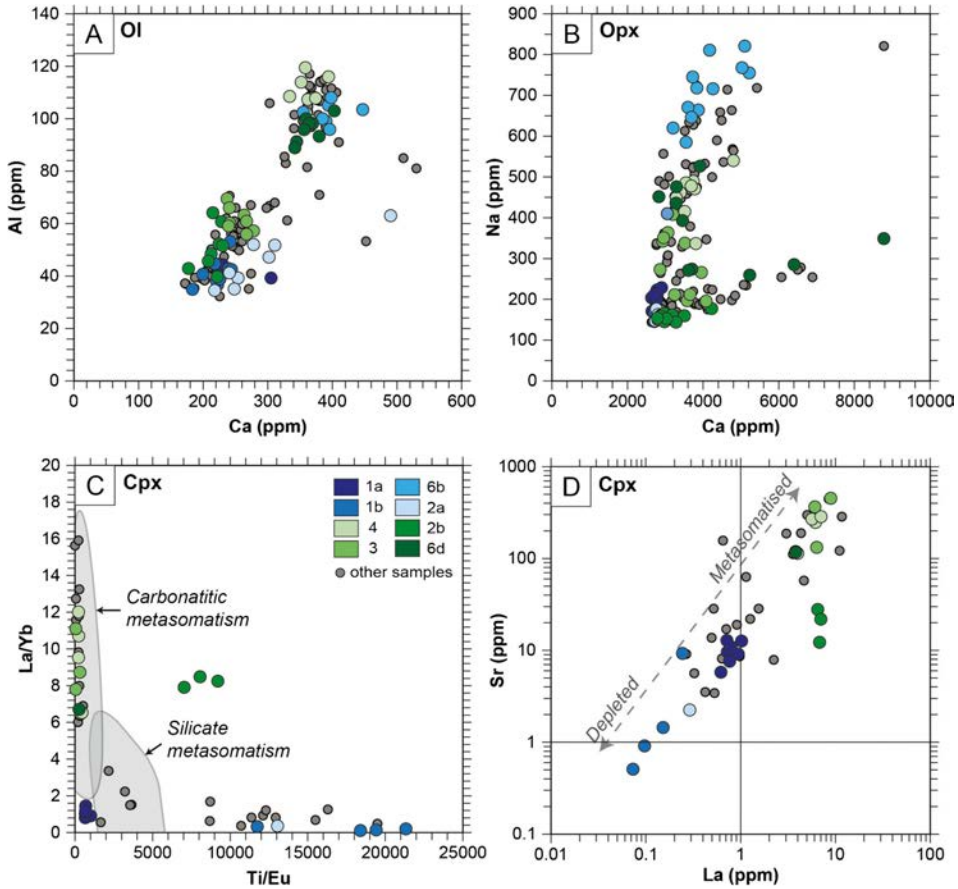


Figure 3. Trace element biplot diagrams from A olivine, B orthopyroxene, and C–D clinopyroxene analyses from the Elliot Lake xenoliths. Carbonatitic and silicate metasomatism domains are after Coltorti et al. (1999). Metasomatised and depleted area of Sr-La diagram are after Tang et al. (2008). Cpx, clinopyroxene; O, olivine; Opx, orthopyroxene. The grey dots represent samples for which whole-rock data could not be acquired.

Source: Legros, Hélène, et al. (2023). Post-Archean Nb-REE-U enrichment in the Superior craton recorded in metasomatised mantle rocks erupted in the 1.1 Ga Midcontinental Rift event. Mineralium Deposita. https://link.springer.com/article/10.1007/s00126-023-01214-7

Implications

- Understanding the evolution of lithospheric architecture is key to constraining/targeting the location of metal transfer and enrichment in the continental lithosphere during the evolution of cratons. The Archean period, especially the Meso- to Neoarchean, is a key period of tectonic transition and enhanced metal endowment. Studies of the Slave and Superior Cratons address these goals within the context of the Metal Earth project.
- Better understanding Archean lithospheric geotherms will be key to constraining how crust and mantle conditions evolve to a point of favouring the production of gold mineralizing environments, predominantly in Neoarchean times.

VIEW OR DOWNLOAD
Legros, Hélène, et al. (2023). Post-Archean Nb-REE-U enrichment in the Superior craton recorded in metasomatised mantle rocks erupted in the 1.1 Ga Midcontinental Rift event. Mineralium Deposita.
https://link.springer.com/article/10.1007/s00126-023-01214-7

Highlights

- First documentation of critical metal enrichment in Superior Craton mantle and the role of the lithosphere as a staging post for metal up-grading
- Results of the bastnaesite dating development project by Legros & Sarkar led to >$100k PhD project funding from the GSC to apply the technique to Superior Craton carbonatites; a great example of technology development and adoption supported by a government agency

High-precision, chemical abrasion ID-TIMS U-Pb geochronology of crustal growth and ore deposition in domains of variable metal endowment across the Superior Province

Lead Researcher: Mike A. Hamilton, University of Toronto

Progress

Amongst Metal Earth partner institution collaborators, Mike Hamilton's role at the Jack Satterly Geochronology Laboratory (JSGL) at the University of Toronto is to produce and interpret high-precision uranium-lead ages for the Metal Earth transect teams. Since the Metal Earth project began, all U-Pb CA-ID-TIMS geochronological report materials have been archived systematically within the MERC data repository.

Work at the JSGL supports multiple projects and the overall goals of Metal Earth, as detailed below.

2020-2021:

- 27 samples submitted to JSGL for precise CA-ID-TIMS geochronology; 25 samples yielded zircon or other datable accessory mineral phases, while 2 samples were barren of U-Pb phases. Although more than four months were lost to a shutdown of the university campus due to the start of the pandemic, full U-Pb TIMS age determinations were completed on 27 samples, and a 2020-2021 U-Pb Metal Earth ID-TIMS Geochronology Report was submitted on these findings.
- Approximately 60 vials of hand-picked zircon separates were prepared and shipped to Jacob Hanley at Saint Mary's University for melt inclusion study in VMS Thematic Project 3a with PhD candidate Priyal Daya. A selection of zircon separates from the Sturgeon transect was prepared and shipped to Chong Ma for LA-ICPMS study.

2021-2022:

- Pandemic-related shutdowns or slowdowns continued intermittently over this period. Twenty-eight samples were submitted to JSGL for precise CA-ID-TIMS geochronology during this time; of these, 25 samples yielded zircon or other datable accessory mineral phases, while 4 samples were barren of U-Pb phases. Full U-Pb TIMS age determinations were completed on 16 samples, and a 2021-2022 U-Pb Metal Earth ID-TIMS Geochronology Report was filed on these findings. Preliminary results were produced and communicated for the remaining 9 samples, all from the Sudbury transect (Haugaard).
- Three days of fieldwork were carried out over late June–early July with R. Haugaard for his Sudbury transect project to introduce him to regional Huronian stratigraphy, the local Archean basement geology north of the SIC, and to Paleoproterozoic deformation/structures, magmatism and metamorphism, as well as sample collection for geochronology.
- Hand-picked zircon separates from 3 samples were shipped to Jacob Hanley at Saint Mary's University for Priyal Daya's melt inclusion study
- Presented a talk at the November 2021 Metal Earth scientific meeting, updating the group on 2020 and 2021 U-Pb TIMS geochronology results

2022-2023

- Analytical progress is underway for all samples submitted during the year 2022-2023; a final 2022-2023 U-Pb Metal Earth ID-TIMS Geochronology Report will be produced after March 2023
- Complex zircon U-Pb datasets from the Sudbury transect deep drillhole samples below the SIC (Vale and Glencore DDHs) remain under continued study to resolve considerable and pervasive shock metamorphic effects.
- Monthly maintenance and updating of the JSGL Mineral Separates Archive and its database, to facilitate routine access by Metal Earth researchers for ancillary chemical and isotopic studies on accessory mineral phases (e.g. laser ablation detrital zircon studies, Hf & O isotopes, Ce4+/Ce3+ (zircon) redox conditions, etc.).
- Participated in the Metal Earth Research Workshop, Ottawa, October 2022.
- Participated in the Metal Earth scientific meetings, Toronto, March, 2023.

Contributions to various journal manuscripts and published papers through the Metal Earth project have been listed in conjunction with the projects described in other sections of this report, and in previous reports.

Future Work

- Anticipated U-Pb TIMS sample analyses for remaining Superior transect carryovers and follow-ups, as well as Thematic project samples.
- Field excursions and sampling with H. Gibson (May, 2023) to further refine the detailed eruptive, intrusive, and mineralization history at Noranda. Very high precision dating to follow through the rest of Year 7.
- Planning for potential Slave craton sampling and analysis and making available dated mineral separates and hand samples (approximately 45 samples of Neoarchean VMS-associated Banting Formation volcanics, and additional key Paleo- and Mesoarchean basement gneisses and Neoarchean granitoids – from an NWT Geoscience Office sampling and dating project I participated in from 2012-2015.

Anticipated Outcomes

- Continued collaboration with ME researchers is aimed at delivering additional peer-reviewed scientific journal publications integrating remaining unreleased transect-level geochronological results (particularly from Chibougamau, Cobalt, Swayze, Matheson, Larder Lake, and numerous Wabigoon transects).
- Synthesis of existing 2017-present high-precision CA-ID-TIMS U-Pb results into a comprehensive set of journal publications covering the eastern and southern Abitibi. Synoptic overview of southern Superior craton geochronology pertaining to crustal evolution and the timing of metallogeny in endowed vs. less-endowed belts.

Implications

This work contributes to our assessment of emerging theories for the accretionary tectonic, magmatic and sedimentary evolution of the southern Superior craton and its economic mineral endowment through high-resolution isotope dilution (ID-TIMS) U-Pb geochronology. A wealth of new age-dating results for annual Metal Earth mapping initiatives helps groundtruth aspects of transect-level geology and geophysics and establishes new constraints on the precise timing of, and linkages between, magmatism, tectonism and metal ore deposition from the camp- to craton-scale. The development of new analytical protocols and efforts to expand dating capacities using novel accessory mineral chronometers directly benefits Metal Earth objectives and strengthens future Canadian geoscience capabilities.

Precision dating of syngenetic ore hosts, or of closely bounding volcanic sequences offer direct ways of understanding spatial-temporal patterns related to Metal Earth objectives. Are strongly metal-endowed greenstone belts fundamentally different in age from lithologically similar but metal-poor belts? Can specific ore deposit-rich geological units (e.g. Blake River Group) be extrapolated across segmented or structurally complex regions into lesser-known greenstone belts? Zircon geochronometry is indispensable in this regard, and with enough data, can be used predictably in new areas.

Furthermore, improved understanding of regional and local (deposit- or camp-scale) structures, mineralized vein systems and relations to major structural breaks can be accomplished if fabrics, host rocks or cross-cutting magmatic units can be dated precisely, particularly those formed in a rapidly evolved, dynamic tectonic setting.

U-Pb geochronology provides quantitative, unambiguous tie points for mapping initiatives on all principal transects and contributes materially to the construction of geological cross-sections and geophysical interpretations at depth. Training the next generation of geoscience HQP in the acquisition and interpretation of state-of-the-art U-Pb geochronology methods and data has been an important project component.

Highlights:

- Geochronological investigations in the Chibougamau transect during 2020-2021 confirmed initial results from the previous year that the volcanic stratigraphy in the southern half of the transect requires significant revision.
- This was demonstrated by the presence of previously unrecognized young felsic magmatism (Phooey Mbr rhyolites; 2714.6 Ma) and now by intrusive granites such as the Hazeur pluton (2711.7 Ma), likely associated with the Nelligan, Philibert & Lac Meston Au zones. These Kidd-Munro assemblage ages also invite comparison to a similar timing of Au mineralization at the Windfall deposit, exposed in the Urban-Barry greenstone belt to the immediate south. An age of 2716.9 Ma for a Cummings sill in the south Chibougamau transect is identical to previous ages for this mafic suite in the northern half of belt. This new data greatly expands the known areal extent of this event, and likely further implicates host mafic volcanics in the south to represent a higher proportion of Cycle 2 magmatism, rather than Cycle 1 Obatogamau Fm. basalts. Two new tonalite-

granodiorite bodies within the Chibougamau batholith define a previously unrecognized youngest component of magmatism at 2695-2697 Ma. [in support of L. Mathieu, P. Bedeaux and students]

- New, high-precision ages for intrusive tonalites and rhyolitic volcanism in the Rouyn-Noranda transect have helped to build on Metal Earth results from 2018-2020 that are radically revising previous interpretations of the timing and pace of the development of this important volcanic centre and establish a more accurate and precise constraint on the age(s) of local ore system(s). [in support of H. Gibson and PhD student Marina Schofield]
- Advances continue to be made in extending the volcanic assemblage stratigraphy from the well-known central Abitibi southwards, from the Benny greenstone belt in the west, eastwards through Temagami, Cobalt and into the Pontiac basement in Quebec (Baby, Belleterre and Lac des Bois greenstone belts). Efforts aimed at constraining the age of turbidite sequences in the Temagami greenstone belt (and in Afton Twp) are ongoing but have already yielded important new data on Porcupine vs. Timiskaming assemblage affinities. [in support of J. Ayer, S. White, and students]
- Zircon from several Swayze belt volcanic and volcaniclastic samples – critical for unravelling the internal stratigraphy and structure in the southern half of the belt – were analyzed by CA-ID-TIMS in order to resolve complexities, inaccuracies or imprecisions produced by earlier LA-ICPMS analysis. The new results have greatly improved the age resolution of each unit and brought into better focus constraints on stratigraphic correlations and regional structures. [in support of T.Gemmell, R. Haugaard, and J. Ayer]
- During 2021-2022, new age determinations finally helped to solve two persistent questions in Atikokan geology. First, a lapilli tuff recognized by B. Lafrance and MSc student Mohamed Farhat was dated at 2779.1 ± 0.8 Ma, providing the first robust age for the Witch Bay Formation. Meanwhile, a maximum age constraint for the timing of gold mineralization and fabric development at the Hammond Reef deposit was established by a sample of host Diversion stock tonalite at 2890.2 ± 1.0 Ma, which represented an important contribution to the MSc study of Gabrielle Fouillard. The age also helps better define the regional extent of Diversion stock plutonism, which has required better delineation to this point.
- Two new zircon U-Pb ages were established for important late- to post-tectonic nepheline syenites from the Bell Lake and Sturgeon Narrows alkalic complexes at 2695.7 ± 0.9 Ma and 2693.2 ± 0.9 Ma, respectively, in the Sturgeon Lake transect. Precise ages on several samples from the volcanic stratigraphy have helped refine and redefine the timing and duration of eruptive episodes in the Fourbay Lake, Lower and Upper Handy Lake, South Sturgeon and Central Sturgeon assemblages. The new age for the Sturgeon Narrows Alkalic Complex imposes a new minimum depositional age for the Timiskaming-like Ament assemblage. [in support of Chong Ma and student M. Tamosauskas]
- Between 2020-2023, over a dozen new high-resolution U-Pb TIMS ages were produced for a variety of felsic volcanic rocks and gabbros sheets (contemporaneous with pillow basalt flows) in the Rainy River greenstone belt. Dated volcanism older than, contemporaneous with, and younger than the rhyolitic host to the Rainy River Au deposit has now been rigorously constrained over a relatively narrow age range. These results, combined with the span of new detailed mapping in the Rainy River transect, define one of the most detailed, comprehensive records of volcanism, plutonism, deformation and timing of Au mineralization of any greenstone belt. [in support of G. Launay]
- First-recorded age results have been established for two felsic volcanic/subvolcanic units on Kinross Gold Corp.'s Great Bear property – south of and outside the main Red Lake camp. The initial results suggest that the volcanic and sedimentary rocks on the property are part of a younger assemblage – possibly equivalent to the Graves or St. Joseph assemblages of the upper sequences – rather than the main (Balmer Fm.) hosting most of the mines at Red Lake proper (though the former are also known hosts to gold deposits). A feldspar porphyry, dated at 2722 ± 1 Ma helps constrain a maximum age for mineralization at Great Bear. [in support of PDF Jack Simmons]

Modern Ocean Crust (Metal Oceans)

Lead Researcher: Mark Hannington, University of Ottawa

Progress

The focus of Metal Oceans in 2022-23 was working more closely with the Metal Earth team to establish the link between microplate formation, greenstone belt assemblages, and magmatic-hydrothermal systems at a scale useful for exploration. This research included quantitative modelling of crustal growth, with direct comparison of modern and ancient terrane assemblages.

- The interpretations of processed geophysical data from the ARCHIMEDES I (SO-267) research expedition were published in several papers. Multibeam, sidescan, and magnetics were processed and incorporated into several new papers and thesis products. Gravity and MT analysis also was advanced and is being incorporated in multiparameter geophysical studies. Seismic data (all 6 lines) with refraction data for 2 long sections were published. Two GEOMAR PhDs (A. Jegen, G. Franz) and two post-doctoral fellows (A. Beniest, A. Avdeeva) completed the interpretation of the geophysical data, including inversions and interpretation of the crustal sections. Processing of the MT data on the Fonualei section revealed significant conductive and non-conductive anomalies that appear to coincide closely with deep structures, seismicity, and near-surface intrusive events (F. Schmid, G. Franz).
- Four MSc and PhD students at uOttawa (J. Kehew, M. Ryan, T. Sitnikova, M. Fassbender) and three post-doctoral researchers (A. Baxter, E. Bethell, C. Galley) have been working on Metal Oceans mapping projects. In 2022-23, most have been nearing completion of their work, shifting from map production to modelling of crustal growth in different microplate systems, with comparisons to crustal architecture of greenstone belts.

  These have included:
  i) arc rifting in the Fonualei Rift of the NE Lau Basin,

  ii) anomalous magmatism associated with the Rochambeau, Futuna, and Niuafo'ou assemblages in the Lau Basin, iii) links to anomalously hot mantle in the NWLSC and RR,

  iv) rift propagation into the southern NFB margin, and

  v) diachronous versus continuous extension in the NE Lau back-arc basin.
- Individual research projects have established type sections for different assemblages. Jessie Kehew and Michael Ryan have nearly completed their work on intrabasinal sedimentation and magmatic productivity. Sitnikova and Fassbender have been focussing on regional-scale evolution of back-arc basins, including structural evolution and petrogenetic evolution. One Honours BSc student (R. Dentelbeck) completed a project on magmatic productivity in the Niuafo'ou assemblage.
- A new postdoctoral fellow (C. Galley) has completed the first large-scale gravity inversions of the NE Lau Basin. The gravity data highlight strong links between the microplate mosaic and mantle upwelling that can be compared to the architecture of greenstone belts. Regional gravity data have been integrated with ship-based gravity from ARCHIMEDES I (SO-267) to improve the inversions. These data

Highlights

Scientific:

- Two papers in Economic Geology on the lithogeochemistry of Lau Basin volcanic rocks (one published; a second in revision). Two MSc theses have been completed (J. Kehew, M. Ryan). Partner researchers at GEOMAR and BGR (A. Beniest, G. Franz, A. Jegen, M. Schnabel) have completed studies of the 2D seismic structure of the NE Lau Basin rifts. One manuscript on the seismic data has been published in G-Cubed (Jegen et al) and a second manuscript is in preparation (Beniest et al.)

are currently being prepared for a publication on the crustal thickness model of the Lau Basin.

- The regional kinematics and stress regime of the northern Lau Basin have been published and are now being integrated into a GPlates-constrained model. The new model is providing a unique solution to the rapid growth of the Niuafo'ou microplate, which is linked to the emergence of the MTJ in the north and the Peggy Ridge transform boundary in the west. One manuscript on the GPlates modelling is in preparation.
- The lithogeochemical compilation of the Lau Basin system has been analyzed and two manuscripts have been written by M. Fassbender (one published, one in review). A machine-learning approach was used to compare mafic and felsic volcanic suites of modern arc-backarc systems and MOR systems to Archean greenstone assemblages in the Abitibi.
- The first paper on felsic volcanic rocks has been published. A parallel study of the mafic volcanic rocks is being revised following review. 40Ar/39Ar dating at OSU was completed and the results are being prepared for publication. These data have constrained the location and timing of non-linear arc rifting, mantle input and microplate growth in the NE Lau Basin.
- Progress has been made on the completion of two new 1:1 million maps of the N. Fiji Basin (A. Baxter, R. Mensing, T. Sitnikova) and the marginal basins of eastern PNG (P. Brandl). A manuscript on the PNG study focused on the

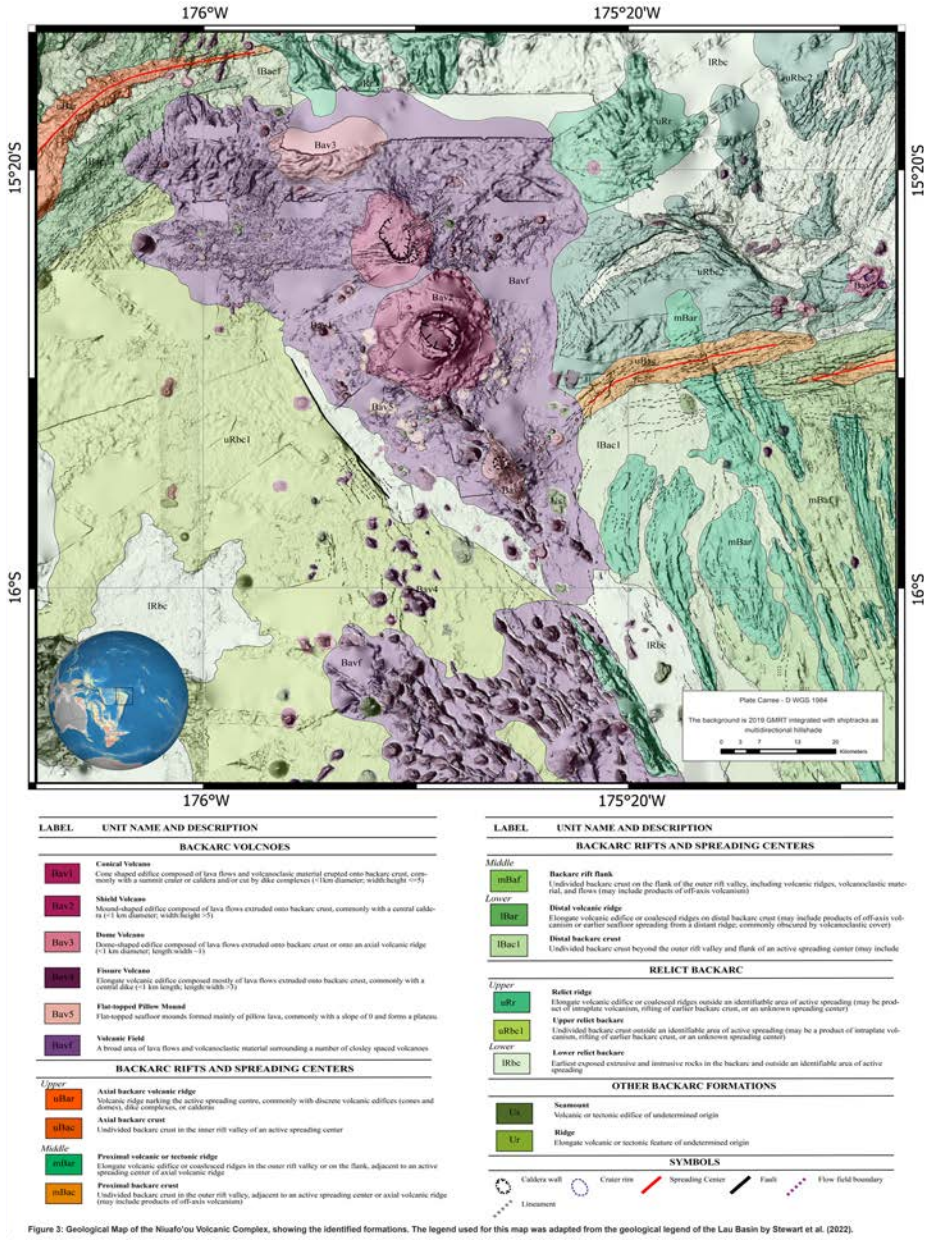


Figure 3: Geological Map of the Niuafo'ou Volcanic Complex, showing the identified formations. The legend used for this map was adapted from the geological legend of the Lau Basin by Stewart et al. (2022).

Geological map of the Niuafo'ou Volcanic Complex. Legend adapted from the geological legend of the Lau Basin map by M. Stewart et al, 2022. Source: Dentelbeck, R. Intraplate Volcanism and Implications for Crustal Growth and Metal Endowment in Back-Arc Basins: Evidence from the Niuafo'ou Volcanic Complex in the Northern Lau Basin. Conference presentation. Prospectors & Developers Association of Canada (PDAC) - Society of Economic Geologists (SEG) Student Minerals Colloquium (SMC), Toronto, ON, March 5-8, 2023. https://merc.laurentian.ca/sites/default/files/703_-_dentelbeck_-_bsc.pdf

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Jegen, A., Dannowski, A., Schnabel, M., Barckhausen, U., Brandl, P. A., Riedel, M., et al. (2023). Extension dynamics of the northern Fonualei Rift and Spreading Center and the southern Mangatolu Triple Junction in the Lau Basin at 16°S. Geochemistry, Geophysics, Geosystems, 24, e2022GC010550. https://doi.org/10.1029/2022GC010550

geodynamic influences of large-scale oblique collisions on regional metallogeny is nearing completion.

- Closer collaboration with MERC researchers was initiated to identify type sections for different assemblages and formations in modern back-arc basins that can be compared to the Abitibi greenstone belt. Two multi-day dedicated workshops were held on this topic in Ottawa and Toronto.
- Preparation for the ARCHIMEDES II Transect (DynaMet) continued, including pre-cruise logistics, submission of contracts for work, diplomatic clearances, securing equipment and preparing shipments to/from the ports of Singapore and Townsville. ARCHIMEDES II was re-scheduled due to Covid as SO-299 and will take place in June-July of 2023.

Milestones and Deliverables

- Completed assemblage-level attributes tables and structural/stratigraphic sections for the Lau, PNG, and North Fiji map sheets (Metal Oceans Team)
- Published 2D and 3D inversions of Lau basin seismic sections, gravity and MT (A. Jegen, A. Beniest, F. Schmid)
- Completed microplate reconstruction of the northern Lau Basin and Fiji Basin in GPlates (A. Baxter, in preparation)
- Completed lithogeochemical comparison of endowed versus non-endowed oceanic settings (M. Fassbender, published and in review)
- Completed planning/logistics for ARCHIMEDES II Transect in the marginal basins of PNG (SO-299, June-July 2023)
- Completed preliminary assessment of crustal structure using 3D gravity and seismic inversions (C. Galley, et al., in prep.)

Use of Human Resources

RA/PDF (A. Baxter, E. Bethell, D. Diekrup): conducted data compilation and synthesis for seafloor mapping; geological interpretations at 1:1 million scale; large-scale tectonic reconstructions; interpretation and quantitative modelling of crustal growth, with direct comparison to architecture and mineral endowment in greenstone belts. Assisted by the Metal Oceans Team. D. Diekrup moved to the Geological Survey of Newfoundland but continues to participate in Metal Oceans and the VMS Sub-project 3b (appended).

PDF (C. Galley): marine geophysical expertise for analysis and inversion of seismic, magnetic, and gravity data in the Lau Basin. Chris will also lead the comparison of crustal density models with interpretations from the Abitibi greenstone belt.

PhD (M. Fassbender): lithogeochemical database compilation; lithogeochemical interpretation of the Lau Basin; comparisons with greenstone belt evolution; global compilation of submarine mafic and felsic volcanic rocks. PhD thesis defense scheduled May 30, 2023.

PhD (T. Sitnikova): regional geological compilation of the Fiji Basin, including magmatic and tectonic evolution of high-heat flow intraoceanic back-arc basin and comparisons with greenstone belt evolution. Continuing in 2023-24.

MSc students (J. Kehew, M. Ryan): targeted 1:100,000 mapping of key areas related to back-arc evolution, microplate formation, and the emergence of magmatic-hydrothermal mineralizing systems. Jessie Kehew and Michael Ryan are completing their work on intrabasinal sedimentation and magmatic productivity. Thesis defenses expected in 2023.

BSc Honours student (R. Dentelbeck): targeted 1:100,000 mapping of the Niuafo'ou assemblage of the NE Lau Basin key with an emphasis on quantifying magmatic productivity and magmatic-hydrothermal activity. Completed in April 2023.

The GEOMAR Team continued to support Metal Oceans objectives, working on the North Fiji Basin and New Hebrides Arc and other regional mapping initiatives, geophysical compilations, modelling, and cruise preparation: S. Petersen, P. Brandl, M. Klischies (completed), A. Krätschell.

Future Work

The focus for 2023-24 will be on completion of the Indo-Australian margin maps (Lau Basin, North Fiji Basin, Bismarck Archipelago) with the aim of recognizing possible ancient analogs of the microplate mosaics in the Abitibi region. We will collaborate with MERC researchers on identifying type sections and features that can be compared to Abitibi assemblages.

Research targets for 2023-24

- Compilation and interpretation of all processed geophysical data from ARCHIMEDES II (DynaMet SO-299). The multiparameter geophysical data focusing on structures related to terrane collision will be prepared for several new publications in 2023-24.

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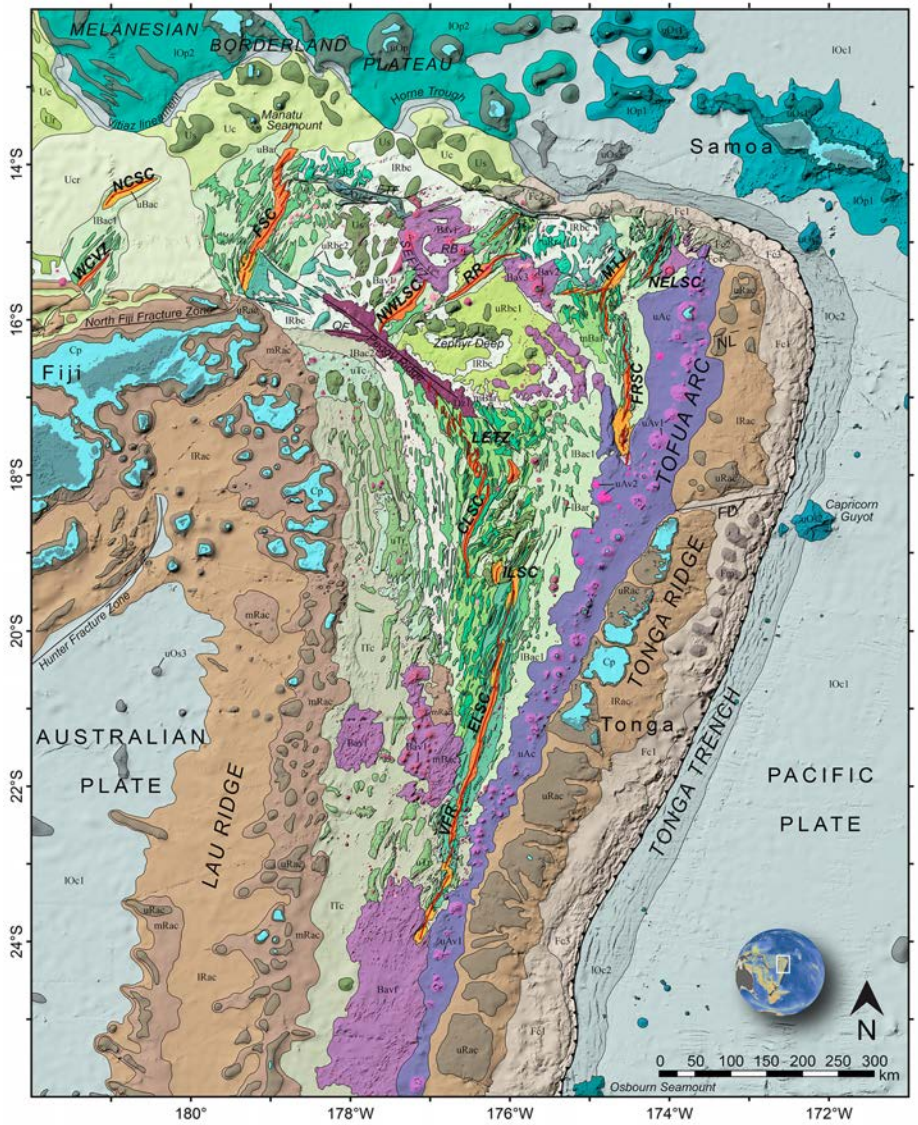
Margaret S. Stewart, Mark D. Hannington, Justin Emberley, Alan T. Baxter, Anna Krätschell, Sven Petersen, Philipp A. Brandl, Melissa O. Anderson, Patrick Mercier-Langevin, Rebecca Mensing, Kaitlyn Breker, Marc L. Fassbender; A new geological map of the Lau Basin (southwestern Pacific Ocean) reveals crustal growth processes in arc-backarc systems. Geosphere 2022;; 18 (2): 910–943. doi: https://doi.org/10.1130/GES02340.1

- J. Kehew and M. Ryan will complete their work on intrabasinal sedimentation and magmatic productivity in the Lau Basin before the end of 2023.
- T. Sitnikova and M. Fassbender will continue their work on regional-scale evolution of back-arc basins, with emphasis on the North Fiji Basin.
- Postdoctoral fellow (C. Galley) will assemble and publish the first large-scale gravity inversions of the NE Lau Basin microplate mosaic, together with comparison of crustal thickness models with the Abitibi seismic and gravity data from Metal Earth.
- A. Baxter will complete the revised regional kinematic and stress regime model of the northern Lau Basin in GPlates. The new model will incorporate propagating rifts, which are not part of the standard GPlates output. This work will be submitted for publication in 2023.
- The first results of 40Ar/39Ar dating of the Lau Basin microplate crust will be prepared for publication by M. Fassbender.
- P. Brandl and M. Hannington will complete their manuscript on large-scale collisions and regional metallogeny in eastern PNG, examining new data on post-subduction remobilization of metals triggered by microplate rotation.
- Preparation of a special issue/reviews volume on "Arc-Rifting and Back-arc Basin Development: Implications for Metal Endowment in Modern and Ancient Oceanic Crust" (see contents below). Results of 2 PhDs and 5 MSc thesis projects that are now completed. 1:1 million geological compilations of tectono-magmatic history, including geophysical data sets.

Future Milestones and Deliverables

- ARCHIMEDES II Transect in the marginal basins of PNG (SO-299 scheduled in 2023)
- Assemblage-level attributes tables and structural/stratigraphic sections for PNG map, including Eastern PNG-New Ireland geodynamics and metallogeny (to accompany 1:1 million map, P. Brandl, new for 2023-24)



Reduced version of the 1:1,000,000-scale geological map of the Lau Basin at the formation level. Source: Margaret S. Stewart, Mark D. Hannington, Justin Emberley, Alan T. Baxter, Anna Krätschell, Sven Petersen, Philipp A. Brandl, Melissa O. Anderson, Patrick Mercier-Langevin, Rebecca Mensing, Kaitlyn Breker, Marc L. Fassbender; A new geological map of the Lau Basin (southwestern Pacific Ocean) reveals crustal growth processes in arc-backarc systems. Geosphere 2022; 18 (2): 910–943. doi: https://doi.org/10.1130/GES02340.1

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Fassbender, Marc & Hannington, Mark & Stewart, Margaret & Brandl, Philipp & Baxter, Alan & Diekrup, David. (2022). Geochemical Signatures of Felsic Volcanic Rocks in Modern Oceanic Settings and Implications for Archean Greenstone Belts. Economic Geology. 118. 10.5382/econgeo.4967.

- North Fiji Basin 1:1 million geological compilation (E. Bethell, T. Sitnikova, new for 2023-24)
- Assessment of crustal structure and mantle anomalies in microplate mosaics using 3D gravity and seismic inversions (C. Galley, in progress).
- Characterization of the mantle sources associated with modern back-arc basin evolution: mafic volcanic rocks (M. Fassbender et al., 2023, in revision)
- Publication of microplate reconstruction and GPlates model of the northern Lau Basin and Fiji Basin (A. Baxter, in progress)
- First-order assemblage-level structural and stratigraphic comparison of the Abitibi and Lau Basin (based on workshop outcomes scheduled for 2022-23)
- Completed PhD (Fassbender) and MSc projects (Kehew, Ryan)
- A Special Publication on Metal oceans will be prepared in 2023-24, including at least 4 Thematic papers and 8 Case Studies.

WATCH NOW!
Chris Galley - *Identifying Neoarchean Seafloor Spreading using a Modern Back-arc Basin Analogue, presented at the Metal Earth scientific meetings, Toronto, March 2023.*

Thematic Papers

- Microplate Solutions to Crustal Growth and Metal Endowment with Implications for Greenstone Belts (Hannington et al.)
- Origin and Evolution of Lithospheric-scale Structures in Oceanic and Arc Crust (Baxter et al.)
- Identifying Neoarchean Seafloor Spreading using Modern Back-arc Basin Analogs: Results of Regional Geophysical Inversions (Galley et al.)
- Linking Geochemical Signatures of Volcanic Rocks to Geodynamics in Modern Oceanic Settings: Examples of Mantle Domains from Microplate Architecture (Fassbender et al.)

Case Studies

- Geology of the Fonualei Rift and Spreading Center (Hannington et al.)
- Geology of the Mangatolu Triple Junction (Mensing et al.)
- Geology of the Rochambeau Rifts and NWLSC (Ryan et al.)
- Back-arc sedimentation in the Lau Basin (Kehew et al.)
- Geology of the Niuafo'ou Volcanic Complex (Dentelbeck et al.)
- Geology of the Louisville Segment and Monowai Volcano, Tonga-Kermadec (Gray et al.)
- Geology of the North Fiji Basin Triple Junction (Besaw et al.)
- Geological Map of the Marginal Seas of Eastern Papua New Guinea: Insights into Regional Metallogeny of the Melanesian Archipelago (Brandl et al.)

Use of Human Resources

- HQP will continue to work on the project, including two MSc and two PhD students (Kehew, Ryan, Fassbender, Sitnikova). The work will shift from map production and case studies to interpretation and modelling of crustal growth. Postdoctoral fellows and research assistants (Baxter, Bethell, Galley) will take over a larger share of the publication process to ensure the timely completion of the projects.

Anticipated Outcomes

- We have developed the first high-resolution structural-petrologic-magmatic framework for microplate evolution and metallogenesis in several large-scale transects across the Tonga arc in the NE Lau Basin, in the high-heat flow North Fiji Basin, and in areas of active continental collision in the marginal basins of Eastern PNG. These results will underpin comparisons with crustal growth and metal endowment of greenstone belts planned for the balance of the Metal Oceans project.
- Results of the project have included establishing type sections for different assemblages that can now be compared to greenstone belt assemblages; documenting the architecture and evolution of different types of microplate boundaries, including triple junctions, ridge-transform boundaries, and arc rifts (from precursors, through inception, to failure); identifying different types of unconformities between assemblages; establishing sedimentary sequence stratigraphy of back-arc and intra-arc sub-basins to identify different stages and styles of arc rifting and back-arc opening; quantitative comparisons of large-scale volcanic centers (magma volumes and area-age relationships as a first-order metric of crustal growth); modelling of microplate mosaics (especially shortening) as a guide to identifying relict architecture in deformed terranes; detailed lithogeo-chemical comparisons of magmatic suites in different types of assemblages and microplate settings.
- New for 2023-24 will be a focus on 3D inversions of crustal structure, density and composition; the relationship between metallogeny and compressional tectonics in marginal

basins of PNG; and criteria for identifying fossil microplate architecture within the established assemblage framework of greenstone belts.

- Results from 2022-23 have been published or are being presented in 30 publications, reports, and other research outputs: 16 papers for peer-reviewed journal articles (5 published or in press, 11 in preparation), 7 student theses, and 7 conference abstracts at national and international scientific meetings.
- Seventeen (17) active participants in the project from institutions have received training as part of the project. An additional 19 collaborators were involved from 7 institutions in Canada and abroad. Members of the Metal Oceans team in Ottawa continue to work alongside researchers at MERC to ensure the results are being applied directly to the Metal Earth objectives. Metal Earth funds have been significantly leveraged through external partnerships, including direct and indirect in-kind contributions. Six members of GEOMAR (Petersen, Brandl, Krätschell, Klischies, Lange, Jegen, Beniest) continue to work directly with the Ottawa Team.

Implications

- New knowledge of the thermal and structural evolution and architecture of modern microplate systems is important for understanding ancient crustal growth and metal endowment. While the modern interactions are mainly driven by subduction, which may or may not have operated in the same way in the Late Archean, the responses to plate stresses in the form of microplate formation and the implications for mantle upflow and development of critical melt and fluid pathways are expected to be very similar. This project is investigating the role of microplates in controlling melt and fluid pathways at relatively shallow to mid-crustal levels – a role that may be common to both modern oceanic crust and ancient greenstone belts.

Relevant Metal Earth themes

- Theme 1. Craton and Greenstone Belt Assembly Study
- Theme 2. Geophysical and Geological transects

Relevant Metal Earth questions

- Question 1. Is there an architectural and or structural control on crustal-scale ore fluid pathways?
- Question 2. How is the structural evolution of major fault systems related to metal endowment? Is there a common structural evolution of endowed structures, does it differ from similar structures in less endowed areas?
- Question 3. How did Archean tectonics differ from Phanerozoic, subduction-driven tectonic models based on Archean crustal architecture and gold and base metal metallogeny?
- Question 4. Data integration and interpretation tools for assessing metal endowment predictability.

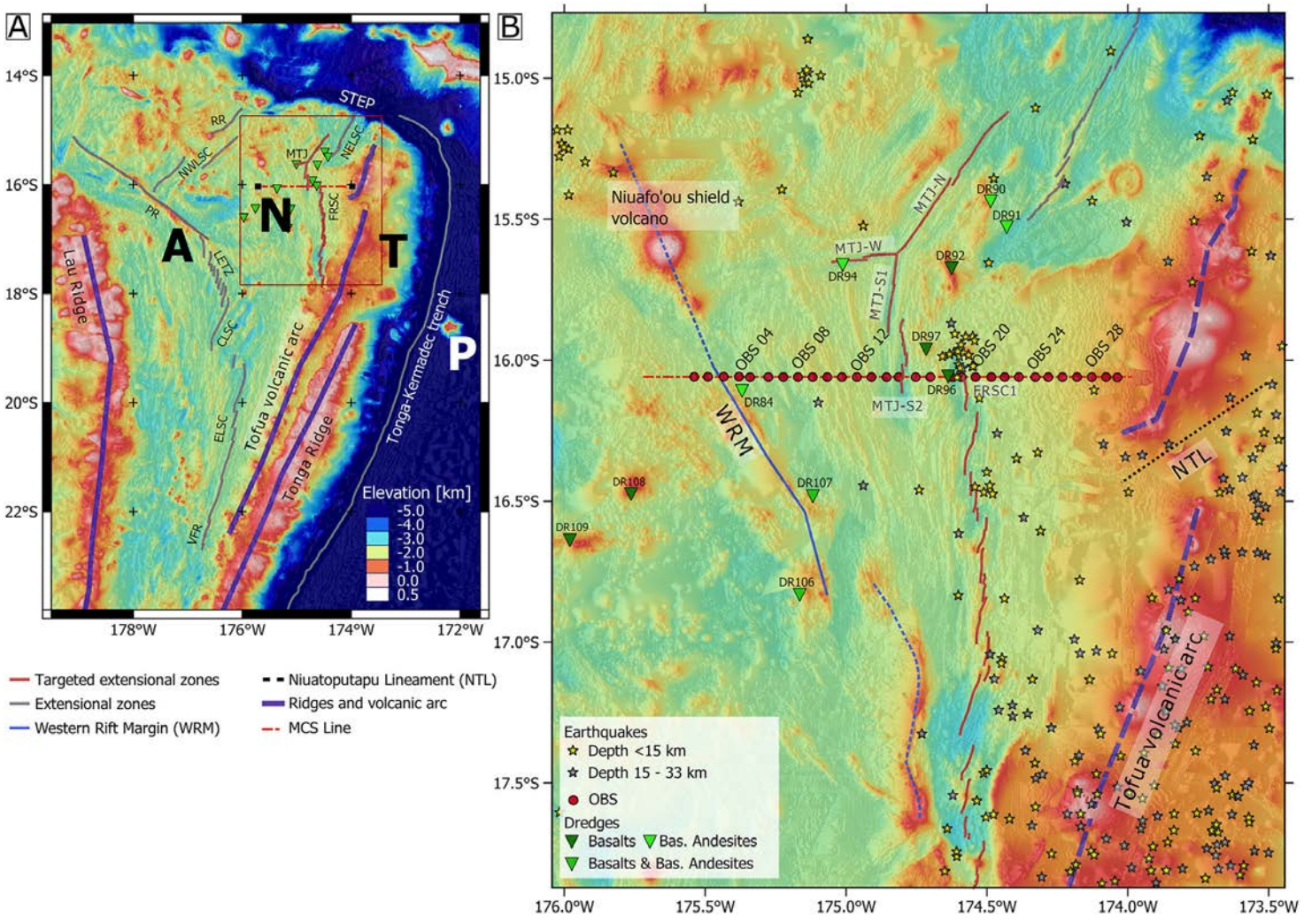
Highlights

Personnel

- E. Bethell, C. Galley, A. Baxter are co-convenors of a Special Session of the GAC-MAC Annual Meeting in Sudbury on Marine Geodynamics and Georesources, May 2023.
- J. Kehew (MSc student of M. Hannington) presented her research on intrabasinal sedimentation and tectonostratigraphy of the Lau Basin at GAC-MAC and Prospectors and Developers Association of Canada (PDAC) - Society of Economic Geologists (SEG) Student Minerals Colloquium.
- T. Sitnikova (PhD student of M. Hannington) presented her research on arc-rifting in a nascent subduction zone of the south Fiji Basin at Prospectors and Developers Association of Canada (PDAC) - Society of Economic Geologists (SEG) Student Minerals Colloquium.
- R. Dentelbeck (BSc Honour's student of M. Hannington) presented her research on the Niuafo'ou volcanic complex at the SEG Student Minerals Colloquium, March 2023, and received one of the undergraduate poster awards.
- M. Fassbender (PhD student of M. Hannington) completed his PhD and defended on May 30, 2023.
- R. Dentelbeck (BSc), A. Gray (MSc), M. Besaw (MSc), defended their theses.

WATCH NOW!
Marc Fassbender - *Geochemical Signatures of Mafic & Felsic Volcanic Rocks in Modern Oceanic Settings, presented at the Metal Earth scientific meetings, Toronto, March 2023.*

VIEW OR DOWNLOAD
Intraplate volcanism and implications for crustal growth and metal endowment in back-arc basins: Evidence from the Niuafo'ou Volcanic Complex in the Northern Lau Basin; Rhian Dentelbeck's 2nd-place poster presented at the PDAC-SEG Student Minerals Colloquium, Toronto, March 2023.



Bathymetric map (data compilation as seen in Stewart et al., 2022) showing the general region (a) as well as a detailed map of the study area in (b). Superimposed are the course of prominent tectonic features, shallow seismicity data from Conder and Wiens (2011) (stars), the course of the multi-channel seismic profile (red, dashed line), the positions of the deployed ocean bottom seismometer (red dots) and the dredge locations of the SO267 expedition (green triangles). The shade of green, chosen for the triangles, reflects how mafic the recovered samples are: Light green fore basaltic andesites, medium shade of green for basaltic andesites and basalts and dark green for basalts. Both the Mangatolu Triple Junction (MTJ) and the Fonualei Rift and Spreading Center (FRSC) are marked by red solid lines in both subplots and their most referenced segments (MTJ-S1, MTJ-S2, and FRSC1) are marked individually with dark gray labels in subplot (b). Other tectonic features such as the Tonga-Kermadec trench, the Tonga Ridge, the Tofua volcanic arc with its Niuatoputapu Lineament (NTL), the Lau Ridge, the Subduction-Transform-Edge-Propagator (STEP), the Niuafo'ou shield volcano, the North-East Lau Spreading Center (NELSC), Rochambeau Bank and Rifts (RR), Northwest Lau Spreading Center (NWLSC), Peggy Ridge (PR), Lau Extensional Transform Zone (LETZ), Central Lau Spreading Center (CLSC), Eastern Lau Spreading Center (ELSC) and the Valu Fa Ridge (VFR) are also marked. Additionally, plates and microplates are marked by bold letters in subplot (a): Australian Plate (a), Niuafo'ou microplate (N), Tonga Plate (T), Pacific Plate (P) after Sleeper and Martinez (2016). The same bathymetry color scale is used in both subplots.

Source: Jegen, A., Dannowski, A., Schnabel, M., Barckhausen, U., Brandl, P. A., Riedel, M., et al. (2023). Extension dynamics of the northern Fonualei Rift and Spreading Center and the southern Mangatolu Triple Junction in the Lau Basin at 16°S. Geochemistry, Geophysics, Geosystems, 24, e2022GC010550. https://doi.org/10.1029/2022GC010550

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Trace Element Geochemistry of Volcanogenic Massive Sulfide Deposits in Archean Greenstone Belts: Implications for Metal Endowment and Geodynamic Settings. R. Penner, University of Ottawa, MSc September 2023. https://ruor.uottawa.ca/handle/10393/45396.

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