MERC

Mineral Exploration Research Centre
at the HARQUAIL School of Earth Sciences

ANNUAL REPORT

2021-22

IN THIS REPORT

MERC

Metal Earth

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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 focused 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, which is one of the largest public geoscience projects in the world.

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

104M largest university-led geoscience project in the world

Message from TAMMY **EGER**

Vice-President, Research
Laurentian University

As a researcher and academic administrator, I am always keen for opportunities to highlight the societal and economic benefits of investing in high-calibre research. Upon reviewing the content of this Annual Report, the scale of the collaborations and quality of research is remarkable, as are the people who put it all together.

As part of Laurentian University and the Harquail School of Earth Sciences, MERC and the Metal Earth project have attracted students, professors, and research associates from all over the world. These highly qualified people not only advance scientific discoveries but they also contribute to the fabric of the university, the community of Greater Sudbury, and to Canada.

To maintain its competitive advantage, Canada must continue to train and attract qualified professionals to work in geosciences. This is critical as we continue to develop our mineral resources in a safe and sustainable manner. In 2021, the Metal Earth project had more than 70 graduate students engaged research. Furthermore, since its inception, Metal Earth has attracted 38 international researchers from Australia, Africa, Europe, the Middle East, and the United States. A number of these researchers have chosen to apply for permanent residence or Canadian citizenship, choosing to live in and contribute to Canada beyond the scope of Metal Earth.

The research conducted by MERC in 2021-22 reaffirms both Sudbury's and Canada's reputation as a global hub for geological knowledge and expertise. The variety of projects, partnerships, presentations, and publications demonstrate Laurentian's strengths in ore deposit geology, geochemistry, geophysics, data analytics, and in communicating research outputs in high-impact publications.

As Vice-President, Research at Laurentian University, it is my pleasure to introduce this annual report outlining the progress and outcomes of MERC and the Metal Earth project. I also congratulate and thank the leadership team, faculty, staff, and students for their dedication to advancing the research mission of MERC and Metal Earth.

WATCH NOW!
About Metal Earth (2021)

Message from ROSS **SHERLOCK**

MERC and Metal Earth Director

44.1M MERC-managed research funds, 2015-2020

I'm pleased to present this annual report, which provides a detailed view of our 2021-22 projects and the remarkable progress and achievements of more than 230 researchers, students, faculty members, and staff who have contributed to MERC and Metal Earth projects during the reporting period.

As demonstrated in this report, MERC and Metal Earth continue to deliver scientific breakthroughs, publish high-impact open-access journal papers, prepare public data releases, organize global events, and host international collaborations. None of this would be possible without our dedicated team and support from funding, industry, government, and institutional partners.

The scope of this report includes year six of Canada's Metal Earth geoscience project, which is rapidly moving towards research synthesis after years of fieldwork. Laurentian University leads Metal Earth, and the project's primary funding comes from the Canada First Research Excellence Fund (CFREF). Metal Earth is continuing to improve our understanding of the processes that result in differential metal endowment.

The cumulative number of publications and presentations continues to rise, and these outputs are attracting increased positive attention from institutions, as well as mining and mineral exploration companies, who have provided more than $80M of in-kind support over the project's life.

As a leading Canadian mineral exploration research centre focused on ore deposits and an arm of the Harquail School of Earth Sciences (HES) at Laurentian University, MERC manages $11M in projects annually and provides a stage for researchers, industry, and students to propel their projects and careers.

As the mineral resource industry continues to invest in exploration to meet global demand, MERC invests in developing partnerships, projects, and research that advances frontiers in geoscience. It's inspiring work, and I am pleased to share it with you as we look forward to 2023.

MERC MEMBERS

Foundation Members

Tier 1 Members

Tier 2 Members

- Agnico Eagle
- Equinox Gold
- Evolution Mining
- Exiro
- GFG Resources
- Gold Fields
- IEP, International Explorers and Prospectors
- KGHM
- McEwen Mining
- Melkinor
- Noble Mineral Exploration
- Pelangio
- SRK Consulting
- Sudbury Integrated Nickel Operation (Glencore)
- Transition Metals
- Vale
- Wesdome

YEAR IN REVIEW: HIGHLIGHTS

As researchers, we look ahead, focused on new discoveries, methodologies, and interpretations that will transform how we understand the Earth, its processes, and its future. That said, we need to sometimes pause and celebrate our wins.

In 2021-22, while students, researchers and administrators were catching up on projects and tasks that were delayed due to the pandemic, they were also making new plans and adjusting timelines, meeting their goals and celebrating milestones. In this report, we include a list of Metal Earth's Top 15 peer-reviewed journal publications, but beyond research outputs, we would also like to summarize and celebrate some notable highlights and stories of the past year.

Dr. Stéphane Perrouty was awarded the William Harvey Gross Award at the GAC-MAC Annual Meeting in Halifax.

Featured faculty

Dr. Stéphane Perrouty earns MDD's Gross Award

In May 2022, Dr. Stéphane Perrouty accepted the Geological Association of Canada (GAC) Mineral Deposits Division (MDD) William Harvey Gross Award, in Halifax.

According to the award criteria, the winner must be less than 40 years old in his/her nomination year and "made a significant contribution to the field of economic geology in a Canadian context." Perrouty's research focuses primarily on orogenic gold systems in Archean and Paleoproterozoic greenstone belts in Canada, West Africa, and South America. He joined the Harquail School of Earth Sciences (HES) in 2018, where he is an assistant professor of Precambrian geology and the MSc Geology program coordinator.

Professor Perrouty is not the first HES faculty member who has been recognized with the Gross award.

Dr. Stéphane Perrouty (right) conducting a field school with HES undergraduate students.

Past Gross Award winners include current and former professors:

- Ross Sherlock
- Catharine Farrow
- Harold Gibson
- Jeremy Richards
- Mark Hannington
- Stephen Piercey
- Jacob Hanley
- Michel Houlé
- Patrick Mercier-Langevin
- Jan Peter
- Michelle DeWolfe *(who earned her PhD at Laurentian)*

Dr. Ross Sherlock (centre) was the SEG 2021-22 Traveling Lecturer, pictured with students and dog Bogart, at the Kerr Mine in Virginiatown, 2018.

Featured faculty

SEG Traveling Lecturer Symposium features Ross Sherlock

In 2021, Ross Sherlock was named a Society of Economic Geologists International Exchange Lecturer.

These are awarded annually to feature widely recognized research in ore deposits science and/or exploration methodology. Lecture sites are typically selected to allow for the greatest possible involvement of academic, industry, and government-based economic geologists.

In 2021-22, Sherlock's' lectures were in webinar format due to COVID travel restrictions. SEG posted the lectures on their SEG Webinars YouTube playlist, and you can watch Ross' presentation, "Controls on Gold Mineralization along the Cadillac Larder Lake Deformation Zone."

WATCH NOW!
Controls on Gold Mineralization along the Cadillac Larder Lake Deformation Zone

Looking ahead to 2023, Laurentian University will host the GAC-MAC joint annual meeting, themed "Discovering Ancient to Modern Earth." The event will take place May 24-27 and feature pre- and post-meeting field trips, workshops, and short courses.

In 2022, Dr. Xuang Meng won a Governor General's Gold Academic Medal for having the highest academic achievement at Laurentian University at the graduate level.

Student spotlight

During the 2022 spring convocation ceremonies, post-doctoral researcher and Laurentian University alumnus, Xuyang Meng, received a prestigious Governor General's Gold Medal for academic excellence at the graduate level.

Meng's PhD in Economic Geology, belonging to the Mineral Deposits and Precambrian Geology program, focused on understanding the formation of porphyry copper deposits in the early Precambrian eon. Governor General Academic Medals are awarded annually to students graduating with the highest academic standing in secondary, post-secondary collegiate, undergraduate, and graduate levels.

Nominated for this achievement by the Harquail School of Earth Sciences (HES), Meng described feeling honoured and humbled to be a recipient. "I am grateful for the encouragement, advice, and help from my supervisors and colleagues at Laurentian, advisors on my PhD committee, and collaborators from around the world. I treasure this award for recognizing our efforts."

Meng's journey was not without challenges. He started his PhD at the University of Alberta under Dr. Jeremy Richards.

Both moved to Laurentian University in 2017, where Richards began a Canada Research Chair (Tier I) position, and Meng was the first PhD student to join the Metal Earth geoscience project. Dr. Richards passed away suddenly in 2019, which was a terrible loss to Meng, the university, and the geoscience community. At that point, Meng considered ending his studies, but pushed on to follow his passions, and those of Dr. Richards.

After earning his degree, Meng became a post-doctoral fellow at the University of Michigan, Ann Arbour, where he continues to make significant contributions to his field. In April 2021, Meng published "*Oxidized sulfur-rich arc magmas formed porphyry Cu deposits by 1.88 Ga,*" in *Nature Communications*.

That paper credits Dr. Richards as a co-author. Dr. Meng has recently accepted a faculty position at China University of Geosciences (Beijing).

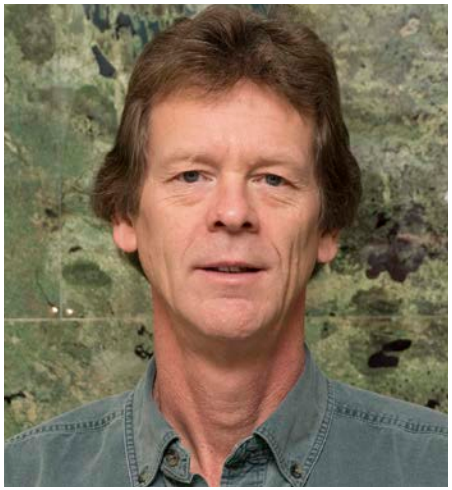
Empowering Partnerships

In early 2022, MERC announced a new partnership with Mine Shift, originally known as Me Too Mining, which will support our efforts to empower leaders, students, and staff to reduce and eliminate workplace harassment.

Mine Shift supports all mining industry employees who are targets of any form of workplace harassment, including sexual assault. Its DIGGER Training Program provides guidance to workers and students on Allyship and Active Bystander Intervention Training. Mine Shift supports those that need extra help and guidance, and its website provides many useful links to clinical and legal resources.

For details, visit metoomining.com, which is transitioning to a new site, mineshift.org.

MINE SHIFT



Dr. Jeremy Richards, an inspirational and influential economic geologist who was focused on providing open-access paper, is memorialized in two SEG Special Volumes. Find them here: segweb.org/store

SEG Special Volumes I & II Dedicated to Dr. Jeremy Richards

The Harquail School of Earth Sciences (HES), and the Mineral Exploration Research Centre (MERC) announced two open-access Special Volumes published by the Society of Economic Geologists (SEG), dedicated to the memory of Jeremy P. Richards, who passed away in 2019. The Volumes are sponsored by BHP, HES and MERC.

In their Foreward, co-authors Keenan Jennings, BHP Vice-President, Metal Exploration, and Pedro J. Jugo, Associate Professor at HES and MERC, wrote that Richards was an inspirational and influential economic geologist who "viewed porphyry and epithermal systems from a holistic perspective, encompassing geodynamics, tectonics, magma chemistry, and metal endowment. This structured and systemic approach to economic geology embodied the mineral systems concept."

Jennings and Jugo also recognize Richards for his early critical assessment of resource extraction on sustainable development and his leadership balancing extraction and responsible custodianship of mineral deposits. The co-authors further explain that Richards was a proponent of providing open access publications, writing: "BHP and HES-MERC are proud to sponsor this memorial volume to honour and promote the dynamic, creative, and socially progressive thinking for which Jeremy was renowned, and to support his vision of Open Access."

Volumes I & II of this SEG Special Publication, *Tectonomagmatic Influences on Metallogeny and Hydrothermal Ore Deposits: A Tribute to Jeremy P. Richards* include a collection of 17 papers. In their Acknowledgements, editors Ali Sholeh and Rui Wang note that the selected papers reflect "the nature and breadth of (Richards') research on tectonics, magma genesis, and hydrothermal ore deposits." The publication was made possible through the generous financial sponsorship of BHP Metals Exploration, the Mineral Exploration Research Centre and the Harquail School of Earth Sciences.

Researcher grows roots

MERC and the Metal Earth project attract researchers and students from all over the world, and we are always pleased to see their careers (and families) grow thanks to the opportunities that they find.

Post-doctoral researcher Gaëtan Launay set his sights on Canada after his PhD defence in France, when he began discussing opportunities with Dan Kontak, a professor at the Harquail School of Earth Sciences. Kontak encouraged Launay to apply for a position with the Metal Earth project, and that's when his new life in Canada began to take shape.

Launay started as lead researcher of the Rainy River transect. Over the past three years, his work focused on the investigation of the crustal architecture of the Rainy River greenstone belt and the Quetico fault. The project also aimed to examine the stratigraphy, volcanology and the petrogenesis of the Rainy River belt to identify the geological environment favourable for the formation of the Au-rich syn-volcanic deposits, such as New Gold's Rainy River deposit.

As the project progressed, Launay developed geologic insights in the transect, such as the existence of older Mesoarchean rocks underlying the Rainy River greenstone belt.

"A thicker older crust may have resulted in lower heat flow into the Neoarchean crust and inhibited the formation of base metal and gold deposits in the Wabigoon subprovince," Launay explained. Interpretation of the magnetotelluric and seismic profiles acquired by Metal Earth provided insights into the fault geometry and geologic processes in the Rainy River greenstone belt. Launay's work also includes a new regional geological map, which will be published soon, with a geophysical dataset. His findings could improve mineral exploration targeting in the Rainy River transect, and others with similar characteristics.

On a personal level, Launay is happy with his life in Sudbury. He and his partner, Marie, enjoy exploring the natural beauty that surrounds them, and sharing their discoveries with visitors from France. Since settling in Sudbury, Marie has also advanced in her career, and both have attained permanent resident status in Canada. Together, they have a son, Milo, who was born in Canada in June 2021, and is a dual citizen.

Metal Earth researcher Gaëtan Launay (right) with his partner Marie and their son, Milo.

In summer 2022, Launay began a new position with the Ontario Geological Survey. It marks further career progression, and Launay is grateful for the experience that led him to it. He recalls how his first experiences in Canada began, in Rainy River in 2019, co-supervising a Metal Earth graduate student from Newfoundland (Mattea McRae) and two field assistants.

One assistant, a Québécois, helped Launay adjust to the diverse people, accents, and cultures in Canada. He also adapted to the terrain. "It was the first time that I used a boat for mapping, and there was new wildlife like bear and moose, which we don't have in Europe," Launay recalled. As an early-career researcher, and a new father, exploring new frontiers and settling in Sudbury has been a rewarding journey, and it all began with MERC and Metal Earth.

Breakthrough Publication

In 2021-22, Metal Earth research associate Taus Jørgensen and his collaborators worked diligently on preparing an open-access dataset and paper, which for the first time, demonstrates the 3D architecture of a metal-endowed and gold-rich VMS ore system at the iconic Noranda District in Québec, elucidating the processes responsible for extreme metal endowment, including syngenetic and later orogenic gold enrichment.

The paper, "The implications of crustal architecture and transcrustal upflow zones on the metal endowment of a world-class mineral district," was published by Jørgensen et al, in summer 2022 in *Scientific Reports*, a Nature Portfolio journal.

Metal Earth has provided unique multiparameter datasets that allow the first-ever investigation of mineral districts from the craton-scale to the scale of individual mineral districts.

Although this pattern of differential metal endowment is underpinned by lithospheric-scale processes, the geological features that cause clustering of deposits remains enigmatic. The integration of geological and geophysical (seismic, gravity, and magnetotelluric) features has produced the first whole-of-crust image through greenstone belts in the Superior Province. Comparing endowed terranes such as the Abitibi with less-endowed terranes such as the Wabigoon shed insight into the crustal architecture of mineral-rich areas and how these may reflect different geologic processes.

Find more open-access Metal Earth datasets at: merc.laurentian.ca/research/metal-earth/public-data

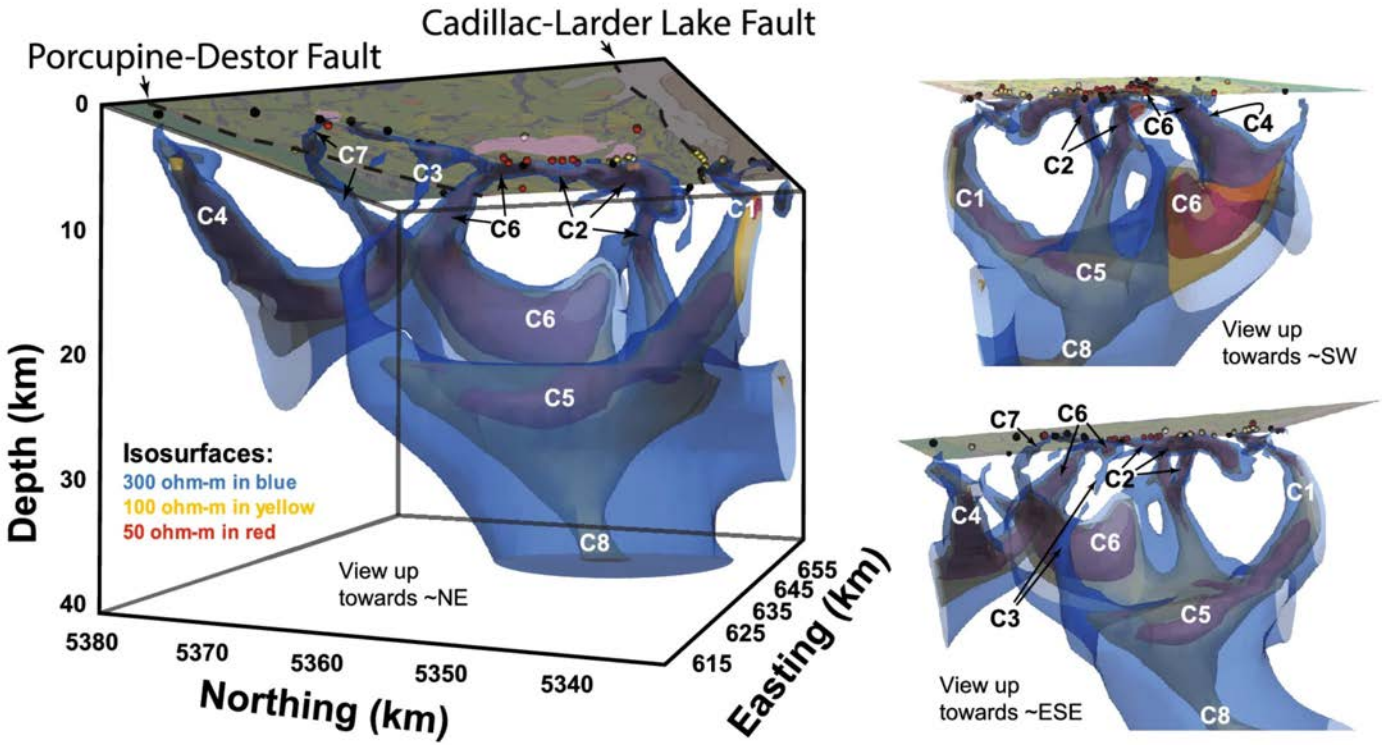
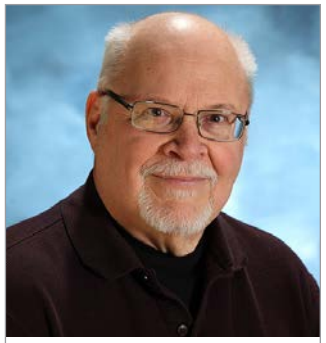


Image extracted from Jørgensen et al (2022), "The implications of crustal architecture and transcrustal upflow zones on the metal endowment of a world-class mineral district." Image original caption: 3D MT model with surface geology (see Fig. 1). C1-8 indicate significant low-resistivity features (see text). 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. This Figure was compiled in Adobe Illustrator (≥v. CC2018 22.0.0) with individual panels created in the open-source ParaView application: paraview.org

MERC PEOPLE

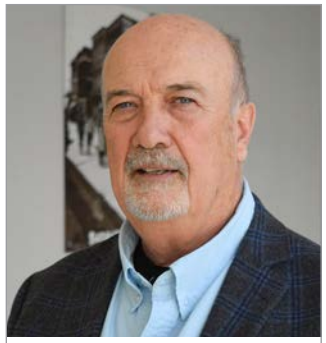
Administration

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



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

Natalie Lafleur-Roy
Finance and Operations Administrative Manager

Courtney Folz
Administrative Coordinator

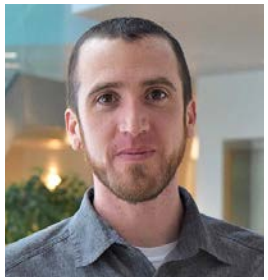
Lynn Bulloch
Communications Manager

MERC PEOPLE

Research Staff


Ademola Adetunji


Saeid Cheraghi


Ben Frieman


Rasmus Haugaard


Taus Jørgensen


Gaëtan Launay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Chong Ma


Jeffrey Marsh


Mostafa Naghizadeh


Kate Rubingh

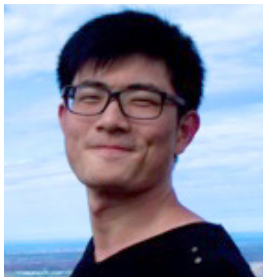

Jack Simmons


Eric Thiessen


Szuszanna Toth


Gyorgyi Tuba

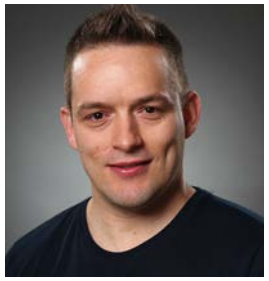

Rajesh Vayavur


Longbo Yang

MERC PEOPLE

Graduate Students - PhD


Sandra Baurier Aymat


Fabiano Della Justina


Thomas Gemmell (OGS)


Hossein Jodeiri Akbari Fam


Klaus Kuster


Theo Lombard


Christopher Mancuso


Dylan McKevitt


Xuyang Meng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Kristine Nymoen


Dustin Peters


Adrian Rehm


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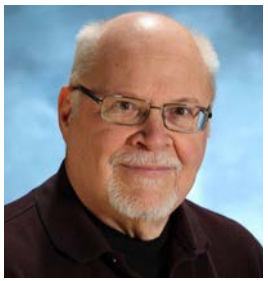

John Ayer


Eric Grunsky


Jeff Harris

Magino

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. The building of the mill has begun, and the open pit is being excavated. A need to better understand the geology of the deposit has prompted the present project. The 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, thus resolving how and when the deposit formed can have important mineral exploration implications.

A summer of field work has been completed in and around the open pit outline of the deposit, and samples have been collected for petrographical characterization of the ore zones, definition of the structures controlling the mineralization, whole rock alteration geochemistry, and Re-Os molybdenite dating. The lab-based analytical work is underway, and early results are very promising.

The next steps are to continue the mapping of the open pit, as new exposures are continuously being created as mining progresses, complete the analytical lab work, and integrate these results into a model that will help guide present and future mineral exploration in this new mining camp.

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.

MSc student Ian Campos (left) presents his research on the Magino deposit at the 2022 Student Minerals Colloquium, Prospectors and Developers Association Convention, Toronto.

VIEW OR DOWNLOAD THE POSTER.

Ormaque – Val d'Or

The Ormaque Deposit is a new gold discovery by Eldorado Gold, within the renowned Val D'Or district in the Archean Abitibi greenstone belt, Quebec. The deposit is the subject of a 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 south-dipping extensional veins, which form multiple gold mineralized intervals of stacked quartz- carbonate-tourmaline veins surrounded by variably mineralized wall-rock.

Structural geology professor Bruno Lafrance visiting Eldorado Gold's Sigma pit, pictured with a reverse shear with a fault-fill quartz-tourmaline-carbonate vein, Val-d'Or, Québec, summer 2022.

The extensional veins are oriented near perpendicular to the fault zones, and thus differ in geometry from that of the nearby world-class Sigma Mine, 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 not only shed new information on the formation of gold deposits in the Val D'Or district, it will also provide new insights on the fault-valve model and formation of orogenic gold deposits worldwide.

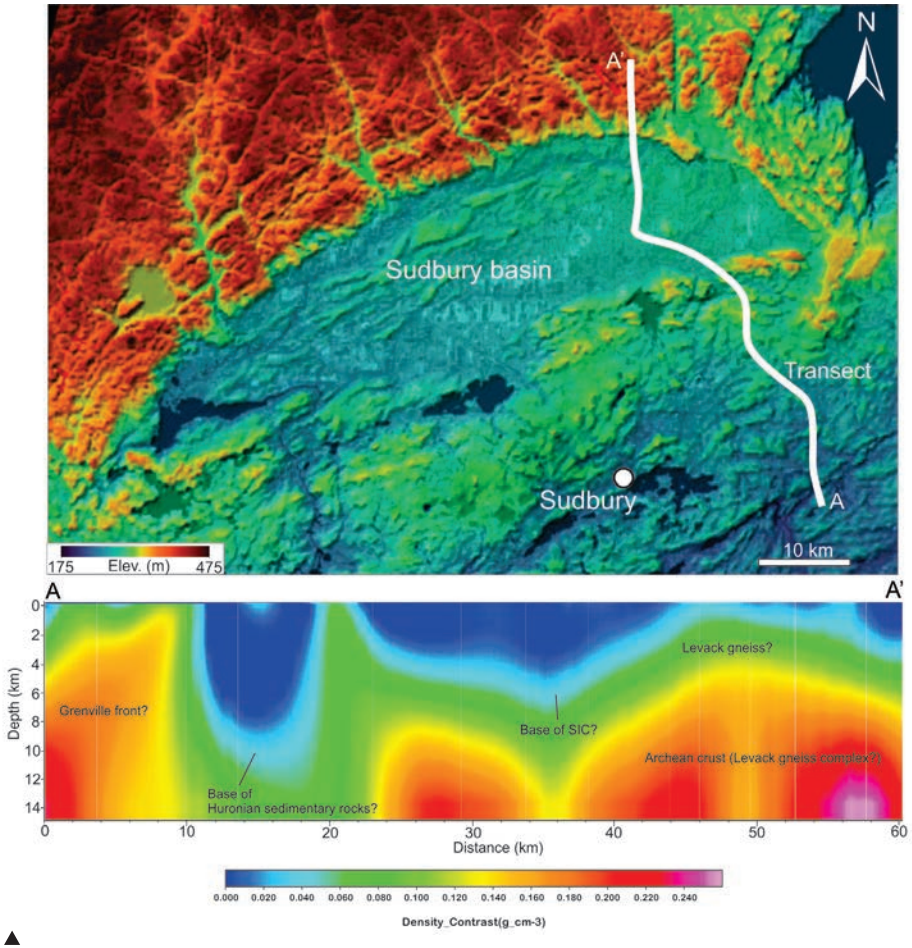
MSc student Shalailah Bhalla (right) presents her research on the Ormaque at deposit at the 2022 Student Minerals Colloquium, Prospectors and Developers Association Convention, Toronto.

VIEW OR DOWNLOAD THE POSTER.

WATCH NOW!
Rasmus Haugaard: Crustal geology of the eastern part of the Sudbury impact crater, April 2022 Partner Meeting

Sudbury CRD Project

Crustal architecture of the eastern part of the Sudbury Igneous Complex



Bottom image: An example of the large scale gravity modelled along the white (A-A') transect. The Sudbury basin and the Sudbury Igneous Complex represents a distinct crustal feature with an overall low gravity anomaly. (Source of DEM map: earthobservatory.nasa.gov/images/148844/sudbury-impact-structure).

MERC initiated this project in November 2020 under the direction of research associate Rasmus Haugaard, in collaboration with his colleagues Rajesh Vayavur, Ademola Adetunji, and Saeid Cheraghi. The Sudbury CRD project is possible thanks to support from an NSERC Collaborative Research and Development (CRD) grant, in partnership with Vale, Glencore, First Cobalt, Kirkland Lake Gold, Cobalt Power, NxGold and the University of Western Ontario.

Scope

The project will complete integration of the geophysical data set, and subsequently, an interpretation of the overall crustal scale geology and associated mineralizing structures.

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.

The complete interpretation of the crustal architecture over the eastern part of the impact structure will help constraining mineralized (Ni, PGE and Cu) structures, their orientation and volume.

Progress

Core samples from some of the deepest drill holes ever drilled were obtained from Glencore and Vale. Importantly, samples from the footwall rocks (crater floor) in 2.8 and 3.1 km depth were collected and shipped for further geochemical analyses. These crater-floor rocks will, for the first time, shed light on the composition and age of the rocks directly underlying one of the largest impact-generated melt sheets in the world. This type of work will furthermore help the geological interpretations of our large-scale geophysical surveys (seismic, MT, and gravity) with the end result to constrain the crustal architecture and related ore deposit systems in the easternmost part of the Sudbury Igneous Complex (SIC).

Sudbury CRD Project (continued)

Crustal architecture of the eastern part of the Sudbury Igneous Complex

Since the project's inception, a geophysical data set has been processed and finalized, including seismic high and lower resolution profiles, MT, gravity and magnetic data.

R. Vayavur presented an abstract and poster at the September 2021 Geoconvention, called Geophysical evidence of upper-crustal Archean basement folding and/or faulting below the East Range of the Sudbury impact crater. A manuscript on this topic is in progress.

Future Work

- Establish the crustal-scale geology from surface to a depth of ca 15 km, pin-point key mineralizing features at the bottom part of the SIC, and address the geological processes behind mineralization
- Finalize a 3D model of the eastern part of the SIC

Anticipated Outcomes

- One paper in a high-impact scientific journal
- One paper in a scientific journal on the geophysical aspects
- Strengthen the collaborative relationship with Glencore and Vale, two key mining and exploration companies in Sudbury

Implications

The Sudbury CRD project will result in valuable research and publications, attracting broad international interest. This could not have been achieved without strong research and industry collaboration.

Highlights

The Sudbury CRD project highlights MERC's strengths collaborating with industry partners who provide access to sites for researchers to investigate the geology at depth. Industry partners benefit from high-impact research publications.

Red Lake - Evolution Mining

An embedded research position with Evolution Mining to refine the structural and stratigraphic framework for the Balmer sequence stratigraphy

This research project was initiated to further refine the stratigraphy at the Red Lake – Campbell mine using field mapping, drill core analysis, geochemistry, and U-Pb LA-ICP-MS geochronology. This project was in partnership with Evolution Mining and conducted by research associate Kate Rubingh with input from Francois Robert, Bruno Lafrance, and Ross Sherlock. The key objectives were to refine the Balmer sequence stratigraphy and provide criteria to correlate stratigraphy across key structural domains. These domains are defined by regional unconformities which separate rocks of the Mesoarchean Balmer (2.99 – 2.96 Ga), and Neoarchean Bruce Channel (2.894 Ga), Confederation (2.75 to 2.73 Ga), and the Huston assemblages (>2714 Ma). This will be used to further define the structural framework for the Red Lake camp, identify potential repetitions of stratigraphy, and establish the geological setting of gold mineralization.

Kate Rubingh, embedded researcher.

▶ Red Lake - Dixie

Structural controls on gold mineralization along the LP Fault, Dixie property, Red Lake

The LP Fault, immediately south of the Red Lake camp in northwest Ontario, hosts the footwall LP Fault Zone and the hanging wall the Dixie Limb Zone and the Hinge Zone. The main objectives of the project are to determine the structural controls on gold mineralization at the three mineralized zones, their relative structural chronology, and absolute timing. The research will involve surface mapping, the collection of drill core structural measurements, the investigation of microstructures under the SEM and optical microscope, and the dating of monazite and xenotime using the LA-ICP-MS instrument at Laurentian University. The project is funded through a partnership with Great Bear Resources Ltd. (Kinross Gold).

The P-T-t-fluid history of metamorphism across gold-bearing structures, Dixie property, Red Lake

Amphibolite and greenschist facies metamorphic assemblages are developed in host rocks that contain shear zones and structures hosting Au mineralization at the Dixie Property, Red Lake, and understanding the metamorphic history in terms of P-T-t-fluid (pressure-temperature-time-fluid) conditions are of interest. The main objectives of this research project are to constrain the number of metamorphic events, the spatial variability of P-T-t-fluid conditions, determine whether significant dehydration and decarbonation reactions occurred at temperatures high enough to mobilize Au in favorable rock types, and determine if there are metamorphic discontinuities across major structures. The research includes investigation and sampling of available drill core, whole rock geochemistry, mineral geochemistry (SEM, EPMA, and LA-ICP-MS), phase equilibrium modelling, and metamorphic geochronology (LA-ICP-MS and garnet geochronology). The project is funded through a partnership with Great Bear Resources Ltd. (Kinross Gold).

▶ Ulu – Blue Star

MERC, in partnership with Blue Star Gold Corp. and Mitacs, will employ a MSc student to undertake a field-based mapping project to outline the structural and stratigraphic framework of the Ulu gold deposit. This project is within the Slave Province in Nunavut, part of the High Lake greenstone belt. The goal of this project is to provide a structural/stratigraphic context for the Ulu deposit, focused on structural observations, geologic mapping and lithogeochemical sampling. These will be combined with standard petrography (transmitted and reflected light) and SEM observations. The project is fully funded and will be supervised by Drs Bruno Lafrance, Ross Sherlock, and Blue Star Gold's technical Team. Fieldwork will be required in the far north of Nunavut, based in a field camp.

▶ International Explorers Inc. (IEP) - Kamiskotia

MERC, in partnership with International Explorers and Prospectors Inc., is seeking a MSc student to undertake a research project to outline controls on volcanogenic massive sulfide (VMS) deposits in the Kamiskotia Volcanic Complex. The goal of this project is to provide insight into the geochemical, alteration and stratigraphic controls on VMS mineralization. The project will utilize existing geochemical and geochronological data for the five deposits, augmented by new lithogeochemical and petrographic sampling. The project will integrate mapping, core logging and lithogeochemical data with petrographic and SEM studies of alteration and mineralization. The project will be supervised by Drs. Stefanie Brueckner University of Manitoba, John Ayer (MERC), Jeff Harris (MERC), and members of IEP's technical team.

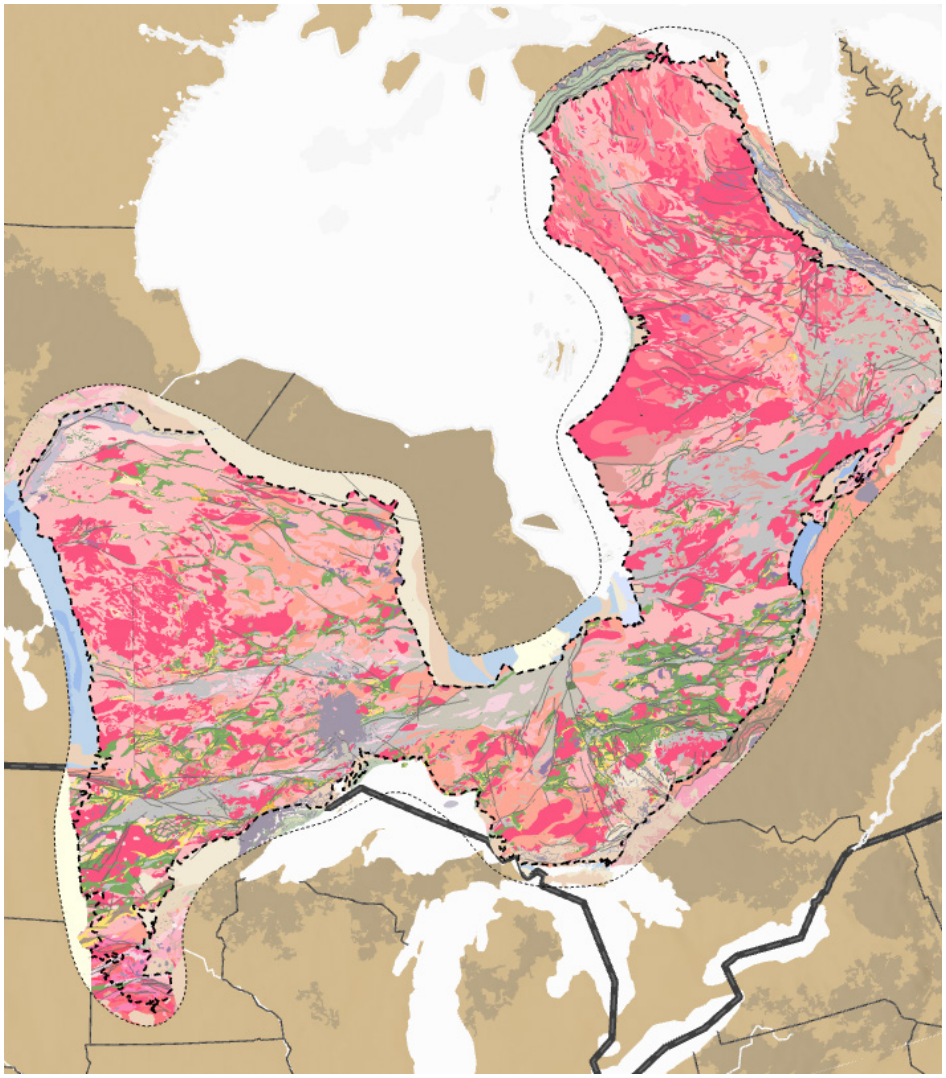
▶ Canada Nickel Corp. (CNC) – Crawford

MERC, In partnership with Canadian Nickel Corporation, will employ an MSc student to undertake a research project to outline controls on nickel mineralization at CNC's Crawford intrusive complex. The goal of the MSc project is to provide insight into the nature and controls on Ni, Co, and PGE mineralization by focusing on the petrography, geochemistry, and mineralogy of the Crawford intrusive complex. The project is fully funded, will be supervised by Dr. Pedro Jugo and CNC's technical team, and will combine core logging, portable XRF analysis, petrography, lithogeochemistry and mineral chemistry.

WATCH NOW!
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 will transform 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 will be 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.

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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 2021-22.

Magmatic, hydrothermal and ore element transfer processes of the southeastern Archean Superior Province implied from electrical resistivity structure

Eric A. Roots, Graham J. Hill, Ben M. Frieman, Philip E. Wannamaker, Virginie Maris, Andrew J. Calvert, James A. Craven, Richard S. Smith, David B. Snyder, Gondwana Research, Volume 105, 2022, Pages 84-95, ISSN 1342-937X, doi.org/10.1016/j.gr.2021.12.004.

Evidence of Magmatism and rifting in the southern Superior craton from the Temagami geophysical anomaly

Ademola Q. Adetunji, Ian J. Ferguson, Rajesh Vayavur, Saeid Cheraghi, Mostafa Naghizadeh, Wesley Whymark, Richard S. Smith, John Ayer, James A. Craven, Precambrian Research, Volume 362, 2021,106310, ISSN 0301-9268, doi.org/10.1016/j.precamres.2021.106310.

On Archean craton growth and stabilisation: Insights from lithospheric resistivity structure of the Superior Province

G.J. Hill, E.A. Roots, B.M. Frieman, R. Haugaard, J.A. Craven, R.S. Smith, D.B. Snyder, X. Zhou, R. Sherlock, Earth and Planetary Science Letters, Volume 562, 2021, 116853, ISSN 0012-821X, doi.org/10.1016/j.epsl.2021.116853.

Seismic imaging of crystalline structures: improving energy focusing and signal alignment with azimuthal binning and 2.5D full-waveform inversion

Brian J G Villamizar, R G Pratt, M Naghizadeh, Geophysical Journal International, Volume 231, Issue 1, October 2022, Pages 615–628, doi.org/10.1093/gji/ggac208.

Addressing geometrical attributes and seismic imaging capability of fault systems in a world-class metal endowed region: Abitibi Greenstone Belt, Canada

Saeid Cheraghi, Alireza Malehmir, Rajesh Vayavur, Pejman Shamsipour, Mostafa Naghizadeh, Rasmus Haugaard, David B. Snyder, John Ayer, Tectonophysics, Volume 833, 2022, 229361, ISSN 0040-1951, doi.org/10.1016/j.tecto.2022.229361.

The implications of crustal architecture and transcrustal upflow zones on the metal endowment of a world-class mineral district.

Jørgensen, T.R.C., Gibson, H.L., Roots, E.A. et al., Sci Rep 12, 14710 (2022). doi.org/10.1038/s41598-022-18836-y

A new geological map of the Lau Basin reveals crustal growth processes in arc-backarc systems

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; Geosphere 2022; 18 (2): 910–943. doi.org/10.1130/GES02340.1

Imaging Neoarchean crustal structures: An integrated geologic-seismic-magnetotelluric study in the western Wabigoon and Winnipeg River terranes, Superior craton

Chong Ma, Mostafa Naghizadeh, Ademola Adetunji, Robert W.D. Lodge, David Snyder, Ross Sherlock, Precambrian Research, Volume 364, 2021,106339, ISSN 0301-9268, doi.org/10.1016/j.precamres.2021.106339.

Mesoarchean diamonds formed in thickened lithosphere, caused by slab-stacking

S. Timmerman, J.R. Reimink, A. Vezinet, F. Nestola, K. Kublik, A. Banas, T. Stachel, R.A. Stern, Y. Luo, C. Sarkar, A. Ielpi, C.A. Currie, C. Mircea, V. Jackson, D.G. Pearson, Earth and Planetary Science Letters, Volume 592, 2022, 117633, ISSN 0012-821X, doi.org/10.1016/j.epsl.2022.117633.

Mapping structural complexity using geophysics: A new geostatistical approach applied to greenstone belts of the southern Superior Province, Canada

R.M. Montsion, S. Perrouty, M.D. Lindsay, M.W. Jessell, B.M. Frieman, Tectonophysics, Volume 812, 2021, 228889, ISSN 0040-1951, doi.org/10.1016/j.tecto.2021.228889.

Origin and Evolution of the Iron-Rich Upper Unit and Fe–Ti–V Mineralization of the Neoarchean Lac Doré Layered Intrusion, Chibougamau, Québec

Nesrine Mokchah, Lucie Mathieu, Journal of Petrology, Volume 63, Issue 3, March 2022, egac006, doi.org/10.1093/petrology/egac006

Crustal growth/reworking and stabilization of the western Superior Province: Insights from a Neoarchean gneiss complex of the Winnipeg River terrane

Chong Ma, Jeffrey Marsh, Robert W.D. Lodge, Ross Sherlock; GSA Bulletin 2022; doi.org/10.1130/B36441.1.

The formation of Neoarchean continental crust by 2 distinct geodynamic processes

D.R. Mole, P.C. Thurston, J.H. Marsh, R.A. Stern, J.A. Ayer, L.A.J. Martin, Y.J. Lu, Precambrian Research, Volume 356, 2021, 106104, ISSN 0301-9268, doi.org/10.1016/j.precamres.2021.106104.

Crustal architecture of the south-east Superior Craton and controls on mineral systems

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, Ore Geology Reviews, Volume 148, 2022, 105017, ISSN 0169-1368, doi.org/10.1016/j.oregeorev.2022.105017.

Recognizing subsurface breccias in Archean terranes: Implications for district scale metallogeny

Marina D. Schofield, Harold.L. Gibson, Bruno Lafrance, K. Howard Poulsen, Jeffrey Marsh, Michael A. Hamilton, Taus R.C. Jørgensen, Precambrian Research, Volume 361, 2021, 106264, ISSN 0301-9268, doi.org/10.1016/j.precamres.2021.106264.

WATCH NOW!
Kristine Nymoen - Isotopic mapping of the eastern Wawa subprovince, April 2022 Partner Meeting

Isotopic Mapping

Lead Researcher: P. Thurston, Laurentian University

PhD student Kristine Nymoen in July 2021, Opatica subprovince (Quebec), collecting granitoid samples for whole-rock and zircon U-Pb-TE-Hf-O isotopic analyses for the Craton Scale project. The helicopter time was sponsored by Kenorland Minerals, which enabled sampling of rocks that have not been dated before, and otherwise would not be accessible.

VIEW OR DOWNLOAD
Scientific Output: *Mole et al in Precambrian Research: The formation of Neoarchean continental crust in the south-east Superior Craton by two distinct geodynamic processes*

Overview

Lithospheric and crustal architecture determines the framework of major tectonic blocks, terranes and their boundaries, represents a first-order control on major geological systems including ore deposits, and therefore, the location of world-class mineral camps. Previous work, particularly by Begg et al. (2009) and Begg et al. (2010), used seismic tomography to demonstrate how gold and Ni-Cu-PGE camps are controlled by major lithospheric discontinuities. In other studies, workers attempting to constrain time-resolved intracratonic lithospheric architecture turned to the mapping of isotopic systems from crustal rocks (particularly granitoids). Champion and Cassidy (2007) used regional Sm-Nd isotopic data to map the crustal architecture of the Yilgarn Craton, and Mole et al. (2013) demonstrated the association between that lithospheric architecture and BIF-hosted iron, orogenic gold, and komatiite-hosted Ni-Cu-PGE systems. These results demonstrated the underlying control of lithospheric architecture and the potential for isotopic mapping as a greenfields area selection tool.

Further work by Mole et al. (2014), using Lu-Hf isotopes, demonstrated that the technique could account for mineral systems of different ages, showing how Ni-Cu-PGE mineralized komatiite systems of the Yilgarn Craton migrated with the changing lithospheric boundary (craton margin) from 2.9 to 2.7 Ga. Similar work has since been performed in West Africa (Parra-Avila et al., 2017), Tibet (Hou et al., 2015), and Canada (Lu et al., 2013); Bjorkman et al. 2015). This project aims to take that technique and apply it to the Superior Craton, in a bid to constrain large-scale intracratonic controls on magmatism, crustal evolution, and mineralization in the Earth's largest Archean terrane. This will be done in a much higher resolution, both spatially and temporally than previously contemplated.

Progress

- Completed Lu-Hf study on the south-east quadrant of the Superior craton, mainly the Abitibi subprovince, involving ~ 200 zircons and over 8000 analyses including the combination of 4 new methods of using zircon geochemistry to constraint magma temperature, state of hydration and oxygen fugacity
- Produced two craton-scale publications, both in journals with high impact factors: *Precambrian Research* and *Ore Geology Reviews*

Future Work

- Synthesis paper on mineral systems in the Abitibi subprovince and neighbouring terranes; Crustal architecture of the south-east Superior Craton and controls on mineral systems: Mole, Frieman, Thurston, Marsh, Jørgensen, Gibson, Stern, Martin, Lu, *Minerals*, submitted 2021
- Use Lu-Hf results to demonstrate older substrate beneath several subprovinces (e.g., northern Geraldton transect, Dryden-Winnipeg River)
- Expand Lu-Hf work to NW Ontario to demonstrate likely antiquity of terranes there and their influence on metallogeny

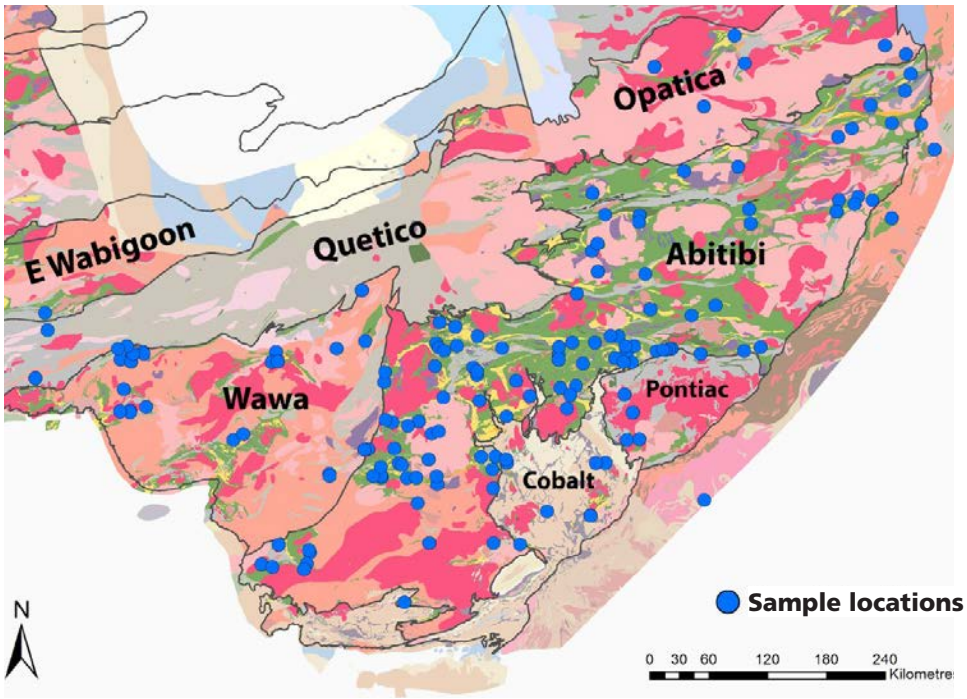
Anticipated Outcomes

- Understanding of differences in crust and mantle in Abitibi vs terranes to the west, which in turn explains differences in metallogeny

Implications

- The rift-based tectonic model in Mole et al., (2021) may cause a move away from simple plate tectonics interpretations for the entire craton
- Recommendation to sample quartzites in northern Sturgeon transect important for overall tectonic interpretation at craton scale

VIEW OR DOWNLOAD
Scientific Output: *Mole et al in Ore Geology Reviews: Crustal architecture of the south-east Superior Craton and controls on mineral systems*



A PhD study commenced in January 2020 to perform detailed spatial isotopic work, along with other items in the study program.

K. Nymoen holding a gneissic sample, the red crystals are garnets.

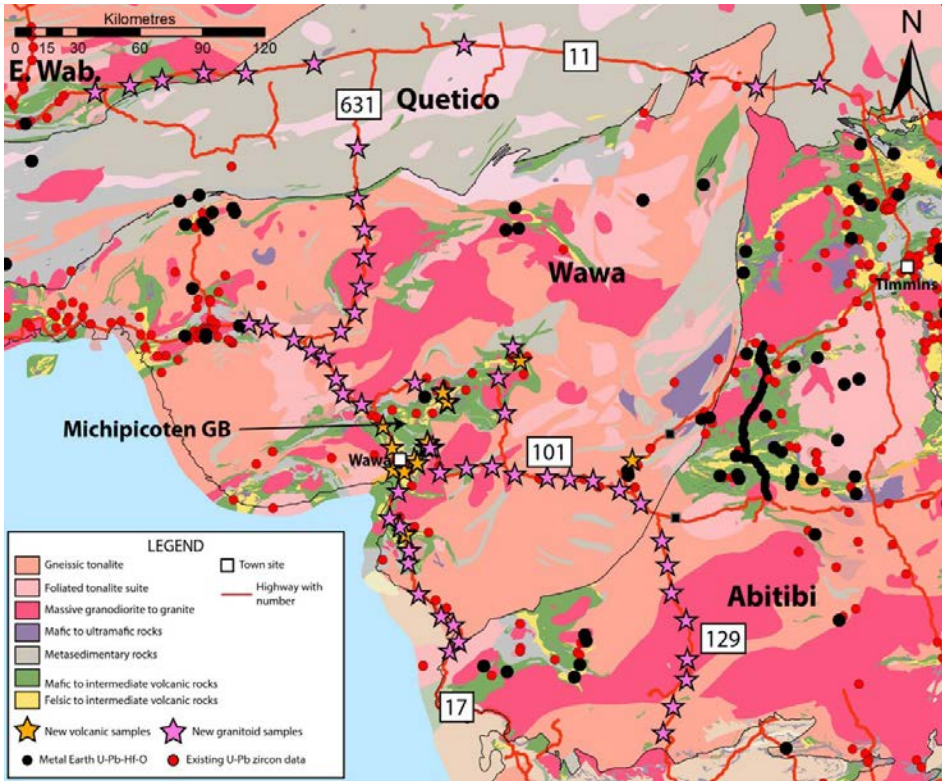
P. Thurston sitting on an outcrop south of Moonbeam. The rock he is sitting on is a tonalite gneiss belonging to the Groundhog River Batholith.

Highlights

PhD student Kristine Nymoen has completed course work and sampling for PhD.

Have related Lu-Hf results to mineral systems.

The rift-based tectonic model in Mole et al. (2021), may cause a move away fromsimple plate tectonics interpretations for the entire craton.



2019 fieldwork in Wawa resulted in 85 samples collected across the region, 20 Fv and 65 granitoids.

K. Nymoen's view of Opatica subprovince (Quebec) from the air, taken while collecting granitoid samples for whole-rock and zircon U-Pb-TE-Hf-O isotopic analyses for the Craton Scale project, July 2021.

Chibougamau

Lead Researcher: Lucie Mathieu, UQAC; report completed by Dr. Paul Bédard, UQAC

WATCH NOW!
Lucie Mathieu - Metal Earth in Chibougamau: the magmatic-tectonic evolution of the north-eastern corner of the Abitibi greenstone belt, April 2022 Partner Meeting

Progress

- Work has resumed on Pierre Bedeaux's postdoctoral geochronology paper from Chibougamau, with a plan to complete it in December 2022
- MSc projects of Patrik Berthoty (PhD transferred to MSc), Alexandre Crépon (PhD transferred to MSc) have been completed in summer and fall 2021
- Projects that progressed: Taylor Wasuita (MSc, year 2), Esther Bou on Sanukitoids (PhD)

Future Work

- Continuing work on sanukitoid magmatism (Esther Bou's PhD, co-funded by NSERC, will be integrated into Metal Earth)

Anticipated Outcomes

- Renewed understanding of ancient magmatism (synvolcanic and syntectonic period)
- Integration to geodynamic framework and renewed comprehension of mineralising systems at regional to local scales
- Contribution to the understanding of the fertility of the Chibougamau Archean greenstone belt

Implications

General insights gained on magmatic systems (including the physico-chemical parameters of magmas) are changing our comprehension of Au-Cu transportation in the ancient crust.

UQAC student Adrien Boucher conducting fieldwork on the Chibougamau Transect Scale Project, summer 2019.

Highlights

- MSc student Nesrine Mokchah published her research results on the Origin and Evolution of the Iron-Rich Upper Unit and Fe–Ti–V Mineralization of the Neoarchean Lac Doré Layered Intrusion, Chibougamau, Québec, *Journal of Petrology*, Volume 63, Issue 3, March 2022, egac006. doi.org/10.1093/petrology/egac006
- MSc student Marie Kieffer published her research on 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*. doi.org/10.1139/cjes-2021-0162
- Marie A. Kieffer, Lucie Mathieu, Pierre Bedeaux, Damien Gaboury, Michael A. Hamilton, Petrogenesis and mode of emplacement of a Neoarchean tonalite–trondhjemite–diorite suite: the Eau Jaune Complex, Abitibi greenstone belt. *Canadian Journal of Earth Sciences* 2021; 59 (2): 87–110. doi.org/10.1139/cjes-2021-0016

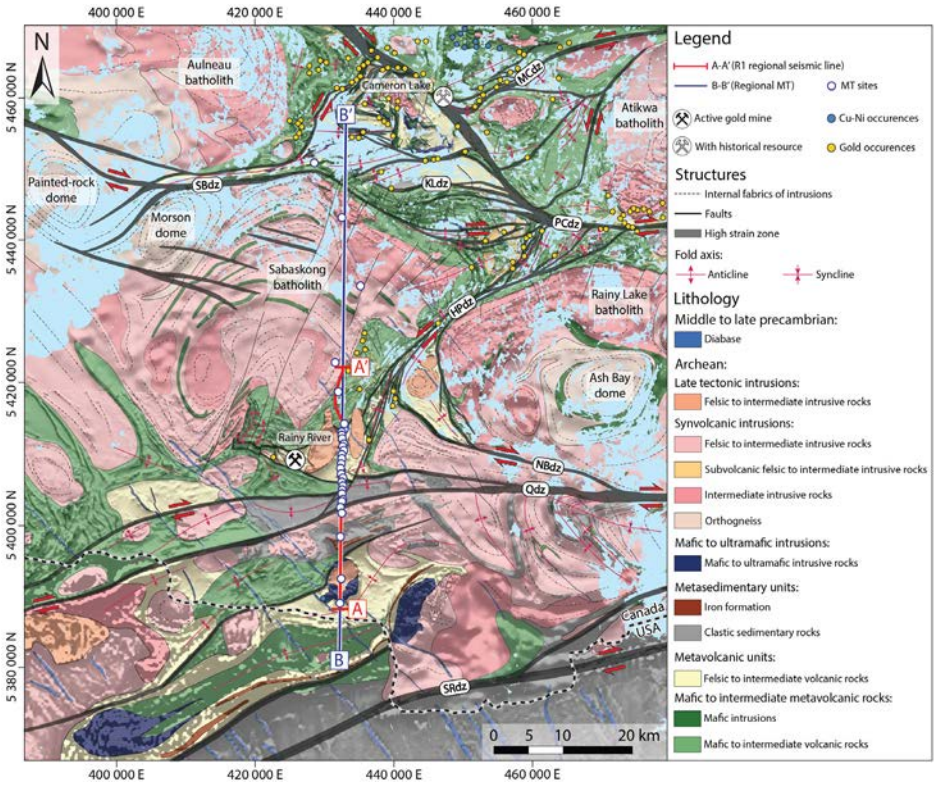
Dr. Lucie Mathieu published the following papers:

- Mathieu, L. 2022. Modeling the chemical heterogeneity of tonalite-trondhjemite-granodiorite intrusive suites, *Lithos*, Volumes 422–423, 106744. doi.org/10.1016/j.lithos.2022.106744
- Mathieu, L. MacDonald, F. 2022. Petrography and Geochemistry of the Intrusive Rocks at the Diorite-Hosted Regnault Au Mineralization. *Minerals*, 12, 128.
- Lucie Mathieu, Ulrich Riller, Lisa Gibson, Peter Lightfoot, 2021. Structural controls on the localization of the mineralized Copper Cliff embayment and the Copper Cliff Offset dyke, Sudbury Igneous Complex, Canada, *Ore Geology Reviews*, Volume 133, 2021, 104071. doi.org/10.1016/j.oregeorev.2021.104071
- Mathieu, L. 2021. Intrusion-associated gold systems and multistage metallogenic processes in the Neoarchean Abitibi Greenstone Belt. *Minerals*, 11, 261. doi.org/10.3390/min11030261

WATCH NOW!
Gaëtan Launay - Geophysical signatures and crustal architecture of variably endowed greenstone belts: New insights from Rainy River and Timmins, April 2022 Partner Meeting

Rainy River

Lead Researcher: Gaëtan Launay, Laurentian University



New regional geological map of the Rainy River greenstone belt. Geological interpretations are based on the compilation and the integration of airborne magnetic maps, the OGS geological maps and the field data (1300 stations) acquired over the Metal Earth project (2019 to 2021).

Overview

The Rainy River transect is a north-south 40 km long transect in the Western Wabigoon Subprovince crosscutting the Quetico deformation zone and the gold endowed volcanic center of Rainy River. This project aims to investigate the crustal architecture of the Rainy River greenstone belt and the Quetico deformation zone in order to improve knowledge of the geodynamic evolution of this area and provide new insights for the identification of mechanisms controlling the gold endowment of deformation zones.

The project also aims to examine the stratigraphy, the physical volcanology and the petrogenesis of the Rainy River greenstone belt to identify the geological environment favorable for the formation of the Au-rich syn-volcanic deposits occurring in the Wabigoon subprovince. These different objectives have been addressed by new geological mapping combined with lithogeochemical and geochronological investigations.

Progress

Detailed mapping performed in the Pinewood Lake and Off-Burditt lakes area showed that these different felsic volcanoclastic packages are similar than those hosting the gold mineralization of Rainy River (Pelletier et al., (2015) and are the explosive expression of the rhyolitic cryptodome occurring in the Off Lake area.

Samples for whole rock major and trace elements geochemistry were collected across the stratigraphy of the Rainy River greenstone belt to characterize the petrogenesis of the different volcanic assemblages. Results highlight crustal contamination of mafic magmas by the lower gneissic crust underlying the Rainy River greenstone belt. Samples for U-Pb detrital and igneous zircon were also collected at different stratigraphic level to constrain the timing of the different volcanic events across the Rainy River greenstone belt. The deposition of the felsic volcanoclastic units of Burditt and Pinewood Lake are coeval (2715-2716 Ma) with the emplacement of the felsic

volcanic unit hosting the Rainy River gold deposit (2716 ± 1 Ma), Pelletier et al. 2015). The rhyolitic cryptodome of Off Lake emplaced at 2721 ± 0.88 Ma provides a minimum age span constraint on the duration of felsic magmatism of ~5 Ma. U-Pb dating of Xenotime inclusions enclosed in gold-bearing pyrite provide an age constraint of 2711 ± 5 Ma for the gold mineralization. These results demonstrate that the Au-Ag-rich sulphides mineralization of Off-Burditt Lakes and Rainy River are related to the same volcanic center and belong to the same short-lived volcanic-hydrothermal system. The presence of inherited zircons (2750-2880 Ma) in the rhyolitic cryptodome of Off Lake confirms the assimilation of the older gneissic crust during the formation of the Rainy River greenstone belt.

Interpretation of seismic, gravity and magnetotelluric data sets and integration with surface geology has been undertaken to produce a crustal scale geological cross section of the Rainy River greenstone belt. Preliminary interpretations show that the crust beneath the Rainy River greenstone belt is relatively thick (Moho at 40 km) and can be subdivided in 3 domains:

- An upper resistive crust (up to 9 km) corresponding to the greenstone belt and characterized by reflectors (sills/dikes?) depicting a regional scale syncline compatible with a dome-and-keel structure.
- A middle reflective crust occurring between 9 and 15 km interpreted as interlayered mafic and TTG gneisses. The middle crust is conductive and forms a dome under the Sabaskong batholith. This upwelling of the mid-lower crust is consistent with the presence of the Morson gneissic dome mapped in the western part of the Sabaskong batholith.
- A lower conductive aseismic ductile homogeneous crust characterized by rare subhorizontal reflectors.

The Quetico deformation zone is characterized by a limited depth extension (12-15 km) and is associated with a weakly conductive corridor. This limited depth extension of the structures may (i) inhibit the circulation of the gold-bearing metamorphic fluids produced in the mid-lower crust (amphibolite facies) and (ii) explain the absence of gold mineralization and hydrothermal alteration along the Quetico deformation zone.

Future Work

Writing is underway for three articles destined for publication in peer-reviewed journals.

Anticipated Outcomes

Geological, geochemical and geochronological data will be released in the Metal Earth geodatabase.

A cross-section across the Rainy River greenstone belt and the Quetico deformation zone with integrated geological and geophysical interpretation will be published in a peer-reviewed journal article.

Crustal-scale comparisons between the Rainy River transect and metal-endowed transects (such as Timmins) will be completed to identify key mechanisms responsible for the genesis of deposits.

Implications

Research activities carried out on the Rainy River greenstone belt will provide better understanding of the geodynamic evolution of this area and identify geological environment favorable for the formation Au-rich syn-volcanic deposits, which represent the most significant source of gold in the Western Wabigoon subprovince.

Detailed structural study of the Quetico deformation zone combined with interpretation of seismic and magnetotelluric dataset will provide:

- New constraints on the crustal architecture of the Western Wabigoon subprovince.
- New insights for identification of geological parameters controlling the gold endowment of the crustal deformation zones occurring in the Superior craton.

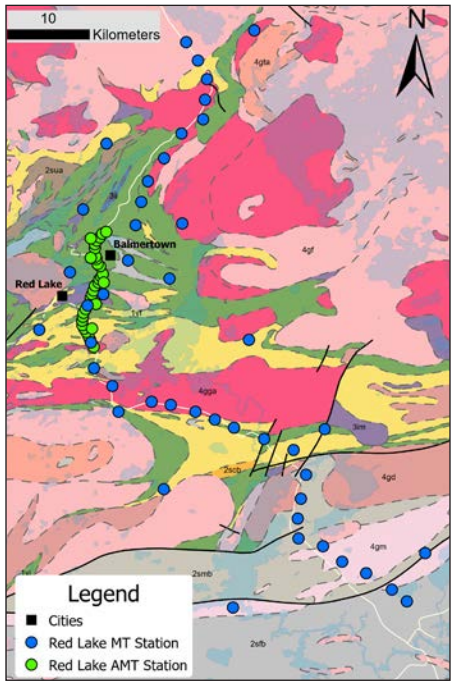
Highlights

Mattea McRae completed her M.Sc. thesis, Chemostratigraphy and structural framework for gold mineralization at the Goliath Deposit, Western Wabigoon Subprovince, Ontario on May 15, 2022. The thesis focused on the synvolcanic gold-rich sulphide deposit of Goliath. zone.biblio.laurentian.ca/handle/10219/3928.

WATCH NOW!
Eric Roots - Large scale resistivity structure of the western Superior, April 2022 Partner Meeting

Red Lake

Lead Researchers: John Ayer, Ademola Adetunji, Laurentian University



Red Lake MT stations (white line shows Lithoprobe Seismic line WS2b)

Progress

The magnetotelluric (MT) data was acquired by Quantec Geosciences for Metal Earth between September 2020 and February 2021. A total of 45 broadband MT (BBMT) and 36 audio-frequency MT (AMT) stations were occupied along the existing Lithoprobe Seismic line WS2b.

The BBMT data has been incorporated with a few Lithoprobe BBMT sites in the region to create the 3D crustal resistivity model that extends from the upper crust to the lower crust/upper mantle. The result is being integrated with existing seismic section for WS2b and other available geologic data to understand the tectonic evolution associated with gold mineralization in the region. Modelling, analysis, and data integration for the AMT dataset is ongoing.

Future Work

The results of the BBMT, integrated with seismic and geologic data will be written into manuscript for publication shortly. The AMT results will be integrated with the work of Jack Simmons, the geological RA working in the region, to understand the structural control on gold mineralization in the region.

Anticipated Outcomes

The MT results will provide a better understanding of the crustal scale architecture and tectonic events associated with the world-class gold district in the Red Lake greenstone belt of the western Superior craton. The MT models will provide support for the structural framework of the mineralized zones around Red Lake camp and the Lithoprobe (LP) fault (Great Bear Resources/Kinross Dixie Project).

Implications

This project demonstrates the efficacy of MT method for imaging the source region and fluid pathways for orogenic gold system in an Archean setting. Variation in resistivity signature is being used to depict differences in the crustal architecture of the endowed and less endowed regions. This enhances the prospectivity for orogenic gold in the underexplored greenstone belts with similar structural and tectonic characteristics to the Red Lake greenstone belt.

Highlights

MT imaging delineates the crustal-scale fluid pathways associated with the RLGB in order to examine the source and pathways of the gold bearing fluids and contributes to the understanding of mineral systems across the region.

The possible in-kind contribution, in the form of large-scale AMT data across the LP fault, from Great Bear Resources/Kinross will help to improve the understanding of the near surface structures, and ultimately the source to sink history/structure.

WATCH NOW!
Tectonic evolution of the western Wabigoon and Winnipeg River terranes in the Sturgeon Lake region

Sturgeon

Lead Researcher: Chong Ma, Laurentian University

Researcher Dr. Chong Ma observing rocks on an outcrop.

VIEW OR DOWNLOAD
Research Output: *Ma, et al: Crustal growth/reworking and stabilization of the western Superior Province: Insights from a Neoarchean gneiss complex of the Winnipeg River terrane*

Progress

- Completed geologic mapping for the MSc project in the summer of 2021.
- Completed sample analyses including whole-rock geochemistry, zircon U-Pb, Lu-Hf, and trace element by LAICPMS and high-precision U-Pb geochronology by TIMS for the MSc project.
- Published a peer-reviewed research paper on the Geological Society of America Bulletin: Chong Ma, Jeffery Marsh, Robert Lodge, Ross Sherlock, 2022. Crustal growth/reworking and the stabilization of the western Superior Province: Insights from a Neoarchean gneiss complex of the Winnipeg River terrane. *Geological Society of America Bulletin*, doi.org/10.1130/B36441.1
- Published four abstracts
- Published one preliminary activities report

MSc student Michael Tamosauskas is in the final stage of writing his thesis. His defense is planned for fall 2022.

At the transect scale, all the field work and sample analyses have been completed. Currently the data are being reduced and put into geologic context for new manuscripts.

Future Work

- Complete the writing and defence of the MSc thesis
- Write the manuscript of a research paper from the MSc thesis
- Write a manuscript about the volcanism of the Sturgeon Lake greenstone belt to be published in a peer-reviewed journal
- Write a manuscript about the syn-volcanic plutons in the Sturgeon Lake greenstone belt to be published in a peer-reviewed journal
- Write a manuscript about the ~2700 Ma orogeny including syn-orogenic sedimentation, plutonism, and deformation in the study area to be published in a peer-reviewed journal

Anticipated Outcomes

- Publish six peer-reviewed papers at the end of the project. Two papers are published and four others are planned in the next two years
- Achieve a new understanding of the geologic history of the Sturgeon Lake greenstone belt and the adjacent Winnipeg River terrane
- Get a better understanding of the metal endowment origins and potentials in the Sturgeon Lake greenstone belt
- Present and share the new results at professional conferences

Implications

The work conducted this year will ensure the successful completion of the MSc project about the nature, formation, and metal endowment potentials of the Ament Bay assemblage that represents the youngest, late-orogenic basin in the study area.

The published research paper about the Winnipeg River terrane revealed certain aspects of the nature of the basement underlying the Sturgeon Lake greenstone belt, which will help constrain the nature and evolution of the greenstone belt during the writing of the new manuscripts.

The new data obtained will markedly revise the geologic history of the Sturgeon Lake region. For example, the metasedimentary rocks of the Vanessa Lake assemblage and the Jutten assemblage to the east of the Sturgeon Lake formed around 2700 Ma instead of 2800 Ma or older.

Highlights

The publication of "Crustal growth/reworking and the stabilization of the western Superior Province: Insights from a Neoarchean gneiss complex of the Winnipeg River terrane" presents a detailed study of a TTG gneiss complex in the southern arm of the Winnipeg River terrane orocline and provides new insights into the tectono-magmatic evolution and cratonization of the western Superior Province. This study demonstrates that, at least locally, the Superior Province underwent episodic crustal reworking from ca. 3060–2700 Ma and a major crustal growth and mantle depletion event at ca. 2910 Ma.

Short Course presentation: Tectonic evolution of the western Wabigoon terrane in the Sturgeon Lake region: implications for understanding structural controls on the greenstone belt and its VMS deposits, in Greenstone Belt Architecture and Metal Endowment of the Superior Craton, SEG 100 Conference, 14–17 September 2021.

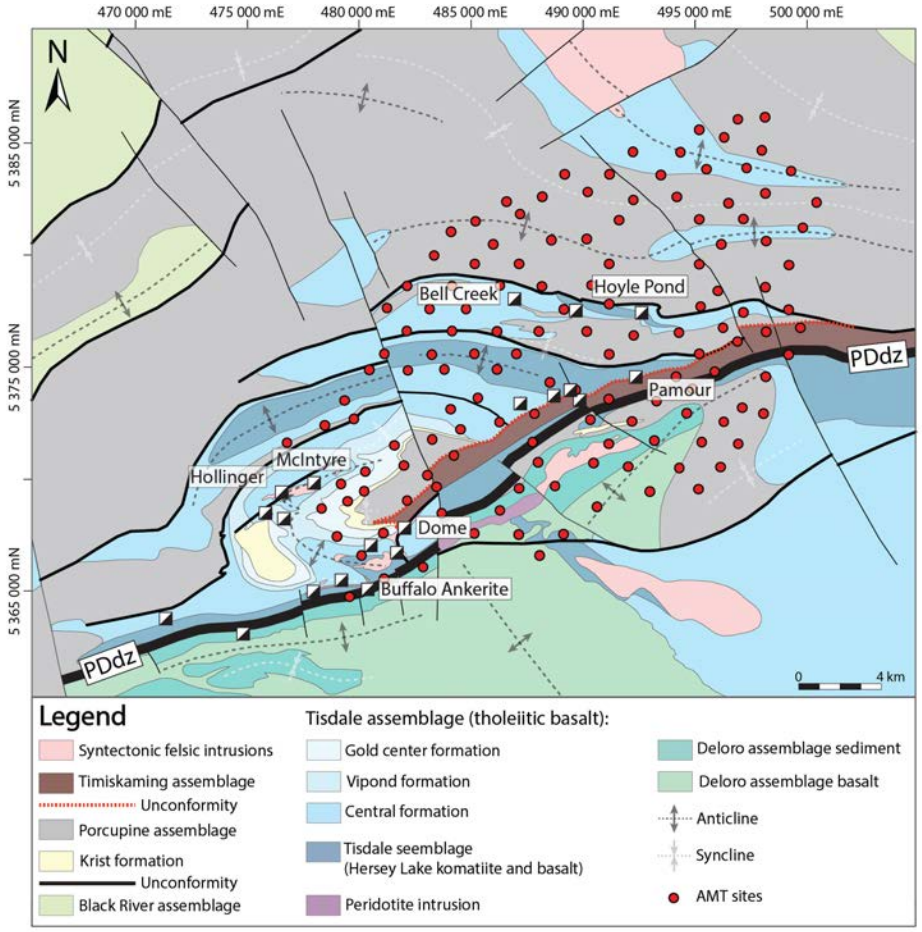
Deformed Ament Bay assemblage. *Photo: Chong Ma*

Southern end of Sturgeon Lake. *Photo: Chong Ma*

WATCH NOW!
Gaëtan Launay - Geophysical signatures and crustal architecture of variably endowed greenstone belts: New insights from Rainy River and Timmins (April 13, 2022)

Timmins

Lead Researchers: Gaëtan Launay, Ademola Adetunji, and John Ayer, Laurentian University



Geological map of the Timmins camp showing the location of the AMT stations and the most important gold deposits.

Progress

The regional Audio Magnetotelluric (AMT) dataset acquired across the Timmins mining camp highlights complex conductivity structures that reflect contrasts of the electrical resistivity between the different rock types and formations of the Timmins area. Preliminary interpretations of the inverted AMT sections emphasize an obvious spatial correlation between electrically conductive anomalies and known gold deposits:

- A large-scale east west trending conductive zone through the Hoyle Pond, Owl Creek and Bell Creek deposits ("new mines trend")
- A low resistivity corridor that lines up with the PDdz
- Folded conductive anomalies underlying the Dome and Hollinger gold mines

Our preliminary interpretations of the AMT survey suggest that these conductive anomalies can be related to (i) the graphitic rich layers in argillites and carbonaceous interflow sediments, (ii) the graphitic-pyrite alteration zones associated with the quartz-gold bearing veins ("grey zones" in Hoyle Township), (iii) graphitic fault zones, and (iv) the serpentinized ultramafic intrusions (Hersey Komatiite) occurring in the Timmins camp. However, to investigate further the geological sources of AMT anomalies, we must ascertain the physical property fingerprints of each rock type and determine how alteration related to the gold mineralization can modify the rock physical properties. Integrating the inverted AMT sections with geology and physical properties will provide new insights for understanding of the geology of the Timmins mining camp and for investigating the crustal architecture and geometry of the deformation zones related to the gold deposits of the world-class Timmins-Porcupine mining camp.

A suite of 250 samples representative of the stratigraphy and the alteration/mineralization of the different gold deposits of the Timmins mining camp has been collected for measurement of the rock petrophysical properties during the 2022 field season.

Samples were collected from drill holes crosscutting the conductive anomalies observed in the PDdz, Bell creek, Hoyle Pond, Hollinger and Pamour areas. The access to these drill holes was made possible thanks to the collaboration of the Ontario Geological survey office of Timmins and the industrial partners involved in this project (Newmont, Lakeshore and International Explorer and Prospector). The GSC Paleomagnetism and Petrophysics Laboratory (Sidney, BC) will realize the measurement of the petrophysical properties of these samples by October 2022.

Future Work

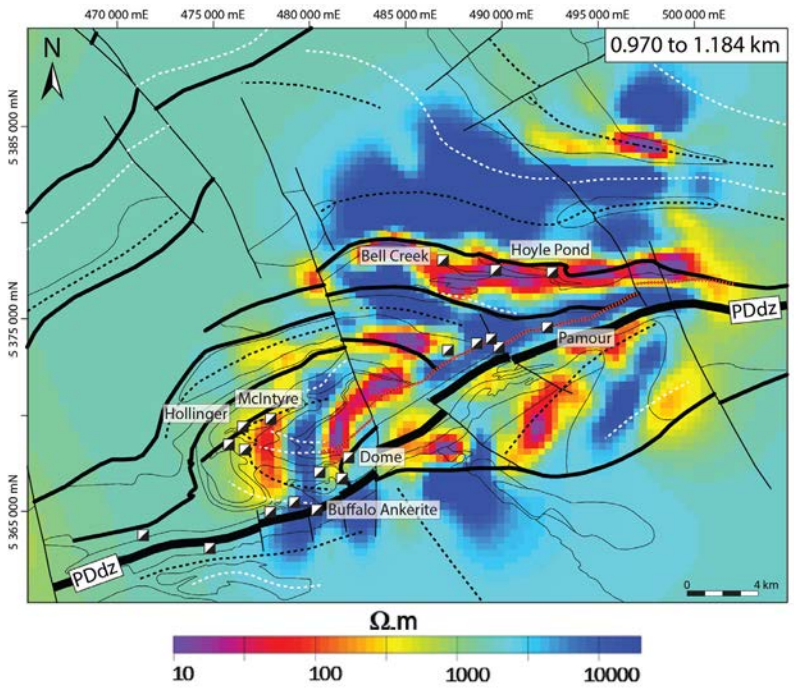
- Process and interpret the results of the rock petrophysical measurement obtained from samples collected during the summer. This work will allow identifying which lithology or structures are responsible of the conductive anomalies identified on the AMT sections.
- Produce geological cross-sections through the conductive structures identified in the inverted AMT sections. These geological sections will integrate the structures, the lithological and the alteration/mineralization facies together with the values of electrical resistivity obtained from the samples collected in the drill holes crosscutting the conductive anomalies.
- Refine the interpretation of the AMT dataset to produce a geological model of the Timmins mining camp.

Anticipated Outcomes

- A much-improved understanding of the subsurface geology associated with gold deposits in the Timmins mining camp.
- Potential new pathfinders for exploration along the PDdz (Timmins-Matheson area) deduced from the geological interpretation of the AMT dataset.
- Results will be published will be published in a peer-reviewed journal paper.

Implications

- New insights for identification of geological and structural parameters responsible of the incredible gold endowment of the Timmins mining camp
- It demonstrates the effectiveness of AMT as a tool for targeting endowed greenstone belts
- The ability to compare and contrast the Timmins camp's crustal architecture and metallogeny with the other Metal Earth transects across endowed areas of the Superior Craton



AMT depth slice (1 km depth) showing the spatial correlation between conductive anomalies and the known gold deposits of the Timmins gold camp.

Highlights

The initial success of this project highlights the strength of integration of crustal scale MT surveys with high resolution, upper crustal scale AMT surveys funded by the partner companies. The in-kind geophysical and detailed geological knowledge contributed from the partner companies adds considerably to the project, and is particularly beneficial when combined with the regional scale geophysical contributions and expertise of Metal Earth's researchers. This type of project greatly expands the scale and effectiveness of our research and represents a powerful model for the benefits of integration of university- and company-sponsored research.

WATCH NOW!
Bruno Lafrance - Research Update on the Atikokan Transect, April 2022 Partner Meeting

Atikokan

Lead Researcher: Bruno Lafrance, Laurentian University

Above: Fun field photos from Gabrielle Fouillard (left) with Olivia Meier (right), and a frog (bottom).

Laurentian University MSc student Gabrielle Fouillard (left) with undergraduate field assistant Olivia Meier, on the shore of Marmion Lake, summer 2021. *Photo: Bruno Lafrance*

Progress

Over the last year, the two MSc students on the transect, Gabrielle Fouillard and Mohamed Farhat, completed their field work; age dating (U-Pb dating of primary zircon and metamorphic monazite using the TIMS at the University of Toronto) and LA ICP-MS at Laurentian; U-Pb dating of detrital zircons (LA ICP-MS at Laurentian); whole rock major and trace element analyses (ALS); element maps of pyrite grains (LA ICP-MS at Laurentian); and the interpretation and integration of their data. Gabrielle and Mohamed are both in the writing phase of their MSc theses and are preparing manuscripts for publication in scientific journals.

Future Work

Gabrielle and Mohamed will complete and defend their theses by the end of 2022, or by April 2023, at the latest. Their theses will be submitted to *Economic Geology and Precambrian Research*.

A new research associate or graduate student will be recruited to assist in the interpretation and integration of the geological results with the seismic and magnetotelluric data along the transect. This was delayed due to the pandemic and international travel restrictions.

Anticipated Outcomes

The anticipated outcomes are two MSc theses, one paper in *Economic Geology* describing and proposing a model for the formation of the Hammond Reef gold deposit, a second paper in *Precambrian Research* on the stratigraphy and geochemistry of the rift sequence Steep Rock Group, and a third paper in *Tectonics or Precambrian Research* on integrating the geology of the belt with the geophysical MT and seismic results along the transect.

In addition to MSc students Fouillard and Farhat, three undergraduate students were trained in the basic tenets of geological mapping and scientific research, and one additional graduate student and/or research associate plus two undergraduate field assistants will be trained by the end of the project.

MSc student Gabrielle Fouillard and Dr. Bruno Lafrance observing a quartz vein hosted in the Marmion Shear Zone - Marmion Lake, Atikokan, summer 2021.

Laurentian University MSc student Mohamed Farhat (left) with field assistant Nicholas Lucas (now pursuing PhD studies at Cambridge University) on the outskirts of the city limit of Atikokan, Ontario, in summer, 2021. *Photo: Bruno Lafrance*

Implications

The research indicates that orogenic gold deposits in the less-endowed Wabigoon subprovince formed earlier and equally along belt-transverse and –parallel major structures, in contrast to orogenic gold deposits in the well-endowed Abitibi subprovince where most deposits occur along major belt-parallel faults or breaks.

Highlights

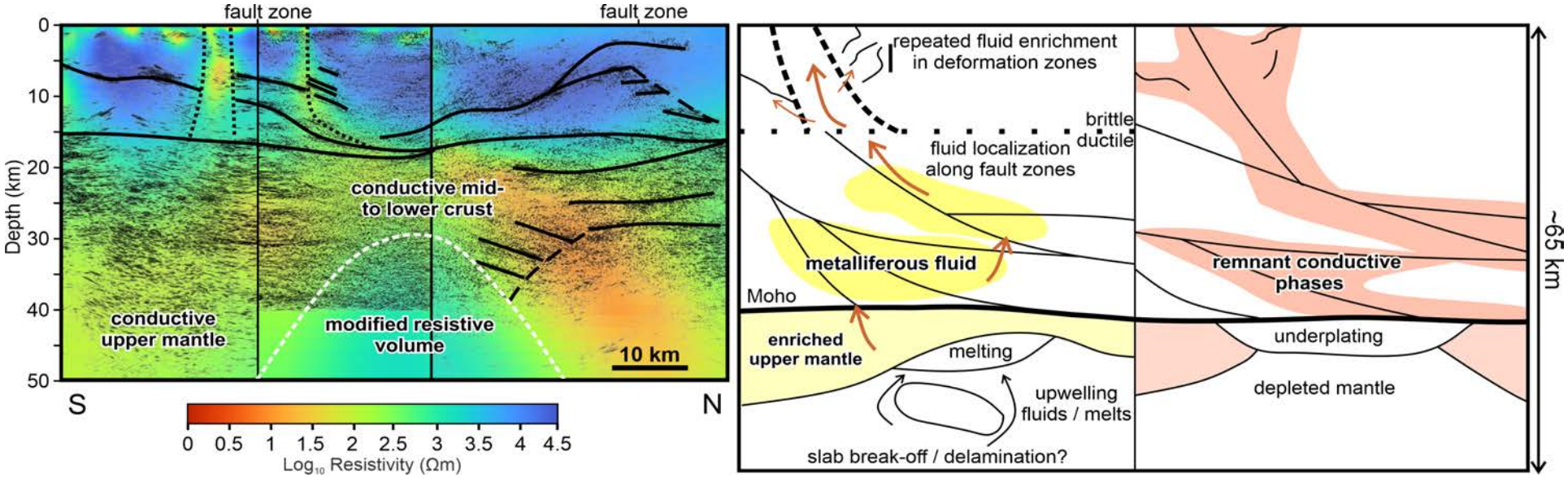
The research on the **Steep Rock** sequence provides a robust and discrete age for rifting during the early NeoArchean. This event can be correlated across the Wabigoon subprovince, and possibly the Superior craton, and thus represents a major tectonic event in the evolution of the Superior craton.

The research on the **Hammond Reef** gold deposit indicates that it formed along a contractional step-over-zone between two major, sinistral, transcurrent faults. As such, its setting is similar to major Archean gold camps in Australia. These results are beneficial to mineral exploration as they explain how gold deposits formed along transcurrent fault zones in the Wabigoon subprovince and provide new targets for mineral exploration.

WATCH NOW!
Fabiano Della Justina - Confident estimates of the Porcupine Destor fault dip angles at depths of a few km, April 2022 Partner Meeting

Geophysics in the Metal Earth Project

Lead Researcher: Richard Smith, Laurentian University



Graphical Abstract: Magmatic, hydrothermal and ore element transfer processes of the southeastern Archean Superior Province implied from electrical resistivity structure, Eric Roots, *Gondwana Research*.

Progress

The paper describing William McNeice's MSc thesis on the usefulness of outcrop magnetic susceptibility measurements was accepted for publication in May 2022.

PhD student Fabiano Della Justina has been working on 3D gravity modelling methods during the last year, using data from the Matheson area. He found that unconstrained modelling gives geologically unrealistic results. It is possible to get realistic results when the depth to the base of the Porcupine Basin is constrained by seismic data. The results in this case are realistic and can be used to infer the thickness of other outcropping material when the surface geology is used as a constraint. However, the results are not completely consistent with previous interpretations, as a seismic reflector is not explained in the density model. If this reflector is hypothesized to be the top of the Deloro assemblage, then the 3D inversion can be used to show that the Deloro gets shallower to the west. In order to get this result, the base of the Porcupine must be remodelled with a 2D assumption and then used as a constraint.

Rajesh Vayavur is working on 3-D potential-field inversion modelling of Metal Earth transects. Inverse modelling for the following traverses has been completed: Malartic, Chicobi (Malartic sub-transect), Swayze, Matheson, Rouyn-Noranda, Sturgeon, Larder Lake, Cobalt, and Timmins. Work is in progress for remaining transects. The results are provided to various transect research

associates for collaborative publications. Independent of this work, Vayavur has been modelling the Chicobi transect to show the utility of density constraints. This work is for a paper that will be resubmitted to *Exploration Geophysics*.

Vayavur is also using geophysical data to unravel the deep structure below the Sudbury Basin and a paper is in preparation on this topic.

The MT data collected on the original Metal Earth traverses has been processed and inverted and has been incorporated into the interpretations for the various transects. One manuscript on the interpretation of the Chibougamau traverse will be submitted to a journal soon.

The MT data more recently acquired at Geraldton, Red Lake, and Timmins has been inverted by research associate Ademola Adetunji and PhD student Eric Roots. At Timmins, the data shows that the upper crust (0 to 10 km depth) is generally resistive, but there are a number of relatively conductive features within the upper crust. These features correspond to, or are parallel to, major crustal structures such as the Porcupine Destor deformation zone and the Buskagau River deformation zone. In many cases one of these more conductive features corresponds to the location of a known deposit.

A manuscript describing the results in the Red Lake area will be submitted to the journal *Geology*.

VIEW OR DOWNLOAD
Research Output: *Active and Passive Seismic Imaging of the Central Abitibi Greenstone Belt, Larder Lake, Ontario, Journal of Geophysical Research: Solid Earth, Feb 2022*

Highlights

This year nine papers that have geophysics students and RAs as their first author have been published or accepted for publication. This adds to two reported last year. Plus, there are seven others currently in preparation or under review.

Hossein Jodeiri Akbari Fam successfully defended his PhD thesis.

New methods have been tested and developed for crooked line seismic processing in a hardrock environment. 3D-CM, 2.5D and 3D multifocusing. The efficacy of these methods will depend on the geology, noise and survey line geometry, so all are important tools in the geophysicist's toolbox.

Eric Roots who is working on the magnetotelluric inversion, has published a conductivity model for the Abitibi Greenstone belt and is working on a model for the Western Superior. This model is a little more complex in that it requires explaining a shift in the fabric from east-west to north-south at different depth that may be a consequence of anisotropy.

On the Swayze East traverse, several different seismic processing approaches including 2D pre-stack dip-moveout (DMO), 3D pre-stack time migration (PSTM), and 3D pre-stack depth (PSDM) migration were tested on crooked-line seismic data. The best results were obtained when employing 3D PSDM processing with coherency migration (3D-CM). This research is a collaboration of Metal Earth with our partners at Smart Exploration (Freiberg University, Germany, and Uppsala University, Sweden). The results of this research were published in an October 2022 paper in *Geophysical Prospecting*.

One paper on technical aspects of the seismic method was published in the journal *Tectonophysics* in June 2022. This paper discusses the ability of the reflection seismic method to identify major crustal structures in the Abitibi Archean greenstone belt. These structures are subvertical or dipping and not always possible to image directly but can sometimes be inferred where interfaces are truncated at a fault.

PhD student Brian Villamizar (University of Western Ontario) worked on full-waveform inversion of seismic data, which has the potential to directly image sub-vertical structures when there is a velocity contrast at or across the fault. Brian's PhD thesis clearly showed some fault structures at Larder Lake and in the north range of the Sudbury Basin.

An improved method of imaging structures is to combine seismic data and gravity data, as both methods depend on the density and gravity to image subvertical structures where seismic is better suited to shallow dips. Christopher Mancuso, in his PhD project, is planning on combining these two data and jointly inverting to image problematic crustal structures. Preliminary results show that the velocity structure is well resolved and can be used to improve the processing of the seismic data.

WATCH NOW!
Brian Villamizar - Structural imaging - 2D/2.5D waveform inversion & azimuthal binning, Larder Lake, April 2022 Partner Meeting

WATCH NOW!
Hossein Jodeiri Akbari Fam - Developing high-resolution multifocusing seismic imaging algorithms, April 2022 Partner Meeting

Improved methodologies for imaging crooked line reflection seismic data have been developed by Hossein Jodeiri Akbari Fam, who graduated with his PhD in May 2022. These include 2.5D and 3D multi-focusing methods. The 2.5D method works well on crooked seismic lines but requires that the data be reduced to a flat datum prior to the processing. The 3D approach can potentially give better results and does not require reducing to a flat datum, as the algorithm can take variable source and sensor elevations into account. However, a high-performance computer is required to run the 3D algorithm due to its computational complexity. The proposed methods can also extract 3D structural information, which provides supplementary information for interpretation and reduces uncertainty in creating geological models. The 2.5D algorithm was published in November 2021 and the 3D algorithm has undergone a round of reviews.

Anticipated Outcomes

The work by Della Justina has helped to understand the deep structure in the Matheson area and has shown the importance of constraints, particularly seismic interfaces in resolving this deep structure. Physical properties and the surface geology alone would not have resolved the geometry of the Deloro in this area.

McNeice's work will provide guidance as to how to use magnetic susceptibilities when modelling magnetic data.

Roots' work shows that anisotropy is present in the western Superior and this has implications for the tectonic construction or geodynamic history of the western Superior province. Similarly, the MT work in Chibougamau will provide evidence for the geodynamic history of the eastern part of the Superior province.

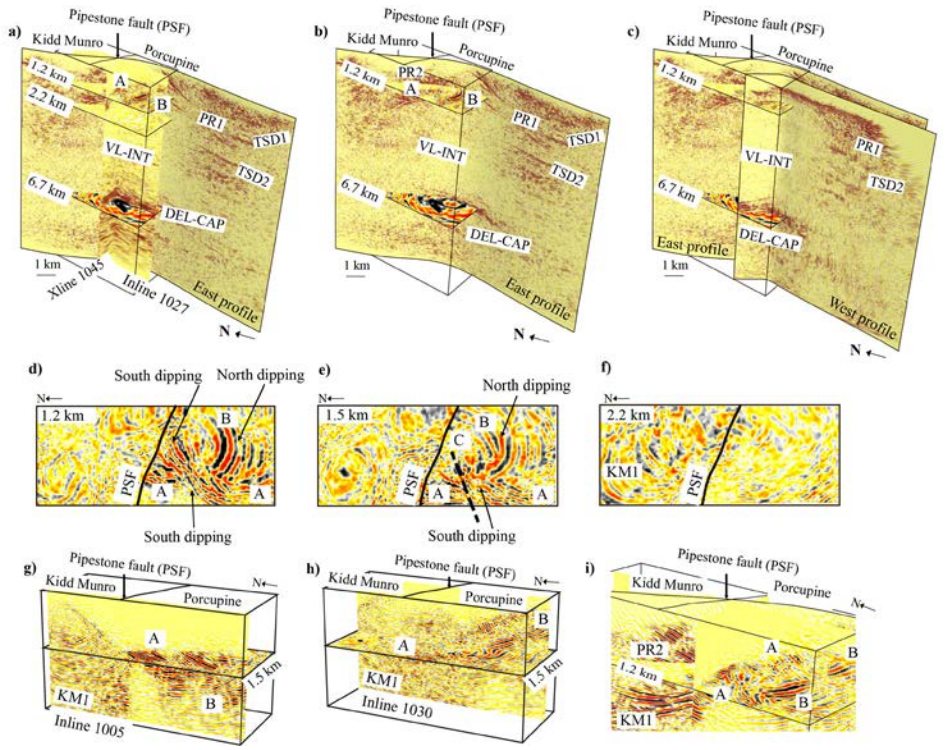
The meta-analysis of the seismic data in all the Metal Earth traverses, will give an indication of the differences between the western and eastern Superior and this could be used to better understand the differences in the metal endowment of the two sides of the Superior.

Implications

Due to Metal Earth, the magnetotelluric method is becoming a standard tool for exploration in greenstone belts, to understand the location and geometry of major crustal structures. Industry is interested in improving the method.

The improved images we are seeing from seismic traverses is helping to understand the crustal structure and its association with mineral systems in Archean terrane.

The 3D gravity inversions and corresponding 3D iso-surface models are helping transect research associates to refine upper-crustal architecture interpretation.



Seismic images from pseudo migrated cube. a) Three-dimensional perspective view along inline 1027, crossline 1045 (Figure 1 shows the location), and depth slices at 1.2 km, 2.2 km, and 6.7 km. b) Migrated section from the east profile showing its intersection with depth slices at 1.2 km and 6.7 km from the pseudo 3D migrated cube. c) Migrated section from the west profile showing its intersection with depth slices at 1.2 km and 6.7 km. d) Depth slice at 1.2 km. e) Depth slice at 1.5km. f) Depth slice at 2.2 km. g) Inline 1005 section and depth slice at 1.5 km. h) Inline 1030 section and depth slice at 1.5 km (Figure 1). h) Surface location of the Pipestone fault (PSF) with zoomed view of (a) near the PSF down to depth of ~ 2 km.

Source: Cheraghi et al. Addressing geometrical attributes and seismic imaging capability of fault systems in a world-class metal endowed region: Abitibi Greenstone Belt, Canada, 2022, Tectonophysics, 883, 229361.

VIEW OR DOWNLOAD
Research Output: *2.5D multifocusing imaging of crooked-line seismic surveys; Geophysics, 2021*

VIEW OR DOWNLOAD
Research Output: *Transformation of magnetic data to the pole and vertical dip and a related apparent susceptibility transform: exact and approximate approaches; Geophysics, Dec. 2021*

Gold Fluid Window

Carl Guilmette, Université Laval and Doug Tinkham, Laurentian University

WATCH NOW!
Gold Fluid Window: Updates, April 2022 Partner Meeting

Garnet in leucosome, north of Manitouwadge, Quetico province. *Photo: Adrian Rehm*

Progress

This reporting period constitutes the second year of the Gold Fluid Window Metal Earth thematic project. The research is primarily performed by three HQP, including a research associate, Antoine Godet, and two Ph.D. students, Adrian Rehm and Diogo Ribeiro. This period was dedicated to further data acquisition, fieldwork, and writing of manuscripts.

The second fieldwork campaign of the project was conducted during summer 2021 in both the Quetico and the Pontiac metasedimentary belts. Metamorphic isograds were mapped in the Geraldton and Thunder Bay areas. More than 400 outcrops were described and about 250 samples were collected.

Laboratory analyses included collection and interpretation of approximately 200 thin sections, 250 whole-rock analyses, in-situ EPMA analyses of minerals, 50 µXRF scanning maps, U-Pb zircon and monazite dating (LASS-IPC-MS) on eight granitoids samples, and 143 Au ultra-low detection limit (PPP-LA-ICP-MS) analyses.

Interpretations of initial results were presented at the 2022 GAC-MAC conference and in Metal Earth scientific review sessions.

Future Work

- Acquire LASS-ICPMS analyses on datable accessory phases from metasedimentary, metabasite and granitoid samples from the Quetico subprovince to constrain the timing of metamorphism igneous crystallization of select bodies
- Acquire quantitative trace element maps of garnet and staurolite from both transects performed in the Quetico (Geralton and Thunder Bay)
- Obtain Lu-Hf isotope ages of garnet growth from both transects performed in the Quetico (Geralton and Thunder Bay) to determine the timing of garnet growth metamorphism, and link those ages to phase equilibrium calculations to constrain timing of metamorphic fluid production

- Planning and completing the third fieldwork campaign that will focus on the Grenville tectonic front, south of Louvicourt (Quebec).

Anticipated Outcomes

This project will generate a new understanding of the metamorphic and tectono-thermal evolution of the Quetico and Pontiac basins. These basins 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 data set 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 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 and Pontiac had similar or differing depositional and tectonometa-morphic evolutions, and how this may have affected endowment in the neighboring structures and subprovinces

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.

Research associate Antoine Godet taking notes on an outcrop in Quetico subprovince, north of Thunder Bay.

Highlights

Successful fieldwork was conducted in both the Quetico and the Pontiac metasedimentary belts.

Acquired ultra-low detection limit (PPP-LA-ICP-MS) Au analyses that yielded very interesting results. In well-endowed areas (Geraldton and Rouyn Noranda transects) a significant Au depletion through the increase of the metamor-phic grade is observed, suggesting Au was mobilized during metamorphism. In contrast, in the barren area (Thunder Bay transect) no depletion of Au was observed across the different metamorphic isograds.

Diogo Ribeiro received two grants from the E4m Centre of $2000 and $250 for his PhD project and to attend the GAC-MAC 2022 conference in Halifax, respectively.

The preliminary results were presented at GAC-MAC 2022 conference by Diogo Ribeiro and Adrian Rehm.

Adrian Rehm received a Queen Elizabeth II Scholarship in Science and Technology, valued at $15,000.

VIEW OR DOWNLOAD
Precambrian Research: Synsedimentary rifting and basaltic-komatiitic volcanism in the Pontiac subprovince, Superior craton (Canada): Implications for Neoarchean geodynamics, Adrian G. Rehm, Taus R.C. Jørgensen, Phil C. Thurston, Harold L. Gibson, Bruno Lafrance

WATCH NOW!
Györgyi Tuba - Barren vs Auriferous Alteration Assemblages in the Larder Lake - Virginiatown Area, March 2021 Partner Meeting

Alteration systematics of barren vs gold-mineralized assemblages along the Larder Lake-Cadillac deformation zone/Larder Lake transect

Lead researchers: Györgyi Tuba and Ross Sherlock, Laurentian University

Channel sampling Timiskaming conglomerate in the Fernland deposit area. Pictured (L-R): Research associate Györgyi Tuba and MSc student Logan Foucault.

Progress

In year six, a regional sampling campaign in the Larder Lake - Virginiatown area was conducted. As a result, about 150 samples of various lithologies were collected along strike and distance profiles of the Larder Lake-Cadillac deformation zones to geochemically and petrographically characterize the variability in alteration style and intensity in the region. In addition, new drill intersections at the Kerr-Addison deposit representing a previously inaccessible mineralization type were logged and sampled. Preliminary geochemical results and interpretation were processed. The manuscript for the first publication of the project was also started.

Implications

The project involves the study of both barren and mineralized alteration assemblages as well as deposits that are virtually identical in geologic setting but very different in gold endowment.

Highlights

Collaboration and data sharing with local exploration companies (in-kind partners) is helping to build a more accurate deposit model. Processing of geochemical data acquired by the industry with an in-depth understanding of the background processes gives them an exploration tool specifically tailored to their deposit.

WATCH NOW!
Haiming Liu: Apply machine learning techniques for data integration modelling in Larder Lake area, April 2022 Partner Meeting

WATCH NOW!
Györgyi Tuba: Update on Phase 2 of the Larder Lake – Virginiatown Alteration Footprint Study, November 2021 Partner Meeting

Factors contributing to metal endowment in the western Wabigoon and Abitibi subprovinces: a mineral prospectivity modelling approach for Precambrian greenstone belts

Lead researcher: Stéphane Perrouty, Laurentian University

WATCH NOW!
Rebecca Montsion - Factors contributing to metal endowment in western Wabigoon & southern Abitibi, March 2021 Partner Meeting

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

Progress

Using the geochemical database generated last year and statistical learning methods, a new 5-dimensional classification scheme was defined for Archean igneous rocks. The manuscript outlining the application of this tool and its associated database release are in the final stages of internal review. Significant sensitivity testing and comparisons to several other Archean greenstone terranes delayed release but improved confidence in the classification scheme's applicability to other geological settings.

Thirty-three explanatory variables (a.k.a., feature maps) were generated to compare the importance of key geological features in magmatic Ni-Cu-PGE, volcanogenic massive Cu-Zn-Pb±Au sulfide (VMS), and orogenic Au systems were captured using novel feature engineering techniques. Importance was ranked for each system using random forests

trained on known mineralization independently in the Timmins and Dryden map areas. The generation of explanatory variables leveraged petrophysical data, new geochemical classification tools (paper 2), and new non-Euclidean (i.e., fluid path) distance measurements.

Random forests mineral prospectively method was trained on known magmatic Ni-Cu-PGE, VMS Cu-Zn-Pb±Au, and orogenic Au mineralization in the Timmins and Dryden areas. This yielded a ranked feature list for each respective map area, which are being compared to draw conclusions about the presence/importance of factors controlling mineralization in the southern Superior Province.

Future Work

A detailed comparison between feature rankings will be performed in fall 2022.

A manuscript outlining the workflow and discussing differences between the two areas is being generated.

Anticipated Outcomes

The major outcomes of this research will be the identification and ranking of factors controlling mineral distribution in greenstone belts. Results will guide

Stéphane Perrouty walking an old forestry cut in Dryden, Ontario.

recommendations on methods that efficiently delineate areas of interest in greenstone belts and prioritizing exploration datasets. Deliverables associated with this work include new geological maps, compiled structural and outcrop database, geochemical database, re-processed geophysical maps, 33 geological feature maps, ranked feature lists for Timmins and Dryden.

Benefits to mineral industry

- New geochemical classification scheme (ultramafic to felsic compositions) for Precambrian igneous rocks regardless of alteration / weathering and texture (i.e., intrusive, extrusive)
- Three new rock favourability indices (magmatic Ni-Cu-PGE, VMS Cu-Zn-Pb±Au, orogenic Au) regardless of alteration/weathering, texture (i.e., intrusive, extrusive) and rock compositions (i.e., ultramafic to felsic)
- New quantitatively based methods for early-stage mineral exploration (feature engineering methods for mineral prospectivity)
- Recommendations for prioritizing exploration data to gather and how to leverage existing databases

Implications

This thematic project is a comparative study utilizing innovative and novel approaches to qualitative understanding which factors control mineralization in the western Wabigoon and southern Abitibi subprovinces of the Superior Province. The study's objective, to compare a modestly endowed region (western Wabigoon) to the world-class southern Abitibi district, follows the Metal Earth plan to understand the controls on mineralization in the Archean greenstone belts. The application and development of new tools such as statistical learning (data science), multi-disciplinary integration (e.g., field geology, GIS, geophysics, geochemistry), and machine learning techniques are generating tools that will improve exploration methods for industry.

Highlights

PhD awards

Northwestern Ontario Scholarship (2021), Young Mining Professionals & Alamos Gold

CSEG Foundation Award (2020), Canadian Society of Exploration Geophysics (CSEG)

Michael Smith Foreign Study Grant (2020) Natural Sciences and Engineering Research Council of Canada (NSERC)

Post-Graduate Scholarship (2020) Natural Sciences and Engineering Research Council of Canada (NSERC)

Queen Elizabeth II Graduate Scholarship in Science and Technology (2020) Canadian Federal Government

Best presentation in Economic Geology (2019), GSA Earth Sciences Student Symposia, Perth, Australia

Innovation in Mining (2019) Young Mining Professionals (YMP) and Orefinders

Joan Bath Bursary (2019), CSM Global and Prospectors and Developers Association of Canada

Goodman School of Mines PhD Fellowship (2018)

Publications

Montsion, R M, Perrouty, S, Lindsay, M D, Jessell, M W, Frieman, B M, 2021, Mapping structural complexity using geophysics: A new geostatistical approach applied to greenstone belts of the southern Superior Province, Canada, *Tectonophysics*. Pg. 228889. doi.org/https://doi.org/10.1016/j.tecto.2021.228889

Montsion, R M, Perrouty, S, Frieman, B M, 2021, Geological and geophysical data compilation for the western Wabigoon and southern Abitibi subprovinces of the Superior Province, Ontario, Canada, *Data in Brief*. 37, 107159. doi.org/10.1016/J.DIB.2021.107159

Montsion, R M, Perrouty, S, Lindsay, M D, Lesher, C M, in prep for submission to *Journal of Geochemical Exploration*, Statistical optimization for 5D classification of Archean igneous rock and application for exploration targeting

WATCH NOW!
Chong Ma - Structures and kinematics of an auriferous shear zone system, April 2022 Partner Meeting

Western Extension

Lead Researchers: Chong Ma, Bruno Lafrance, and Stéphane Perrouty, Laurentian University

Progress

This was the second field season for this project. Detailed geologic mapping was conducted in three key areas: the Red Pine property in the Jubilee Stock area (Michipicoten greenstone belt), the Wesdome property in the Mishi and Eagle River mines (Mishibishu greenstone belt), and the Ridout deformation zone of the Swayze greenstone belt.

Field data collection including large-scale geologic maps of key outcrops, deformation and kinematic data, stratigraphic columns of selected conglomeratic units, and cross-sections of representative units, is complete.

Completed analyses of zircon U-Pb, Lu-Hf, and trace element for 22 samples from 2021.

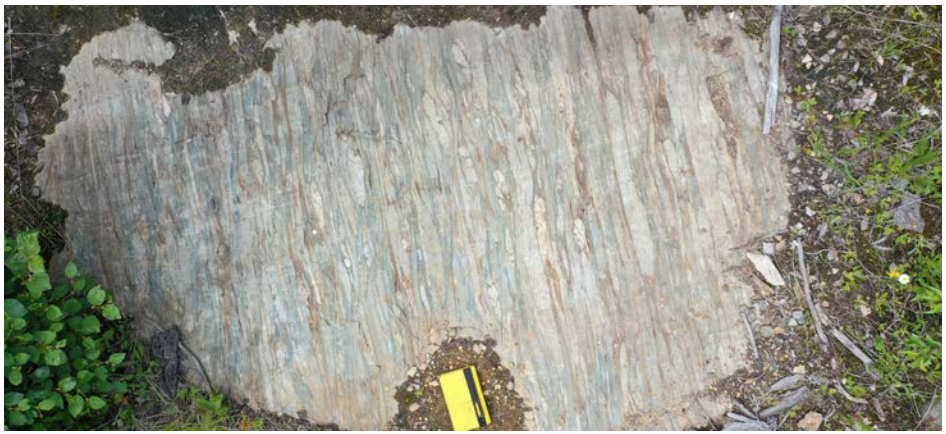
About 30 oriented and 60 regular samples were sent out for thin sections; about 60 samples were sent out for whole-rock geochemistry. A total of 41 samples were sent out for zircon separation in 2022, which will be analyzed for zircon U-Pb, Lu-Hf, and trace element by laser ablation.

Highlights

The mapping in the Ridout deformation zone of the Swayze greenstone belt this summer suggests that the conglomerate unit in the area is part of the Timiskaming basin in the Larder Lake area, which is based on the compositions of clasts and the depositional age according to literature data. The mapping also confirms that the deformation style and history of the Ridout deformation zone is nearly identical to those of Larder Lake-Cadillac deformation zone.

Therefore, the Larder Lake-Cadillac deformation zone at least extends to the Swayze greenstone belt. A summary of the detailed dataset will be presented.

Timiskaming conglomerate outcrop along the Metal Earth Swayze east R2 seismic line. *Photo: Chong Ma*



Highly strained Timiskaming conglomerate in the Ridout deformation zone. *Photo: Chong Ma*

WATCH NOW!
Magmatic Cr-Ni-Cu-PGE Thematic Projects, March 2021 Partner Meeting

Superior Margin Ni-Cu-PGE – Raglan Thematic Project

Lead Researcher: Michael Lesher

Progress

The Circum-Superior whole-rock lithogeochemical compilation was updated and includes ~34,600 unique whole-rock analyses for the Cape Smith Belt (62%) and surrounding domains in Nunavik, as well as the Thompson Nickel Belt, Labrador Trough, Roberts Lake Syncline, Belcher Fold Belt, Richmond Gulf, Sutton Inliers, Fox River Belt, Winnipegosis Komatiite Belt, Lake Superior Region, and various dyke swarms. The database is planned for publication as a Geological Society of Canada Open File report.

An assay database for mineralized samples in the Cape Smith Belt was completed and contains 430,000 unique analyses.

150 samples collected during this study were analyzed for trace elements and QA/QC was completed.

Thin sections of drill core collected during the 2019 field season were scanned and petrographic examination was completed.

In-situ mineral analyses (olivine) by EM-PA-SEM for major-minor elements was completed, including 1450 analytical points from 483 grains in 120 samples.

Future Work

McKevitt had some unavoidable delays completing planned work in 2021-2022. Remaining work includes writing three journal manuscripts for submission as the thesis, the first of which will be an expanded version of a GSC Open File Report.

Anticipated Outcomes

Better understanding of the geochemistry and petrogenesis of mafic-ultramafic rocks in the Cape Smith Belt, New Québec and similarities to and differences from other parts of the Circum-Superior Belt

Delineating the subvolcanic plumbing system in the Cape Smith Belt, including petrogenetic and therefore spatial relationships between the Raglan, Delta, and Expo Ungava-Méquillon parts of the system

PhD student Dylan McKevitt conducting fieldwork in July 2019, Cape Smith Belt, northern Quebec (Lat: 61.4769898333; Long: -73.842864). *Photo: Michel Houle*

Determine the ability of olivine (which is rarely preserved in the Cape Smith Belt and therefore understudied) to constrain the petrogenesis of the mafic-ultramafic rocks in the Cape Smith Belt

Implications

At the craton scale, the results from this study will be integrated with our previous work in the Thompson Nickel Belt and previously published work for other parts of the Circum-Superior Belt to better understand why some parts of the Circum-Superior Belt (e.g., Ragan, Thompson) contain world-class Ni-Cu-PGE mineralization, why some parts (e.g., Expo-Méquillon, Labrador Trough) are only moderately mineralized, and why some parts are only poorly mineralized (remainder). Resolution of such differences is a primary objective of Metal Earth.

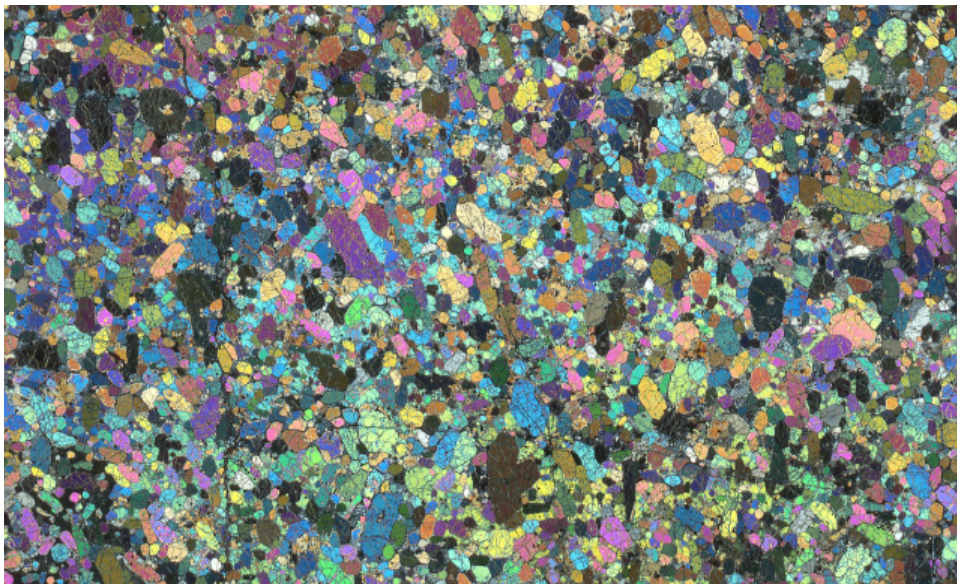
At the regional scale, this study has confirmed that mineralization in the Cape Smith Belt is hosted by channelized lava flows, channelized sills, and channelized dikes that have incorporated sulfide from S-rich sediments, and that the magma that formed all mineralized bodies was derived from similar (likely the same) source region(s) in the mantle, but that the mineralization formed at more-or-less the same time in multiple "parallel" flow-through systems at multiple stratigraphic levels, and did not form in a single "serial" flow-through system. This greatly increases the possibility for finding additional mineralization at similar and different stratigraphic levels. Constraining the reasons for the differences in the magnitudes (Raglan >>> Expo-Méquillon >> Delta) and Ni/Cu ratios (Raglan > Expo-Méquillon >> Delta) of the mineralization will provide additional constraints on the differences between the different segments of the Circum-Superior Belt.

Highlights

The geochemical database, including proprietary analyses from Glencore Ltd. (Raglan area) and Canadian Royalties Ltd. (Expo-Méquillon area) has already been given to the companies. This will expand the size and increase the quality of their databases considerably and – together with our interpretations of the petrogenetic relationships between the mineralized Raglan, Delta, and Expo-Méquillon parts and unmineralized other parts of the system – aid them in mineral exploration in the Cape Smith Belt.

Our results show that the magmas that formed the mineralized parts of the system are fundamentally different from those that formed the unmineralized parts of the system (as shown by our previous work) and that the Expo-Méquillon parts of the system did not feed the Raglan parts of the system (as suggested by other workers).

Check out: McKevitt, D J; Lesher, C M; Houlé, M G, *Regional lithogeochemical synthesis of mafic-ultramafic volcanic and intrusive rocks in the Cape Smith Belt, Nunavik, northern Québec*, in Targeted Geoscience Initiative 5: Advances in the understanding of Canadian Ni-Cu-PGE and Cr ore systems - Examples from the Midcontinent Rift, the Circum-Superior Belt, the Archean Superior Province, and Cordilleran Alaskan-type intrusions; Geological Survey of Canada, Open File 8722, 2020 p. 99-115, doi.org/10.4095/326883



Photomicrograph of an mesocumulate komatiite (olivine peridotite) containing fresh olivine, Raglan Formation (Lowermost Chukotat Group), east-central Cape Smith Belt, Nunavik. wDoubly-polarized transmitted light; field of view ~25 mm x ~40 mm. *Photo: D. McKevitt*

WATCH NOW!
Klaus Kuster - Geochemistry and petrogenesis of komatiitic rocks in the Superior Province, April 2022 Partner Meeting

Superior Cr-Ni-Cu-PGE Thematic Project

Lead Researcher: Michael Lesher, Laurentian University

PhD student Klaus Kuster stands with an outcrop featuring massive chromitite (the darker color rock, from his feet to his shoulders); peridotite occurs above and below.

Progress

- Continued compilation of the litho-geochemistry of komatiitic rocks in the Superior Province (MB-ON-QC). Thus far, more than 11,000 samples are included in the database with ~50% classified as a komatiitic rocks, ~20% as komatiitic basalts, and ~30% associated non-komatiitic basalts.
- Continued compilation of the lithogeochemistry of iron formation facies (sulfide-hematite-magnetite-silicate) in the Superior Province (MB-ON-QC). Thus far, ~2,000 unique iron formation facies and geochemical data have been compiled.
- Compilation of geological and geochemical data of the Shebandowan mine (ON) extracted from public and available private sources.
- Fieldwork, core logging, and sampling in the Ring of Fire (Blue Jay) and Shebandowan areas.
- Submission of samples from Shebandowan and Blue Jay for whole-rock major and trace-element lithogeochemical analyses.

Future Work

- Continue compilation of whole-rock lithogeochemical data for komatiites, komatiitic basalts, basalts, and iron formation facies in the Superior Province. Database work is currently the most advanced topic of the thesis and interpretation and results are intended to be released as a Geological Survey of Canada open file report and a journal publication.
- Field work in the Lac des Montagnes and Lac Fed areas of northern Québec in July 2022.
- Field work in the Ring of Fire area in August 2022 to log and sample drill cores in the Blue Jay (AT-12) and Blackbird areas for inclusions of chromite.

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).

(continued on page 55)

Highlights

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.

WATCH NOW!
Michael Lesher - Genesis of Sublayer and Associated Ni-Cu-PGE Mineralization in the SIC, November 2021 Partner Meeting

Superior Margin Ni-Cu-PGE – Sudbury Thematic Project

Lead Researcher: Michael Lesher, Laurentian University

Progress

Chapter 4 of Wang's PhD thesis "Genesis of Sublayer in the Sudbury Igneous Complex" was accepted for publication in a Special Issue of *Economic Geology* dedicated in memory of Prof. Anthony J. Naldrett, who was a world leader in Ni-Cu-PGE deposits. It was published online in July 2022.

Future Work

The three spin-off projects that were generated from this project, funded by NSERC and Vale Ltd., are progressing well, although they have been delayed by ~12 months due to COVID, the CCAA process at Laurentian University, and access to rental field vehicles.

The PhD student researchers responsible for these spin-off projects are:

- Dustin Peters (PhD Candidate), Genesis of Main Mass, Sublayer Norite, Footwall Breccia, and Associated Ni-Cu-PGE Mineralization on the North Range of the Sudbury Igneous Complex
- Sandra Baurier-Aymat (PhD Candidate), Genesis of Main Mass, Sublayer Norite, Footwall Breccia, and Associated Ni-Cu-PGE Mineralization on the South Range of the Sudbury Igneous Complex
- Henning Seibel (PhD Candidate), Genesis of Offset Dikes and Associated Ni-Cu-PGE Mineralization in the Sudbury Igneous Complex

PhD student Sandra Baurier Aymat stands on rusty massive sulfide breccia in transition to unmineralized Sublayer Norite. Foy Embayment, Sudbury, Ontario, September 19, 2022. *Photo: Henning Seibel*

Anticipated Outcomes

- Better understanding of sources of Ol-bearing mafic and ultramafic inclusions in the Sublayer of the SIC, which are characteristic of mineralized portions of the basal contact of the complex and offset dikes; some are anteliths, or "cognate xenoliths," some are local xenoliths, and others are exotic xenoliths
- Determination of an intermediate crustal depth of formation for the exotic Ol-bearing mafic and ultramafic inclusions in the Sublayer of the SIC, which is different from recent models proposing deep or shallow levels of impact excavation
- Better understanding of the relationship between these inclusions and mineralization, which appears to be due to the more refractory nature of ultramafic inclusions and their hydrodynamic equivalence to 1-3 cm diameter sulfide melt droplets, their formation during thermomechanical erosion of footwall rocks, and emplacement as congested suspensions during gravity flow
- Wang's 2022 paper in *Economic Geology* integrates these results to provide additional constraints on the impact history of the SIC and the genesis of the associated Ni-Cu-PGE mineralization.

Implications

The Sudbury (ON), Raglan (QC), and Thompson (MB) Ni-Cu-PGE camps all occur along the margin of the Superior Craton and are all much better endowed than the much smaller (albeit higher grade) deposits within the Superior Craton (e.g., Abitibi, Shebandowan). All can be attributed to the emplacement of mantle-derived

Highlights

Wang graduated in Dec 2019 and has published three papers in high-profile journals: one in *Geology* (one of the top general geoscience journals) and one in *Journal of Petrology* (the top petrological journal), and one in *Economic Geology* (one of the top mineral deposits journals).

The *Geology* paper that the exotic xenoliths show impact shock textures with mineral compositions that indicate middle-crustal depths of equilibration, not very shallow or very deep impact as proposed in previous studies.

Most other magmatic Ni-Cu-PGE sulfides form by incorporation of sulfide xenomelts from crustal sources and this study has shown that this also applies to Sudbury, even though it formed from a crustal impact melt rather than a mantle-derived magma.

Many other magmatic Ni-Cu-PGE sulfides are associated with mafic-ultramafic inclusions, which are typically poorly characterized. This study has shown that the association is attributable less to fluid-dynamic controls and more to survivability.

Fluid dynamic constraints suggest that the Ni-Cu-PGE mineralization in the SIC likely did not form by gravitational settling of exsolved sulfide droplets from and through the Main Mass impact melt sheet (too slow, wrong timing), which has been long considered to be the prevailing model, but more likely by thermomechanical erosion of sulfides in brecciated footwall rocks at the base of the melt sheet that were generated during formation and collapse of the central peak ring. Most of the current exploration models for Sudbury rely on very well-established empirical associations, but the results of this project completely change the model for ore genesis and localization, which reopens some of the empirical observations (e.g., metal depletion in the Main Mass, ore localization in footwall embayments) to different interpretations and therefore different applications in exploration.

VIEW OR DOWNLOAD
Research Output: *Wang, Y, et al. Genesis of Sublayer, Footwall Breccia, and Associated Ni-Cu-Platinum Group Element Mineralization in the Sudbury Igneous Complex, Economic Geology (2022) 117 (8): 1791-1807.*

magmas (Nipissing and East Bull Lake intrusive suites in the case of Sudbury) being focused along the craton margins. In the case of Raglan and Thompson (and all deposits other than Sudbury), the mineralization formed in the magmas as they were emplaced into sulfide-rich, but generally metal-poor country rocks and generated Fe-sulfide xenomelts that interacted with the magma to increase the Ni-Cu-PGE contents.

In the case of Sudbury, the impact melted older but similar and generally lower-grade Ni-Cu-PGE mineralization in 2.4 and 2.2 Ga mafic intrusions, forming Fe-Ni-Cu-PGE xenomelts.

The differences in endowment (Sudbury >>> Thompson ~ Raglan >> other deposits) reflect the size and thermal energies/efficiencies of the systems (meteorite impacts >>> thicker channelized sills and lavas >> smaller/thinner channelized sills/lavas).

As we have previously shown, the depths and compositions of the magma sources, and the final compositions of the magmas affect Ni/Cu/PGE ratios, but not ore genesis. Better understanding of these differences in metal endowments are a fundamental objective of Metal Earth.

Continued from page 53 - Superior Cr-Ni-Cu-PGE Thematic Project

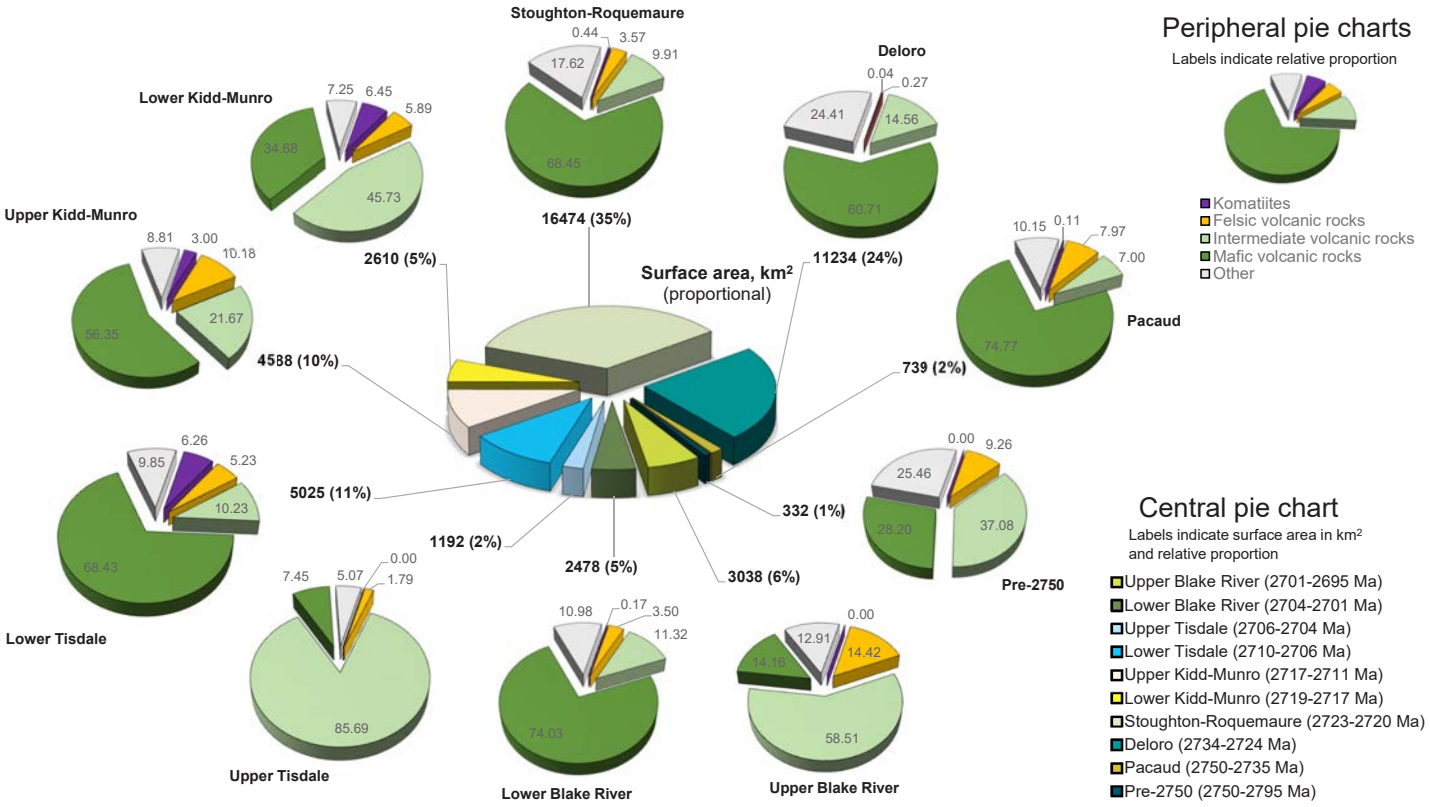
- Better understanding of the controls on formation of Cr mineralization in komatiitic magmas and the influence of magma composition (komatiite vs komatiitic basalt vs basalt) and relationship (if any) to particular facies of iron formation

Implications

There is a recently discovered and very 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 differences between more mineralized and less mineralized terranes is a fundamental goal of Metal Earth.

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



This figure shows a central pie chart representing the estimated surface area of each volcanic assemblage in the Abitibi subprovince. The smaller peripheral pie charts represent the calculated relative proportions of komatiitic, mafic, intermediate, and felsic volcanic rocks of each volcanic assemblage. These estimates were facilitated by the construction of the assemblage-scale and lithological compilations of the Abitibi subprovince.

Progress

A lithological compilation for the Abitibi Greenstone Belt was generated across Ontario and Quebec. The compilation relies mainly on the mapping carried out over the years by the Quebec (~1:20,000 scale) and Ontario (~1: 50,000 scale) geological surveys and consist of >50,000 polygons. Importantly, it shares a common legend across the Ontario-Quebec boundary that allows for estimating geological features for the entire Abitibi. The legend merger was done by translating the Quebec legend that contains 135 legend entries for the Abitibi region in Quebec, into the Ontario legend that comprise ~20 legend entries for the Abitibi region in Ontario. The lithological compilation was used in conjunction with the previously generated assemblage-level compilation to quantify geological features (e.g., ultramafic, mafic, intermediate, and felsic volcanic rocks) within each Abitibi volcanic assemblage facilitating a comparison between richly-endowed and poorly endowed assemblages.

Progress concerning the comparison with the modern ocean floor (Metal Oceans) consists of the development of a proxy table. This table attempts to assign proxies for assemblages and their formation types in a modern oceanic arc to back-arc setting to facilitate a comparison to the ancient environment where the geological features are predominantly going to be based on their lithological and geochemical nature.

Future Work

- Continued refinement of the Abitibi greenstone belt compilations and quantification of the geological attributes.
- Compare and contrast assemblages and use the quantitative analyses to investigate the relationship to major structures and VMS deposits, including Au-rich VMS.
- Perform a pre-deformation palinspastic reconstructions to identify unique combinations of geological events or conditions that correlate with VMS endowment and allow comparison with the modern ocean floor (Metal Oceans)

Anticipated Outcomes

As an outcome, the project aims to improve on the VMS model that is mainly based on deposit to district scale research. The 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 there are fundamental differences in assemblage-scale tectonic, magmatic and crust-mantle processes that impact metal endowment during greenstone belt construction.

This research will improve on our understanding of these fundamental controls on VMS endowment, and provide new insights into Archean tectonics and metallogeny.

Implications

The 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 compliments Metal Earth's Transect, Craton, and Metal Ocean research.

Highlights

An assemblage-level and lithological compilations of the Abitibi greenstone belt that includes the Quebec and Ontario sides will be useful to companies doing exploration in the area and might serve as the backbone of many scientific breakthroughs relying on big datasets.

WATCH NOW!
Taus Jorgensen - Quantifying geological features using an assemblage-level compilation of the Abitibi Greenstone belt, April 2022 Partner Meeting

VIEW OR DOWNLOAD
Research Output: *Jorgensen, T. R. C., Gibson, H. L., Roots, E. A., Vayavur, R., Hill, G. J., Snyder, D. B., & Naghizadeh, M. (2022, Aug 29). The implications of crustal architecture and transcrustal upflow zones on the metal endowment of a world-class mineral district. Sci Rep, 12(1), 14710.*

Petrogenetic Evolution of the Abitibi Greenstone belt

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

WATCH NOW!
Octavio Vite-Sanchez - Mafic volcanic rocks of the Blake River Group, April 2022 Partner Meeting

Taus Jørgensen (left) and Octavio Sanchez-Vite observing an outcrop, Chapais area in the northeastern part of the Abitibi Greenstone belt province.

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 subproject 1b is therefore to compare variably VMS endowed volcanic assemblages within the Abitibi Greenstone Belt (AGB), focusing on geochemistry and petrogenetic evolution. By combining our results with those of subproject 1a (which will compile other assemblage-scale attributes, including volumes of volcanic products, area-age relationships, etc.), we hope that we can identify the unique combinations of geological events or conditions that correlate with regional VMS endowment.

During the period April 1, 2021 to March 31, 2022, the following work has been done:

- Continued geochemical compilation of volcanic rocks in the AGB using government, academic and industry sources. We are still waiting for about 3000 analyses from the Ontario Geological Survey.
- Field work in the Abitibi Greenstone Belt: about 10 weeks total, covering the Chapais area in the NE (oldest volcanic assemblages, i.e. pre-2750 Ma, including the Des Vent Formation and the Chrissie Formation), and the Gemini-Turgeon area north of La Sarre (Théo Formation, possible equivalent to the Pacaud Assemblage in Ontario). We collected 227 rock and core samples that were sent to ALS for geochemical analyses. Furthermore, 12 archive pulp samples from the pre-2750 Ma Fecteau Formation (S of Chapais) were also reanalyzed to get better precision on the trace elements. All of this new data fills stratigraphic and geographic gaps in the current geochemical database of the Abitibi.

Taus Jørgensen, who is in charge of subproject 1a, visited us in Chapais for about a week. This allowed great discussions in the field and will facilitate continued strong collaboration between subprojects 1a and 1b.

The geochemistry of volcanic rocks in the Blake River assemblage was further interpreted, and compared with VMS endowment in different areas of the Blake River Group. Some petrological processes were modelled. This work was presented at the Partners Meeting in April 2022. There seems to be a spatial association between contaminated mafic volcanic rocks and VMS endowment, for example in the Noranda camp and the Doyon-Bousquet-LaRonde camp.

BSc student Enza Magnier, who worked for INRS as a summer student in 2021, looked at thin sections from the Théo Formation for her BSc thesis at UQAM. She described the petrography, alteration and metamorphism of the volcanic rocks. This information will be integrated in project 1b, specifically in PhD student Octavio Sanchez-Vite's second paper (see below).

Future Work

Future work (April 2022 to end of project) is planned as follows, with each step yielding a publication in an international journal:

The mini-project on geochemistry of mafic to intermediate volcanic rocks in the Blake River assemblage will be completed. We will also try to look at felsic volcanic rocks.

A paper will be written on the very poorly known geology and geochemistry of the oldest volcanic assemblages in the AGB in Quebec, based largely on new data.

VMS endowed volcanic assemblages will be geochemically compared to those with less or no endowment.

Anticipated Outcomes

VMS project 1, including subproject 1b, will produce a better understanding of the constructional history of the Abitibi greenstone belt. In particular, we will shed light on the poorly known early phase (about 2790-2730 Ma) of this constructional history. We will clarify which volcanic assemblage is well-endowed with VMS deposits, and why, from a petrogenetic point of view. 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).

Field assistant Enza Magnier conducting fieldwork next to the Obatogamau River.

Field assistant Enza Magnier from UQAM (Montreal) and Pierre-Simon Ross in Lake des Vents, Chapais area in the northeastern part of the Abitibi Greenstone belt province.

Crust-Mantle Processes Responsible for VMS Endowment during the evolution of Archean Greenstone Belts: Nature of Assemblage Boundaries

Lead researcher: Jack Simmons, Laurentian University

Progress

As the basis for characterising lithostratigraphic assemblages and reconciling disparate geodynamic models for the late-stage evolution of the Superior Craton, this project has so far involved:

- The compilation of existing geo chemical and geochronology data from across the Superior Craton
- Detailed mapping of geologically significant outcrops of the Porcupine and Timiskaming assemblages in the Abitibi Subprovince
- Sampling of metasedimentary successions from across the Abitibi Subprovince
- Core logging of a newly-discovered gold-endowed metasedimentary and metavolcanic sequence (Great Bear deposit) in the Red Lake Greenstone Belt of the Uchi Subprovince (collaboration with Great Bear Resources/Kinross)
- Submission of geological samples to Overburden Drilling Management Limited (ODM) for zircon separation
- Submission of geological samples to ALS Global for whole-rock major, minor and trace element analysis
- Preparation and imaging of zircon (using a Tescan Vega 3 Scanning Electron Microscope at Laurentian University) from samples from the Abitibi, Quetico and Uchi subprovinces
- Submission of porphyry samples from the Great Bear deposit for isotope dilution-thermal ionization mass spectrometry (ID-TIMS)

Future Work

To facilitate the completion of this project, the trace element composition, U-Pb isotopic ratios and Lu-Hf isotopic ratios will be determined for zircon separates from the Abitibi, Quetico and Uchi subprovinces using a Thermo Neptune Plus Multicollector ICPMS at Laurentian University in late-2022/early-2023.

The isotope data for zircon from the Great Bear gold deposit in the Uchi Subprovince will be used to determine the age of the stratigraphy hosting gold mineralisation and will result in the writing and publication of an articleon the host stratigraphy. This new isotope data from the Abitibi Subprovince will also be compared with pre-existing detrital and igneous zircon data (e.g., Frieman et al., 2017; Nielsen in prep) to reconstruct the provenance of sediments and the late-stage evolution of the Abitibi Subprovince.

Anticipated Outcomes

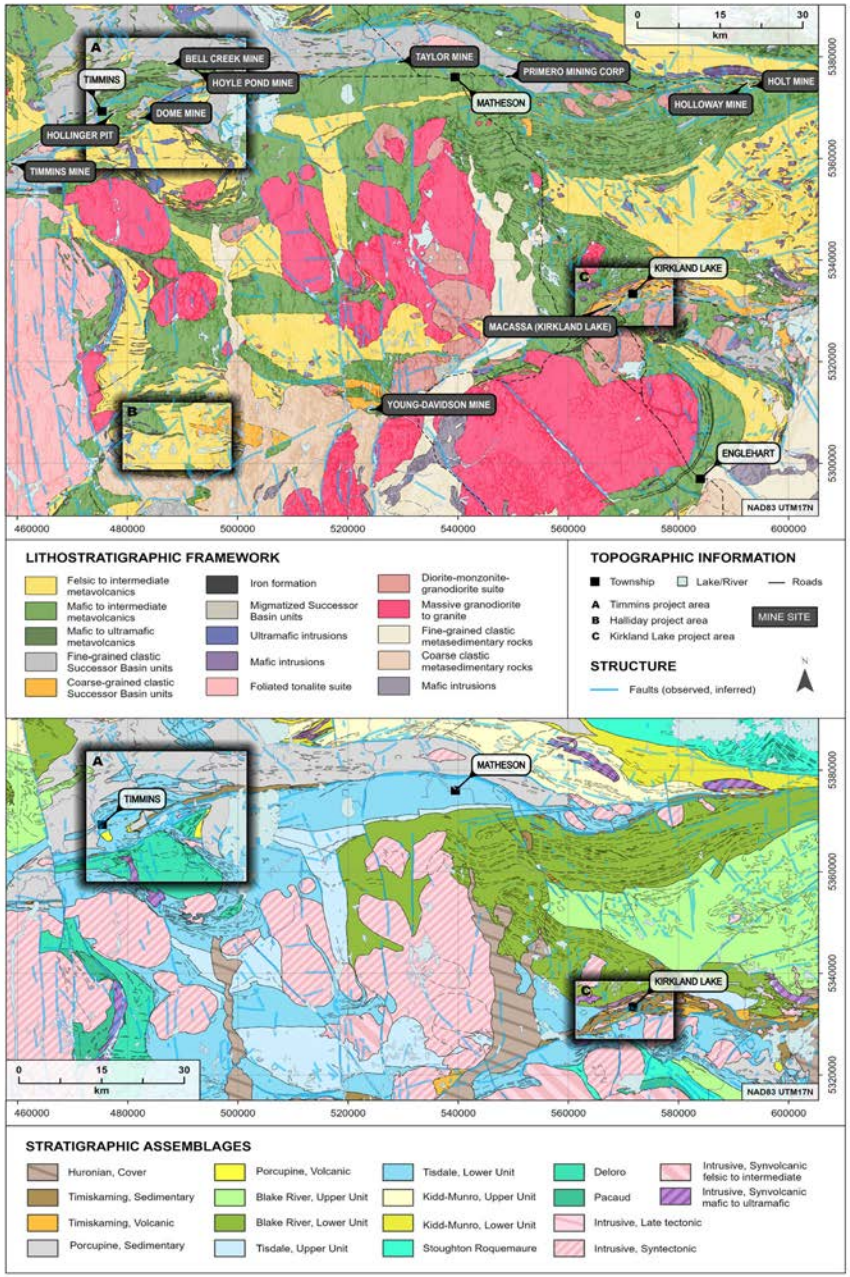
The results from this project will be presented to industry partners and at scientific conferences. In addition, at least two papers will be submitted to leading scientific journals for publication:

Paper 1: A gold-endowed Archean cryptodome associated with a crustal-scale fault: stratigraphic, geochemical and U-Pb isotopic constraints from the Great Bear orogenic gold deposit, Red Lake Greenstone Belt, Superior Craton, Canada.

Paper 2: Reconciling geodynamic models for the late-stage Neoarchean evolution of the Abitibi Greenstone Belt.

Highlights

- Co-author on "Crustal resistivity footprint of a world-class orogenic gold district in the Red Lake Greenstone Belt, western Superior craton," a paper recently submitted to *Geology*
- Developed a new geological field guide for the Kirkland Lake gold camp



Implications

In the context of Objective 1 of Metal Earth's core research goals, new stratigraphic, geochemical and isotopic data collected as part of Paper 1 from the newly discovered Great Bear orogenic gold deposit will help test existing models for gold mineralisation in the Red Lake Greenstone Belt. This research could also lead to new exploration targets across the Uchi Subprovince. Insights from field mapping in the Abitibi Subprovince and U-Pb isotope analysis of zircon will similarly help test existing geodynamic models for the late-stage evolution of the Abitibi Subprovince, potentially transforming our understanding of Earth's early evolution. New geochronology data collected as part of these projects will also form part of an extensive geochronology database, previously compiled by Meek et al. (2020) under the auspices of Metal Earth's R & D project and contribute to Objective 2 of Metal Earth's core research goals.

A red fox interrupts mapping near Kirkland Lake, Ontario, July 2022. *Photo: Jack Simmons*

◀ Figure 1. Lithostratigraphic map and assemblage map for part of the Abitibi Subprovince in Ontario (Coordinate system: NAD1983 UTM17). The A - Timmis, B – Halliday, and C - Kirkland Lake areas will be primary areas of study in the Abitibi Subprovince. Lithostratigraphic data derived from Montsion et al. (2018). Assemblage data derived from Ayer et al. (2005). Multi-Directional Hillshade Model from ESRI's Living Atlas, sourced from Airbus, USGS, NGA, NASA, CGIAR, NLS, OS, NMA, Geodatastyrelsen, GSA, GSI and the GIS User Community.

Figure 2. a) Poorly-sorted, largely monomictic volcaniclastic deposits of the ca 2687 Ma Krist Formation, Porcupine Assemblage, defined by clasts of feldspathic rhyodacite in crystal-rich framework (Timmins, Ontario – Site A in Figure 1). b) Spinifex texture within a komatiite that is hosted by the ca 2687-2685 Porcupine Assemblage (Site B in Figure 1). c) Poorly-sorted conglomerate of the Porcupine Assemblage (Site B in Figure 1). d) Hyaloclastite (and possible peperite) at the contact between the komatiite in part (b) and the conglomerate in part (c) (Site B in Figure 1). e) Outcrop of the Three Nations Formation, Timiskaming Assemblage (E of Site A).

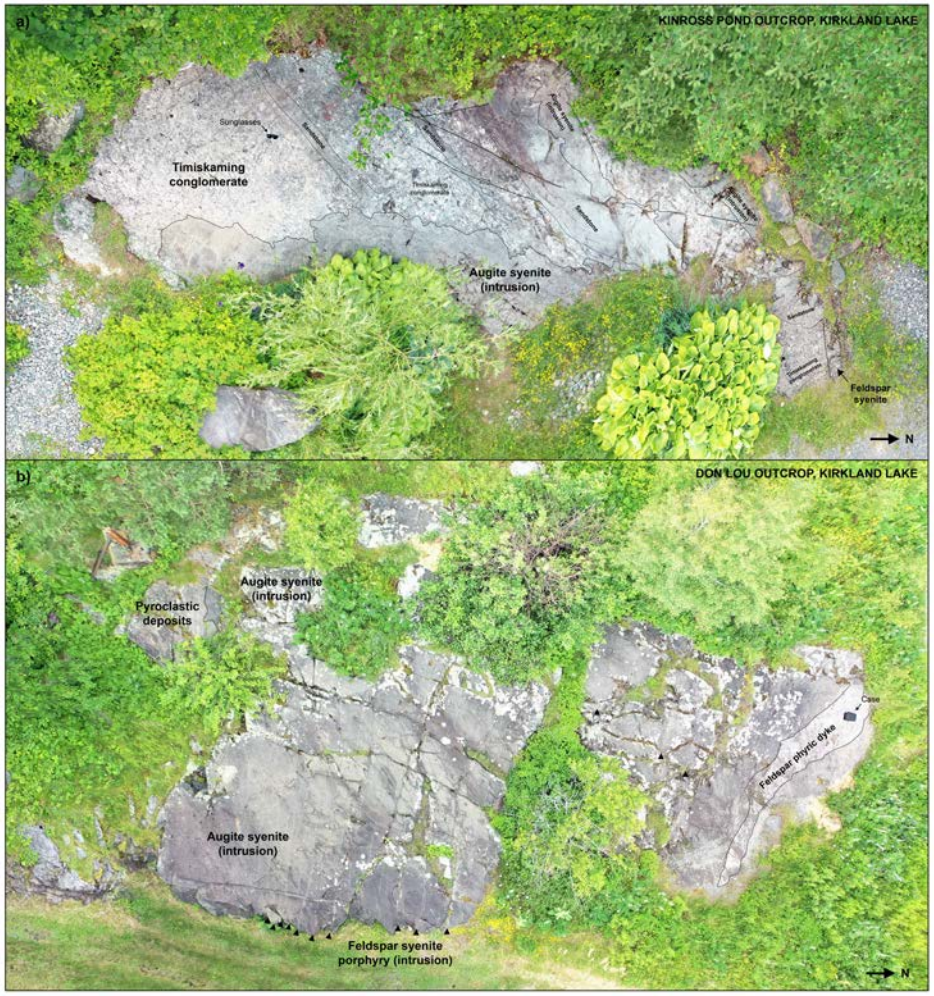
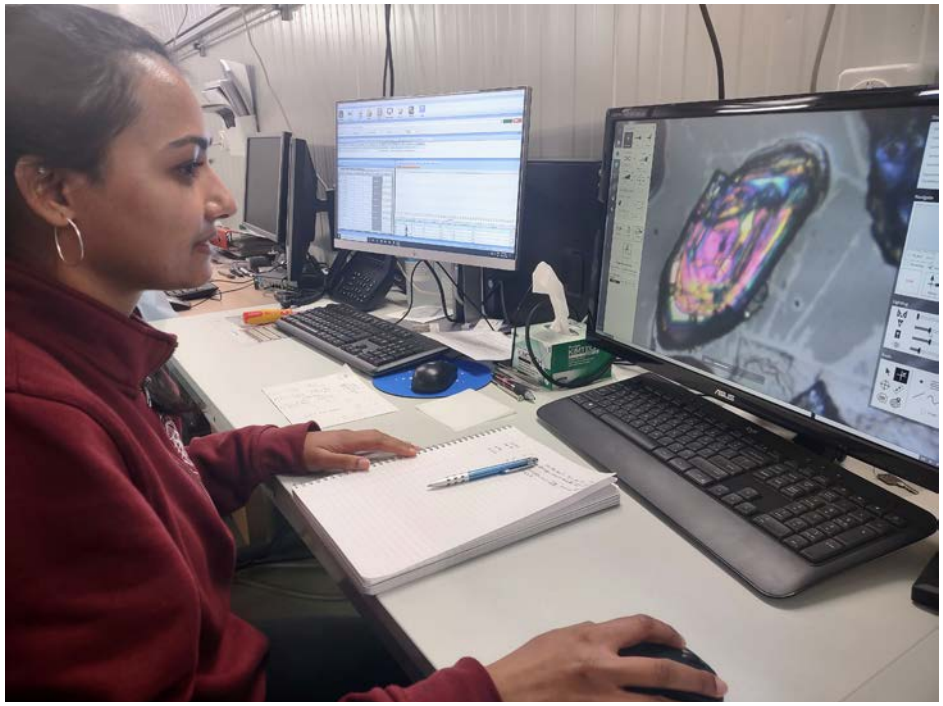


Figure 3. a) Plan view image of the Kinross Pond outcrop in Kirkland Lake showing syenites intruding conglomerate and sandstone of the ca 2669 Ma Timiskaming Assemblage (Site C in Figure 1). b) Plan view image of the Don Lou outcrop in Kirkland Lake showing syenites intruding pyroclastic deposits of the Timiskaming Assemblage (Site C in Figure 1).

WATCH NOW!
Priyal Daya - Melt inclusions associated with Archean volcanogenic massive sulphide deposits, April 2022 Partner Meeting

VMS
Melt inclusion and associated host zircon geochemistry

Lead Researcher: Jacob Hanley, Saint Mary's University



PhD student Priyal Daya in Geneva, Switzerland, analyzing melt inclusions in zircon; May 2022.

Progress

The primary progress made in Year 6 was the determination and comparison of the relative metal tenor/ratios in melt inclusions in pre-, syn-mineralization igneous lithologies and through comparisons to published literature on ore metal tenors, determine if melt inclusions preserve metal tenors/ratios consistent with metal endowments in the actual deposits.

A total of ~400 melt inclusions and their host zircon domains were analyzed by LA-ICP-MS at the University of Geneva in April-May 2022, from 10 lithologies including 6 regional lithologies spanning the volcanic assemblages pre-, syn- and post-VMS (Pacaud, Kidd Munro, Blake River, Deloro, Tisdale, Porcupine) and 4 lithologies as immediate hosts to VMS mineralization at the LaRonde and Kidd Creek Deposits.

Key findings include:

- Metal endowments vary from assemblage to assemblage and are not reflected in whole rock lithogeochemical data owing to the effects of degassing and/or post-crystallization subsolidus alteration. In particular, the Cu-Pb-Zn systematics of melt inclusions reflect the relative Cu-Pb-Zn endowment of their host VMS terrains.
- Several VMS hosting volcanic assemblages were saturated in metal enriched (Cu-As-Sb-Te-Co-Ni-Pb-Zn) sulfide phases prior to, or at the time of, emplacement, eruption. The compositions of these sulfide phases reflect accessory metal endowments in the actual VMS ores, clearly differing from deposit to deposit.
- Differences in host zircon chemistry are recognized that reflect the entrapment conditions and host magma chemistry; linking these characteristics to melt chemistry will provide constraints on P-T-fO2, parameters that cannot be resolved through bulk analyses.

Future Work

- Analysis of Lu-Hf isotopes in host zircon (Memorial University)
- U-Pb geochronology (SHRIMP; ID-TIMS; LA-ICP-MS) of index zircons hosting melt inclusions to confirm the relative age of antecrystic/autocrystic zircon domains and their associated melt inclusions (Memorial University; Boise State University; Geological Survey of Canada)
- Reconciliation of host zircon chemistry to melt inclusion chemistry, with the aid of cathodoluminescence imaging (SMU)

Anticipated Outcomes

The compositional and geochronological systematics of melt inclusions will delineate the "fertility" of volcanic assemblages at Kidd Creek and LaRonde relative to barren assemblages in the Abitibi subprovince and provide fundamental parameters that can be used to ultimately evaluate controls on metal tenors of VMS systems. It is now unambiguous that such parameters cannot be accurately established using bulk rock geochemistry as these whole rocks represent the final product "end-stage" of eruption/emplacement and have experienced deleterious post-entrapment alteration such that primary metal contents are not represented. As well, the project is providing first order constraints on how melt chemistry tracks with source composition and is will provide documentation of the heterogeneity of source regions, as well as the state of sulfide and volatile saturation in those source regions.

Implications

The application of whole rock and isotope methods have been unsuccessful in evaluating the influence of crustal/magma fertility on the metal endowment of Archean VMS districts. In particular, the reasons for the differences in deposit metal tenor and reconciliation of the magmatic metal budgets with ore deposit size and grade have not been resolved. Part of the challenge in evaluating primary VMS-related magma chemistry is the pervasive alteration/deformation/metamorphism of key igneous lithologies that bracket (temporally) the mineralizing events. Melt inclusion studies are one of the few routes to quantifying the composition of ore-causative magmas and the processes leading to differential endowments/tenors in VMS camps in the Abitibi.

The research activities outlined here align perfectly with the goals and expected outcomes of Metal Earth. A coordinated, in-depth, multi-disciplinary, and multi-parameter assemblage scale comparison of VMS endowment is novel. In particular, the application of melt inclusions to Archean VMS districts is completely innovative and has not been done previously anywhere. This research in progress addresses a knowledge gap in our understanding of the processes responsible for differential VMS endowment during the evolution of greenstone belts and will provide a new understanding of Archean metallotectonic processes, an underlying theme of Metal Earth.

WATCH NOW!

Watch: (in less than 5 minutes) Priyal Daya's winning PDAC-SEG Student Minerals Colloquium video: Melt inclusions associated with Archean volcanogenic massive sulphide deposits: constraints on the pre-eruptive metal and volatile content of magmas, March 2021

Highlights

Novelty: The melt inclusion data generated on the barren and mineralized volcanic assemblages is the first data of its kind for any Archean environment on Earth. The first manuscript is in progress and will provide a benchmark for integrated melt inclusion-zircon geochemistry studies in VMS terranes.

Student peer recognition: The research has resulted in an invitation for P. Daya (Ph.D.) to present her work at the international workshop on oxygen fugacity in magmatic systems in Trieste, Italy in September 2022. She is one of two Canadians invited to present at this venue. Daya also earned first place in the PhD category at the PDAC-SEG Student Minerals Colloquium in March 2021.

International collaboration building: The success of the recent analytical session at the University of Geneva has led to a renewed partnership between Canadian and Swiss melt inclusion researchers, enabled by the Metal Earth program. Several spin-off collaborations are planned that will involve a team of researchers in Canada interacting regularly with ore deposits specialists in Geneva and accessing those analytical facilities for routine research. These include Jacob Hanley and Priyal Daya (SMU), Jan Peter (GSC), Steve Piercey (MUN), and Patrick Mercier-Langevin (GSC).

WATCH NOW!
David Diekrup - Sulfide Geochemistry: VMS Thematic Project, November 2021 Partner Meeting

Crust-Mantle Processes Responsible for VMS Endowment during the evolution of Archean Greenstone Belts: Trace metal constraints on the setting and source of metals.

Lead Researcher: D. Diekrup, University of Ottawa

Progress

During Year 6 this project focused on the development of the VMS trace element database at the core of the 3b, including quality control, transformation into a machine-readable format, and preliminary analysis. The database now contains over 3900 individual analyses from more than 320 Canadian VMS deposits and massive sulfide showings. Additional information for the deposits has been compiled, including host rock characteristics and mineralogy, and integrated in the overall database. Initial statistical analyses have been carried out with important relationships not previously recognized beginning to emerge.

Version 1.0 of the database was published in an open file in collaboration with partners at the Geological Survey of Canada. Initial results from statistical analysis have been compiled and presented during the Metal Earth partner meetings.

Petrographic work by T. Monecke at Colorado School of Mines has focused on a subset of samples from the Matagami District, with emphasis on the abundance and distribution of critical trace elements. A parallel study of 700+ polished sections from 20 additional deposits in the Abitibi Greenstone Belt was commissioned (I.M. Kjarsgaard). These data will be used to guide a comprehensive study of pyrite geochemistry in the different deposits for comparison with global trace element databases.

Future Work

The focus of the subproject has now advanced to an interrogation of the database using multivariate statistics and machine learning. R. Penner is in the second year of his MSc thesis on this topic under the supervision of D. Diekrup (now at Newfoundland Geological Survey).

L. Patterson commenced an externally-funded MSc thesis project at Colorado School of Mines on the petrography and trace element geochemistry of samples from the Matagami District. Together with the study of samples from other deposits in the Abitibi Greenstone Belt, these data will be used to establish key mineralogical controls on trace element distribution in Archean VMS.

A selection of WR samples of unaltered volcanic rocks from the Ontario Geological Survey is being assembled with the assistance of T. Gemmell and S. Prefontaine. These samples will be analyzed for ultratrace metals to gain a better understanding of the possible source rock controls on trace metal distribution in Archean VMS.

D. Diekrup (GSNL) will continue to be involved in the project as a volunteer and will co-supervise the MSc project on machine learning. As a result of the early departure of Diekrup, no additional funding will be sought for this sub-project.

Anticipated Outcomes

Subproject 3b will deliver a comprehensive trace element and mineralogical database of VMS deposits in the Abitibi Greenstone Belt. Multivariate statistics and machine learning approaches will be aimed at establishing regional time-stratigraphic and spatial control on the distribution of key trace elements, with an emphasis on:

- lithogeochemical control on trace element geochemistry with links to crustal-scale fluid flow, the sizes and grades of the deposits, and their source rocks;
- key trace element signatures of deposits in well-endowed versus poorly endowed assemblages and greenstone belts;

Highlights

Publication of a core database of trace element geochemistry for subproject 3b.

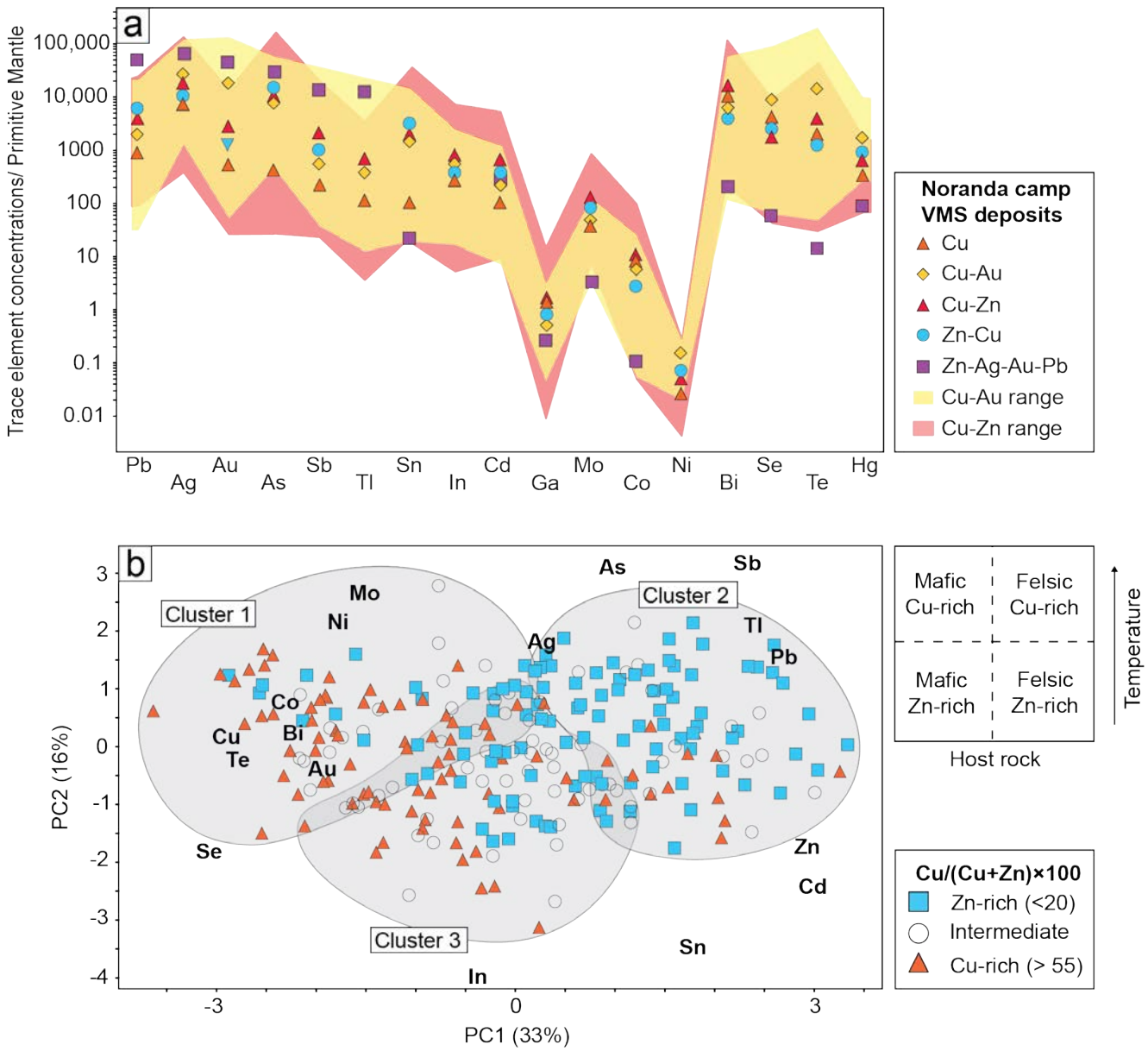
Significant progress on R. Penner's MSc thesis on "Influences on Volcanogenic Massive Sulfide Endowment in Archean Greenstone Belts from Trace Element Geochemistry," which was presented at the PDAC-SEG Student Minerals Colloquium (online).

- trace element signatures of the leached volcanic footwall;
- comparisons of Archean deposits to modern VMS-forming systems.

An important goal is to identify trace element pathfinder associations that can be applied to other target lithologies (e.g., BIF and argillite) in the ore-hosting assemblages.

Implications

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 belts assemblages. Systematic trace element behaviour in VMS have 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.



Trace element signatures of pyrite in VMS deposits of the Superior Province, as a guide to mineral endowment. a) Multi-element profiles (spider diagrams) of concentrations of trace elements in pyrite from deposits of the Noranda district. Pyrite from the main camp Cu-Zn and Cu deposits is enriched in Bi, Co, Ni, Se, and Sn; Cu-Au deposits are enriched in Au, Se, and Te; and Zn-Ag-Au-Pb are enriched in As, Sb, and Tl. b) Principal Components Analysis and Hierarchal Clustering of pyrite samples from VMS deposits of the Superior Province show a strong correlation of these elements with the bulk Cu/(Cu+Zn) grade ratios of the deposits, reflecting a combination of source rock and temperature of ore formation.

Data Analytics

WATCH NOW!
Jeff Harris - Data Analytics: A Review, November 2021 Partner Meeting

WATCH NOW!
Pouran Behnia - Data Integration Model (DIM) For Rouyn-Noranda VMS Mineralization, April 2022 Partner Meeting


Jeff Harris


Eric Grunsky


Pouran Behnia


Haiming Liu


Mostafa Naghizadeh

▲

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

VIEW OR DOWNLOAD
Data-driven gold potential maps for the Chibougamau area, Abitibi greenstone belt, Canada

The team includes:

- Jeff Harris, PhD; *mineral prospectivity mapping, team lead (former GSC)*
- Eric Grunsky, PhD; *leader in geochemical analysis and mineral prospectivity mapping (former GSC)*
- Pouran Behnia, PhD; *GIS specialist (former GSC)*
- Haiming Liu, PhD; *mineral prospectivity mapping and geochemistry (has since retired from Data Analytics project, summer 2022)*
- Mostafa Naghizadeh, PhD; *3D geophysics*

The Data Analytics team is applying machine learning languages such as Random Forests (RF) to data collected from the Metal Earth transects to produce 2D and 3D mineral potential models (MPMs).

Progress

The team worked on data from the Noranda/Rouyn, Larder Lake, Chibougamau, Sturgeon, Swayze, Rainy River, and Cobalt Transects. The MPMs are complete, with the exception of Rainy River.

Six manuscripts have been prepared. One has been published, four have been submitted, and another is close to submission. All of the papers focus on mineral prospectivity mapping (MPM). The manuscripts include:

- Swayze; F. Maepa et al, *Support vector machine and artificial neural network modelling of orogenic gold prospectivity mapping in the Swayze greenstone belt, Ontario, Canada; Ore Geology Reviews*
- Noranda/Rouyn; P. Behnia et al, submitted
- Chibougamau; Harris et al, submitted
- Sturgeon Lake; Parsa et al, submitted
- General paper on uncertainty in MPM processing; Parsa et al, published
- Larder Lake; Liu et al, in progress

Future Work

We have started a project dealing with the spatial association of regional faults and the 3D seismic and geophysical data – focusing on the strike, dip and depth of faults comparing barren and fertile greenstone belts. We have submitted a short course proposal on Mineral Prospectivity Mapping to GAC-MAC to be held in Sudbury in 2023. We will start work on remaining Metal Earth Transects, and we will begin organizing and populating the Metal Earth Z: Drive with completed project results.

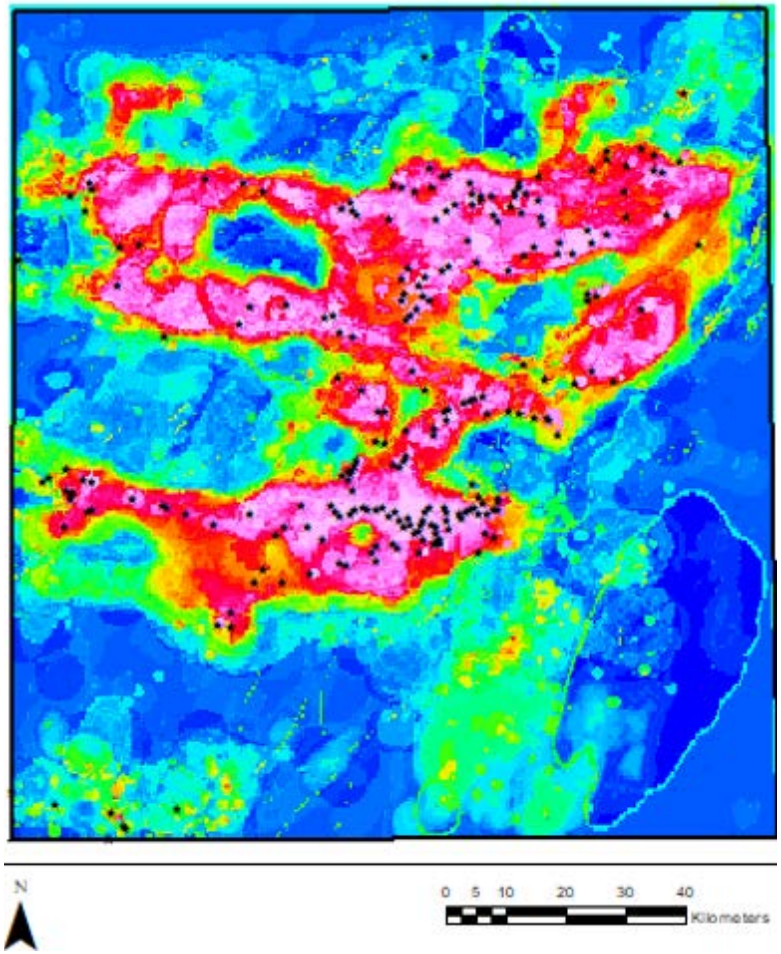
Anticipated Outcomes

- Establish mineral prospectivity maps for each transect focused on Au and VMS; provide the data to industry
- Conduct research using the best predictors established by Random Forest (RF) analysis as well the study of faults in relation to 3D seismic and geophysical data to shed light on why some transects are fertile while others are barren with respect to mineralization. We will accomplish this task through: a study of the best predictors for Au and VMS as calculated by the machine learning languages across each transect; and a study of regional faults and crustal architecture in relation to the 3D seismic and geophysical data as well as geologic and geochemical data.

Implications

The MPMs produced and the research on why some belts are fertile while others are barren will greatly assist exploration activities in Ontario and Quebec.

The development of data integration and analysis methodologies will greatly assist in regional and site-specific exploration.



A gold mineral prospectivity map featured in the paper: "Data-driven gold potential maps for the Chibougamau area, Abitibi greenstone belt, Canada," November 2022, *Ore Geology Reviews*.

WATCH NOW!
Haiming Liu - Multivariate Statistical Analysis of Lithogeochemical Data of the Larder Lake Area , November 2021 Partner Meeting

Highlights

The MPMs produced will aid industry in the exploration for new resources in well-developed (known) areas as well greenfield areas.

VIEW OR DOWNLOAD
Improving Mineral Prospectivity Model Generalization: An Example from Orogenic Gold Mineralization of the Sturgeon Lake Transect, Ontario, Canada

WATCH NOW!
Benoît Quesnel: Toward an integraded understanding of the auriferous fluid flow system(s), April 2022 Partner Meeting

WATCH NOW!
Guillaume Barré: Application of multiple sulfur isotopes to determine the influence of seawater sulfates on the structure of Archean VMS deposits, April 2022 Partner Meeting

Fluid Source & Pathways: Source to Sink

Lead Researcher: Georges Beaudoin, Université Laval

VIEW OR DOWNLOAD
Research Output: *Research Output: Kieffer, M. et al: 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, CJES, May 2022.*

Field installations for geophysical data acquisition.
Photo taken by Y. Nemati during her field season, summer 2021.

Outcrop showing multiple vein generations with cross-cutting relationships and conjugate vein arrays.
Photo: B. Quesnel, Stormy/Dryden transect, Ontario, summer 2019

Progress

B. Quesnel, C. Scheffer, and G. Beaudoin prepared a review paper dealing with the variation of stable isotope composition of vein minerals and fluids from orogenic gold deposits worldwide. The paper has been accepted in a Springer SGA Special Publication. They also collaborated with M. Kieffer, P. Bedeaux, and L. Mathieu from the Chibougama transect team to write a journal article comparing the stable isotope composition of veins minerals between two variably gold-endowed orogenic systems: the Moly-Degagné/ Guercheville and the Val d'Or systems. The paper was published in *CJES* in May 2022.

B. Quesnel and C. Scheffer also collaborated with M. Schofield to produce a paper regarding the alteration systems of the Powell Block, which has also been accepted and is currently under corrections. They collaborated with B. Lafrance on another paper dealing with the structural geology of the Cadillac Group along the Malartic segment of the Larder Lake Cadillac Deformation zone, Quebec, and implications for gold mineralization. The paper has been accepted in *CJES*. In addition, they submitted a paper in Chemical Geology related to the application of the clumped-isotope thermometer for mesothermal deposits in collaboration with other Metal Earth researchers, such as G. Beaudoin, G. Raymond, and T.R.C Jørgensen, and collaborators from the GSC. Finally, the analytical results for (O, C, H) stable isotopes on samples collected during the summer of 2021 are almost completed and computed to complete the regional stable isotope database. They also sampled and analyzed minerals from orogenic gold veins associated with major fault zones of various endowments, to compare the isotopic signature of the vein minerals in each.

C. Scheffer and B. Quesnel ended their contract in Spring 2022 but remain active collaborators on ongoing projects.

G. Raymond is finishing his MSc and is now working as a coordinator and research associate for the Source to Sink project. He is working on submitting a paper related to his MSc (Constraints on gold endowment along the Augmitto-

Bouzan segment (Abitibi subprovince, Quebec) orogenic gold deposit, from stable isotopes (O, C, H) and 3D fluid flow modeling) by the end of 2022. Along with his MSc, he collaborated with the previous research associates B. Quesnel and C. Scheffer, as well as other co-authors, on a paper addressing the use of clumped isotopes in Archean orogenic systems (Augmitto-Bouzan, Abitibi, Quebec).

M. Herzog outlined three papers (one online; two in preparation) towards his PhD.

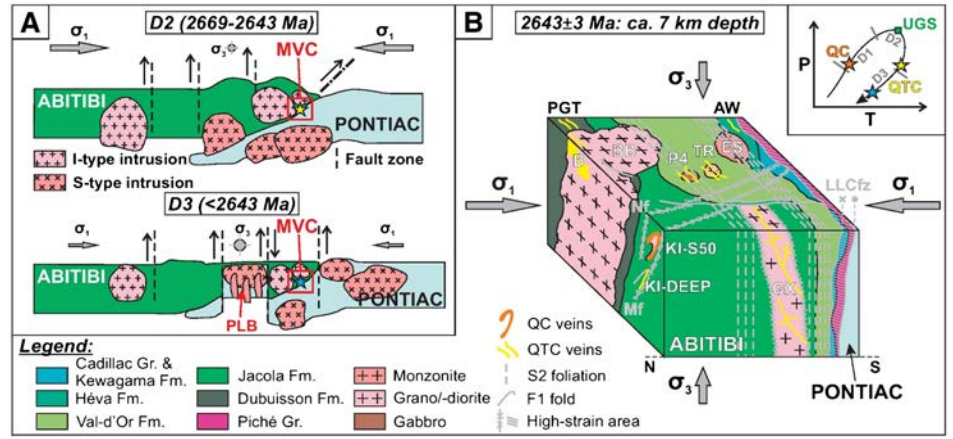
The papers entailed:

- detailed U-Pb xenotime geochronology of orogenic gold mineralization throughout the Malartic-Val-d'Or camp - MVC (through µXRF at Université Laval and in-situ geochronology by LA-ICP-MS at Laurentian) online in *Mineralium Deposita*;
- detailed sulfur isotopic compositions of pyrite, chalcopyrite and pyrrhotite associated with different hydrothermal events and particularly gold mineralization styles in the MVC with an emphasis on gold precipitation and sulfur depositional processes (through in-situ SIMS work at UWA and quantitative LA-ICP-MS mapping at UQAC);
- the implications of primary polymetallic (Te-Bi-Ag-Au) inclusions hosted in homogeneous sulfide domains and the potential and particularly processes associated with remobilization of those inclusions into texturally-late gold hosted in sulfide fractures, which commonly contain carbonates-chal copyrite – looking more into a comparison between the more and more invoked Bi-melt model (scav enging gold from hydrothermal fluids) vs. "only" Te-rich hydrothermal fluids (through TEM at UWA).

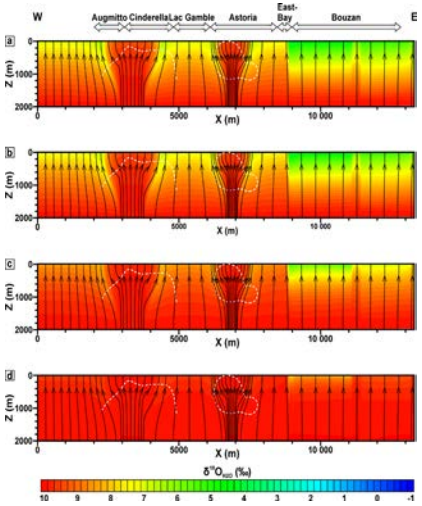
Y. Nemati arrived in Canada on Feb. 2021. Her field season took place during the 2021 summer semester, and she managed to acquire borehole geophysical data of 3 wells. Since the 2021 Fall semester, she has been processing her data from which the preliminary results were presented at the Metal Earth meeting in April 2022. Y. Nemati presented her results in June at the 2022 PDAC convention, both as a presentation and as a poster.

I. Siles Malta finished all the proposed analytical methods, including (1) geological mapping, (2) detailed petrographic analyses, (3) whole-rock geochemistry, (4) mineral chemistry, (5) phase equilibria modeling, (6) U-Pb monazite and zircon geochronology, and (7) Lu-Hf garnet geochronology.

I. Siles Malta has also been collaborating with Brazilian researchers and is a o-author of a peer-review paper in *Lithosphere* (2022).



▲ A schematic geodynamic setting of the Abitibi and Pontiac subprovinces (not to scale) at the time of major N-S shortening (D2) and contemporaneous orogenic gold mineralization recorded in the MVC at ca. 2643 Ma, as well as subsequent exhumation and dextral strike-slip movement (D3) involving a hydrothermal event at ca. 2607 Ma (modified from Feng et al. 1992). b A block model (not to scale) showing the structural relationships of gold mineralization observed in the MVC, including major orogenic gold mineralization at ca. 2643 Ma. The small inset shows a schematic pressure–temperature-time-path of the Abitibi-Wawa Orogeny including major deformation periods and the timing of auriferous hydrothermal events recorded in the MVC. AW = Akasaba West, B = Beaufor, BB = Bourlamaque Batholith, ES = East Sullivan monzonite, GX = Goldex,KI-S50 = Kiena-S50, KI-DEEP = Kiena-Deep, LLCfz = Larder Lake-Cadillac fault zone, MVC = Malartic-Val-d'Or Camp, PGT = Pascalis Gold Trend, P4 = Plug #4, PLB = Preissac-Lacorne batholith, QC = quartzcarbonate veins, QTC = quartz-tourmaline-carbonate veins, TR = Triangle, UGS = upper greenschist facies, orange star = QC mineralization, yellow star = QTC mineralization, blue star = hydrothermal overprint. From Herzog et al. 2022, *Mineralium Deposita*.



▲ 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.

WATCH NOW!

M. Herzog: Geochemical Constraints on Gold Mineralization in the Neoarchean Malartic-Val-d'Or Camp, Abitibi Subprovince, Canada, April 2022 Partner Meeting

G. Barré completed the installation of the LA-ICP-MS and started the development of an analytical procedure for S isotopes in sulfides, as well as trace elements in silicates (e.g., tourmaline, garnet, etc.) and sulfides. He designed his research project regarding the characterization of sulfur reservoirs and seawater influence on Archean VMS deposits in the Abitibi and completed the fieldwork in 2021. At Université Laval, G. Barré also installed a new extraction line built for bulk samples for triple S isotope analyses. This line is now routinely used.

Future Work

Despite the end of their contract, B. Quesnel and C. Scheffer will 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.

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

G. Raymond is working on previous ongoing projects developed by B. Quesnel and C. Scheffer the paper on the stable isotope composition of orogenic veins and fluids along the Cadillac-Larder Lake Break, as well as a comparative study of the stable isotope composition of veins across multiple deformation zones of various gold endowments of the Superior Province. During summer 2022, G. Raymond will continue the sampling of the Larder-Lake to Kirkland Lake area for orogenic gold-related veins to complete the stable isotope database of the Cadillac Larder Lake deformation zone. When he returns, he will do the corrections for his MSc thesis and submit an article related to his thesis to a peer-reviewed journal for publication. Simultaneously, he will keep collaborating with B. Quesnel, and C. Scheffer on the two aforementioned projects. He will also support transect research projects with his skills and laboratory facilities to study fluids when required.

M. Herzog is finishing writing the final two manuscripts and will eventually do his Ph.D. thesis defense.

Y. Nemati will be working on the method to finish analyzing all the different sections of her study area. When finished, she is going to publish the first paper on her work. Afterward, she will try to develop a machine learning model to analyze the data.

I. Siles Malta is exclusively dedicated to writing his Ph.D. thesis and scientific articles.

G. Barré will complete the development of an analytical procedure on the new LA-ICP-MS that he installed at Université Laval. He plans to prepare two scientific papers. The first will be regarding the first development of S isotopes by LA-IC-PMS. The second paper will be on the S isotopic signature of the Archean seawater associated with VMS deposits, based on the fieldwork of summer 2021 and S isotopes analyses done in France in January 2022.

Anticipated Outcomes

B. Quesnel and C. Scheffer anticipate submitting by 2023 at least two other scientific papers regarding 1) the variation of stable isotope composition of vein minerals and fluid(s) that have percolated in orogenic deformation zones between Sub-provinces of the Superior Province and 2) the variation of

WATCH NOW!

Guillaume Raymond: Constraints on gold endowment at the Augmitto-Bouzan segment (Abitibi subprovince, Quebec) orogenic gold deposit, from stable isotopes (O,C,H) and 3D fluid flow modeling, April 2022 Partner Meeting

the stable isotope composition of veins mineral and fluids along the Cadillac Larder Lake Deformation Zone. They also anticipate that their accepted papers will be published by the end of 2022 to 2023.

G. Raymond anticipates that his paper on the Augmitto-Bouzan segment, related to his MSc, will be submitted by the end of the year. He also anticipates that the paper on the stable isotope composition of veins across the Cadillac-Larder Lake break will be submitted to a journal in early 2023, since a lot of work has already been done by B. Quesnel and C. Scheffer, and their ongoing collaboration will help accelerate the process.

M. Herzog anticipates that one of his papers will be published, one will be submitted to a journal and one will be ready for submission. His Ph.D. defense will also follow.

Y. Nemati anticipates that she will submit her first paper in 2022, or early 2023 and will participate in at least one other conference.

G. Barré anticipates the submission of two scientific papers and that the LA-ICP-MS will be ready for multiple sulfur isotopes analyses.

Implications

- Compare 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. Identify the sources of fluids and sulfur in Superior Province gold deposits.
- Determine hydrothermal features that explain the metal accumulation of endowed areas versus those that are less endowed. Understand fluid generation during metamorphism of sedimentary rocks (timing and P/T conditions), the sources of volatiles (including sulfur, a critical ligand for gold transport to deposition sites), the processes involving fluid at the deposit and the timing of hydrothermal fluid pulses in order to better constrain what are the key parameters required to form a deposit.

Highlights

G. Raymond completed his MSc seminar presentation.

Y. Nemati received the Young Mining Professionals' Joan Margaret Stewart New Canadian Scholarship in December 2021.

The new LA-ICP-MS facility will enable in situ sulfur isotope analysis, a method for rapid determination of S isotope composition.

The Metal Earth team at Université Laval. Back row (L-R) Yasaman Nemati, Bruna Coldebella, Isaac Siles-Malta, Rita Rodrigues dos Santos, Micheal Herzog, Benoît Quesnel, Christophe Scheffer, Guillaume Barré, Diogo Miguel Teixeira Ribeiro, Antoine Godet and Prof. Georges Beaudoin. Front row (L-R) Prof. Crystal LaFlamme, Prof. Carl Guilmette and Prof. Bertrand Rottier.

WATCH NOW!
Diogo Riberio - Metals, Sulfur and Chlorine Mobility & Implications for Gold Mineralizing Systems, November 2021 Partner Meeting

WATCH NOW!
Yasaman Nemati - Assessing the geophysical attributes of hydrothermally altered gold deposits, April 2022 Partner Meeting

WATCH NOW!
Hélène Legros - Mantle Group: Paleo- to Mesoproterozoic lithospheric modification of the Superior and Slave craton: association with metal and REE mineralization, April 2022 Partner Meeting

Mantle Group

Lead Researcher: Graham Pearson, University of Alberta

VIEW OR DOWNLOAD
Research Output: *Mesoarchean diamonds formed in thickened lithosphere, caused by slab-stacking; Earth and Planetary Science Letters, August 2022*

Progress

- Tree River diamonds paper published in EPSL
- Elliott Lake mantle xenolith paper submitted. Link found between lithospheric enrichment in critical metals and carbonatitic magmatism and metasomatism in Superior craton.
- New U-Pb dating approach for REE carbonates developed – being applied to Thor Lake, Slave craton.
- 3500 diamonds already examined for the for Adia/Lynx Lake diamond/ lithosphere Project. PhD Pezzara has started. Initial X-ray work has identified a number of inclusions that should be usable for elastic thermobarometry
- Cu isotope work on mantle xenoliths 90% complete but data rather confusing
- New Eoarchean terrane discovered in Slave craton, 3.8 Ga rocks, third oldest in Canada.

Future Work

- Nd isotope analyses and element mapping of Thor Lake
- Published paper in international journal PDF (Legros & Sarkar)
- Complete work on perovskite reference materials
- 2 verified Pv RMs for use in critical metal dating and tracing (Sarkar)
- Publish perovskite work Published paper in international journal (Sarkar)
- Further fieldwork in Tree River area, NWT
- Discover more Mesoarchean diamonds and gold (Pearson, Reimink, Pezzara)
- Analytical work on N Slave Eoarchean rocks and writing paper for "Geology"
- Publication in "Geology" – target journal (Reimink, Stoian, Pearson, Sarkar)
- elastic thermobarometry work to document Meso-Neoarchean lithospheric architecture of the western Superior (PhD student Pezzera)

Anticipated Outcomes

- Improved understanding of crustal architecture and evolution in the Slave craton via constraining the extent of the new Eoarchean terrane. Better understanding of how lithospheric architecture evolution plays into models of gold mineralization in the Slave craton.
- New establishment of international perovskite standard for dating and tracing REE / critical mineral deposits.

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 also enhanced metal endowment. Study both the Slave and Superior cratons specifically addresses these goals within the context of the Metal Earth project. The Tree River project specifically highlights the dramatic differences in the depth and geotherms of lithospheric building blocks that formed the Slave craton. It highlights the possible concurrent thin lithosphere, greenstone belt / gold mineralisation link, showing how such mineralisation shut-down after the stabilisation of a uniformly thick lithosphere.

Highlights

Jason Hinde, Masters Student, graduated and is now working as a Geoscientist for Apex, Edmonton

Tree River work allowed the discovery of a new Eoarchean Terrane in Arctic Canada – currently being evaluated regarding its link to younger terranes and the mineral potential of the Slave Craton

Successful U-Pb dating application of REE carbonates to the Thor Lake REE deposit. First dating of mineralisation at Thor Lake showing it is significantly post-magmatic

Tree River diamonds and their implications of the evolution of the lithospheric architecture of the Slave craton published: S. Timmerman, J. Reimink, A. Vezinet, F. Nestola, K. Kublik, A. Banas, T. Stachel, R.A. Stern, Y. Luo, C. Sarkar, A. Ielpi, C.A. Currie, C. Mircea, V. Jackson, D.G. Pearson (2022) Mesoarchean diamonds formed in thickened lithosphere, caused by slab-stacking. Earth and Planetary Science Letters, 592, 117633.

WATCH NOW!
Mark Hannington: Modern Ocean overview and progress, April 2022 Partner Meeting

Modern Ocean Crust Project (Metal Oceans)

Lead Researcher: Mark Hannington, University of Ottawa

VIEW OR DOWNLOAD
Research Output: *Stewart, M. et al: 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.*

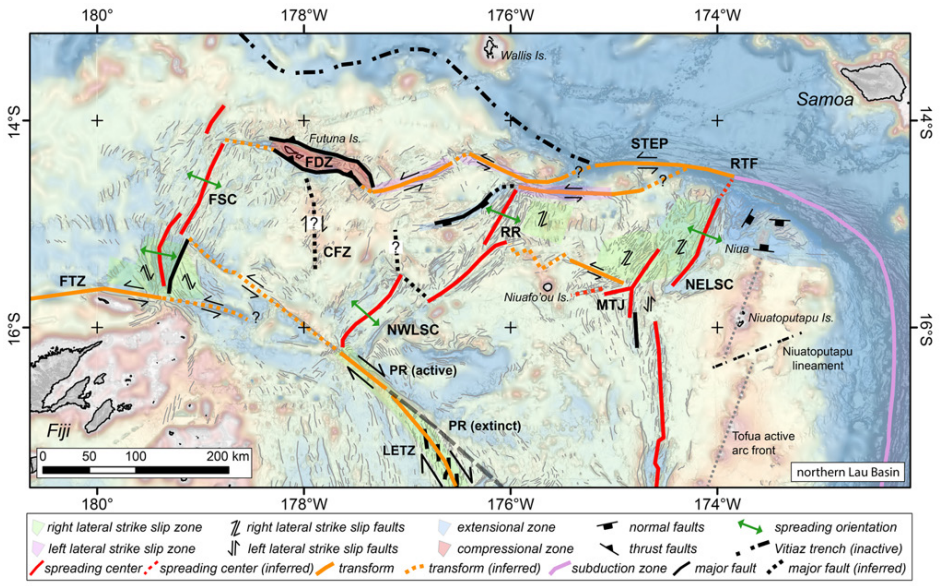
Progress

Interpretation and reporting on processed geophysical data from ARCHIMEDES I (SO-267). Multibeam, sidescan, and magnetics (ship-based and AUV) were processed and incorporated into several new publications and thesis products. Gravity and MT analysis also was advanced and are being incorporated in multiparameter geophysical studies. Seismic data (all 6 lines) with refraction data for 2 long sections were interpreted and reported. 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 and seismicity and near-surface intrusive events (F. Schmid, G. Franz). Full results are being prepared for publication as individual reports in 2022-23.

Seven MSc and PhD students at uOttawa (Mensing, Besaw, Gray, Kehew, Ryan, Sitnikova, Penner) have been working on Metal Oceans mapping projects. In 2022-23, most will complete their work, shifting from map production at 1:100,000 and 1:250,000 to interpretation and modelling of crustal growth in different microplate systems, with direct comparisons to crustal architecture of greenstone belts.

These comparisons include i) arc rifting associated with the Mangatolu Triple Junction (MTJ), ii) mature back-arc opening associated with the NFBTJ, iii) the Rochambeau, Futuna, and Niuafo'ou assemblages in the NE Lau basin, iv) anomalously hot mantle in the NWLSC, v) caldera formation in response to arc rifting on the Louisville Segment of the Tonga arc, vi) diachronous versus linear extension in the NE Lau back-arc basin, and vii) rift propagation into the southern NFB margin.

Individual research projects are establishing type sections for different assemblages; documenting the structure 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; sedimentary sequence stratigraphy of back-arc and intra-arc sub-basins; quantitative comparisons of large-scale volcanic centers (magma volumes and area-age relationships as a first-order metric of crustal growth). Alexandra Gray completed her thesis on the formation and evolution of large-scale submarine calderas. Jessie Kehew and Michael Ryan are completing their work on intrabasinal sedimentation and magmatic productivity. Results have been summarized for publication as individual reports and for a special issue in 2023.



Mapping structure in back-arc basins - Figure 1 of 3: Tectonic assemblage map of the northern Lau Basin (from A. Baxter) showing the breakup of the back-arc region in response to microplate rotation. Major volcanic centers are developed at triple junctions (indicated in red).

A new postdoctoral fellow (C. Galley) was hired to begin large-scale gravity inversions of the NE Lau Basin microplate mosaic. These results are revealing the granular nature of microplate crust beyond the presently identified plate boundaries. The gravity data highlight strong links to mantle upwelling that can be compared to the architecture of greenstone belts. Regional gravity data are being integrated with ship-based gravity from ARCHIMEDES I (SO-267) to improve the inversions.

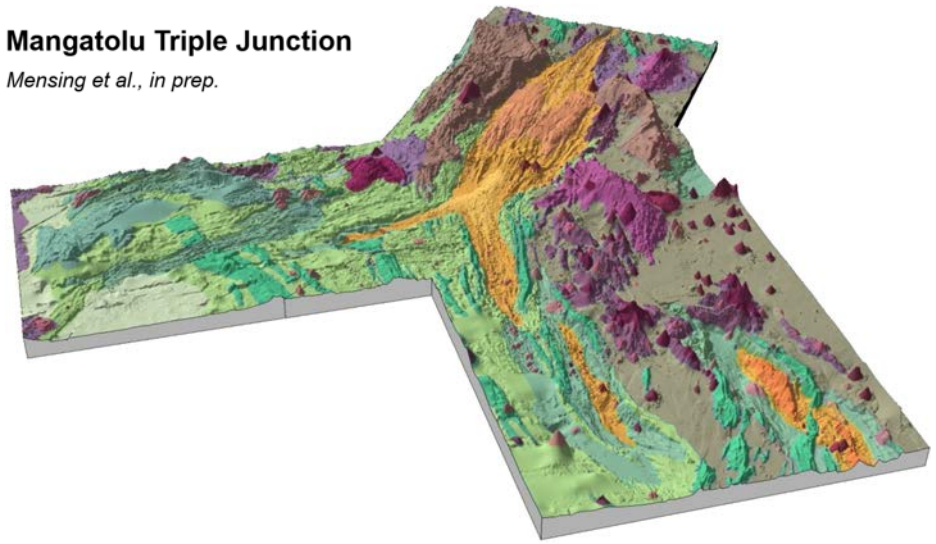
The regional kinematics and stress regime of the northern Lau Basin (Baxter et al., 2020; Anderson et al., 2021) have been developed into a Gplates-constrained model. The new model is providing a unique solution to the rapid growth of the Niuafo'ou microplate, which is linked to the emergence of the MTJ in the north and the Peggy Ridge transform boundary in the west. The new model incorporates propagating rifts, which are not part of the standard Gplates output. This work will be submitted for publication in 2022-23.

The lithogeochemical compilation of the Lau Basin system (795 unique sample locations supplemented with new samples from ARCHIMEDES I) has been analyzed and two manuscripts have been written by Marc Fassbender. Analysis of Sr, Nd, Hf and Pb (double spike) isotope ratios by TIMS and multi-collector ICP-MS has been completed at GEOMAR (A. Sandhu). The first results of 0Ar/39Ar dating at OSU also were received (M. Fassbender). These studies are constraining the location and timing of arc rifting, mantle input and microplate growth. 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 is accepted for publication. A parallel study of the mafic volcanic rocks is being submitted shortly.

A manuscript on our second 1:1 million compilation of the marginal basins of eastern PNG (P. Brandl) is nearly completed and will complement the first 1:1 million geological map of the Lau Basin published in *Geosphere* (Stewart et al., 2022). The PNG study is focused on the geodynamic influences of large-scale collisions on regional metallogeny.

Progress has been made on the completion of new 1:1 million maps of the N. Fiji Basin (A. Baxter, R. Mensing, and T. Sitnikova) and the Coriolis Troughs and Jean Charcot Troughs in the New Hebrides and Vanuatu (M. Anderson, D. Summer).

Collaboration with MERC researchers was initiated to identify type sections for different assemblages and formations in modern back-arc basins that can be meaningfully compared to the Abitibi greenstone belt. The focus is on identifying different types of assemblages and unconformities between assemblages; compiling sedimentary sequence stratigraphy in rift sub-basins; quantitative comparisons of the structure and evolution of large-scale silicic versus mafic submarine calderas; and comparing modern microplate architectures to relict structures in deformed terranes. A dedicated workshop on this topic is scheduled for mid-2022-23.



Mapping structure in back-arc basins - Figure 2: 1-250,000 scale geological map of the Mangatolu Triple Junction (MTJ in Figure 1 from R. Mensing) showing the development of a 600 km3 central volcanic complex at the intersection of 3 spreading centers.

Preparation for the ARCHIMEDES II Transect (DynaMet) continued through Year 6, including pre-cruise logistics, submission of contracts for work, diplomatic clearances, securing equipment and preparing shipments to/from the ports of Singapore and Townesville (confirmed). ARCHIMEDES II was postponed from its original cruise dates of May-June 2021 and has now been rescheduled as SO-299 in June-July of 2023.

A new lithogeochemical study is underway focusing on 810 high-quality analyses in the area of ARCHIMEDES II (Manus-New Ireland Basin and Woodlark subprovinces) led by P. Brandl. This compilation will be supplemented with new samples collected during ARCHIMEDES II and will include major and trace element geochemistry by ICP-MS in Germany, Sr-Nd-Hf and Pb (double spike) isotope studies by TIMS and multi-collector ICP-MS, and 40Ar/39Ar dating.

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

Milestones:

- Final Lau Basin 1:1 million Geological Map and publication
- Manuscript to accompany 1:1 million Geological Map of PNG
- Preparation for PNG Transect ARCHIMEDES II (rescheduled for June-July 2023)
- Completed (2 MSc thesis projects: Gray and Besaw)
- Recruiting (1 new PhD, 2 new MSc, 1 new post-doctoral fellow)

Deliverables

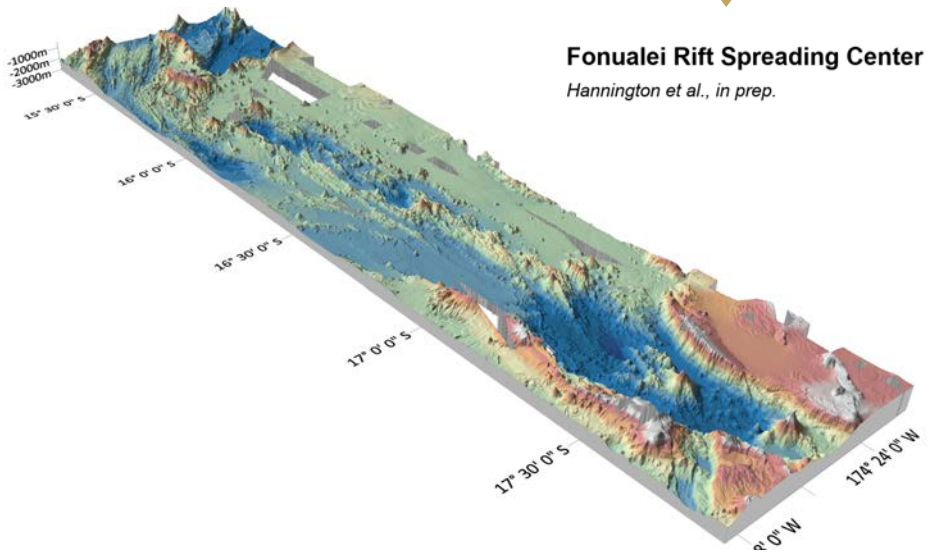
- NE Lau Basin Transect (published in Frontiers in Earth Science)
- Lau Basin Geological Map (published in Geosphere)
- Lau Basin felsic volcanic lithogeo chemistry (accepted for Economic Geology)
- Lau basin mafic volcanic lithogeo chemistry (ready for submission to Economic Geology)
- 7 Oral and poster presentations at Student Minerals Colloquium (PDAC, SEG, GAC-MAC)
- Special session of MDD-GAC-MAC on modern arc-backarc tectonics (London, Ontario)

Future Work

Specific research targets for 2022-23 are:

- Published report on the nature of the crust just prior to rifting; imaging of the Fonualei Rift in the NE Lau Basin
- Comparison of the styles of faulting and the role of pre-existing basement structures in the NE Lau Basin, North Fiji Basin, marginal basins of PNG, and greenstone belts
- Assessment of crustal structure in microplate mosaics using 3D gravity and seismic inversions to obtain a comprehensive profile of the crust at microplate edges
- Characterization of the magma plumbing systems during micro plate formation, including mapping and sampling of volcanic centers at emerging microplate boundaries of the NE and NW Lau Basin; the emphasis will be on consequences or mantle flow, melt sources and pathways in the microplate context
- Comparison of structural and lithostratigraphic makeup of modern assemblages and microplates with potentially analogous structures of the Abitibi greenstone belt.

The focus for 2022-23 will be on modern-ancient comparisons, working closely with the Metal Earth Team to establish the link between microplate formation, greenstone belt assemblages, and magmatic-hydrothermal systems at a scale that is useful for distinguishing endowed and non-endowed terrane. This research will focus on quantitative modelling of crustal growth, with direct comparison to the architecture and mineral endowment of different microplate assemblages. One emphasis will be on microplate boundaries with the aim of recognizing possible ancient analogs in the Abitibi region. We will collaborate with MERC researchers on identifying type sections and features that can be compared to modern assemblages.



Mapping structure in back-arc basins - Figure 3: Bathymetric map of the Fonualei Rift Spreading Center in the NE Lau Basin, showing foundering of the crust and an axial volcano at the propagating tip of the rift.

Areas of particular focus will be different types of unconformities between assemblages, sedimentary sequence stratigraphy, and the structure and evolution of large-scale silicic and mafic submarine calderas, with the aim of comparing modern microplate architectures to relict structures in deformed terranes.

Milestones:

- Complete 2D and 3D inversions of Lau basin seismic sections, gravity and MT
- Microplate reconstruction of the northern Lau Basin and Fiji Basin in GPlates

- North Fiji Basin 1:1 million geological compilation (new for 2022-23)
- Assemblage-level attributes tables and structural/stratigraphic sections for the Lau, PNG, and North Fiji map sheets (new for 2022-23)
- Lithogeochemical comparison of endowed versus non-endowed oceanic settings (Fassbender PhD)
- ARCHIMEDES II Transect in the marginal basins of PNG (SO-299 scheduled in 2023)

Deliverables *(submitted for publication):*

- NE Lau Basin and Fiji Basin tectono-magmatic history, including geophysical data sets
- Lithogeochemical comparison of endowed versus non-endowed oceanic settings
- Eastern PNG-New Ireland geodynamics and metallogeny (to accompany 1:1 million map)
- RPM techniques applied to seafloor mapping (Klischies PhD submitted for publication)
- 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)

Most HQP from Year 6 will continue to work on the project. Two MSc and two PhD students (Kehew, Ryan, Fassbender, and Sitnikova) will shift their work from map production to interpretation and modelling of crustal growth in different assemblage types and at different types of microplate boundaries, with direct comparisons to crustal architecture of greenstone belts. The focus for these comparisons will be in the mapped regions of the North Fiji Basin and Northern Lau Basin, where several different types of structures are represented (e.g., MTJ formed by arc-rifting versus NFBTJ formed by mature back-arc opening; emerging triple junctions of the NWLSC, Rochambeau, and Niuafo'ou assemblages; rift propagation into the NFB plate boundary at Monzier Rift).

Anticipated Outcomes

Using coordinated multiparameter geophysics, geochronology and geochemistry, we have developed the first high-resolution structural-petrologic-magmatic framework for microplate evolution and metallogenesis in several large-scale transects across the termination of 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 architecture 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 the structure and evolution of large-scale silicic versus mafic submarine calderas; modelling of microplate mosaics (especially shortening) as a guide to identifying relict architecture in deformed terranes; detailed lithogeochemical comparisons of magmatic suites in different types of assemblages and microplate settings.

Results from 2021-22 will be presented in 34 publications and reports: 15 papers for peer-reviewed journal articles (3 published or in press, 12 in preparation), 6 student theses, and 13 conference abstracts at national and international scientific meetings (See Publications).

Seventeen active participants in the project from 4 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 and Laurentian in on-line (and now in-person) workshops to ensure the results are being applied directly to the Metal Earth objectives. ME funds have been significantly leveraged through external partnerships, including direct and indirect in-kind contributions. Six members of GEOMAR (Petersen, Brandl, Krätschell, Klischies, Graber, Mensing) continue to work directly with the Ottawa Team.

New for 2022-23 will be a focus on 3D inversions of crustal structure, density and composition in the Lau Basin and adjacent areas; the relationship between metallogeny and collisional tectonics in marginal basins of PNG; a comprehensive lithogeochemical comparison of modern submarine volcanism and volcanic suites of the Abitibi; and criteria for identifying fossil microplate architecture within the established assemblage framework of greenstone belts. We will collaborate with MERC researchers on identifying type examples for different assemblages, which can then be compared to ancient crustal growth that is favourably disposed to mineral endowment.

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.

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Marc Fassbender - Geochemical Signatures of Felsic Rocks in Modern Oceanic Settings

Highlights

Scientific:

Using coordinated multiparameter geophysics, geochronology and geochemistry, we developed the first high-resolution structural-petrologic-magmatic framework for microplate evolution and metallogenesis in several large-scale transects: across the termination of the Tonga arc in the NE Lau Basin, in the high-heat flow North Fiji Basin, and in actively rifting forearc crust of the New Ireland Basin in PNG. This work established the first complete and same-scale structural, magmatic, and geophysical framework of modern microplate domains for comparison with ancient greenstone belts.

The first 1:1 million geological maps of Lau basin and Marginal Basins of Eastern PNG were completed (the first published in the Geological Society of America). A classification of structures in the NE Lau Basin was published in Frontiers in Earth Science, and two papers on the lithogeochemistry of Lau Basin volcanic rocks have been prepared for Economic Geology (one accepted; a second ready for submission). Two MSc theses have been completed (A. Gray, M. Besaw), and one PhD on remote predictive mapping techniques in ocean mapping has been prepared for publication in Marine Geology (M. Klishies). Partner researchers at GEOMAR and BGR (A. Beniest, G. Franz, A. Jegfen, M. Schnabel) have completed their studies of the 2D seismic structure of the NE Lau Basin rifts and the associated magnetic, gravity and MT that will be incorporated into our developing model of the basin.

Personnel:

A. Baxter, M. Stewart, M.O. Anderson were co-convenors of a Special Session of the GAC-MAC Annual Meeting in London, Ontario, November 2021, Advances in Marine Geology and Geodynamics and Their Application to Understanding Modern and Ancient Seafloor Metallogeny.

R. Penner (BSc student of M. Stewart) was the Keating-Boyle prize winner for his poster on the Geological mapping of the SE Futuna Volcanic Zone, Lau Basin, presented at the Special Session of GAC-MAC London, Ontario.

J. Kehew (MSc student of M. Hannington) was selected to represent the Earth Sciences in the special Celebration of Women in Science at the University of Ottawa, presenting her research on intrabasinal sedimentation and tectonostratigraphy of the Lau Basin.

T. Sitnikova (PhD student of M. Hannington) was sponsored by the Norwegian Scientific Academy for Polar Research (Polar Academy in Longyearbyen) to participate in the Arctic Margins Tectonics Summer School on Svalbard Island.

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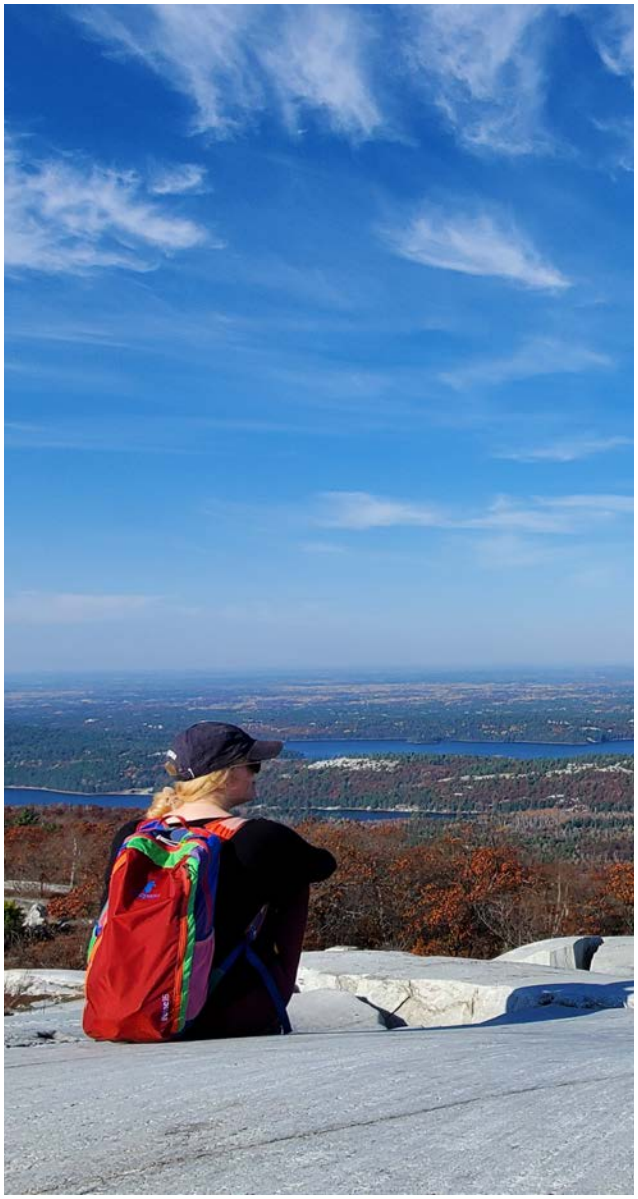

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