



67th ANNUAL MEETING

VIRTUAL EVENTS

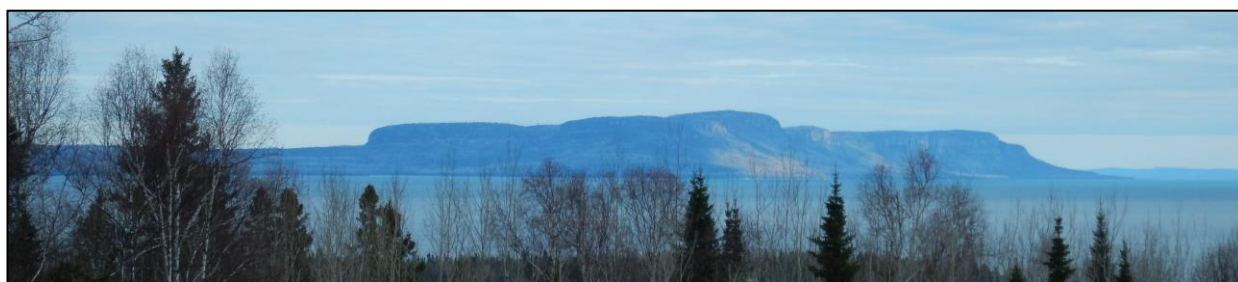
May 11, 14, 18, 21, 2021

Hosted by:

Peter Hollings, Mark Smyk, and Mark Jirsa

Co-chairs

**Lakehead University and
Minnesota Geological Survey**



The Sleeping Giant

**The 66th Annual meeting originally planned for 2020 in Mountain Iron, Minnesota, was cancelled due to the Covid-19 pandemic, and thus, no Proceedings Volume 66 was produced. To mitigate potential impact from the ongoing pandemic, the 67th Annual meeting was held in a virtual format. As a result, there were no fieldtrips, and only this Part 1 of Proceedings Volume 67 was produced.*

We would like to thank the Lakehead University Technology Services Centre, particularly Blain Boyd, Shawn Hartviksen and John Bonofiglio, for providing the Zoom account and technical support for this virtual meeting.

Proceedings Volume 67, Part 1: Program and Abstracts

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Reference to material in Part 1 should follow the example below:

Authors(s), 2021, abstract title. 67th Institute on Lake Superior Geology Proceedings v. 67, Part 1-Program and Abstracts, p. XX

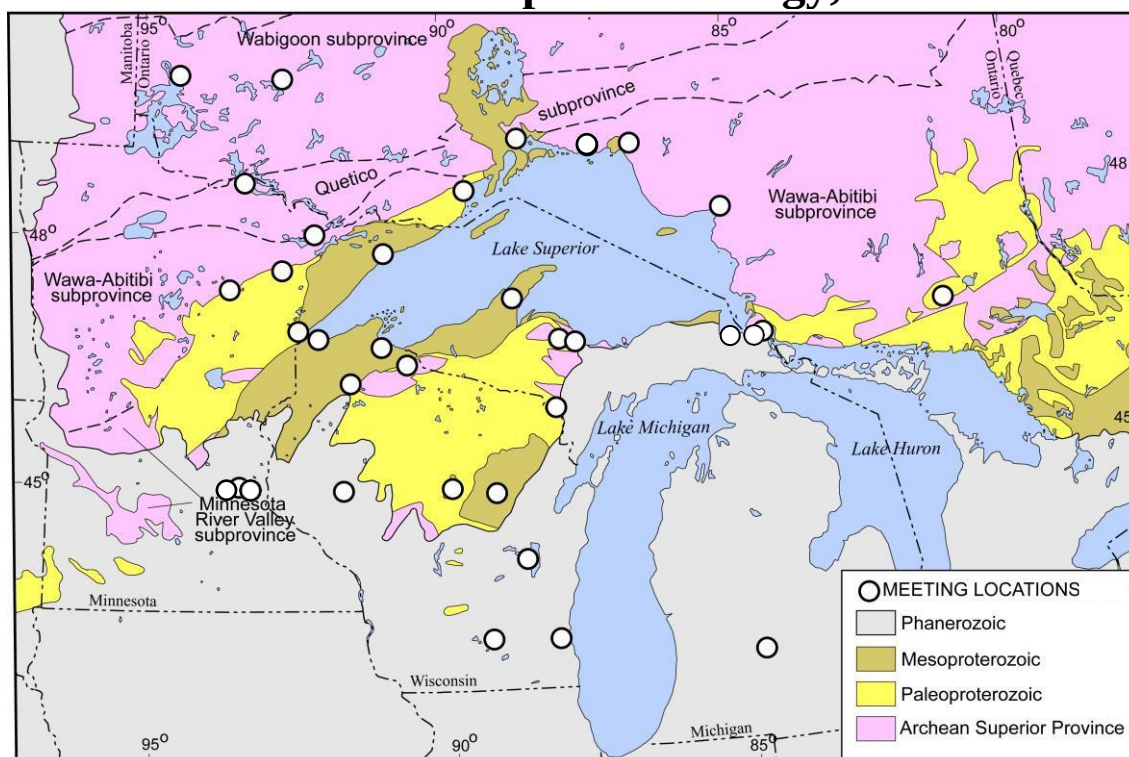
Published by the 67th Institute on Lake Superior Geology and distributed by the ILSG Secretary:

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Digital version of the volumes are available on-line at
<http://www.lakesuperiorgeology.org>.

ISSN 1042-99

Institutes on Lake Superior Geology, 1955-2019



#	Year	Meeting Location	Chairs
1	1955	Minneapolis, Minnesota	C.E. Dutton
2	1956	Houghton, Michigan	A.K. Snelgrove
3	1957	East Lansing, Michigan	B.T. Sandefur
4	1958	Duluth, Minnesota	R.W. Marsden
5	1959	Minneapolis, Minnesota	G.M. Schwartz & C. Craddock
6	1960	Madison, Wisconsin	E.N. Cameron
7	1961	Port Arthur, Ontario	E.G. Pye
8	1962	Houghton, Michigan	A.K. Snelgrove
9	1963	Duluth, Minnesota	H. Lepp
10	1964	Ishpeming, Michigan	A.T. Broderick
11	1965	St. Paul, Minnesota	P.K. Sims & R.K. Hogberg
12	1966	Sault Ste. Marie, Michigan	R.W. White
13	1967	East Lansing, Michigan	W.J. Hinze
14	1968	Superior, Wisconsin	A.B. Dickas
15	1969	Oshkosh, Wisconsin	G.L. LaBerge
16	1970	Thunder Bay, Ontario	M.W. Bartley & E. Mercy
17	1971	Duluth, Minnesota	D.M. Davidson
18	1972	Houghton, Michigan	J. Kalliokoski
19	1973	Madison, Wisconsin	M.E. Ostrom
20	1974	Sault Ste. Marie, Ontario	P.E. Giblin
21	1975	Marquette, Michigan	J.D. Hughes
22	1976	St. Paul, Minnesota	M. Walton
23	1977	Thunder Bay, Ontario	M.M. Kehlenbeck

#	<u>Year</u>	<u>Meeting Location</u>	<u>Chairs</u>
24	1978	Milwaukee, Wisconsin	G. Mursky
25	1979	Duluth, Minnesota	D.M. Davidson
26	1980	Eau Claire, Wisconsin	P.E. Myers
27	1981	East Lansing, Michigan	W.C. Cambray
28	1982	International Falls, Minnesota	D.L. Southwick
29	1983	Houghton, Michigan	T.J. Bornhorst
30	1984	Wausau, Wisconsin	G.L. LaBerge
31	1985	Kenora, Ontario	C.E. Blackburn
32	1986	Wisconsin Rapids, Wisconsin	J.K. Greenberg
33	1987	Wawa, Ontario	E.D. Frey & R.P. Sage
34	1988	Marquette, Michigan	J. S. Klasner
35	1989	Duluth, Minnesota	J.C. Green
36	1990	Thunder Bay, Ontario	M.M. Kehlenbeck
37	1991	Eau Claire, Wisconsin	P.E. Myers
38	1992	Hurley, Wisconsin	A.B. Dickas
39	1993	Eveleth, Minnesota	D.L. Southwick
40	1994	Houghton, Michigan	T.J. Bornhorst
41	1995	Marathon, Ontario	M.C. Smyk
42	1996	Cable, Wisconsin	L.G. Woodruff
43	1997	Sudbury, Ontario	R.P. Sage & W. Meyer
44	1998	Minneapolis, Minnesota	J.D. Miller & M.A. Jirsa
45	1999	Marquette, Michigan	T.J. Bornhorst & R.S. Regis
46	2000	Thunder Bay, Ontario	S.A. Kissin & P. Fralick
47	2001	Madison, Wisconsin	M.G. Mudrey & Jr., B.A. Brown
48	2002	Kenora, Ontario	P. Hinz & R.C. Beard
49	2003	Iron Mountain, Michigan	L. Woodruff & W.F. Cannon
50	2004	Duluth, Minnesota	S. Hauck & M. Severson
51	2005	Nipigon, Ontario	M. Smyk & P. Hollings
52	2006	Sault Ste. Marie, Ontario	A. Wilson & R. Sage
53	2007	Lutsen, Minnesota	L. Woodruff & J. Miller
54	2008	Marquette, Michigan	T.J. Bornhorst & J. Klasner
55	2009	Ely, Minnesota	J. Miller, G. Hudak, & D. Peterson
56	2010	International Falls, Minnesota	M. Jirsa, P. Hollings, T. Boerboom, P. Hinz & M.Smyk
57	2011	Ashland, Wisconsin	T. Fitz
58	2012	Thunder Bay, Ontario	P. Hollings
59	2013	Houghton, Michigan	T.J. Bornhorst & A. Blaske
60	2014	Hibbing, Minnesota	J. Miller & M. Jirsa
61	2015	Dryden, Ontario	R. Cundari & P. Hinz
62	2016	Duluth, Minnesota	J. Miller, C. Schardt, & D. Peterson
63	2017	Wawa, Ontario	A. Pace, A. Wilson, & T.J. Bornhorst
64	2018	Iron Mountain, Michigan	L. Woodruff, W. Cannon, & E.K. Stewart
65	2019	Terrace Bay, Ontario	P. Hollings & M.C. Smyk
66	2020	<i>Meeting cancelled due to Covid-19 pandemic</i>	
67	2021	Virtual meeting	P. Hollings, M. Smyk, M. Jirsa

Sam Goldich and the Goldich Medal

Sam Goldich received an A.B. from the University of Minnesota in 1929, a M.A. from Syracuse University in 1930, and a Ph.D. from the University of Minnesota in 1936. During World War II Sam worked for the U.S. Geological Survey in mineral exploration. In 1948, Sam returned to the University of Minnesota, and became Professor and Director of the Rock Analysis Laboratory the following year. He rejoined the U.S. Geological Survey in 1959 and was appointed as the first Branch Chief of the Branch of Isotope Geology. Sam returned to academia in 1964 when he went to Pennsylvania State University. He left PSU in 1965 and moved to the State University of New York at Stony Brook, where he stayed for 3 years. Restless yet again, he moved to Northern Illinois University in 1968 where he was a professor until his retirement in 1977. Sam's final move was to Denver where he became an emeritus at the Colorado School of Mines. Sam died in 2000, less than a month before his 92nd birthday.

In the late 1970's, Geological Society of America Special Paper 182, which included seminal geochronological studies by Sam Goldich and coworkers on the Archean rocks of the Minnesota River Valley, was nearing completion. At this time various ILSG regulars began discussing the possibility of recognizing Sam for his pioneering work on the resolution of age relationships and thus the geology of Precambrian rocks in the Lake Superior region. Three members, R.W. Ojakangas, J.O. Kalliokoski and G.B. Morey, presented the idea to the ILSG Board of Directors in 1978. The Board approved the creation of an award, provided funding could be obtained. It was suggested that collecting one or two dollars at registration for a dedicated account would provide resources for striking the medal. A general request was made to the ILSG membership for donations and Sam himself offered a challenge grant to match the contributions. In total \$4,000 was collected and thus began the work of creating the Goldich Medal.

The initial Goldich Award was presented to Sam by G.B. Morey in 1979 and consisted of a large paper proclamation. For the actual medal, G.B. Morey consulted with the foundry on production details, while Dick Ojakangas and Jorma Kalliokoski worked on the design of the award, suggesting that it be given for "outstanding contributions to the geology of the Lake Superior region." Simultaneously, a committee of J.O. Kalliokoski, W.F. Cannon, M.M. Kehlenbeck, G.B. Morey, and G. Mursky developed the Award Guidelines that were approved by the ILSG Board. By 1981 all the elements of the Goldich Award had come together, and the second recipient, Carl E. Dutton, Jr., received the Goldich Medal for 50 years of significant contributions to the understanding of the geology of the Lake Superior region. Since the beginning, the Awards Committee has consisted of individuals representing industry, government and academia, with each member of the Committee serving for three years. The medal is now awarded every year at the annual ILSG meeting.

Reference:

Morey, G.B. and Hanson, G.N. (editors). 1980. Selected studies of Archean gneisses and Lower Proterozoic rocks, southern Canadian Shield. Geological Society of America, Special Paper 182, 175 p.

Prepared by various Goldich Medal Awardees, 2007



INSTITUTE ON LAKE SUPERIOR GEOLOGY GOLDICH MEDALLION

Goldich Medal Guidelines

(Adopted by the Board of Directors, 1981; amended 1999)

Preamble

The Institute on Lake Superior Geology was born in 1955, as documented by the fact that the 27th annual meeting was held in 1981. The Institute's continuing objectives are to deal with those aspects of geology that are related geographically to Lake Superior; to encourage the discussion of subjects and sponsoring field trips that will bring together geologists from academia, government surveys, and industry; and to maintain an informal but highly effective mode of operation.

During the course of its existence, the membership of the Institute (that is, those geologists who indicate an interest in the objectives of the ILSG by attending) has become aware of the fact that certain of their colleagues have made particularly noteworthy and meritorious contributions to the understanding of Lake Superior geology and mineral deposits.

The first award was made by ILSG to Sam Goldich in 1979 for his many contributions to the geology of the region extending over about 50 years. Subsequent medallists and this year's recipient are listed in the table below.

Award Guidelines

- 1) The medal shall be awarded annually by the ILSG Board of Directors to a geologist whose name is associated with a substantial interest in, and contribution to, the geology of the Lake Superior region.
- 2) The Board of Directors shall appoint the Goldich Medal Committee. The initial appointment will be of three members, one to serve for three years, one for two years, and one for one year. The member with the briefest incumbency shall be chair of the Nominating Committee. After the first year, the Board of Directors shall appoint at each spring meeting one new member who will serve for three years. In his/her third year this member shall be the chair. The Committee membership should reflect the main fields of interest and geographic distribution of ILSG membership. The out-going, senior member of the Board of Directors shall act as liaison between the Board and the Committee for a period of one year.
- 3) By the end of November, the Goldich Medal Committee shall make its recommendation to the Chair of the Board of Directors, who will then inform the Board of the nominee.
- 4) The Board of Directors normally will accept the nominee of the Committee, inform the medallist, and have one medal engraved appropriately for presentation at the next meeting of the Institute.
- 5) It is recommended that the Institute set aside annually from whatever sources, such funds as will be required to support the continuing costs of this award.

Nominating Procedures

- 1) The deadline for nominations is November 1. Nominations shall be taken at any time by the Goldich Medal Committee. Committee members may themselves nominate candidates; however, Board members may not solicit for or support individual nominees.

- 2) Nominations must be in writing and supported by appropriate documentation such as letters of recommendation, lists of publications, curriculum vita's, and evidence of contributions to Lake Superior geology and to the Institute.
- 3) Nominations are not restricted to Institute attendees, but are open to anyone who has worked on and contributed to the understanding of Lake Superior geology.

Selection Guidelines

- 1) Nominees are to be evaluated on the basis of their contributions to Lake Superior geology (sensu lato) including:
 - a) importance of relevant publications;
 - b) promotion of discovery and utilization of natural resources;
 - c) contributions to understanding of the natural history and environment of the region;
 - d) generation of new ideas and concepts; and
 - e) contributions to the training and education of geoscientists and the public.
- 2) Nominees are to be evaluated on their contributions to the Institute as demonstrated by attendance at Institute meetings, presentation of talks and posters, and service on Institute boards, committees, and field trips.
- 3) The relative weights given to each of the foregoing criteria must remain flexible and at the discretion of the Committee members.
- 4) There are several points to be considered by the Goldich Medal Committee:
 - a) An attempt should be made to maintain a balance of medal recipients from each of the three estates—industry, academia, and government.
 - b) It must be noted that industry geoscientists are at a disadvantage in that much of their work is not published.
- 5) Lake Superior has two sides, one the U.S., and the other Canada. This is undoubtedly one of the Institute's great strengths and should be nurtured by equitable recognition of excellence in both countries.

Goldich Medalists

1979	Samuel S. Goldich	1998	Zell Peterman	2016	Mark A. Jirsa
1980	<i>not awarded</i>	1999	Tsu-Ming Han	2017	Philip Fralick
1981	Carl E. Dutton, Jr	2000	John C. Green	2018	Val W. Chandler
1982	Ralph W. Marsden	2001	John S. Klasner	2019	Mark Severson
1983	Burton Boyum	2002	Ernest K. Lehmann	2021 Allan MacTavish	
1984	Richard W. Ojakangas	2003	Klaus J. Schulz	<i>(Not awarded 2020)</i>	
1985	Paul K. Sims	2004	Paul Weiblen		
1986	G.B. Morey	2005	Mark Smyk		
1987	Henry H. Halls	2006	Michael G. Mudrey		
1988	Walter S. White	2007	Joseph Mancuso		
1989	Jorma Kalliokoski	2008	Theodore J. Bornhorst		
1990	Kenneth C. Card	2009	L. Gordon Medaris, Jr		
1991	William Hinze	2010	William D. Addison &		
1992	William F. Cannon		Gregory R. Brumpton		
1993	Donald W. Davis	2011	Dean M. Rossell		
1994	Cedric Iverson	2012	James D. Miller		
1995	Gene La Berge	2013	Tom Waggoner		
1996	David L. Southwick	2014	Laurel Woodruff		
1997	Ronald P. Sage	2015	Rodney J. Ikola		

Goldich Medal Committee

Serving through the meeting year shown in parentheses.

Dan England (2017-2022) Eveleth Fee Office (Committee Chair)

Steve Kissin (2018-2023) Lakehead University

Dorothy Campbell (2020-2024) Ontario Geological Survey

Terms of the committee members have been extended 2 years due to cancelation of the 2020 meeting and the logistical difficulties of voting during the 2021 virtual meeting. Presentation of the award to Allan MacTavish was to have occurred at the 2020 meeting, but was delayed one year.

2021 GOLDICH MEDAL RECIPIENT

ALLAN MACTAVISH



Citation for **Allan MacTavish**

ILSG members, Goldich Medal recipients and guests, it is my privilege to present the citation for this year's recipient of the Goldich Medal, Allan MacTavish.

Allan received his Bachelor of Science (B.Sc.) degree in geology from Laurentian University in 1977. Over the past 44 years, he has spent much of his career working as an economic geologist in the Lake Superior region, both in the mineral exploration industry and with the Ontario government. Early on, Allan also somehow found the time to be a part-time graduate student at Lakehead University, where he completed a Master of Science (M.Sc.) thesis entitled "The Geology, Petrology, Sulphide and Platinum-Group Element Mineralization of the Quetico Intrusions, Northwestern Ontario" in 1992. Since completing

this project, much of Allan's work has been focussed on the evaluation of copper-nickel-platinum group element (Cu-Ni-PGE) deposits.

While working in the private sector, Allan has led numerous field exploration programs in the Lake Superior region that have targeted Cu-Ni-PGE, volcanogenic massive sulphide and gold deposits. Most notably, he has served since 2007 as Exploration Manager for Magma Metals (Canada) Ltd./Panoramic PGMs (Canada) Ltd. and most recently as Vice President Project Manager with Clean Air Metals Inc., with a primary focus on the Thunder Bay North Cu-Ni-PGE project. At Thunder Bay North, Allan has led teams of geoscientists from the grassroots exploration phase, through to mineral resource delineation. The initial exploration success at Thunder Bay North, largely attributed to Allan's leadership, sparked a staking rush in the Nipigon Embayment and consequently, a flurry of exploration activity and investment in the region. Although exploration activity in the project area has waxed and waned over the past 14 years, Allan's persistence is now paying off, with Clean Air Metals having reported a significant mineral resource expansion during the winter of 2021, along with an exciting new intersection of high-grade massive sulphides. Furthermore, his work on the Thunder Bay North project, and his support of academic research work into the Current Lake intrusive complex, has made significant contributions to our understanding of chonolith-hosted magmatic sulphide deposits and the greater Midcontinent Rift system.

One of Allan's most notable skills is his competence as a field mapping geologist, an aspect of geology that has largely become a lost art. This skill was developed through his long list of positions, including a stint as a Field Geoscientist with the Ontario Geological Survey, during which he mapped the Montcalm greenstone belt. Even in the private sector, any project under Allan's watch can be counted on to include solid geological mapping. This steadfast belief in the core fundamentals of geology has led to a significant advancement in our understanding of many geological districts in the Lake Superior region, including the Hemlo gold camp, the Coldwell

complex, the Nipigon Embayment, the Atikokan-Quetico district and the Abitibi greenstone belt. Understanding the importance of a solid foundation in geological mapping as part of the training for future geoscientists, Allan has also been a long-time supporter of the Precambrian Research Centre (PRC), focussing his contributions toward the PRCs mapping school and the students therein.

It was during Allan's time working on his M.Sc. project, when I was a fellow graduate student, that I first got to know him. I quickly gained an appreciation for his knowledge and enthusiasm for the science of geology. I consider myself fortunate that, shortly after graduation, I became one of the many aspiring geoscientists who have benefitted from Allan's mentorship when he hired me as a field assistant for a short-term project. More recently, the Lakehead University Student Chapter of the Society of Economic Geologists (SEG) has also been privy to Allan's wisdom and knowledge. Since its inception in 2014, he has served as the Industry Representative for the SEG student chapter, assisting the group with fundraising and field trip endeavours, most notably trips to Arizona and Ireland. The Geology Department at Lakehead University has long known the benefit of having Allan as an associate, whether as a voice for industry to help direct departmental decisions, or as an employer hiring a geology student during or immediately following their studies.

Allan's contributions to the Institute on Lake Superior geology are many. He has tirelessly supported the ILSG by serving as a Board member, Goldich Award Committee member, Annual Conference planning committee member, and as an individual contributor to the ILSG Student Travel Scholarship. Dating back to 1985, Allan is credited as an author for 7 abstracts and 4 field trip guides, plus as an editor for 3 field trip guidebooks. Allan has led field trips for ILSG annual meetings, most recently the Coldwell Complex trip at the 2019 Terrace Bay meeting. He was also the co-organizer and field trip leader for the 2017 ILSG Iceland Geological Field Trip, and organized and led the 2020 Hawaii Geological Field Trip, which also happened to be the last ILSG in-person event to occur prior to the onset of the global Covid-19 pandemic (let's all hope that we can once again get together for ILSG field trips in 2022).

Anyone who has had the pleasure of knowing Allan over the years immediately becomes aware of his enthusiasm for geoscience and his deep knowledge of the rocks of the Lake Superior region. Allan's contributions to the understanding of the geology of the Lake Superior region, as well as his unwavering support of the Institute on Lake Superior Geology, make him a worthy recipient of the 2021 Goldich Medal.

*Submitted by Mark Puumala, M.Sc., P.Geo.
Senior Manager, Resident Geologist Program
Ontario Geological Survey*

Honoring the Pioneers of Lake Superior Geology

(Adopted by the Board of Directors, 2016)

Preamble

At the suggestion of Gene LaBerge, the 2016 executive board agreed to implement a program to recognize historic pioneers in the understanding of geology in the Lake Superior region. Beginning with the 2017 annual meeting, nominations will be accepted from the membership for geologists whose work was conducted primarily before inception of the institute in 1955. Biographical sketches of those pioneers will be presented at future annual meetings so that all might appreciate the value of their contributions. Selection of nominees will be decided in part by the organizing committee of each year's annual meeting, in consultation with the Board, to ensure equitable geographic representation in the selection process.

Award Guidelines

- 1) Nominations from the membership will be submitted via the Institute web site and forwarded to the Chair of the next Annual Meeting. The nominations will be no more than half a page in length and will summarise the contribution of the nominee.
- 2) The Organising Committee will select one or two individuals to be highlighted at the next Annual meeting and submit those names to the Board for approval.
- 3) The nominator will be requested to prepare a brief presentation to be given during the next annual meeting with a summary to be included in the Proceedings volume.
- 4) Unsuccessful nominations will be kept by the Secretary for two years and forwarded to the next meeting Chair; these nominations may be resubmitted at a later date.

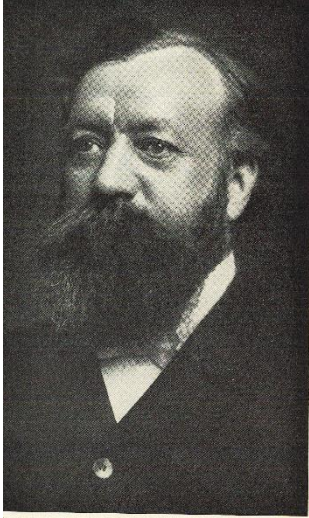
The Board will review this award every five years.

Pioneers of Lake Superior Geology

2017 Douglass Houghton (1809-1845)

2018-2020 *not presented*

2021 Newton Horace Winchell (1839-1914)



2021 Pioneer of Lake Superior Geology Newton Horace Winchell (1839-1914) “Minnesota’s Geologist”

Citation by Jim Miller, Former Associate Professor, University of Minnesota Duluth and Senior Geologist, Minnesota Geological Survey, with insights from author Sue Leaf.

Newton Horace Winchell was first director of the Minnesota Geological and Natural History Survey at the University of Minnesota from 1872 to 1898. During his 26 year tenure, Winchell and his staff visited every corner of the state to document its bedrock geology, mineral deposits, quarry stone resources, glacial deposits and landforms, paleontological record, modern flora and fauna, and hydrologic framework. The survey’s findings were recorded in 24 Annual Reports, which summarized each year’s accomplishments and commonly totaled hundreds of pages, and in a six-volume final report. Pdfs of these reports are all available from the University of Minnesota Digital Conservancy (<https://conservancy.umn.edu/handle/11299/708>).

As skillfully told in Sue Leaf’s (2020) engaging and intimate biography of Winchell’s private and professional life, Newton Horace Winchell (NHW) was born and raised as the middle child in a large family near the New York-Massachusetts-Connecticut borders. At the age of 15 after 8th grade, he began teaching in small schools in the area. In 1857, he moved to Ann Arbor, Michigan to live with his older (by 15 years) brother Alexander, who was a professor of natural history at the University of Michigan and director of the Michigan Geological Survey. Over the next 12 years, NHW worked as an elementary school teacher/principal in various southern Michigan towns, got married, had two children, and also intermittently took classes at the U of Michigan. In the summer of 1860, he was hired by the Michigan Geological Survey as a botanist and explored the coastlines of Lakes Huron and Michigan. NHW completed his BA degree in 1866, committed to geology as a profession, and began to work more regularly for the Michigan Survey. In 1869, he completed his MS degree at U of Michigan and became Assistant State Geologist under his brother. In 1870, the Michigan legislature defunded the geological survey, which prompted NHW to work the summers of 1871 and 1872 for the Ohio Geological Survey. In July 1872, University of Minnesota president, William Folwell, offered NHW the position of director of the newly created Minnesota Geological and Natural History Survey. With an initial legislative appropriation of \$1000 per year, Folwell estimated that the survey would need 20 years to accomplish its task of conducting “a thorough geological and natural history survey of the State”. In addition, he would be responsible for teaching two geology courses each year and organizing a natural history museum. NHW accepted the offer, and began field work that fall.

The first six field seasons of the Survey (1872-1877), NHW and his small staff focused their attention on the geology, geomorphology, paleontology, and economic geology of southern Minnesota counties. In 1876, Winchell’s responsibility for the University museum was relieved by the hiring of zoologist, Clarence Herrick, as museum director. NHW’s other non-survey obligation of teaching college classes was removed just before the 1879 field season by the hiring of another zoologist, Christopher Hall, who was also appointed assistant director of the survey. Additionally significant hires in 1879 were those of glacial geologist Warren Upham and paleontologist Edward Ulrich. Although NHW was well versed in both these disciplines, their contributions and other staff hires in the 1880’s, freed Winchell to devote many months of field

work per year over the next decade and to accomplish his most challenging task –deciphering the Precambrian geology of northeastern Minnesota.

The Paleozoic, Cretaceous and Quaternary geology of southern and western Minnesota was summarized in Volumes 1 (1884; 673 p.) and 2 (1888; 671 p.) of the final report written by NHW and Upham. The paleontology of Ordovician and Cambrian rocks (at the time interpreted to be Upper and Lower Silurian) and of Cretaceous rocks was summarized in the 1200+ page Volume 3 that was published in two parts (pt. 1 – 1895; Pt. 2 - 1897).

The task of mapping and deciphering the Precambrian geology of northeastern Minnesota started in the summer of 1878 when NWH and three others paddled along the Lake Superior shoreline from Duluth to the Canadian border. In all, they collected over 300 samples. Then, from September to November of that same year, NHW and two Ojibwe guides paddled and portaged from Grand Portage, to Lake Vermilion, down the Embarrass, St. Louis and ultimately the Mississippi rivers to Minneapolis – a 500+ mile trek! Winchell devoted most of his remaining field seasons to northern Minnesota geology with the able assistance of his son (Horace), his son-in-law (Uly), and his brother (Alexander). With iron mining taking off on the Vermilion Range (1st ore shipped -1884), and then the Mesabi Range (1st ore shipped - 1892), much of NHW's attention was focused on that geology. Also, beginning the mid-1880's, Winchell regularly employed petrography to better understand the granite, gabbro, greenstone, and basalt that he encountered. In fact, in 1895, he took a year-long "sabbatical" to Paris to learn petrographic methods from the French petrographers Fonque and Michel-Levy. Still, as I highlighted in an ILSG talk in 2004, Winchell struggled mightily to understand the genesis of Precambrian crystalline rocks. In the introduction of Volume 4 of the Final Report (1899), wherein he summarizes his studies of northern Minnesota geology, NWH comments: "Here [among the crystalline rocks] the geologist is deprived of his usual guides and guys, and finds himself floundering in a muddy sea of innumerable conflicting currents".

Some other notable aspects of Winchell's remarkable career include his role in the development of the first scientific journal exclusively devoted to geology – The American Geologist. He served as its managing editor and publisher from its inception in 1888 to its merger with Economic Geology in 1905. Part of his motivation for creating this journal was to give a voice to state survey geologists which had the potential of being dismissed by academics and experienced overreach by the USGS. Also, as a founding fellow, NHW was instrumental in the creation of the Geological Society of America, also starting in 1888. After the Minnesota survey ended in 1899 and he got closure on Volumes 5 (1900, Uly Grant's PhD thesis) and 6 (1901, atlas of county geologic maps), NHW focused the final decade of his life on archeological studies with the Minnesota Historical Society, particularly as they applied to native peoples who lived in the midcontinent before, during and after the last glacial episode. He published *Aborigines of Minnesota* in 1911 (743 p. 642 figures, 32 plates). As Sue Leaf points out, this well received book was "comprehensive in scope, methodical in approach, and meticulous in detail; a worthy companion to the voluminous *Geology of Minnesota*." Winchell died on May 2, 1914 due to surgical complications at the age of 74.

Newton Horace Winchell's geological survey took the blank canvas of Minnesota's landscape (Fig. 1) and began the process of revealing the rich diverse geology that we now recognize (Fig. 2) and continue to embellish and improve upon. As Sue Leaf's book proclaims in its title, Newton Horace Winchell indeed deserves the designation as "Minnesota's Geologist," and as one of the great pioneers of Lake Superior geology.

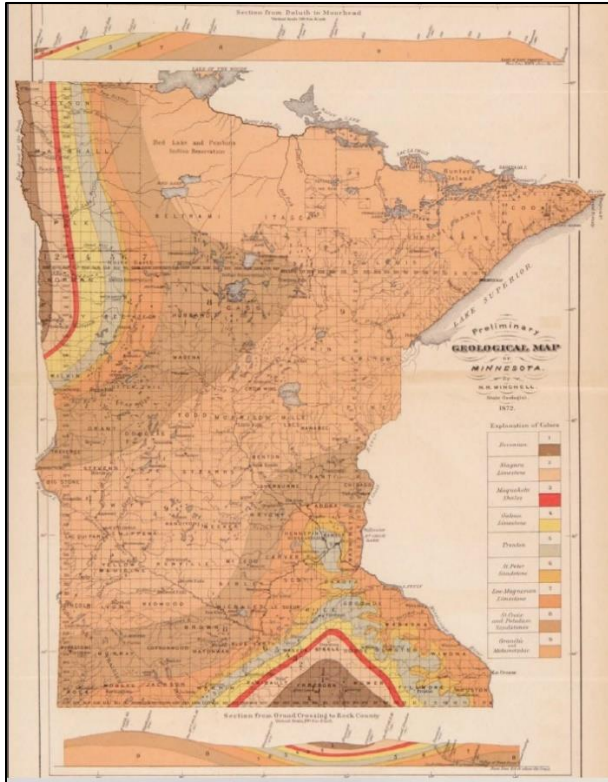


Figure 1 – Geological map of Minnesota in 1872 at the beginning of the Minnesota Geological and Natural History Survey (Annual Report #1).

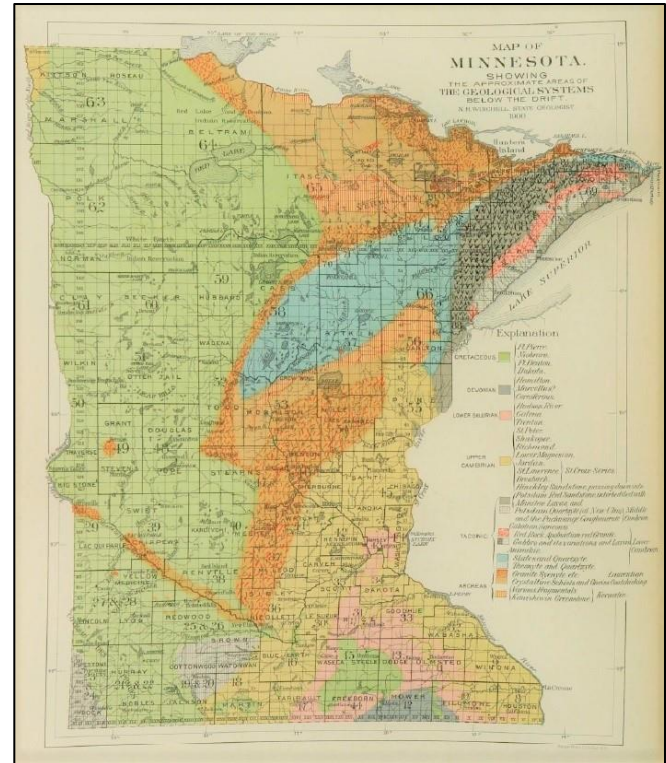


Figure 2 – Geological map of Minnesota in 1900 at the end of the Minnesota Geological and Natural History Survey (Final Report, V. 6).

References

- Leaf, Sue, 2020, Minnesota's Geologist - The Life of Newton Horace Winchell. University of Minnesota Press, Minneapolis, MN, 261p.
- Miller, James D., 2004, N.H. Winchell's study of the Keweenaw Supergroup rocks of northeastern Minnesota, 1872-1900. Proceedings and Abstracts, 50th Institute of Lake Superior Geology, Duluth, MN, p. 117-118.

In Memoriams

The ILSG lost four of its' long-time members since our last in-person meeting in 2019. Brief descriptions of their professional lives follow, excerpted from online obituaries and tributes. They were active members throughout their professional careers and beyond. They all made significant contributions to the science and to the Institute. They will be missed.

Ronald Seavoy passed away on March 25, 2020. He was born July 6, 1931 in New York City and was raised in Chicago. He received his Bachelor of Science degree in Geology in 1953 from the University of Michigan, and his Master of Arts (1963) and PhD (1969) in History from Michigan. He served in the U.S. Army from 1953-1955. He was hired by the Department of History at Bowling Green State University in 1965 where he taught U.S. Constitutional History, U.S. Business History, as well as numerous survey courses until his retirement in 1991 as Professor Emeritus. Ron is the author of ten books and nineteen articles on the subjects of American business history, famine in developing countries, political economy, and mining exploration. Before and while employed as a historian, Ron worked as an exploration geologist for Canadian Johns Manville, International Nickel Company, Alcoa, Burwest, Western Nuclear, and Cleveland Cliffs Mining. He was a member of the Organization of American Historians, the Society of Economic Geologists, and the Institute of Lake Superior Geology. Over the many years of Ron's involvement with ILSG, he donated thousands of dollars to the Mancuso Student Research Award, which was named for Ron's good friend and colleague.

John Klasner passed away on July 15, 2020. John was born June 22, 1935 in Flint, Michigan. He attended Michigan State University and Michigan Technological University where he graduated with degrees in geology and geophysics. He worked in mineral and oil exploration in the US, Canada, Africa, and the Middle East. John then became a geology professor and directed the honors program at Western Illinois University. He also was employed by the USGS for mapping in the Upper Peninsula of Michigan and Northern Wisconsin. John was a member of several professional organizations, including the Institute on Lake Superior Geology.

John Heine passed away August 17, 2020 in Duluth. He was born in Minneapolis and graduated from University of St. Thomas in St. Paul. John moved to Duluth and pursued graduate studies in the Geology Department at the University of Minnesota Duluth. During his 30+ year career with the Natural Resources Research Institute (NRRI), Minerals & Metallurgy Strategic Research Initiative, he worked on a wide variety of field- and laboratory-based geological studies to better understand the mineral characteristics and mineral potential of the state. He retired from the NRRI in 2020 after an accomplished career. John loved field work, and he never stopped learning and teaching.

Thomas Waggoner of Negaunee, Michigan, died December 7, 2020. Tom acquired an MSc in geology at Michigan State University, and worked for Cleveland Cliffs Mining. He helped Cliffs make the transition from underground mining of direct shipping ore to surface mining and production of taconite pellets, which are now the life blood of iron mining in the Lake Superior region. The success of his contributions is best measured by 40 years of continual production of pellets from the Empire and Tilden mines. During his long career with Cliffs (1965-1997), Tom actively participated in the teaching function of the Institute on Lake Superior Geology. He led 45 field trips for various organizations, and made numerous poster and oral presentations at annual meetings of the Institute. After his retirement in 1997, he continued to serve the mining industry. Tom remained active in ILSG, leading a field trip during the Iron Mountain meeting in 2018 and attending the Terrace Bay meeting in 2019. We all benefited from his knowledge, enthusiasm, and support. He will be sorely missed by all who knew him.
(excerpted from a tribute by Alan Strandlie, December 10, 2020)

Eisenbrey Student Travel Awards

Because the 2020 meeting was canceled, and the 2021 meeting is virtual, no awards are granted. The program will continue when it's safe to travel and meet in-person.

The 1986 Board of Directors established the ILSG Student Travel Awards to support student participation at the annual meeting of the Institute. The name “Eisenbrey” was added to the award in 1998 to honor Edward H. Eisenbrey (1926-1985) and utilize substantial contributions made to the 1996 Institute meeting in his name. “Ned” Eisenbrey is credited with discovery of significant volcanogenic massive sulfide deposits in Wisconsin, but his scope was much broader—he has been described as having unique talents as an ore finder, geologist, and teacher. These awards are intended to help defray some of the direct travel costs of attending Institute meetings, and include a waiver of registration fees, but exclude expenses for meals, lodging, and field trip registration. The number of awards and value are determined by the annual Chair in consultation with the Secretary and Treasurer. Recipients will be announced at the annual banquet.

The following general criteria will be considered by the annual Chair, who is responsible for the selection:

- 1) The applicants must have active resident (undergraduate or graduate) student status at the time of the annual meeting of the Institute, certified by the department head.
- 2) Students who are the senior author on either an oral or poster paper will be given favored consideration.
- 3) It is desirable for two or more students to jointly request travel assistance.
- 4) In general, priority will be given to those in the Institute region who are farthest away from the meeting location.
- 5) Each travel award request shall be made in writing to the annual Chair, and should explain need, student and author status, and other significant details.

Successful applicants will receive their awards during the meeting.

Joe Mancuso Student Research Awards

The 2005 Board of Directors established the ILSG Student Research Fund with \$10,000 US from the Institute's general fund to encourage student research on the geology of the Lake Superior region. A minimum of two awards of \$500 US each for research expenses (but not travel expenses) will be made each year. Students are expected to present their research orally or during a poster session at an ILSG meeting. The award winners will also be automatically eligible for the Eisenbrey Travel Awards. To allow the fund to grow, the Fund will receive one-half of any additional proceeds from each annual meeting, after all other commitments and expenses are covered.

- The ILSG Board of Directors will be responsible for selecting a minimum of two awards each year. The ILSG Treasurer will issue the awards.
- The ILSG Student Research Fund is available for undergraduate or graduate students working on geology in the Lake Superior region.
- The applications are due to the ILSG Secretary by August 31st of each year. Awards will be made by October 1st of each year.
- Names of the award recipients will be announced at the next annual meeting and posted on the ILSG website.
- Details of the application process can be found on the ILSG web site.
- The proposal will need to be signed by the researcher's supervisor.

The 2012 Board of Directors approved modification of the fund's name, adding "Mancuso" to reflect the many contributions of Joseph Mancuso to the organization and sizeable donations made in his name by Ronald Seavoy, Joe's colleague and friend. "Doc Joe," as he was known by his students, taught geology for 36 years at Bowling Green State University, Ohio. He advised many graduate students in field-oriented research, and frequently brought them to Institute meetings. Joe was the 2007 Goldich Medalist.

In fall 2020, the ILSG Board of Directors selected one student to be granted research funding of \$1000.00 from the Joe Mancuso Student Research Fund. The awardee was:

Ann Marie Prue

University of Minnesota-Duluth, MSc, Department of Earth and Environmental Sciences,

TOPIC: *Multi-method Geochemical Investigation of the Neoarchean Soudan Iron Formation, NE, Minnesota.*

[editor's note: She is presenting her research at this meeting]

Doug Duskin Student Paper Awards

Because the virtual format of this meeting would likely complicate the process of judging student presentations, no awards are granted. The awards program will continue when it's safe to travel and meet in-person.

Each year, the Institute selects the best of student presentations and honors the presenters with a monetary award. Funding for the award is generated from registrations of the annual meeting, and from generous donations to the fund in honor of Doug Duskin—an exploration geologist and long-time friend of the Institute. The 2012 ILSG Board of Directors approved adding Doug's name to the award to acknowledge his contributions, and distribute those donations in a manner that would have pleased him. The Duskin Student Paper Committee is appointed by the Meeting Chair. Criteria for best student paper—last modified by the Board in 2001—follow:

- 1) The contribution must be demonstrably the work of the student.
- 2) The student must present the contribution in-person.
- 3) The Student Paper Committee shall decide how many awards to grant, and whether or not to give separate awards for poster vs. oral presentations.
- 4) In cases of multiple student authors, the award will be made to the senior author, or the award will be shared equally by all authors of the contribution.
- 5) The total amount of the awards is left to the discretion of the meeting Chair in conjunction with the Secretary, but typically is in the amount of about \$500 US (increase approved by Board, 10/01).
- 6) The Secretary maintains, and will supply to the Committee, a form for the numerical ranking of presentations. This form was created and modified by Student Paper Committees over several years in an effort to reduce the difficulties that may arise from selection by raters of diverse background. The use of the form is not required, but is left to the discretion of the Committee.
- 7) The names of award recipients shall be included as part of the annual Chair's report that appears in the next volume of the Institute.

Student papers will be noted on the Program.

Board of Directors

Board appointment continues through the close of the meeting year shown in parentheses, or until a successor is selected.

The terms of Board members have been extended 2 years due to cancellation of the 2020 meeting, and the difficulties of virtual voting by the membership during the 2021 meeting.

Mark Smyk (2019-2024) – Lakehead University

Esther Stewart (2018-2023) – Wisconsin Geological & Natural History Survey

Anthony Pace (2017-2022) – Ontario Ministry of Energy, Northern Development and Mines

Pete Hollings - Secretary (2016-2024) – Lakehead University

Mark Jirsa – Treasurer (2017-2022) – Minnesota Geological Survey (retired)

REPORT OF THE 65th ANNUAL MEETING OF THE INSTITUTE ON LAKE SUPERIOR GEOLOGY

Terrace Bay, Ontario

Lakehead University and the Ontario Geological Survey (OGS), hosted the 65th Annual Institute on Lake Superior Geology on May 07 – 10, 2019 at the Terrace Bay Cultural Centre, Terrace Bay, Ontario. The meeting consisted of two days of technical sessions with pre- and post-technical session field trips. Mark Smyk (OGS) and Pete Hollings (Lakehead University) were co-chairs for the 2019 meeting. Invaluable advice and logistical support was provided by Dean Main and Michelle Malashewski of the Township of Terrace Bay's Community Development department. Access to the Terrace Bay Public Library was graciously provided by Mary Deschatelets, Library CEO. Patty Cobin and Ted Bornhorst (A.E. Seaman Mineral Museum, Michigan Technological University) handled pre-meeting registration. Ted also supplied the poster boards.

Generous contributions to the ILSG general fund and in support of 2019 student travel scholarships came from: Abitibi Geophysics, Barrick Gold Corporation, Benton Resources Corp., Geological Society of Minnesota, Greenstone Gold Mines, Landore Resources Canada Inc., Noront Resources Ltd., North American Palladium Ltd., Northwestern Ontario Prospectors Association, Panoramic PGMs (Canada) Limited, Premier Gold Mines Limited, Stillwater Canada Inc., Superior Lake Resources Limited, Thunder Bay Community Economic Development Commission, Wesdome Gold Mines Ltd., and Wolfden Resources Corporation. Individual Contributors to Student Travel Scholarship were: Al MacTavish, Mary Kay Arthur, L. Gordon Medaris, Jr. and Nick Swanson-Hysell. Total meeting registration was 114, which included 15 students. Welcoming remarks were provided by Terrace Bay Mayor Jody Davis. Elder Raymond Goodchild of Pays Plat First Nation provided traditional blessings for the meeting.

Proceedings Volume 65 was published in two parts. Part 1 – Program and Abstracts, compiled and edited by Mark Puumala (OGS), contains 51 published abstracts for 32 oral and 19 poster presentations. Students presented 6 oral and 3 poster presentations. Part 2 – Field Trip Guidebooks, was compiled and edited by Al MacTavish and Pete Hollings. It contains descriptions of four pre-meeting and four post-meeting field trips.

The 65th ILSG marked the first time in the Institute's long history that its annual meeting was held in Terrace Bay. The meeting location enabled organizers to offer trips that showcased a variety of Archean and Proterozoic rocks along the north shore of Lake Superior. Although the majority of the field trips had been offered at previous ILSG annual meetings (e.g. Marathon 1995; Nipigon 2005), they greatly benefitted from the new mapping, research, discoveries and interpretations that had taken place in the intervening years. Local exploration companies graciously provided information and access to their properties. Unfortunately, a late spring precluded visiting the Slate Islands (lake ice) and the Midcontinent Rift-related carbonatites and diatremes in the Dead Horse Road area (snow). Slate Islands trip delegates were provided with an impromptu, "eclectic" field trip along Highway 17 between Schreiber and Marathon by Mark Smyk. Those who planned to see the MCR carbonatites and diatremes switched to other available trips.

A list of field trips is provided below:

Pre-meeting field trips (and leaders) on Tuesday, May 07:

- 1) Slate Islands (Pete Hollings, Lakehead University)*
- 2) Midcontinent Rift-related carbonatites and diatremes (Shannon Zurevinski, Lakehead University)*
- 3) Geology of the western Schreiber-Hemlo greenstone belt (Seamus Magnus, Ontario Geological Survey)
- 4) Geology of the Nipigon area (Philip Fralick, Lakehead University and Rob Cundari, Ontario Geological Survey)

*(*denotes cancelled due to snow/ice conditions)*

Post-meeting field trips on Friday, May10:

- 5) A stratigraphic transect across the northern flank of the Midcontinent Rift near Rossport (Pete Hollings, Lakehead University)
- 6) Geology of the Coldwell alkaline complex (Allan MacTavish, Panoramic PGMs (Canada) Limited and David Good, Western University)
- 7) Building and ornamental stone sites of the Marathon area (Peter Hinz, Ministry of Energy, Northern Development and Mines)
- 8) Geology of the past-producing Winston Lake Cu-Zn Mine (Mark Puumala and Mark Smyk, Ontario Geological Survey).

Pre- and post-meeting field trips attracted 172 registrants, once again reaffirming their integral role in the allure and success of ILSG annual meetings.

The vast majority of registrants and invited guests attended the annual ILSG banquet on Wednesday night. Although a Homer Award overview presentation was given, no “recipients” were identified during the 2019 annual meeting!

As always, a highlight of the post-banquet activities was presentation of the 2019 Goldich Medal. This year’s very deserving recipient was Mark Severson. Mark’s wife, Laurie, and daughter, Allison, attended the banquet and award ceremony. The Goldich Medal citation was presented by George Hudak, his colleague for many years. George described Mark’s contributions to ILSG and to the greater understanding of Minnesota’s geology over several decades during his time as a student, in his role at the Natural Resources Research Institute-University of Minnesota Duluth, in his collaborations with the Minnesota Geological Survey and later in the mining and exploration industry. Mark is indeed a worthy recipient of this prestigious award.

The 65th ILSG included a radical departure from the usual post-banquet guest speaker tradition. In lieu of a guest speaker, Master of Ceremonies, Mark Smyk, moderated a trivia contest entitled “ILSG Geo-Pardy.” It tested our delegates’ knowledge of ILSG history (e.g. past host cities, Goldich Medalists), geology in pop culture and “fun facts” about Lake Superior geology. Scores were tabulated and winners were announced the following day. Donated prizes and bragging rights attended the “awards ceremony.”

In 2019, the student paper committee had its usual difficult job of selecting the best among six excellent oral presentations and three poster presentations for the Doug Duskin Student Paper Awards. The 2019 committee comprised Katarina Bjorkman (Bjorkman Prospecting), George Hudak (Natural Resources Research Institute–UMD) and David Good (Western University). The committee awarded three prizes with best talk going to Sophie Kurucz for her talk on “*Paleoproterozoic snowball earth? Sedimentology and geochemistry of a Huronian glacial cycle*”

and runner up prizes going to Kira Arnold (*Geology and geochemistry of the Terrace Bay Batholith, N. Ontario*) and Munira Afroz (*Sulfur, Carbon, and Oxygen Isotope Geochemistry of ~2.93 Ga Mesoarchean Chemical Sedimentary rocks in the Red Lake Area, Ontario*) Eisenbrey Student Travel Grants were given to nine students: Paul Bielski (Lakehead) \$200, Kira Arnold (Lakehead) \$200, Jaqueline Drazan (UMD) \$400, Jackie Wrage (University of Michigan) \$600, Brittany Ramsay (Lakehead) \$200, Munira Afroz (Lakehead) \$200, Thomas Bodden (MTU) \$500, Sophie Kurucz (Lakehead) \$200 and Chanelle Boucher (Lakehead) \$200. The Institute's Board of Directors met on Wednesday, May 8, 2019 and a brief overview of the meeting is provided below:

1. Accepted report of the Chairs for the 64th ILSG, Iron Mountain, Michigan; as printed in the 2019 Proceedings Volume, and minutes of last Board meeting, May 16, 2018 (Hollings)
2. Received, discussed, and accepted 2018-2019 ILSG Financial Summary (Jirsa).
3. Received, discussed, and accepted 2018-2019 Report of the Secretary (Hollings).
4. Approved Mark Smyk as on-going ILSG Board member
5. Approved Mountain Iron, Minnesota as the site for the 66th annual ILSG meeting, hosted by Mark Jirsa, with help from Amy Radakovich and Terry Boerboom, all of the Minnesota Geological Survey. The dates of the meeting were set for May 12-15, 2020.
6. There was discussion as to future meeting locations, with Sudbury being suggested as a possibility. In addition, Esther Stewart has been in discussion with Rob Lodge and Dyanna Czeck about hosting a meeting in Wisconsin.
7. Discussed and approved replacing Klaus Schultz as the "member from government" on Goldich Committee (end of term 2019) with Dorothy Campbell (OGS).
8. Liability Insurance for the Institute was discussed and approved by the Board as an ongoing, annual expense. The Treasurer will investigate further to ensure that insurance is in place for the 2020 meeting.
9. It was approved that the Treasurer should purchase 10 Goldich medals, as only one remains.
10. Discussed and approved renewal of Pete Hollings as Institute Secretary (end of term 2022). This was later approved by a vote of the membership.

The 65th ILSG meeting was a great success and we wish to thank all the people who contributed to that success, including staff of the Ontario Geological Survey and Lakehead University who were pressed into action as editors, field trip leaders and drivers. The Township of Terrace Bay was extremely hospitable in providing facilities (including the Cultural Centre, Library and Bowling Alley), suggestions and liaison services. We enlisted five different businesses to admirably handle our many catering needs in trying to "spread business around" in both Terrace Bay and neighbouring Schreiber. We heard many favourable comments from local people and businesses, not only about our patronage, but also about their interactions with ILSG delegates. They were thrilled to have us. We even received coverage in the local newspaper, provided by a reporter who tagged along on a field trip and popped by the Technical Sessions. We were happy that we were finally able to host the annual meeting in Terrace Bay. It was well worth the wait!

Like most ILSG annual meetings hosted in smaller communities in Ontario, attendance was lower in 2019. However, those who did attend thoroughly enjoyed the meeting, facilities and field trips. Always flexible and understanding, our delegates took any changes in programming in stride.

We continue to encourage student attendance and new delegates in ensuring a healthy future for the Institute. We appreciate the support of our respective organizations, the Ontario Geological Survey and Lakehead University, and recognize the efforts that everyone made in travelling, attending, presenting and participating in activities that made the a 65th Annual Meeting what we feel was a great success. We encourage others to consider hosting and contributing to future meetings. It is truly a rewarding experience.

Mark Smyk and Pete Hollings
Co-Chairs, 65th Institute on Lake Superior Geology

TECHNICAL PROGRAM

(Times are EDT)

TUESDAY, MAY 11, 2021

SESSION 1

- 9:45-10:00 **Welcome, introduction, and instructions (meeting chairs)**
- 10:00-10:20 **Paul Bielski and Philip Fralick**
Comparisons of Archean Iron Formations deposited at Shallow vs Deeper Depths
- 10:20-10:40 **Bailey Drover, Mary Louise Hill, and Shannon Zurevinski**
The deformation and alteration of granitoid plutons in the Wabigoon subprovince
- 10:40-11:00 **Manuel Duguet**
Geochemistry and Age of Archean Volcaniclastic and Mafic Intrusive Rocks, Georgia Lake Area, Quetico Subprovince, Northwestern Ontario
- 11:00-11:20 **Seamus Magnus**
Chemostratigraphy of the western Schreiber-Hemlo Greenstone Belt—Results and Regional Implications
- 11:20-11:40 **Brittany Ramsay, Philip Fralick, Stefan Lalonde, Paul Bielski, and Laureline Patry**
Environmental Control of Seawater Geochemistry in a Mesoarchean Peritidal System, Woman Lake, Superior Province
- 11:40-12:00 **Michael Tamosauskas, Robert Lodge, M.A. Chong, Rasmus Haugaard, and Ross Sherlock**
The provenance, depositional environment and metallogenic implications of the Ament Bay Metasedimentary Assemblage, Sturgeon Lake Greenstone Belt, Northwest Ontario
- 12:00-12:20 **Val W. Chandler V. W and Mark Jirsa**
Three-dimensional geologic mapping of Precambrian rocks in Minnesota: The creation of “removeable” geologic layers using gravity and magnetic data interpretation
- 12:20-12:40 **Planavsky, Noah**
Negative Carbon Dioxide Emissions through Enhanced Silicate Weathering and the Lake Superior Region

FRIDAY, MAY 14, 2021

SESSION 2

9:45-10:00 **Introduction and instructions**

10:00-10:20 **Benjamin Drenth, Bill Cannon, Klaus Schulz, and Robert Ayuso**
Geophysical insights into Paleoproterozoic tectonics along the southern margin of the Superior Province, central Upper Peninsula, Michigan

10:20-10:40 **Megan Landman and Mary Louise Hill**
Archean Orogenesis to Proterozoic Rifting: A structural history of Pass Lake, Thunder Bay, Ontario

10:40-11:00 **Seamus Magnus**
Proterozoic Geology of the Schreiber–Terrace Bay Area

11:00-11:20 **Ann Marie Prue and Latisha Brengman**
Preliminary pXRF results from Precambrian rocks of northern Minnesota

11:20-11:40 **Nicholas Swanson-Hysell, Margaret Avery, Yiming Zhang, Eben Hodgkin, and Terry Boerboom**
The paleogeography of Laurentia in its early years: new constraints from the Paleoproterozoic East-Central Minnesota batholith

11:40-12:00 **Michael Easton**
The Critical Mineral potential of carbonatite and alkalic complexes in Ontario

12:00-12:20 **Mark Puumala and Robert Cundari**
Critical Minerals Exploration and Development Potential in Ontario

12:20-12:40 **Robert Cundari, Mark Puumala, Riku Metsaranta, and Dorothy Campbell**
Critical Mineral Potential on the North Shore of Lake Superior; Elements to ‘Structure’ our future

POSTER SESSION

14:00-14:05 **Introduction to 5-minute author summaries**

14:05-14:10 **Benjamin Gallagher and Marcia Bjornerud**
Reconstructing the hydration and carbonation history of the Presque Isle peridotite, Marquette Michigan: Insights into mechanisms of carbon sequestration in ultramafic rocks

14:10-14:15 **Tara Lemke, Evan Weber, and Robert Lodge**
Characterization of Hydrothermal Alteration and Sulfide Ores at the Lynne Zn-Cu-Pb Deposit, Oneida Co. WI.

- 14:15-14:20 **Trevor Nelson, Rory Johnson, Robert Lodge, Chong MA, Jeffery Marsh**
U-Pb geochronology and zircon trace-element geochemistry from granitoid plutons in the Neoarchean Sturgeon Lake greenstone belt, Ontario, Canada
- 14:20-14:25 **Dana Peterson, P. Bedrosian and C. Finn**
3-D Modeling of the Duluth Complex from geophysical data
- 14:25-14:30 **Rebecca Price, Shannon Zurevinski, and Roger Mitchell**
A newly discovered orbicular occurrence within the Good Hope carbonatite, north of Marathon, Ontario
- 14:30-14:35 **Shelby Short, Lillian Glodowski, and Robert Lodge**
Geochemistry and Petrography of Volcanic and Intrusive Rocks Hosting the Lynne Cu-Zn-Pb Deposit, Oneida County, WI
- 14:35-14:40 **Esther Stewart, Billy Fitzpatrick, and Eric Stewart**
Geologic mapping identifies bedrock folds that may be significant for increased probability of arsenic detection in water wells
- 14:40-15:30 **Breakout room discussions with Poster Presenters**

TUESDAY, MAY 18, 2021

SESSION 3

- 9:45-10:00 **Introduction and instructions**
- 10:00-10:20 **Paul Bedrosian, Max Pace, and Katerina Zamudio**
Geophysical mapping of the eastern arm of the Midcontinent Rift in Upper Michigan
- 10:20-10:40 **Sophie Mueller, J. Degraff, and D. Lizzadro-Mcpherson**
Structural Analysis and Interpretation of Deformation along the Keweenaw Fault System West of Lake Gratiot, Keweenaw County, Michigan
- 10:40-11:00 **Nicholas Craik and Phil Fralick [presentation cancelled]**
Tracing redox pathways of the Mesoproterozoic Copper Harbour Conglomerate, Michigan
- 11:00-11:20 **Ted Bornhorst**
Evolved seawater as the source of salinity for metamorphic-dominated ore-forming hydrothermal fluids of the Keweenaw Peninsula native copper district, Michigan

11:20-11:40 **Tien Grauch and S.J. Heller**

Integration of geophysical evidence indicates that anorthosite composes a significant portion of Grand Marais ridge, an inferred basement high in western Lake Superior

11:40-12:00 **Laurel Woodruff and Tien Grauch**

Possible implications of a non-Archean Grand Marais Ridge, western Lake Superior

12:00-12:20 **Eben (Blake) Hodgins, Nicholas Swanson-Hysell, Daniel Stolper, Andrew Turner, James DeGraff, Andrew Kylander-Clark, and Mark Schmitz**

Final inversion of the Midcontinent Rift during the Rigolet Phase of the Grenvillian orogeny

FRIDAY, MAY 21 2021

SESSION 4

9:45-10:00 **Introduction and instructions**

10:00-10:20 **Matthew Brzozowski, Peter Hollings, Allan MacTavish, Dawn Evans-Lamswood, Abraham Drost, and Derek Wilton**

Mineralizing processes in the Current Lake and Escape Lake conduit-type PGE–Cu–Ni deposits of the Thunder Bay North igneous complex, northwestern Ontario, Canada

10:20-10:40 **David Good**

A Practical Approach to Using Incompatible Elements to Define Geochemical Correlation and a Common Mantle Source: Example Crystal Lake Gabbro and the Duluth Complex

10:40-11:00 **Kyle Lachance, Jackie Kleinsasser, Adam Simon, Dean Peterson, and George Hudak**

Identifying the genesis of Fe-Ti oxide- and sulfide-bearing ultramafic intrusions in the Duluth Complex through sulfide geochemical analysis

11:00-11:20 **Jackie Kleinsasser, Adam Simon, Dean Peterson, and George Hudak**

Textures and geochemistry of ilmenite and titanomagnetite in Fe-Ti oxide-bearing ultramafic intrusions of the Western Margin of the Duluth Complex, Minnesota

11:20-11:40 **Amartya Kattamalavadi, Jackie Kleinsasser, Adam Simon, Dean Peterson, and George Hudak**

Olivine Geochemistry from Fe-Ti Oxide-Bearing Ultramafic Intrusions in the Duluth Complex, MN

11:40-12:00 **Dave Dahl, Stacy Saari, and Thomas Lee**

Availability of Historical Airborne Geophysical Survey Data at Minnesota DNR

12:00-12:20 **Allan MacTavish, Peter Hinz, Mary Kay Arthur, Robert Chataway, Jim Edberg, Tom Erickson, Steve Fox, Joan Furlong, Jim Gerlich, Lindsay Smith, and David Wilhelm**

Island of Hawaii Field Trip, February 11-21, 2020

12:20-12:30 *Closing remarks*

MAY 21-AWARDS EVENING

19:00-20:30

- Words of welcome (chairs)
- ILSG updates
- Goldich Medal presentation to *Allan MacTavish*
- 2022 ILSG meeting plans—*Sudbury Ontario*
- Honoring the Pioneers of Lake Superior Geology—*Newton Horace Winchell* (by Jim Miller and Sue Leaf)
- Closing remarks

ABSTRACTS

Geophysical mapping of the eastern arm of the Midcontinent Rift in Upper Michigan

BEDROSIAN, Paul A, PACE, Max, and ZAMUDIO, Katrina D.

Geology, Geophysics and Geochemistry Science Center, U.S. Geological Survey, Denver, CO

The western arm of the Midcontinent Rift system (MRS), extending from western Lake Superior into Kansas, is somewhat understood due to exposures of MRS igneous and sedimentary rocks, scattered drillholes, and seismic imaging. By comparison, the eastern rift arm (ERA), extending from eastern Lake Superior through lower Michigan is poorly understood, with almost no outcropping volcanic rocks south of Michipicoten and Caribou Islands in Lake Superior, few boreholes that intercept MRS rocks, and the majority of the rift concealed beneath the Michigan basin. Seismic reflection sections in the eastern Lake Superior basin (Behrendt et al., 1990; Mariano and Hinze, 1994) and in Lake Michigan (Cannon et al., 1991) provide the primary constraints on the gross structure of the ERA. Unlike the western rift arm, which has undergone considerable post-rift shortening (Cannon et al., 1993), the ERA appears less deformed, with perhaps as much as 30 km of rift clastic and volcanic rocks preserved within a broadly symmetric basin (Behrendt et al., 1988) and about 5 km of anticlinal relief on the top of the volcanics (Mariano and Hinze, 1994). Under Paleozoic cover in the eastern part of Michigan's Upper Peninsula, the ERA western margin is inferred from linear northwest-trending potential-field anomalies (Fig. 1a, b) and the occurrence of MRS basalt and rhyolite beneath ~2 km of Paleozoic and MRS clastic rocks in the St. Amour drillhole (Ojakangas and Dickas, 2002).

In this examination of the ERA, we present results of a recent magnetotelluric survey over the ERA and a 3D electrical resistivity model derived from these data. The ERA is clearly imaged as a 150-km wide conductive rift basin with a sharp western margin and an irregular eastern margin that traces the distribution of mapped MRS clastics in Ontario (Fig. 1c). The lowest resistivities ($10 \Omega \cdot \text{m}$) correspond to the Jacobsville Ss, imaged as an east-dipping horizon extending to 2-3 km depth beneath the edge of the Michigan basin. Underlying the Jacobsville are moderately conductive rocks ($100\text{-}500 \Omega \cdot \text{m}$) that thicken basinward to 8-10 km depth with a nested inner basin that may be 20 km or more deep. The rift-fill rocks are attributed to a combination of Oronto Grp. clastics and MRS basalts, which cannot be separately distinguished within the resistivity model.

In map view, the resistivity model at 10 km depth (Fig. 1d) shows along-rift changes in resistivity with a wavelength of ~50 km. Though data coverage is limited, both magnetic and gravity data (extending north into Lake Superior) show a similar pattern of highs and lows. A seismic reflection profile parallel to the rift axis (LS-15; Mariano and Hinze, 1994, their Fig. 7) interprets folding of the rift sedimentary and volcanic section and infers several kilometers of relief along strike.

The linearity of the western rift margin suggests that both the thickest sections of rift basalt and Jacobsville are fault bounded. Together with the evidence for along-strike folding and faulting, we suggest the current structure of the ERA reflects post-rift NW-SE compression oriented along the rift axis, with the western margin marked by a transform fault (likely a reactivated normal fault of MRS age). Extrapolating farther north, we speculate that left-lateral offsets within the broad magnetic high that follows the western side of the ERA reflect a series of *en echelon* faults that together conspired to shorten the ERA by several tens of kilometers or more.

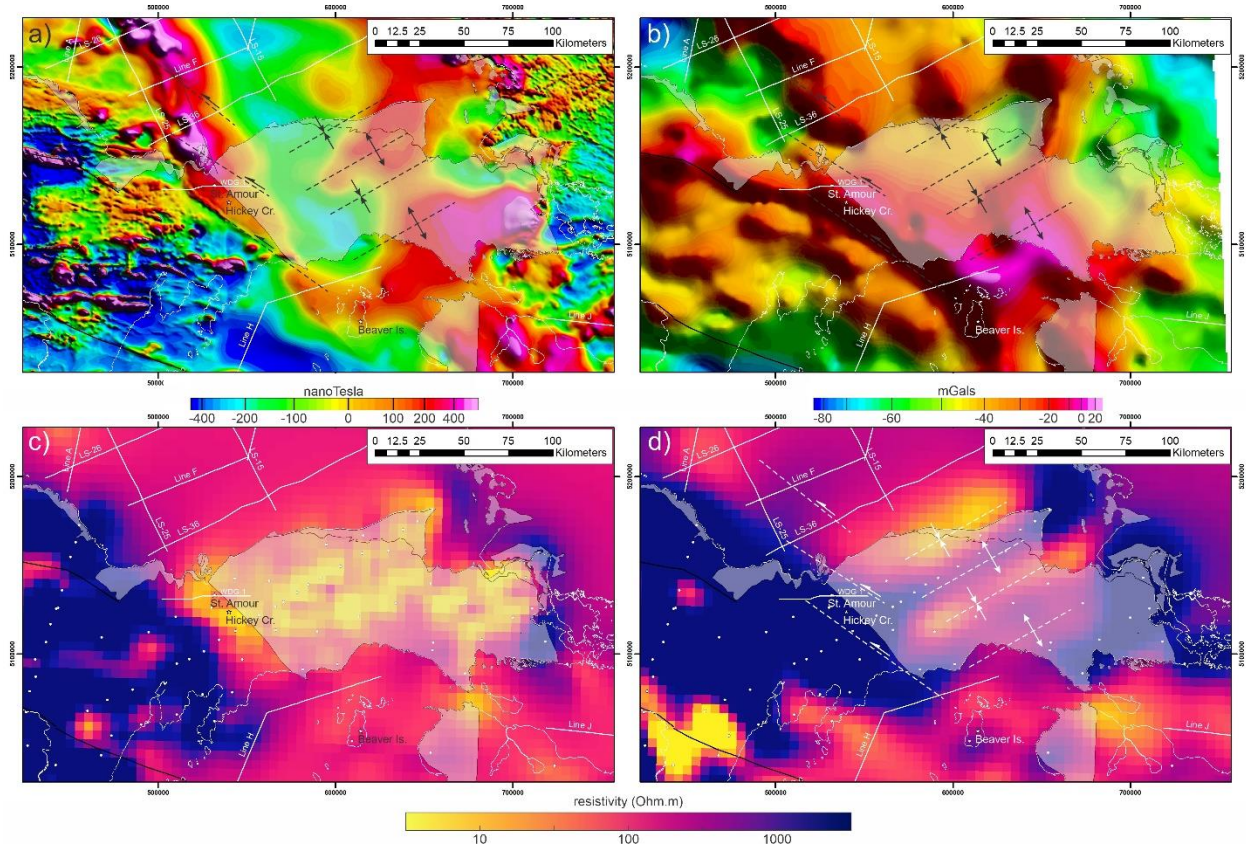


Figure 1. (a) magnetics, (b) gravity, (c) resistivity at 1 km depth and (d) resistivity at 10 km depth. Shaded regions show mapped or inferred MRS clastic rocks. White circles, stars, and lines indicate magnetotelluric stations, deep drillholes, and seismic reflection lines, respectively. Faults are shown in black. White dashed lines show interpreted structures. Potential field data are from Anderson and Grauch (2018).

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Comparisons of Archean Iron Formations deposited at Shallow vs Deeper Depths

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The occurrence of iron formation (IF) during the Archean is well documented, however the mechanisms of their genesis are poorly understood within shallow waters and even more so within the deep-ocean. At the same time our understanding of Archean deep-ocean chemistry is also limited and poorly constrained. To address these issues, multiple shallow and deeper water iron formations were analysed by coarse and fine-scale geochemical analysis. The fine-scale method entailed using Laser Ablation Inductively Coupled Mass Spectrometry (LA-ICP-MS) alongside Scanning X-Ray Fluorescence (XRF), while the coarse-scale analysis is done with bulk rock geochemistry.

The IFs used in this study were all deposited at approximately 2.7 Ga in different depositional settings. The shallow water IF is from Beardmore and Lake St. Joseph, which are both instances of deltaic sediments intermingled with sections of cherty-IF, and magnetite layers directly within deltaic distributary mouth bars. The deeper water IFs are from Temagami and Timmins in Ontario and Soudan, Minnesota. These IFs contain no discrete siliciclastic strata within the main body of IF, where chert and iron oxides are the dominant lithology. While the true depths of these deeper water formations are unknown, the lack of non-chemical sedimentary rock, excluding thin slate strata, and no storm-related sedimentary structures within layering suggests some distance from landmasses and depths from below storm wave base to abyssal. Siliciclastic turbidites from Beardmore have been included in this study to assist in identifying trends related to detrital contamination.

Rare earth element (REE) concentrations, normalized with post-Archean Australian shale (PAAS), and analysed by bulk rock geochemistry, show similarities between deeper and shallow water deposits. The deeper water IFs contain pronounced HREE enrichment with prominent Eu and Y anomalies while shallow water IF do not show consistent Y anomalies but do contain relatively smaller Eu anomalies (Figure 1) despite siliciclastic contamination. Y/Ho is largest within the deep water IF with mainly superchondritic ratios from 28 to 55. Shallow water IF contains near chondritic (~28) ratios. The smaller Eu and Y anomalies are interpreted to be a combination of weaker Eu anomalies present in shallower water (cf. Planavsky et al., 2010) and contamination by siliciclastics, which have non-anomalous values. The lack of superchondritic Y/Ho in the shallow water IF samples is odd as Y anomalies are thought to be largest in shallow water during the Archean (cf. Planavsky et al., 2010) which may relate to a scavenging disequilibrium with the surrounding seawater as deeper water IF contain a consistent Y anomaly (Figure 1).

Trace element analysis of redox sensitive elements U, V, and Cr have a strong relationship with Al_2O_3 , indicating significant contributions of these elements from detrital material, especially within shallow water IF. However, V/Fe and Cr/Fe ratios in deeper water IF are comparable to shallow water ratios while having much lower levels of detrital contamination (i.e., Al_2O_3) (Figure 2). This indicates Cr and V were enriched in the precipitated phase, adding extra Cr and V to the sediment. These elements are more soluble in oxidizing fluids, but their solubility greatly decreases in reducing environments, e.g. the Archean deeper ocean. Thus, they required the presence of some oxygen in the weathering environment, but were reduced and precipitated in the Archean deeper ocean. Th/U ratios of IF samples may be used to identify enrichments of U, or depletions of Th,

relative to the ratio found within igneous rock at a given time. At 2.7 Ga, the Th/U ratio within crustal rock was approximately 3.9, which is imprinted into the seawater ratio from the weathering and breakdown of minerals containing this ratio. Deep water IF contains low Th/U ratios in bulk rock geochemistry (Figure 2) and has even lower ratios (<1) in laser ablation data, which is less affected by detrital contamination. Shallow water IF bulk geochemistry shows values near that of average crustal rock, with variance around this value (~3.9).

A more detailed understanding of differences between shallow and deeper water IF is obscured by the inevitable presence of detrital contamination. However, it is evident that Eu anomalies are larger and redox elements are enriched in deeper water IF. Shallow water IF may be more susceptible to changes in water chemistry within the deltaic depositional environment causing anomalous and/or variable REE and trace element geochemistry compared to the similar geochemistry between different deeper water IFs.

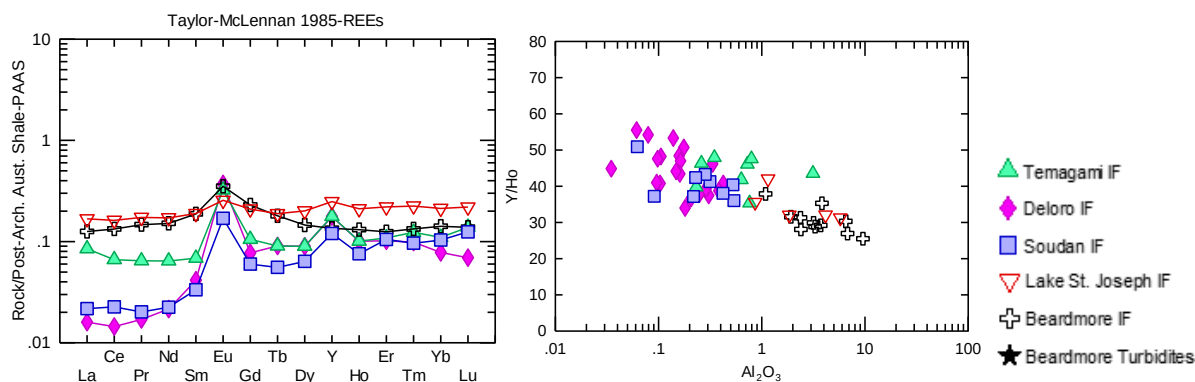


Figure 1. REE analysis. Note that the flatter pattern of the shallow IF is due to contamination.

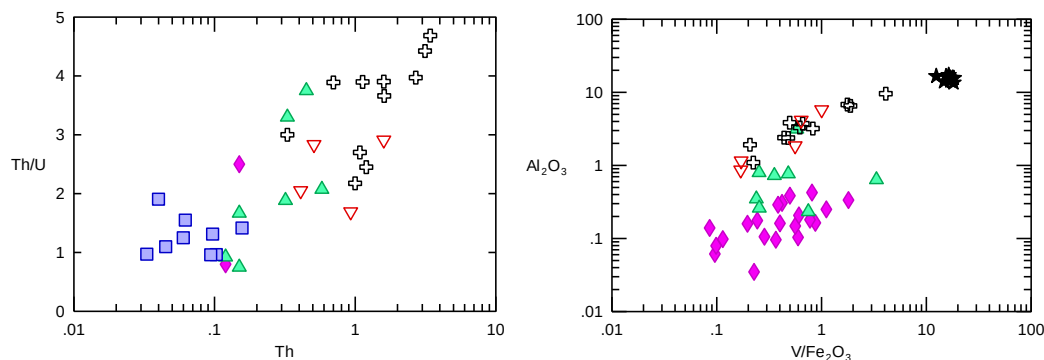


Figure 2. Redox element analysis. Shallow water IF and turbidites correlate while deep water IF contains similar V/Fe_2O_3 ratios despite much lower amounts of Al_2O_3 (detritus).

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Evolved seawater as the source of salinity for metamorphic-dominated ore-forming hydrothermal fluids of the Keweenaw Peninsula native copper district, Michigan

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The Mesoproterozoic Midcontinent rift of Michigan's Keweenaw Peninsula hosts the world's largest accumulation of native copper. For more than 60 years, it has been generally accepted that burial metamorphic processes generated ore-forming hydrothermal fluids. However, Brown (2006) reasoned that metamorphic processes could not generate high enough salinity. This constraint requires an outside source of salinity. He proposed a hybrid hydrodynamic evolved meteoric water and metamorphic ore-forming fluid at depth and down-dip below the native copper deposits in the fluid source zone. Brown's envisioned meteoric waters evolved during descent through the Oronto Group clastic sedimentary rocks and the salinity was dissolved from postulated evaporite horizons and/or scattered cement. An additional genetic constraint is that the ore-forming fluids were abnormally low in sulfur leading to the precipitation of native copper rather than copper sulfides (White, 1967). Because of very low sulfur magmas and degassing of sulfur upon eruption, the rift-filling Portage Lake Volcanics (PLV), host rocks of the native-copper deposits, and stratigraphically equivalent rocks of the source zone are sulfur-poor. Metamorphism of the source zone rocks resulted in sulfur-poor metamorphic ore-forming fluids. Brown's hydrodynamic evolved meteoric water model lacks a mechanism to satisfy the constraint of very low sulfur fluids. Further, the reasoning presented by Bornhorst and Mathur (2017 and 2018) suggests that hydrodynamic evolved meteoric water had limited to no significant role in the ore-forming fluids.

A role for seawater in generation of the native copper ore-forming fluids was proposed by Livnat (1983). However, seawater has not been widely accepted since the PLV were subaerially deposited and until recently there was only the debatable possibility of an incursion of seawater into the rift during deposition of the Nonesuch Formation. Recent evidence (Jones et al., 2019) suggests that the Nonesuch and underlying Copper Harbor Formations were deposited in a "braided fluvial-evaporitic shoreline-marine embayment triplet." Johnson (1985) documented an extensive subaqueous emplaced volcanic layer in the Keweenaw Peninsula and Isle Royale in the upper part of the PLV basalts which are otherwise subaerially deposited. This layer may have been deposited during an incursion of seawater into the rift. Incursions of seawater are also possible during times of PLV interbedded minor clastic sediments when volcanism waned. Thus, there is likely a long history of seawater incursion into the Midcontinent rift and a significant volume of seawater could have penetrated deeply into the PLV. As the PLV was buried into the fluid source zone, the contained seawater (formation water) evolved. A plausible mechanism is needed to satisfy the constraint of very low sulfur fluids.

Blättler et al. (2020) have shown that low sulfate levels in seawater occurred during the late-Mesoproterozoic which would have required less depletion of sulfur. When seawater penetrates mid-ocean basalts in vicinity of hydrothermal vents it becomes heated and evolves as it reacts with and alters the host basalt. At 130-150°C anhydrite begins to precipitate; the solubility of anhydrite is retrograde (Antonelli et al., 2017). The precipitation of anhydrite (CaSO₄) depletes sulfate from seawater and if there is sufficient Ca, precipitation of anhydrite removes most of the sulfate. As the partially evolved seawater and its host basalts continue to be heated, albitization of basalt releases Ca into the seawater which results in complete removal of any remaining sulfate. Breakdown of olivine and pyroxene releases Mg into the fluid but it is bound up in secondary Mg minerals, such as chlorite, leaving the fluid both sulfur- and Mg-poor. At yet higher temperatures

(> 250°C) the water-rock reactions continue to release Ca to the fluid, which accumulates, producing a Ca-rich brine (Antonelli et al., 2017; Tivey, 2007). Oceanic and continental rifts undergoing greenschist to amphibolite facies metamorphism are known for CaCl₂-rich, Mg-poor brines, also enriched in leached Na, K, and Cu among other elements (Tivey, 2007; Hardie, 1983).

This model for modern mid-ocean basalts is applicable to the generation of native copper ore-forming fluids. The PLV basalts are tholeiitic, similar to mid-ocean ridge basalts, and have undergone extensive albitization. The rocks in the source zone have been subjected to temperatures exceeding the temperature of precipitation of anhydrite, hence the seawater could have become depleted in sulfur and enriched in Ca before undergoing burial metamorphism. Kelly (2020) demonstrated that probable primary fluid inclusions formed during precipitation of native copper are filled by Ca-rich fluids with up to 30 equivalent weight percent CaCl₂. Published light stable isotope data are permissive of a hybrid evolved seawater and metamorphic-dominated ore-forming fluid originating from the source zone. Such a hybrid cannot be isotopically distinguished from metamorphic-only fluid. The combination of low sulfate seawater and anhydrite precipitation provides a viable mechanism to generate evolved seawater that provides an outside source of salinity for the ore-forming fluids without sulfur. Lengthy incursions of seawater into the Midcontinent rift supports the hypothesis that evolved seawater may have played an important role in the generation of burial metamorphic-dominated native copper ore-forming fluids.

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Mineralizing processes in the Current Lake and Escape Lake conduit-type PGE–Cu–Ni deposits of the Thunder Bay North igneous complex, northwestern Ontario, Canada

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The Thunder Bay North igneous complex (TBNIC), located approximately 50 km northeast of Thunder Bay, comprises a series of small mafic–ultramafic intrusions that occur in the vicinity of several other similar intrusions, including the Sunday Lake, Saturday Night, and Thunder intrusions to the southwest, and the Seagull, Disraeli, and Hele intrusions to the northeast. The intrusions of the TBNIC comprise the 1106.6 ± 1.6 Ma Current Lake (Bleeker et al., 2020), Escape Lake, Lone Island Lake, and 025 intrusions, all of which were emplaced proximal to the east–west trending Quetico Fault System. Of these intrusions, the Current Lake (CL) and Escape Lake (EL) chonoliths host significant orthomagmatic Ni, Cu, and platinum-group element (PGE) mineralization, and have been in active exploration since 2005. Although few theses have been completed on the Current Lake (Chaffee, 2015) and Escape Lake (D'Angelo, 2013) chonoliths, the mechanisms that generated the variable styles of PGE–Cu–Ni mineralization in these spatially associated chonoliths, and their genetic relationships have never been formally characterized. This presentation highlights some of the preliminary results from a three-year collaborative effort between Clean Air Metals, Lakehead University, and Memorial University, with the ultimate goals of developing robust mineralization models for and characterizing the genetic relationships between the CL and EL intrusions.

Although both the CL and EL chonoliths have been actively explored, the most extensive work has been conducted on the CL chonolith, resulting in an indicated resource of 12 Mt at 1.48 g/t Pt, 1.4 g/t Pd, 0.28% Cu, and 0.17% Ni for CL, and 4.3 Mt at 0.92 g/t Pt, 1.18 g/t Pd, 0.52% Cu, and 0.28% Ni for EL (Kuntz and Jones, 2021). The CL chonolith contains five variably mineralized zones (from north to south) — the Current Lake, Bridge, Beaver Lake, Cloud, and 437 zones. The southernmost portion of the conduit is represented by the unmineralized Southeast Anomaly. The EL chonolith has been divided into two sections (from north to south) — the Escape and Steepledge Lake sections. Both conduits dip gently to the south, with their lowest points being adjacent to the E–W trending Escape Lake Fault. Primary base-metal sulfides (BMS) in both systems largely comprise pyrrhotite, pentlandite, and chalcopyrite; BMS occur in the CL system throughout the chonolith in the Current Lake and Bridge zones, and at the base and top of the chonolith in the Beaver Lake and Cloud zones, respectively.

Metal tenors in the CL and EL systems are similar, being enriched in Cu and the Pt-group PGEs relative to Ni and the Ir-group PGEs, and exhibiting a distinct negative Ru anomaly, a feature not commonly observed in other Ni–Cu–PGE systems globally (e.g., Eagle and Jinchuan). The anomalously low Ru concentrations are likely the result of clinopyroxene fractionation at depth. Copper/Pd ratios in the Current Lake and Beaver Lake zones of the CL chonolith, and Escape Lake and Steepledge Lake sections of the EL chonolith, are indistinguishable and largely within the range of mantle values, suggesting that significant amounts of sulfide were not removed at depth. Although most of the samples from both systems have mantle-like Cu/Pd and Pd/Pt ratios, data

from the Southeast Anomaly, Escape Lake, and Steepledge Lake zones trend towards high Cu/Pd and low Pd/Pt ratios, suggesting that some Pd may have been removed by segregation of limited sulfide liquid at depth. If the Southeast Anomaly is considered the feeder to the CL system, then this may suggest that sulfides are located deeper in the feeder system. Numerical modeling suggests that, although the CL system is characterized by slightly higher R factors than the EL system (~12,000 vs. ~7,000), there was not a significant variation in R factor along the length of the conduits, with variations in bulk-rock metal concentrations largely representing variable accumulations of sulfide. In both systems, the Pt-group and Ir-group PGEs, and Au correlate with Pd, suggesting that the physical separation of residual Cu-rich liquid from monosulfide solid solution did not play a role in generating the mineralization. Variations in Ni/Cu–Mg and Pd/Pt–Pd/Ir ratios suggest that the concentrations of Ni and Ir in the CL system appear to be controlled, in part, by the accumulation of olivine towards the Southeast Anomaly. The fact that rocks in this zone are olivine-poor suggests that olivine may be located at depth in the feeder system. Systematic inverse correlations between Fe–S–Cu–Ni–Pd–Pt (+ spikes) and Mg–Ca–Cr–Ti (– spikes) throughout the thickness of the Current Lake Zone suggest multiple influxes of metal-rich magma into the system. The abundance of these inverse correlations at the base and top of the Beaver Lake–Cloud zones suggest that the dynamics of magma flow varied along the length of the conduit, likely as a result of the variable conduit morphology. Bulk assimilation of the granitic and sedimentary country rocks is unlikely to have played a role in sulfide saturation as there are no systematic mixing trends in La/Zr–Th/Nb between the host and country rocks. Although it is possible that the large variation in S/Se values could be the result of contamination by BMS from the granitic and sedimentary country rocks, it is also possible that the variation resulted from S loss and very low R factors (< ~1,000). The importance of local S addition for, and the timing of, sulfide liquation remains unclear, but is one of the critical questions that will be assessed in the Clean Air Metals–Lakehead University–Memorial University partnership.

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Three-dimensional geologic mapping of Precambrian rocks in Minnesota: The creation of “removeable” geologic layers using gravity and magnetic data interpretation

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As part of the National Geological and Geophysical Data Preservation Program (NGGDP) of the U. S. Geological Survey, the Minnesota Geological Survey (MGS) compiled geophysical models from past and on-going investigations to create three-dimensional representations of several Proterozoic basins, consisting of elevation contours and inferred bedrock geology of the underlying basement surfaces. Thus defined, the Proterozoic basins are represented as removeable, three-dimensional layers in the Precambrian bedrock map of the state. The NGGDP-MGS work focused on several basins including those associated with the Sioux Quartzite, the Animikie Group, the sedimentary rocks of the Midcontinent rift system, and the somewhat more complicated basin enclosing the North Shore Volcanic Group and the Duluth Complex (NSVG-DC). In this presentation we will focus on the results from the main bowl of the Animikie basin and the adjoining NSVG-DC basin. Figure 1 presents the elevations estimated for the basement of these two basins.

The basement elevations estimated for the main bowl of the Animikie basin are primarily based on Euler analysis, a semi-automated depth interpretation scheme, in which a non-magnetic basin sequence is assumed to overlie an assortment of anomaly sources that suitably approximates a basin floor. Correspondingly much of the Animikie sequence consists of non-magnetic slates and grauwackes, with anomaly sources restricted to iron-formation near the base of the sequence, or to sources within the underlying Archean basement. The Euler results were cross-checked in a few areas by conventional, two-dimensional modeling, and the geology of the inferred basin floor is based on extrapolating the bedrock geology of adjacent areas, as guided by gravity and magnetic anomaly signatures. The results (Figure 1) indicate that northern and western margins of the Animikie basin are rimmed by a shallow (0-1.5 km elevation) shelf. The northern part of the shelf has been previously inferred from earlier investigations, but the western shelf is somewhat novel, and it appears to be significantly controlled by NW-striking structures. Several prominent sources underlying the Animikie sequence are interpreted to be strongly magnetic, consistent with iron-formation-bearing horizons, and the steep northward dips interpreted for some of these sources are most consistent with Archean rocks in the region. The deeper parts of the basin are locally below -4 km elevation, including the area along the basal contact of the NSVG-DC basin. This ~5 km.-thick Animikie sequence could presumably continue to the east in some fashion beneath the NSVG-DC sequence. Such a scenario has implications for the metallogenesis and upper crustal geology of the region.

Euler analysis cannot resolve the base of a magnetic sequence, so the base of the NSVG-DC basin is estimated along twenty two-dimensional gravity and magnetic models that transect the complex in strategic areas. Of these, ten models have been recovered and revised from earlier investigations and ten models have been created specifically for this study. Wherever possible, modeling has been constrained by geology mapped at the bedrock surface (Jirsa and others, 2012) and by rock-property data (Chandler and Lively, 2011). The modeling results were used to compile basement elevation contours beneath the land surface, and these contours were smoothed and merged with elevation contours beneath Lake Superior, which were compiled from 3-d gravity modeling and seismic reflection interpretations (Allen and others, 1997). The two lowest parts of the NSVG-DC sequence are interpreted lie ~-15 km. below MSL, and are plausible candidates for major feeder zones. A prominent basement high separates these two lows, and it appears to

ultimately connect with major basement ridges beneath Lake Superior, including Walter White ridge to the south, and with the Grand Marais ridge to the east. Estimated dips along the base of the NSVG-DC basin generally range from 25 to 60 degrees, with the steepest dips inferred along the northern and western basal contacts. A shelf-like structure inferred beneath the northwestern margin of the NSVG-DC basin lies roughly along-strike with the shelf inferred beneath the northern margin of the Animikie basin.

The interpretations presented here represent our current “best guess” of subsurface structure, based on available data, and many improvements should be possible in the future. As such, the interpretations presented here should serve as a helpful starting point for future three-dimension investigations, including the gravity, magnetic, and electromagnetic studies that has been recently initiated by the U. S. Geological Survey in the region.

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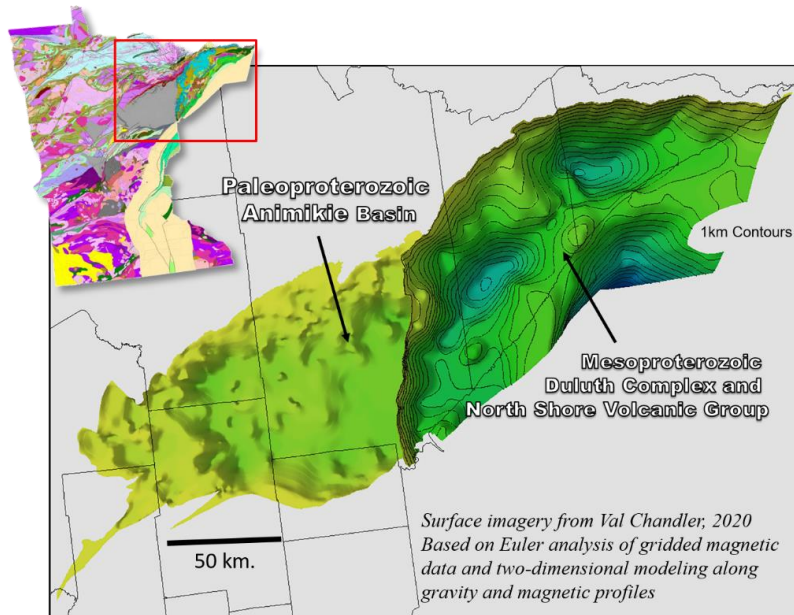


Figure 1. Estimated elevation of the basement surface below the main bowl of Animikie basin and the combined igneous sequences of the North Shore volcanic Group and the Duluth Complex. Elevations are relative to mean sea level, and range from 0 to 2,000 m. (yellow), -2,000 to -5,000 m. (light green), -5,000 to -15,000 m. (green), and <-15,000 m. (blue). Elevations beneath the North Shore Volcanic Group- Duluth Complex basin are highlighted with 1000 m. contours.

Tracing redox pathways of the Mesoproterozoic Copper Harbour Conglomerate, Michigan

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The history of Earth's oxygenation is key to understanding the evolution of life, the emplacement of important mineral deposits, and the cycling of oxidative weathering products through time. Many studies have been particularly focused on atmospheric and oceanic oxygenation during the Archean to Paleoproterozoic – denoting the Mesoproterozoic as part of the ‘Boring Billion’, a time of general stability or stagnation of many Earth processes. During the ‘Boring Billion’ oxygen was thought to have been stalled at low concentrations relative to today. This idea has largely been put forth by researchers utilizing deep sea black shales as a proxy for continental weathering patterns

Many studies of atmospheric oxygen within the Mesoproterozoic are contradictory to one another, likely due to sampling of deep ocean settings where oxygen cannot penetrate, and lack of abundant studies on terrestrial sediment. To reach results more representative of the ancient atmosphere, choosing a depositional setting that has been well documented as subaerial, and/or being able to constrain the weathering history of the system is imperative. In this work sedimentological and geochemical evidence from the subaerial red-bed deposits and carbonates of the unmetamorphosed Copper Harbour Conglomerate were collected with the aim of better understanding and constraining the spatial and temporal fluctuations of atmospheric oxygen levels during the Mesoproterozoic.

The Copper Harbour Conglomerate of the Keweenaw Peninsula, Michigan is a progradational alluvial to lacustrine sedimentary sequence representing the first continuous infilling of the Midcontinent Rift basin after the cessation of associated volcanic activity at ~1.1 Ga. Within the formation are pervasive carbonate cement (calcrete) lenses as well as a stromatolitic horizon located in its uppermost portion. The purpose of this study was to examine the oxidative weathering products (siliciclastics), groundwater-precipitated carbonates (calcrete), and pond/lacustrine-precipitated carbonates (non-biogenic precipitates and stromatolites) found within the Copper Harbour Conglomerate to determine the relative oxygenation of the atmosphere at the time of deposition (~1085 Ma).

ICP-MS and ICP-AES methods, both whole rock and preferential carbonate extraction, were utilized to determine the whole rock and carbonate geochemistry of the rock types within the upper Copper Harbour Conglomerate. By analyzing the redox sensitive metals (e.g., Fe, Mn, V, and U) and rare earth elements (e.g., Ce anomaly), theoretical constructions of the hydrological pathways of these elements can be developed. This allows understanding of the redox environment during early diagenesis.

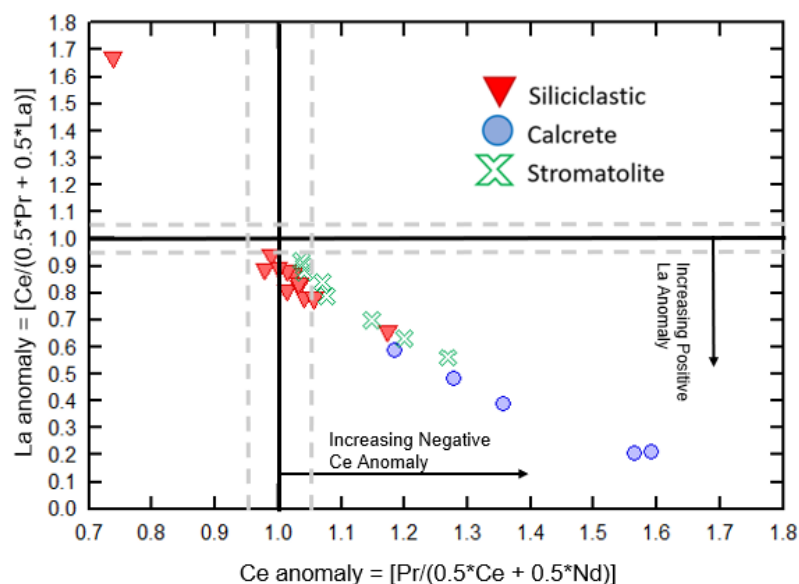


Figure 1: La and Ce anomalies (PAAS normalized) of calcrete, stromatolite, and siliciclastic samples in the

interacted with oxygen. The anomaly for the stromatolites is less than that of the calcrete which can be attributed to the lower residency time of surface water (in which the stromatolites form) compared to groundwater. The siliciclastic samples do not show a positive or negative Ce anomaly. This is likely due to abundance of primary, unweathered material contained within the samples themselves.

Similar results were obtained from the redox sensitive elements Fe, Mn, V, and U. Surficial weathering of the basaltic sediment induced by significant atmospheric oxygen levels resulted in the development of Fe hydroxides and oxyhydroxides pervasive throughout the sediment of the Copper Harbour Conglomerate. In this system Mn was staying in solution for a longer time, on average, than Fe and became concentrated within the groundwater and precipitated out with the calcrete. The oxidized forms of V and U were readily weathered from the basalt and held in solution until encountering the reducing biochemical reactions of the decaying bacterial component of the stromatolites or becoming oversaturated within the groundwater and precipitating out with the calcrete.

By breaking down the sub-environments of the three sample types in this study, a clear progression and hydrologic geochemical evolution of the broader depositional environment could be traced out. There was enough oxygen in the atmosphere for pervasive oxidative weathering at surface and for the studied redox sensitive elements to maintain their oxidized state through surface and groundwater transportation – only being removed through oversaturation or local reduction via organic decomposition. These results indicate that atmospheric oxygen was present in greater concentrations ~1085 Ga than previously thought. This also leads into the idea that Earth's oxygenation may have been variable in relatively short time spans.

Figure 1 shows the Ce and La anomalies of the samples taken in the study area. The calcrete samples have the strongest negative Ce anomalies, indicating they have the least abundance of Ce and therefore have previously had the greatest interaction with oxygen, either due to abundance of oxygen or elapsed reaction time. This makes sense because calcrete is formed by the evaporation of groundwater near surface (i.e., subaerial) and takes thousands of years to form. The stromatolite samples show a slight negative Ce anomaly which indicates the fluids they formed from had previously

Critical Mineral Potential on the North Shore of Lake Superior; Elements to ‘Structure’ our future

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In March 2021, the Ontario Government released a Critical Minerals Framework Discussion Paper which outlines Ontario’s proposal for developing a critical minerals strategy as well as a draft critical mineral list. Critical minerals are defined as “...raw materials needed to produce many products and specialized technologies. The minerals that a jurisdiction deems “critical” depends on its geology, as well as its own domestic and economic priorities.” (<https://www.ontario.ca/page/critical-minerals>). This abstract and associated presentation provides a general synopsis of the geology and existing models for several critical mineral enriched mineralization styles (“deposits” *sensu lato*) related to the Proterozoic Midcontinent Rift (MCR) along the northwestern shore of Lake Superior. The specific deposit types highlighted are: orthomagmatic platinum group elements deposits in MCR-related intrusions (PGE-Ni-Cu-Cr-Co) , polymetallic hydrothermal vein deposits (Ag-rich, Pb-Zn-Cu-rich U-rich types; U-Ni-Zn-Cu-Co-Sb-Bi-barite-fluorite) and hydrothermal polymetallic breccia complex related deposits (Deadhorse Creek diatreme type; U-Be-Zr-Hf-Y-Ce-Nb-Ti-V-Cr-REE).

Platinum Group Elements (PGE) have long been a subject of exploration interest north of Lake Superior. Since the discovery of PGE mineralization at the Thunder Bay North (TBN) project, the region has seen relatively steady exploration efforts targeting similar chonolith-hosted magmatic sulphide deposits. Larger MCR-related mafic-ultramafic intrusions, including Sunday Lake and Seagull, have also been explored for magmatic sulphides. These PGE prospective intrusions are interpreted to have been emplaced early in MCR history through crustal-scale structures (Bleeker et al., 2020). Hart and MacDonald (2007) stated the importance of deep-seated structures, specifically the Black Sturgeon fault, as conduits for early, primitive melts and subsequent emplacement of the early mafic-ultramafic units (e.g. Hele, Seagull, Kitto, Disraeli). Furthermore, Heggie (2012) recognized that the emplacement of the TBN complex was primarily controlled by a macro-structure (i.e. Archean Quetico fault) during MCR magmatism which provided a zone of weakness for the intrusive complex to develop. Many of these mineralized intrusions are relatively removed spatially from the historically mapped extent of rocks related to the MCR highlighting the larger structural footprint of the rift and its related fault systems.

The silver-bearing veins in the Thunder Bay area have been subject to considerable historical mining and more recently, renewed exploration interest. The critical mineral potential of these vein systems is not well established, although examples of similar vein systems (e.g. deposits at Cobalt) were a source of critical minerals (e.g. Kissin, 1992). The vein systems are organized in 2 groups known as the Mainland and Island belts (cf. Franklin et al., 1986). The Mainland Belt deposits (e.g., Beaver, Badger, Silver Mountain) occur in Rove Formation sedimentary rocks immediately below the contact with Logan diabase sills. The veins locally extend upwards into the sills, with silver-rich portions of the systems bound by locally silicified shale. The Island Group deposits (e.g. Silver Islet Mine) are characterized by fracture-filled vein systems oriented perpendicular to a northeast-trending swarm of gabbroic (Pigeon River) dykes. The Mainland and Island group veins contain similar mineral assemblages of acanthite and native silver associated with base-metal sulphides, fluorite, barite, quartz, and calcite. The Island group differs from the Mainland group in that they locally contain a nickel-cobalt sulpharsenide suite of minerals often termed 5-elements veins (Ag-Bi-Co-Ni-As). The Island and Mainland group are present in or near crustal-scale, extensional listric faults that formed throughout the main episode of MCR extension which then became reverse faults at the termination of that event (Smyk and Franklin, 2006). Similar to the mafic-ultramafic

intrusions hosting PGE mineralization, polymetallic vein systems have a wider spatial distribution than the mapped extent of MCR related rocks and thus may serve as a tool for mapping rift related structures and hydrothermal systems.

Uraninite (pitchblende) was documented by Franklin (1978) and occurs in quartz veins and vein breccias in association with hematite, magnetite and/or pyrite within the Archean basement rocks of the Sibley basin (Sutcliffe, 1991). Uranium mineralization is associated with fracture zones related to north- to northwest-striking regional structures such as the Black Sturgeon fault, and has been dated at 1094 Ma (Ruzicka and LeCheminant, 1984), supporting a model similar to the genesis of lead-zinc veins in the Dorion area (Franklin and Mitchell, 1977; Smyk and Franklin 2007). The model invokes mineralizing hydrothermal fluids generated by MCR-heating inducing leaching of uranium and other metals from uraniferous basement pegmatites or basal sedimentary strata in the Sibley Group (ibid). The fluids which migrated through permeable Pass Lake formation sandstone precipitated metals in stratigraphic traps at or near the Archean unconformity (ibid). Although the timing of these veins is considered broadly coeval with the Ag-rich veins of the Mainland and Island silver-belts, the variable metal signatures of different vein systems (Ag-rich vs U-rich vs Pb-Zn-Cu-rich) remains relatively poorly understood. In addition, their trace critical mineral contents have not been investigated extensively.

The Dead Horse Creek volcanoclastic breccia complex is host to a diverse group of highly altered heterolithic breccias and mafic to intermediate dikes that have been explored for rare earth elements, uranium, yttrium, cerium, zirconium and hafnium (Zurevinski et al., 2019). The Dead Horse Creek Complex has been divided into 5 subcomplexes, referred to as North, South, East, West and Central and described as altered heterolithic breccias that have undergone varying degrees of alteration and are variably radioactive (Sage 1982; Smyk et al., 1993). Exploration has mainly been focused on the mineralized zones at the West Dead Horse and the North Dead Horse subcomplexes. The West Dead Horse subcomplex has been described as “diverse, exotic, hydrothermally altered and rare metal mineralized” (ibid). The main mineralized zone at the West Dead Horse Subcomplex is small; however, the grade and style of mineralization highlights the importance of following up on larger, underexplored structures elsewhere in the Dead Horse Complex. Uranium-beryllium-zirconium mineralization was introduced via A-type granitic fluids along fault structures that crosscut the genetically unrelated breccias. Subsequently, niobium-titanium-vanadium-chromium-bearing alkaline fluids were introduced into the same fault system. These reacted with the pre-existing mineral assemblage and created the observed exotic mineralogy (Potter and Mitchell 2005).

The recognition of structures that were formed or re-activated during the Midcontinent Rift event is integral to understanding the location and timing of all the deposit types noted above. Bleeker et al, (2020) have made significant advances in the understanding of the timing of intrusions and subsequently the overall geodynamic evolution of the MCR. It has been noted that younger and more voluminous magmatism was focussed into the central rift as the lithosphere thinned and rifted apart, whereas the older intrusions (e.g. Thunder Bay North, Tamarack and others) were emplaced farther afield. This lithospheric thinning may have been an important factor in the location of structurally controlled hydrothermal deposits surrounding the Lake Superior basin as the majority of the vein systems are hosted in faults parallel to the rift axis, proximal to the rift margin. Distance from rift axis may have also had a bearing on the type of mineralization present in the vein systems as specific arrays of deposits appear to have differing metal signatures. The structural controls on the deposits, whether deposit controlling faults are primary MCR-related or reactivated Archean structures, remain important to understanding the structural evolution of the MCR and may help to further elucidate the nature of metallogeny in the region. Apart from the intrusion-hosted PGE deposits, the polymetallic vein deposits outlined here (Ag-rich, U-rich, Pb-Zn rich, Deadhorse Creek-type) are all generated by fluids derived from heat related to the MCR (Smyk and Franklin, 2007). The composition of the polymetallic veins is a product of the nature of the diverse ore-related fluids, and the geochemistry of the host rocks and their relative interactions and contributions of metals. Understanding

the structures which host all the deposit types outlined here and their relative timing, along with refining tectonic/structural evolution of the MCR, will be integral to furthering our understanding on the controls on these critical deposit types.

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Availability of Historical Airborne Geophysical Survey Data at Minnesota DNR

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The collections of exploration and scientific research data housed at the Minnesota Department of Natural Resources include a large volume of unpublished airborne geophysical survey deliverables, including maps, flight line profiles, flight records, interpretation reports, and other materials. An effort to discover, organize and make accessible these materials has uncovered 131 non-government pre-GPS mineral exploration airborne geophysical surveys representing 156,192 line kilometers of acquired data. The effort has accomplished several goals:

- From a collections perspective, segregation of these airborne survey deliverables from other exploration project records has succeeded in greatly reducing the physical volume of mineral exploration materials remaining to be handled in other curation and cataloging activities. Large maps, typically on Mylar, have been indexed and collected into vertical map cabinets. Folders of flight line profiles have been indexed at the survey level and stored in archival quality office boxes on a space efficient mobile shelving system. Contractor technical reports and irregular documents such as 35mm strip films and nine-track magnetic tapes have also been indexed, boxed and stored in the mobile shelving system. This single episode of curation activity has addressed some 30% of the volume in the collections.
- The effort has introduced the geography of mineral exploration data collections to newer mineral potential geoscientists in the Division, and provided big-picture orientation to historical exploration program data that is often reused in support of geologic survey mapping, university research, and natural resource land management activities.
- Scanned products of the organizing effort include 1) PDF/A archive format files of all maps, reports and similar documents, 2) color-indexed TIFF image files of all inventoried airborne geophysical survey map sets, and 3) georeferencing links files for all inventoried map images (georeferenced to UTM zone 15, NAD83). These files provide a critical backup to otherwise irreplaceable hard copy. An effort to make these and other collections products more easily accessed, viewed, searched and downloaded is currently in development.
- Four index files have been developed: 1) a surveys index based on flight line extents contains acquisition footprints (multi-part polygons) and survey attributes for the 131 surveys, 2) a maps index based on the 860 maps contains map tile footprints and map tile attributes (some survey map sets have up to 18 tiles, with up to 4 map sheets per tile), 3) a flight lines index contains line traces and line attributes for the 8,778 flight lines represented on the 129 map sets, and 4) a documents index spreadsheet based on inventory of the document collection contains metadata for each of the 1,089 documents curated during the effort. Availability of these indexes serves dual purpose, first as a finding aid, and secondly as an orientation and quality control aid for the curation of much of the follow up geologic, ground geophysical, and geochemical mineral exploration data sets archived at Minnesota DNR.

Mineral exploration magnetic-EM survey data comprise 89% of flight line content (138,786 line km). Magnetics-only surveys represent 10% of the data, and 1% is from a regional AFMAG (passive EM) reconnaissance survey over the Duluth Complex. Locations in Minnesota targeted by these surveys include the Archean Wawa and Wabigoon Subprovinces, Proterozoic bedrock on

the Mesabi and Cuyuna iron ranges and in areas of west-central, east-central, and southwestern Minnesota. Most of the surveys are based on ¼ mile flight line spacing.

For geologic mappers these surveys provide context for site surveys and drill core locations, and additional information about Minnesota's concealed bedrock terranes. For instance, many of the surveys have flight orientations different than government sponsored magnetic surveys; and formational EM conductors mapped in areas such as the southern part of the Animikie basin may enhance geologic interpretation in areas mostly devoid of magnetic anomaly detail. EM data may also provide information on surficial material features such as gravels or conductive clays.

Obviously, more work can be done to round out the inventory of non-government airborne geophysical surveys in Minnesota. GPS-based airborne survey data sets, which are digital and less susceptible to physical loss, are yet to be indexed, and indexing staff are aware of about 20 additional historical non-government airborne surveys in Minnesota that might potentially be targets for future donation (if they still exist). These additional historical airborne surveys are partially evidenced, either through coarse index maps, or clusters of named ground target sites, or staff knowledge of survey area vicinities for which no footprints are found in the collections.

The flight line profiles, which hold the actual magnetic, EM, and occasional radiometric survey data are now curated at the survey level and indexed at the flight line level. But they are still without backup and vulnerable to physical loss. These flight line profiles are an obvious target for a future National Geological and Geophysical Data Preservation Program (NGGDPP) proposal to scan and convert the hard copy records to PDF/A format, for preservation and access.

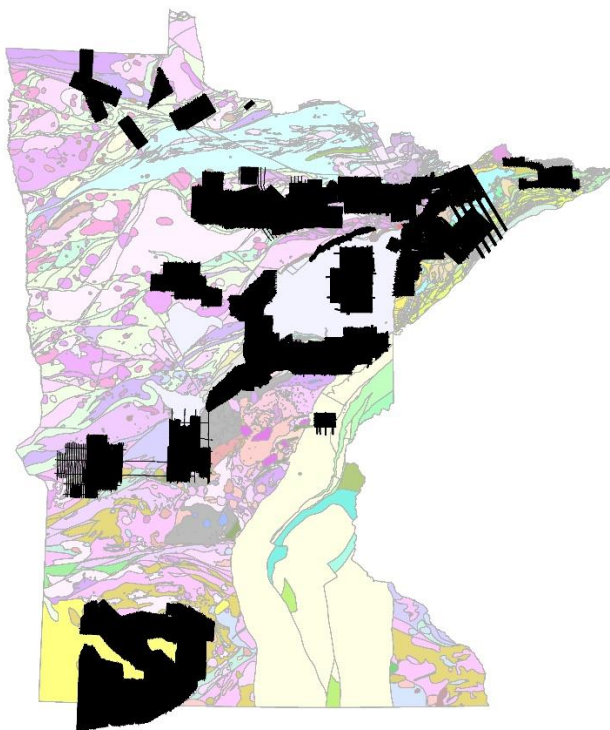


Figure 1: Acquisition footprints for the non-government pre-GPS airborne geophysical surveys inventoried during current effort. Bedrock geology - Minnesota Geological Survey map S-22.

Geophysical insights into Paleoproterozoic tectonics along the southern margin of the Superior Province, central Upper Peninsula, Michigan

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The southern margin of the Archean Superior Province in the central Upper Peninsula of Michigan was a nexus for key Paleoproterozoic tectonic events involved in the ~2.1 Ga rifting of proposed Archean supercraton Superia and subsequent assembly of Laurentia. Interpretations of the region's tectonic history have historically been hampered by extensive Pleistocene glacial and Paleozoic sedimentary cover and a lack of appropriate geophysical data. These rifting and orogenic events formed geologic effects that are readily mappable with modern geophysical methods. New aeromagnetic and gravity data provide a critical means of mapping and interpreting the complex geological framework through cover, allowing development of significantly richer geographical and process-based perspectives on all these tectonic events (Drenth et al., in press). Existing interpretations of Archean and Paleoproterozoic contacts and structure (e.g., James et al., 1961; Bayley et al., 1966) are carried >30 km eastward under Paleozoic cover (Fig. 1). The progression of ~2.1 Ga rift-related sedimentation and magmatism recorded in rocks of the Dickinson Group are clearly expressed as a geographically extensive and largely concealed tectonic feature of the southern Superior Province. Geophysical interpretations provide evidence for plausible ~2.1 Ga intrusive magmatism, such as a previously unrecognized swarm of mafic northeast-striking dikes cutting Archean rocks and multiple granitic bodies. Effects of the ~1.87-1.83 Ga Penokean orogeny include the clearly imaged Niagara fault zone suture, abundant evidence for thin-skinned thrusting and folding in the Menominee iron district, and speculative emplacement of an allochthonous sedimentary sequence in the Calumet trough. Numerous east-west trending structures likely originated, or were significantly reactivated, by post-Penokean deformation. Metamorphic events at ~1.76 Ga and ~1.65 Ga may correspond to orogenies involving younger, outboard Paleoproterozoic crustal provinces recognized in southern Laurentia. For example, the previously unrecognized West Branch fault, separating the Dickinson Group from Archean rocks, is shown to be a major structure in the region and is a proposed expression of ~1.76 Ga thick-skinned deformation documented elsewhere in the region. Oblique disruptions of crudely east-west striking structures have robust geophysical expressions and are speculatively connected to transpressive deformation at ~1.65 Ga.

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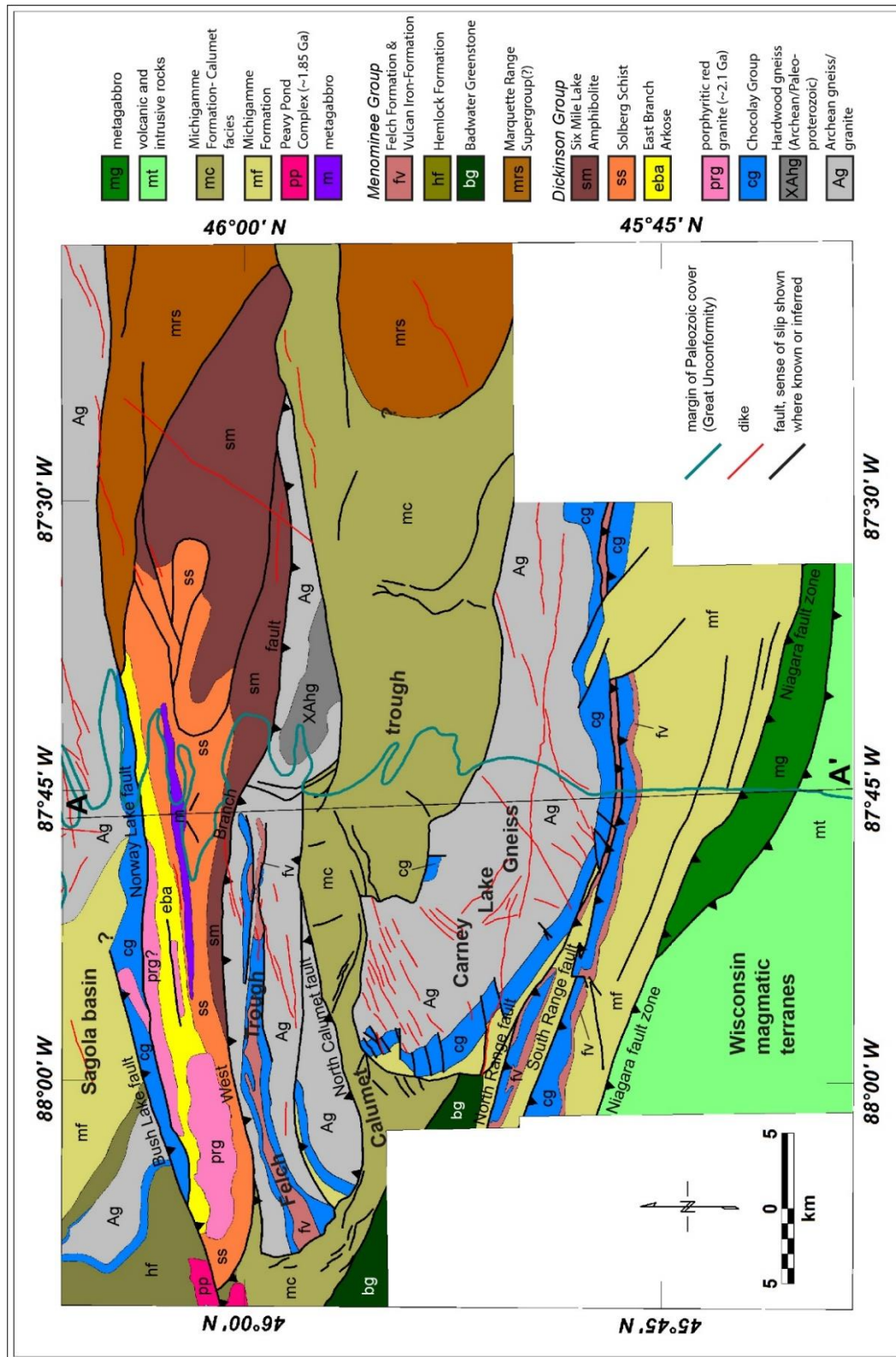


Figure 1: Plan view of interpretations (Drenth et al., in press). All units Paleoproterozoic unless otherwise noted.

The deformation and alteration of granitoid plutons in the Wabigoon subprovince

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Ongoing research suggests that the brittle deformation, ductile deformation and associated metasomatism/hydrothermal alteration studied in 12 granitoid plutons across the Wabigoon subprovince provide evidence for coeval brittle-ductile deformation at the amphibolite facies of metamorphism consistent with Archean-aged oblique convergence (transpression). Approximate outcrop locations where the brittle and/or ductile deformation were studied are shown in figure 1. Four hundred and two structural measurements of fractures and faults along with approximately 95 thin sections were used to assess the degree of deformation /metamorphism and the metasomatism of various granitoid plutons across the subprovince.

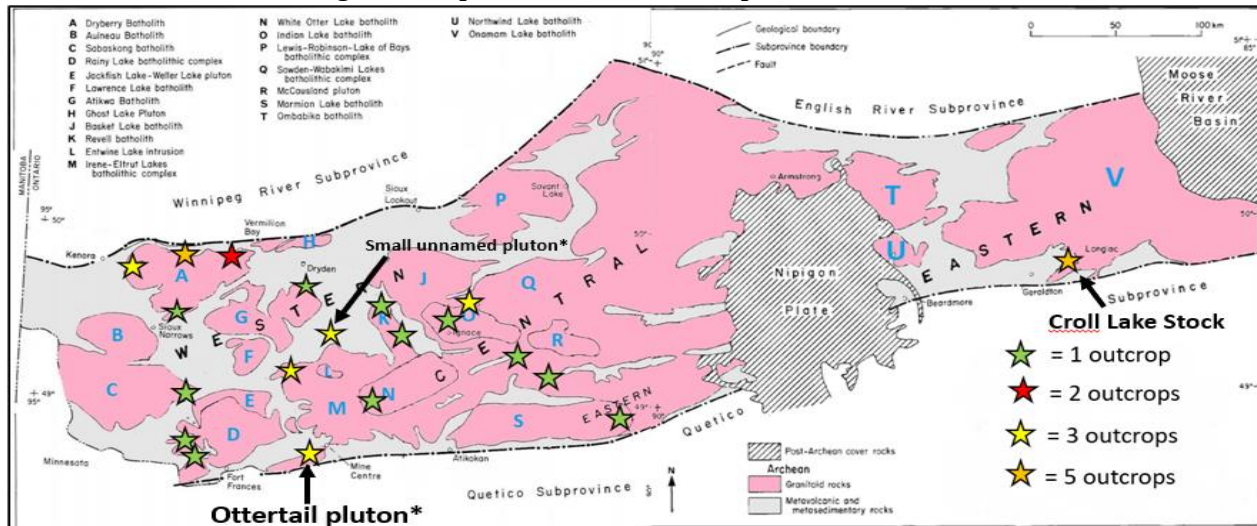


Figure 1. Modified map from Blackburn et al. (1991) showing the approximate outcrop locations where the brittle and/or ductile deformation of the granitoid plutons were studied.

Brittle deformation features common to all plutons include chlorite $\pm$ epidote shear veins and unfilled fractures. Shear veins show a conjugate strike-slip relationship in the field and are seen with dips ranging from 15° to 90° . Average and median dips of the shear veins is roughly $70^\circ \pm 10^\circ$ for each pluton studied. These shear veins are seen with sub-horizontal slickenlines that have pitches ranging from 00° to 33° . Although conjugate relationships are noted in the field, the orientation of the shear veins are quite variable across outcrops of individual plutons and the subprovince. These shear veins are also commonly seen defining the fabric in narrow shear zones present in the plutons across the Wabigoon subprovince. Many of the plutons also have quartz veins that have been subsequently ductilely deformed. These ductilely deformed quartz veins are commonly associated with narrow shear zones and are typically boudinaged with strong undulose extinction, subgrains and serrated grain boundaries. The ductile overprint of the quartz veins demonstrates coeval brittle-ductile deformation and is seen in the Sabaskong batholith, the Dryberry batholith, the Ottetail pluton, the Atikwa batholith and the Revell batholith.

Although the plutons studied appear to lack a notable macroscopic deformation fabric, thin section analysis shows that dislocation creep mechanisms were active in both quartz and feldspar mineral phases during peak metamorphic conditions. Deformation microstructures commonly seen

in quartz across all plutons studied include undulose extinction, serrated grain boundaries and subgrains. Feldspars have undulose extinction, subgrains, serrated grain boundaries, intragranular microfractures and deformation twins. Evidence for dislocation creep in feldspars indicates that the metamorphic grade of the plutons is consistent with the amphibolite facies of metamorphism.

Alteration of the plutons is directly related to brittle fracturing. Alteration minerals commonly seen adjacent to brittle fractures include chlorite, epidote group minerals, biotite, sphene, calcite, sericite, and muscovite with lesser amounts of hematite. The degree of alteration is most notable near the margins of the plutons where strain is concentrated.

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Geochemistry and Age of Archean Volcaniclastic and Mafic Intrusive Rocks, Georgia Lake Area, Quetico Subprovince, Northwestern Ontario

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The metaturbidites of the Georgia Lake area in the Quetico Subprovince host 2 peculiar types of rock: volcaniclastic rocks that are mafic to intermediate in composition and mafic intrusive rocks that likely were emplaced when the turbidites were unconsolidated. The volcaniclastic rocks were described first on the shoreline of Lake Jean by Williams (1988), who interpreted them as sedimentary rocks derived from the erosion of nearby ultramafic bodies. A similar interpretation was given by Valli, Guillot and Hattori (2004), but they suggested a komatiite basalt as the source. Field work conducted during the summer 2019 showed that these rocks are very likely the result of deposition and local reworking of either ash from a volcanic plume or a distal part of a pyroclastic flow. Analyses of newly acquired and historical geochemical data were performed to, first, assess the level of contamination of these volcaniclastic rocks by the surrounding turbidites and, second, to compare it with possible source in the area such as the numerous Archean mafic sills and veins that intruded the turbidites. The least contaminated members of the volcaniclastic rocks fall in the fields of boninites and siliceous high-magnesium basalts in various discriminant diagrams such as SiO_2 versus MgO , TiO_2 versus MgO , SiO_2 versus Cr and TiO_2 versus Cr (Pearce and Reagan 2019). TiO_2 content of the mafic intrusive rocks compared to that of the volcaniclastic rocks (respectively >1 wt.% and less than 0.6 wt. %) show that the former are unlikely to be the source of the volcaniclastic rocks. On primitive mantle-normalized incompatible element diagram, volcaniclastic rock compositions show moderate to strong enrichment in light rare earth elements (LREE) and depletion in heavy rare earth elements (HREE), with negative anomalies in niobium, tantalum and titanium and positive anomalies in zirconium and hafnium, as summarized in Duguet (2020). Although being more enriched in REE, the mafic intrusive rocks display similar fractionation pattern than those of the volcaniclastic rocks but with negative anomalies in zirconium and hafnium. LA-ICP-MS U-Pb dating on zircon of a volcaniclastic rock yielded a mean age of 2702 ± 3 Ma that is interpreted as its depositional age (Figure 1). These volcaniclastic rocks came either from the Wabigoon Subprovince to the north or the Wawa Subprovince to the south. Such rocks remain to be identified in these areas and the closest candidates may be the andesitic volcanic rocks of the Shebandowan greenstone belt to the south. Different process can generate boninitic magmas, but based on the geological setting and previous studies, an arc/fore-arc environment is favoured. The mafic intrusive rocks are also very interesting because they were intruded at the time when the sediments were deposited. This would rule out an accretionary prism environment for the Quetico Subprovince because active volcanism coeval with turbidite sedimentation is more common in back-arc and/or rifted arc settings. However, the calc-alkaline chemistry, which also display similarities with sanukitoid plutons in the area, contradicts this interpretation. The geodynamical implications of this remain to be investigated and a more complex scenario involving either rifted fore-arc/arc or subduction polarity flips should be investigated.

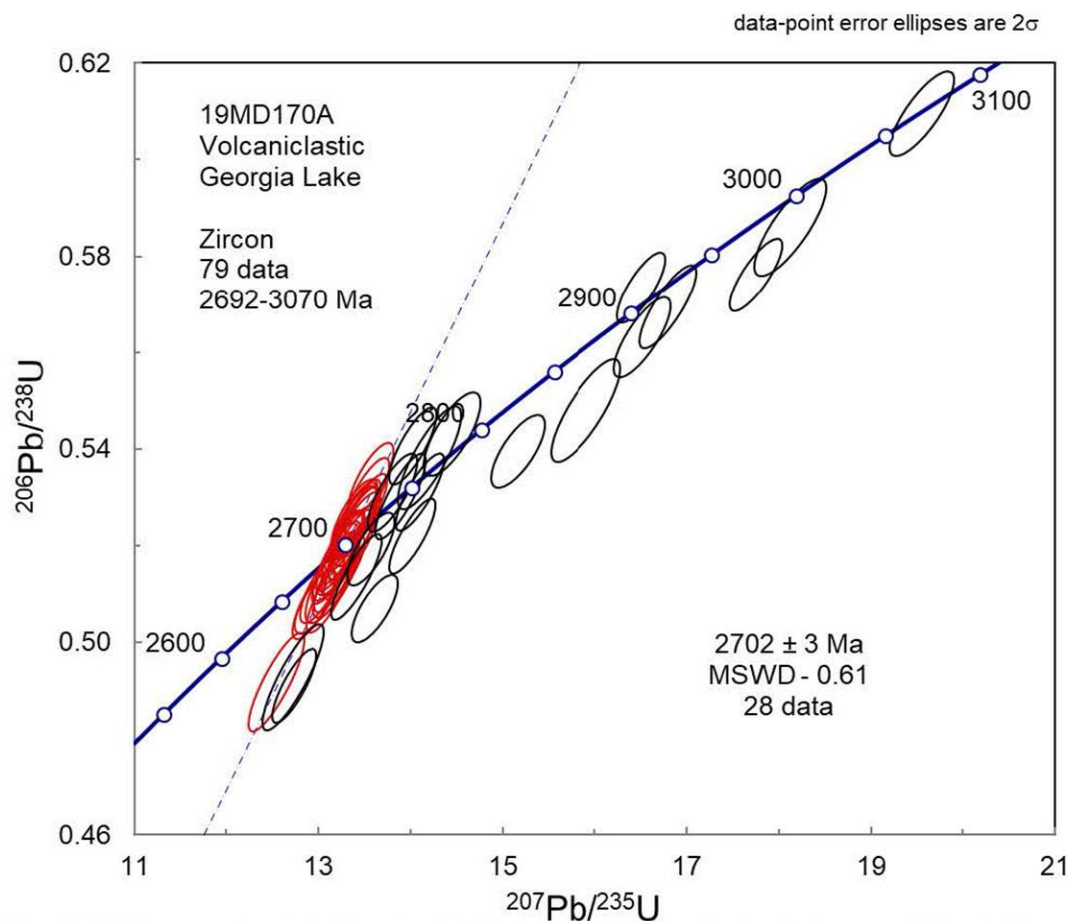


Figure 1. Concordia plot for a volcaniclastic rock from the Georgia Lake area showing the main zircon population at 2702 ± 3 Ma ($n=28$) reflecting the age of deposition. Geon 28, 29 and 30 grains are also present. Data from Sutcliffe (2020).

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The Critical Mineral potential of carbonatite and alkalic complexes in Ontario

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There are more than 50 carbonatite and/or alkalic complexes in Ontario ranging in age from Neoarchean to Jurassic (Figure 1). Although there are numerous reports and compendia on them (Sage 1991; Woolley and Kjarsgaard 2008), from a mineral exploration standpoint, there is little guidance available with respect to determining which complexes might have higher mineral potential than the others, especially for niobium and the rare earth elements (REE). Recent academic studies on alkaline and carbonatitic magmas by Nabyal et al. (2020) and Ballouard et al. (2020) indicate that calcio-carbonatites associated with coeval feldspathoidal-dominated silicate rocks (e.g., ijolite, nepheline syenite) are more likely to host niobium and/or REE mineralization than are calcio-carbonatites found with other igneous rock associations. This presentation examines this suggestion with respect to carbonatite and alkalic complexes in Ontario; more details are found in (Easton 2020). It should be noted that many of the complexes in Ontario, especially the carbonatite complexes, are typically poorly exposed, known only through limited diamond-drill hole data, and only major element geochemical data are available for most.

Neoarchean alkaline intrusions in Ontario do not have phonolite to phono-trachytic rock compositions and thus are not considered as having high REE potential. This also applies to the *circa* 1090-1065 Ma Kensington-Skootamatta intrusive suite in the Grenville Province. In contrast, mafic end-members of the Frontenac intrusive suite (*circa* 1180-1155 Ma) in the Grenville Province are characterized by high TiO₂, P₂O₅ and alkali (Ba, K, Rb, Sr) contents, have bulk rock compositions of basaltic trachyandesite to trachyandesite, and have the potential to host iron-oxide (P-rich) mineralization (Easton 2019).

Using the suggestion that phonolite to phono-trachytic rock compositions may be a predictor or favourable rare element mineralization in carbonatite and alkalic complexes reduces the number of potential targets from more than 40 to ~10. The more favourable complexes are associated with feldspathoidal-bearing intrusive rocks and known pyrochlore and/or significant apatite occurrences. Most occur in 3 main areas of the province associated with areas of crustal extension and/or mantle upwelling. Specifically, 1) the Paleoproterozoic Argor Complex is proximal to the Circum-Superior Orogen; 2) the Manitou Island, Iron Island and Burritt Island complexes, and the Lavergne fenite, are all associated with the Ottawa–Bonnechere graben where it impinges on the former trace of the Sudbury dike swarm mantle plume at *circa* 1238 Ma; and, 3) Although proximal to the Midcontinent Rift (MCR), the Firesand River, Good Hope and Prairie Lake complexes were emplaced between 1163 and 1143 Ma, suggesting that they may be a far-field effect of the Grenville Orogen rather than the MCR. The Mesoproterozoic Lackner, Nemegosenda and Seabrook complexes along the Kapuskasing Structural Zone also have exploration potential. Acquisition of modern trace element geochemistry from these 10 complexes may help to further refine their potential to host rare element mineralization.

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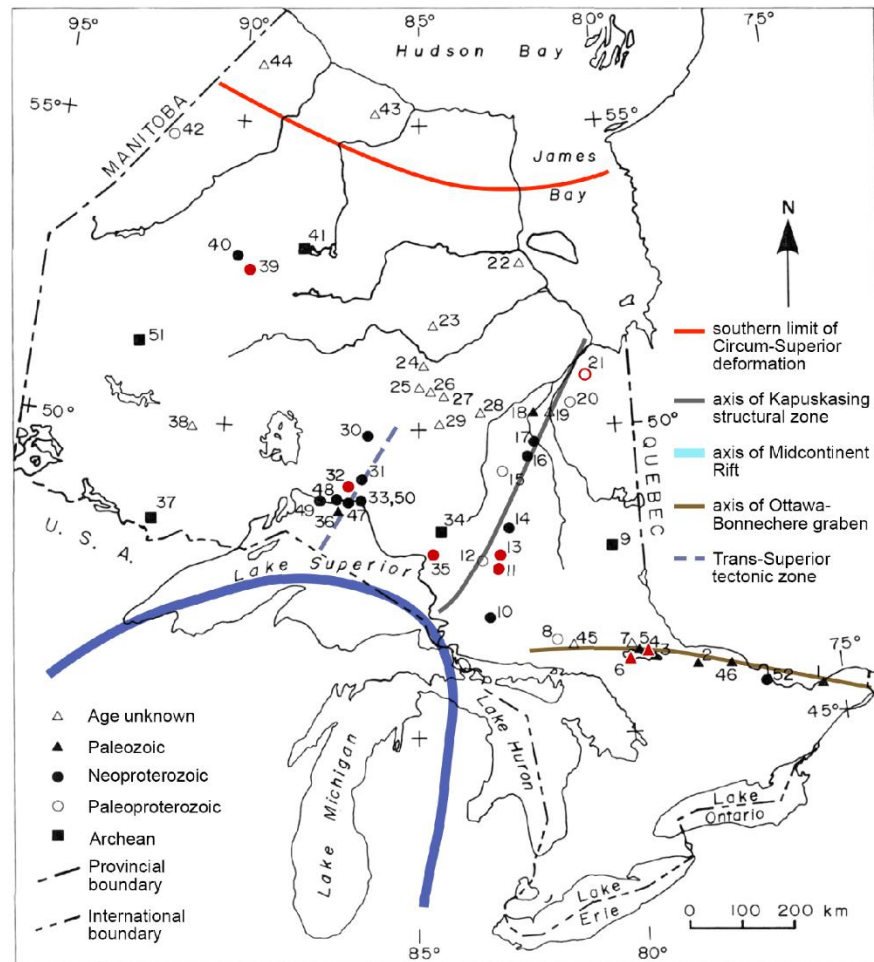
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| 1. Eastview carbonatite(s) | 27. Kingfisher River East aeromagnetic anomaly |
| 2. Brent Crater | 28. Martison Carbonatite Complex |
| 3. Callander Bay Alkalic Complex | 29. Nagagami River Alkalic Complex |
| 4. Manitou Island Alkalic Complex | 30. Chipman Lake fenites and carbonatite dikes |
| 5. Burritt Island Alkalic Complex | 31. Killala Lake Alkalic Complex |
| 6. Iron Island Alkalic Complex | 32. Prairie Lake Carbonatite Complex |
| 7. Lavergne carbonatite | 33. Port Coldwell alkalic complex |
| 8. Spanish River Carbonatite Complex | 34. Herman Lake Alkalic Complex |
| 9. Otto alkalic complex | 35. Firesand River Carbonatite Complex |
| 10. Seabrook Lake Carbonatite Complex | 36. Slate Islands diatremes |
| 11. Lackner Lake Alkalic Complex | 37. Poohbah Lake Complex |
| 12. Borden Township Carbonatite Complex | 38. Sturgeon Narrows Alkalic Complex |
| 13. Nemegosenda Lake Alkalic Complex | 39. Schryburt Lake Carbonatite Complex |
| 14. Shenango Township alkalic rock | 40. Big Beaver House Carbonatite Complex |
| 15. Cargill Township Carbonatite Complex | 41. Wapikopa River Alkalic Complex |
| 16. Teetzel Township carbonatite | 42. Carb Lake Carbonatite Complex |
| 17. Clay-Howells Alkalic Complex | 43. Gooseberry Brook aeromagnetic anomaly |
| 18. Hecla-Kilmer Alkalic Complex | 44. Niskibi Lake aeromagnetic anomaly |
| 19. Valentine Township Carbonatite Complex | 45. Nemag and Lusk lakes fenites |
| 20. Goldray Carbonatite Complex | 46. Allan Lake Carbonatite |
| 21. Argor Carbonatite Complex | 47. Dead Horse Creek diatreme |
| 22. Lawashi River aeromagnetic anomaly | 48. McKellar Creek diatreme |
| 23. Poplar River aeromagnetic anomaly | 49. Gold Range diatreme |
| 24. Albany Forks Carbonatite Complex | 50. Neys diatreme |
| 25. Little Drowning River aeromagnetic anomaly | 51. Springpole Lake |
| 26. Kingfisher River West aeromagnetic anomaly | 52. Sullivan Island Carbonatite Complex |

Figure 1. Locations of carbonatite complexes, alkalic complexes, aeromagnetically inferred alkalic and/or carbonatite complexes and areas of fenite and carbonatite dikes in Ontario. Also indicated are the traces of the southern limit of the Circum-Superior Orogen, the Kapuskasing Structural Zone, the Midcontinent Rift, and the Ottawa-Bonnechere graben. Complexes with higher estimated exploration potential are indicated in red. Figure modified from Sage (1991).

Reconstructing the hydration and carbonation history of the Presque Isle peridotite, Marquette Michigan: Insights into mechanisms of carbon sequestration in ultramafic rocks

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The Presque Isle peridotite is a serpentinitized lherzolite that occupies about 500,000 m² on the northern outskirts of Marquette, Michigan. The age of the Presque Isle peridotite is not known, although it and a similar body, the Deer Lake Peridotite, exposed about 25 km to the WSW, have been assumed to be Neoproterozoic (Sims, 1991; Sasso, 2016). Both ultramafic masses lie within an area of Neoproterozoic (2.7 Ga) rocks -- the tonalitic to granodioritic Compeau Creek Gneiss -- near the southern edge of the Superior Craton, about 10 km north of the Great Lakes Tectonic Zone. If the peridotites are Neoproterozoic, they may represent cumulate bodies related to metabasalt/ greenstone units mapped as the Mona and Kitchi Schists in the Marquette region. However, there is another ultramafic body in the area, the mineralized Yellow Dog peridotite found 40 km northwest of Marquette, that is related to the ca. 1.0 Ga Midcontinent Rift -- part of a dike swarm emplaced into Paleoproterozoic metasedimentary rocks of the Baraga Group. In the absence of direct geochronologic constraints, a Mesoproterozoic age for the Presque Isle and Deer Lake peridotites cannot be ruled out, although their irregular, non-tabular shapes are quite different from the fracture-controlled form of the Yellow Dog intrusions.

The Presque Isle peridotite is overlain nonconformably by a unit that has been mapped as the ca. 1.0 Ga Jacobsville Sandstone (a late rift-filling unit). However, the sedimentary material just above the unconformity is a rubbly conglomerate about 2 m thick with a greenish matrix and irregularly shaped red-orange clasts of chalcedony -- very different in character from the typically well sorted, quartzose Jacobsville Fm. In places along the contact, it is in fact difficult to distinguish the highly altered peridotite from the overlying sedimentary rocks.

Despite the uncertainties about the igneous age and origin of the Presque Isle peridotite and the time at which it was exposed to weathering in the geologic past, extensive unvegetated exposures of the peridotite at the northern tip of Presque Isle Park make it possible to reconstruct a detailed relative chronology of fluid flow, deformation and weathering processes that altered the rock over time. Based on field, thin section, XRD and stable isotope analyses, we infer the following sequence of events, recording progressive cooling and exhumation of the peridotite from depth.

1) *Percolative infiltration by water-rich fluids*

The least altered parts of the Presque Isle peridotite still have recognizable igneous textures and record an early period of pervasive, percolative flow by aqueous fluids that altered the original olivine crystals to lizardite along grain boundaries and transgranular cracks. Phase relations for ultramafic rocks (Philpotts and Ague, 2009) suggest this happened at temperatures below 500-600°C, depending on depth. XRD analysis also indicates the presence of minor talc in these rocks, which could indicate metamorphism at slightly higher temperatures (up to ca. 650°).

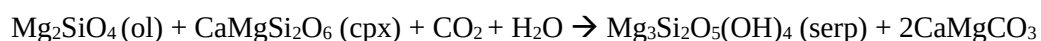
Serpentine also occurs in centimeter-scale curvilinear seams within the Presque Isle peridotite. These seams are typically meters apart but variably oriented and intersecting, and thus do not appear to have been influenced by a consistent external stress regime. Although the seams represent a morphologically distinct style of serpentinization, they may be temporally linked with the grain-scale alteration of the rocks. The serpentine seams exhibit small-scale transverse fractures whose spacing is comparable to their width; such features have been interpreted in other peridotites to reflect the significant volume increase (close to 40%;

Klein and Le Roux, 2020) that occurs with serpentinization. This early serpentinization event does not seem to have been associated with significant deformation.

2) *Tectonically-influenced hydrofracturing and reaction-induced fracturing by CO₂-rich fluids*

Carbonate material in different forms cuts across serpentinized areas of the peridotite. The simplest carbonate occurrences are NW-striking, vertical dolomite-serpentine veins with fibrous crack-seal textures indicating incremental, dilational opening. These are spatially associated with vertical WNW-trending dextral faults with dolomite slickenfibers. The orientation of the veins relative to the faults is consistent with their formation as tensile fractures in a dextral shear zone. The crack-seal texture of the vein fillings suggests repeated, perhaps seismically induced, fluid flow and hydrofracturing events at depths shallow enough that the rocks deformed brittlely. In a few samples, carbonate crystals have terminated faces, suggesting they grew into open space or a dense vapor phase; this too implies shallow depths of formation.

More geometrically complex carbonate masses are 5-10 cm thick ‘rinds’ around pods of less altered peridotite. These have crude ‘onion-skin’ layers and transverse veins that create a mesh-like appearance, and are similar to features attributed to reaction-induced fracturing by Jamtveit *et al* (2008). Like the crack-seal veins, the carbonate meshes consist mainly of dolomite. Oxygen isotope values for both the vein and mesh carbonates are consistently negative ($\delta^{18}\text{O}$ VPDB between -6.57 and -11.89) and suggest that the mineralizing fluids came from meteoric water. These fluids must have carried enough dissolved CO₂ to cause reactions such as:



3) *Deep near-surface weathering under high CO₂ conditions*

Beginning about 5 m below the unconformity, the peridotite has a strikingly different color and composition. The rock mass consists of at least 30% carbonate (dolomite, magnesite, rhodochrosite), some of it massive, with intervening areas of reddish material that represents extremely altered olivine and serpentine. As one approaches the unconformity, even the serpentine has been altered to a residuum of fine-grained quartz or chalcedony and opaque minerals, likely Fe and Mg oxides. This deep weathering may reflect long-term leaching by surface fluids in late Proterozoic time under higher atmospheric CO₂ levels than at present. The large amount of carbonate near the unconformity indicates that the rock continued to be reactive even after the original olivine had already been altered to serpentine.

The complex hydration and carbonation history of the Presque Isle peridotite provides a natural analog for physical and chemical processes that might be emulated for carbon sequestration in ultramafic rocks if carbon capture becomes technologically and economically feasible.

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A Practical Approach to Using Incompatible Elements to Define Geochemical Correlation and a Common Mantle Source: Example Crystal Lake Gabbro and the Duluth Complex

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This presentation focuses on fundamental principles of igneous geochemistry to provide a practical approach for identifying geochemical correlations between mafic rock units in the MCR. A common approach will aid in development of a rift-wide classification strategy and knowledge of the geographic extent of defined mafic rock series. This level of information is key to understanding the nature of mantle sources across the rift. The ultimate goal is to provide useful criteria to guide ongoing exploration for Cu-Ni-PGE deposits in the MCR.

There is a seemingly infinite array of methods to combine geochemical criteria and trace element data to derive useful petrogenetic models to explain mafic rocks, but most are not necessary for a regional scale study such as this. By defining a clear hypothesis, it is possible to simplify the number of elements used to a manageable and reliable few. In this case, a widely known concept that igneous rock sequences which have not been contaminated by crustal material, and that have similar incompatible trace element patterns were derived from a similar mantle source. With this objective in mind, it is not necessary to consider elements that are susceptible to hydrothermal alteration or are associated with plagioclase. Thus, U, Th, Ta, Nb, Zr and the REE provide a definitive range of elements for making comparisons and drawing conclusions regarding correlation (but do not necessarily show rocks are co-genetic). In those rare instances where there is evidence for mantle metasomatism, K, Ba and Sr abundances should be considered.

A practical approach applies 4 steps: 1) elimination of samples considered to have undergone crustal contamination by evaluation Th/Nb (>0.2), 2) cleaning the data set of unrelated or outlier samples using REE patterns or the λ_1 vs λ_2 plot, 3) testing for evidence of clinopyroxene fractionation (La vs. Sm), and 4) inspection and comparison of twice normalized (primitive mantle and Lu) extended trace element diagrams. Two examples are presented: 1) the Babbitt intrusion of the Duluth Complex is compared to the Crystal Lake gabbro, and 2) the Current Lake intrusion is compared to the Lower Suite (Simpson Island traverse) of the Osler Volcanic Group.

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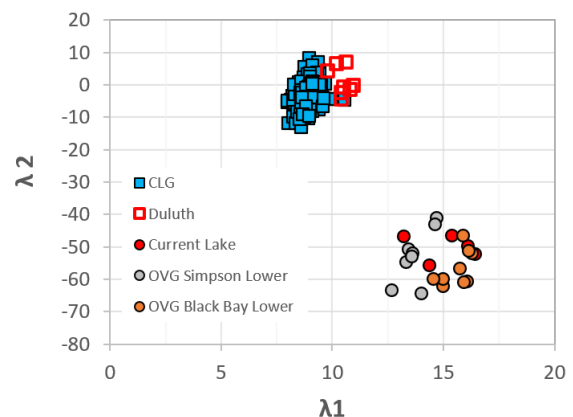
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Integration of geophysical evidence indicates that anorthosite composes a significant portion of Grand Marais ridge, an inferred basement high in western Lake Superior

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The Midcontinent Rift System (MRS) is expressed geophysically by a semi-linear, regional gravity high that trends across the Midcontinent and Great Lakes region of North America. The gravity high is interrupted by two prominent, semicircular gravity lows, which have been interpreted from modeling and seismic-reflection sections as basement highs of Archean granite (Allen et al., 1997). One is centered southwest of Isle Royale in western Lake Superior (Grand Marais ridge) and the other over Bayfield Peninsula (White's Ridge). Allen et al. (1997) suggest that the Archean granite highs were pre-rift features that remained high while lava basins of the MRS subsided adjacent to them. Hart et al. (1994) questioned the presence of granitic rocks underlying Grand Marais ridge (GMR) because heat flow measurements there are much lower than is typical for Archean granitic upper crust. They argued that the region must instead be underlain by rocks of low radiogenic heat production, such as gabbro, extending to at least 15 km depth. However, gabbro has high densities and would not produce the observed gravity low. Thus, the geophysical observations appear contradictory.

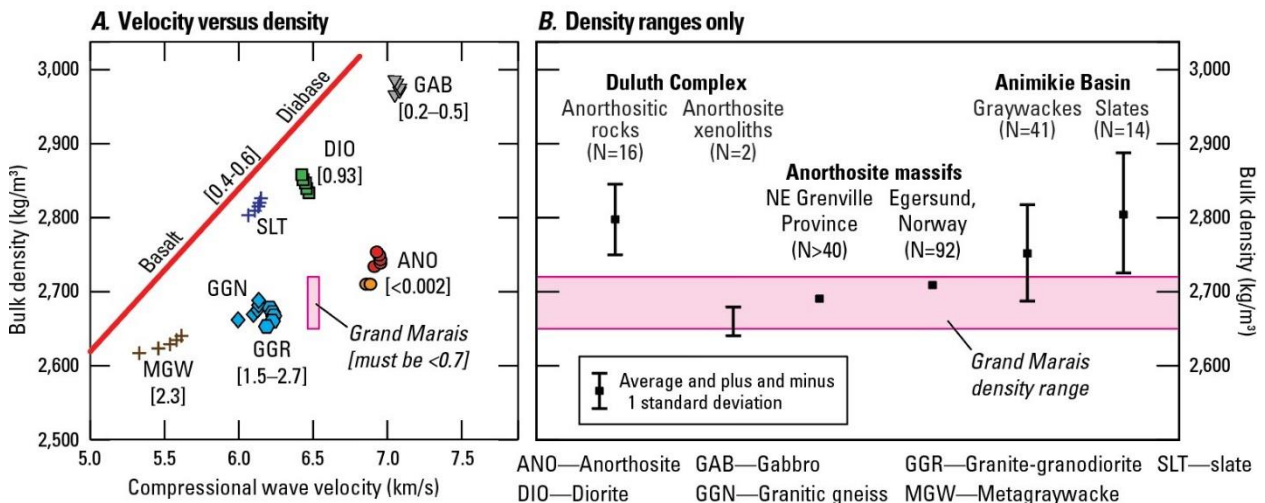


Figure 1. Physical properties of rock types compared to the ones inferred for Grand Marais ridge. (A) All velocity-density point data are from Christensen and Mooney (1995), representing means at 5, 10, 15, 20, 25 km depths, except for two additional sites for anorthosite (orange), which are from Birch (1961), measured at 2 kbars. The regression line representing Keweenaw basalt and diabase is from Halls (1969). Typical radiogenic heat production by rock type (in brackets) in $\mu\text{W}/\text{m}^3$ are from Hasterok et al. (2018) except for anorthosite, which is from Roy et al. (2021). (B) Statistics for Duluth Complex and Animikie Basin densities were analyzed from the database of Chandler and Lively (2011). Representative densities for the NE Grenville and Egersund massifs are from Keary and Thomas (1979) and Smithson and Ramberg (1979), respectively. N is the number of samples measured.

Bouguer gravity, seismic-reflection, seismic-refraction, and heat-flow data suggest that the rock types composing GMR to a depth of about 15 km have densities of 2,650–2,720 kg/m^3 (Hutchinson et al., 1990; Allen et al., 1997), compressional-wave velocities of about 6.5 km/s (Luetgert and Meyer, 1982; Hutchinson et al., 1990; our own velocity analyses), and radiogenic heat production

values of no more than $0.7 \mu\text{W}/\text{m}^3$ (Hart et al., 1994). These inferred GMR physical properties are compared to the same properties compiled globally and measured locally for rock types likely to occupy the subsurface of western Lake Superior (Fig. 1). As already noted, the granitic rocks have densities and velocities closest to the GMR suite of properties, but the heat production is too high. The mafic and intermediate rocks (Fig. 1A) and metasedimentary rocks of the Animikie Basin (Fig. 1B) are too dense. The latter also are likely to have heat production that is too high (noted next to MGW on Fig. 1A).

If the values compiled for anorthosite (Fig. 1A) are representative for the MRS, the low heat production fits but velocities are too high for anorthosite to be the sole rock type underlying GMR. However, if added in significant volume to felsic rock types, for example, the velocity and the heat generation could be combined to result in the desired physical properties for the whole rock column. Alternatively, the lower densities for anorthosite xenoliths and massifs elsewhere (Fig. 1B) hint that the compiled values are not representative; the xenolith source may have velocities that match those of GMR. In any case, anorthosite likely constitutes a significant volume of GMR.

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Final inversion of the Midcontinent Rift during the Rigolet Phase of the Grenvillian orogeny

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The Keweenaw Fault is a major structure associated with inversion of the Midcontinent Rift; it thrusts ca. 1093 to <1086 Ma rift volcanic and sedimentary rocks atop the post-rift Jacobsville Sandstone in northern Michigan. Given the position of folded Jacobsville Sandstone in the footwall of the fault, its depositional age provides a maximum age constraint on faulting. Previous detrital zircon U-Pb geochronology used laser ablation-inductively coupled plasma mass spectrometry (LA-ICPMS) that led to an interpretation of a ~950 Ma maximum depositional age for the Jacobsville Sandstone and to argue that motion on the Keweenaw Fault must postdate the ca. 1080 to 980 Ma Rigolet Phase of the Grenvillian orogeny (Craddock et al., 2013; Malone et al., 2016). In this study, we reproduced similar low-precision maximum age constraints on detrital zircons using LA-ICPMS, then we dated the youngest detrital grains at high-precision by chemical abrasion-isotope dilution-thermal ionization mass spectrometry (CA-ID-TIMS). Our revised maximum depositional age is based on the youngest detrital zircon dated by CA-ID-TIMS and contemporaneous with the 1000–980 Ma Rigolet Phase of the Grenvillian orogeny. This revised maximum age constraint overlaps with U-Pb LA-ICPMS dates on syn- to post-kinematic calcite veins within the brecciated fault zone of the Keweenaw Fault that yield lower intercept dates that are also contemporaneous with the Rigolet Phase of the Grenvillian orogeny. From these age constraints, we infer that the Jacobsville Sandstone was deposited during the final inversion of the Midcontinent Rift during the Rigolet Phase of the Grenvillian orogeny, just before reverse motion on the Keweenaw Fault. This deposition and subsequent reverse faulting is contemporaneous with development of the Grenville Front during the Rigolet phase of the Grenvillian orogeny. These data demonstrate the propagation of Rigolet-aged orogenesis into the continental interior ca. 580 km from the Grenville Front.

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Olivine Geochemistry from Fe-Ti Oxide-Bearing Ultramafic Intrusions in the Duluth Complex, MN

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The Duluth Complex is a series of mafic intrusions in northeastern Minnesota which formed 1.1 billion years ago as part of the Midcontinent Rift System. On the southern side of the Complex, specifically on the western margin, it hosts 14 different ultramafic intrusions which bear Fe-Ti oxides, known as oxide bearing ultramafic

intrusions, or OUIs.

There are currently three competing hypotheses about how these OUIs formed, but none of them have been rigorously tested. However, there are many minerals present in these OUIs which can be

used as proxies to discover more about their genesis, such as olivine. Since olivine is a solid

solution mineral and is typically one of the first minerals to crystalize from a melt phase, we can gain a lot of information about the way the magma formed from its composition alone. Two OUIs in particular, Titac and Longnose, were studied in thin section using a variety of tools, including a petrographic microscope, a scanning electron microscope (SEM), and an electron probe microanalyzer (EPMA). The petrographic microscope and SEM showed the different textures in which olivine formed. In Titac, olivine appears to be tubular in shape and fractured. In Longnose, olivine appears to form in a ropy shape, and is heavily striated. There is evidence of fracturing, but not as much as in Titac. In addition, there is evidence of deformation, shown by grain boundary bulging of Fe-Ti oxides and plagioclase present. In both intrusions, the olivine is heavily serpentinized. Under the EPMA, compositions of olivine were measured, of olivine in OUIs as well as olivine in surrounding host rocks (troctolites). The results of this analysis can be seen in Figure 1. In the OUI rocks, it was found that forsterite content was overall higher than the host rock in both intrusions ($\sim\text{Fo}_{60}$ to $\sim\text{Fo}_{70}$), with Longnose having a higher content than Titac. It also appears to be very consistent throughout the drill core for both. In addition, the host rocks have much lower amounts of forsterite ($\sim\text{Fo}_{60}$ to $\sim\text{Fo}_{35}$), with the Longnose (both OUI rock and host rock) having a higher forsterite content overall. The higher forsterite content in the OUI rocks can likely be attributed to the abundance of Fe-Ti oxide minerals, which leach out iron from the area, leaving the olivine with a higher forsterite content. The higher forsterite content in Longnose

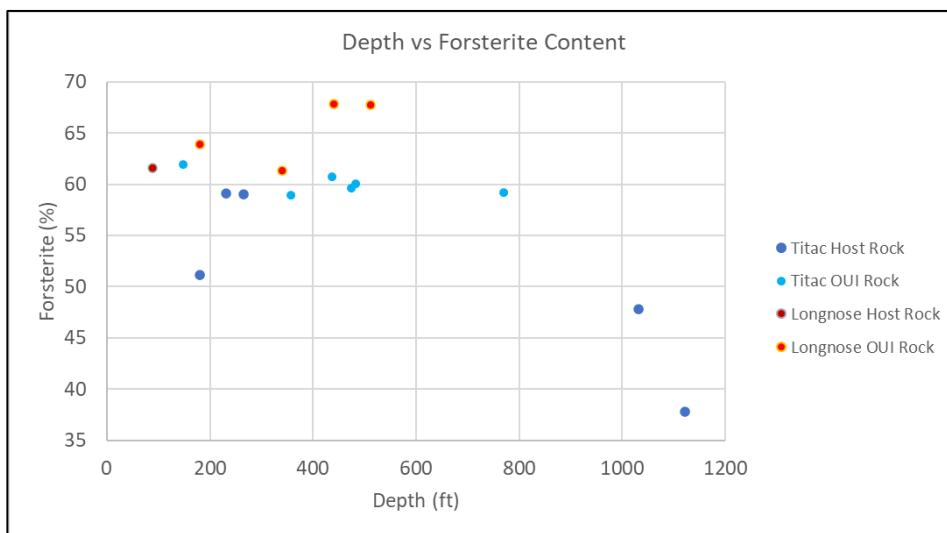


Figure 1: Depth vs Forsterite content in Titac and Longnose. Both the surrounding host troctolites and the OUI rocks themselves were analyzed, and results can be seen [here](#).

indicates that the magma which formed it is relatively more primitive than the magma which formed Titac. The forsterite content is consistent with the findings of Miner (1995) in her thesis about the Longnose body¹. We also compare the forsterite content to the content of nickel in the olivine (trace). We can see that there is overall more nickel in the Longnose OUI, and this is most likely due to the lower modal abundance of sulfide minerals compared to Titac.

¹ Miner, G. C., 1995. Aspects of the Petrogenesis of the Longnose Fe-Ti-Oxide-Rich Ultramafic Body, Duluth Complex, MN. Washington University Department of Earth and Planetary Sciences.

Textures and geochemistry of ilmenite and titanomagnetite in Fe-Ti oxide-bearing ultramafic intrusions of the Western Margin of the Duluth Complex, Minnesota

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The Duluth Complex hosts numerous undeveloped mineral deposit types, including Cu-Ni, PGE, Mn, Fe-Ti±V, and others. Significant Fe-Ti±V mineralization has remained particularly unstudied over the past 20 years and represents one of the United States' most promising domestic resources of these energy- and infrastructure-critical metals. Fe-Ti±V mineralization is hosted in ~14 Fe-Ti oxide-bearing ultramafic intrusions (known in the literature as OUIs) along the Western Margin. Although most are broadly similar in mineralogy, three contrasting genetic models have been proposed to explain the source of Fe and how the deposits formed. Because there exists incredibly scarce geochemical evidence to support or refute any of the three models, and the main objective of this project is to unravel the genesis of Fe-Ti±V oxide-bearing ultramafic intrusions.

Focusing on the Longnose and Titac (Section 34) OUIs, two well-drilled intrusions ~40 km apart hosted in the Partridge River and Western Margin intrusions, respectively, we used detailed optical and microbeam methods to compare the textures and compositions of Fe-Ti oxides (ilmenite, titanomagnetite, and magnetite) to gain insight into their origin and cooling history. Both intrusions show similar complex textures despite differing proportions of ilmenite and titanomagnetite, with Longnose typically having higher amounts of ilmenite. Titanomagnetite contains extensive ilmenite and pleonaste ((Fe,Mg)Al₂O₄). Ilmenite is present as primary grains and as 'oxy-exsolution' lamellae in titanomagnetite (e.g., Buddington and Lindsley, 1964) as thin trellis-type lamellae, thicker bands of sandwich-type lamellae, and titanomagnetite-hosted granular exsolutions (Fig. 1). Pleonaste is present in ilmenite at or near the contacts between titanomagnetite and ilmenite as large, granular blebs and as 'dog tooth' symplectites that are triangular intergrowths with ilmenite (Fig. 1b). In titanomagnetite, pleonaste exsolution is present as lamellae and cubic granules and within and around ilmenite sandwich-type

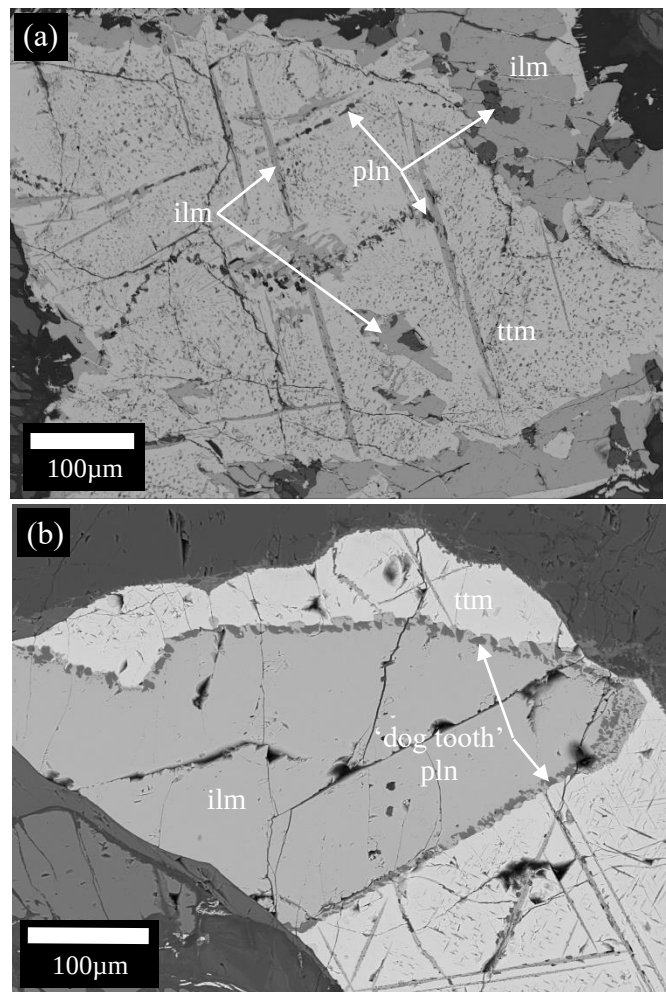


Figure 1 – BSE images of Fe-Ti oxides from Longnose (a) and Titac (b). Multiple types of exsolution and oxy-exsolution are present. Ilmenite – ilm; titanomagnetite – ttm; pleonaste – pln.

exsolution is present as lamellae and cubic granules and within and around ilmenite sandwich-type

lamellae as both vermicular symplectites (Fig. 2a) and blebs. Hematite lamellae are present in ilmenite from both OUIs, which indicates the original ilmenite-hematite_{ss} decomposed during cooling below 750–675°C to form the hematite exsolution rods (Lindsley 1991). These textures indicate that both magnetite-ulvöspinel_{ss} and ilmenite-hematite_{ss} were present and that cooling and oxidation-reduction reactions induced the various exsolution textures observed, starting at >900°C (Turnock and Eugster 1962).

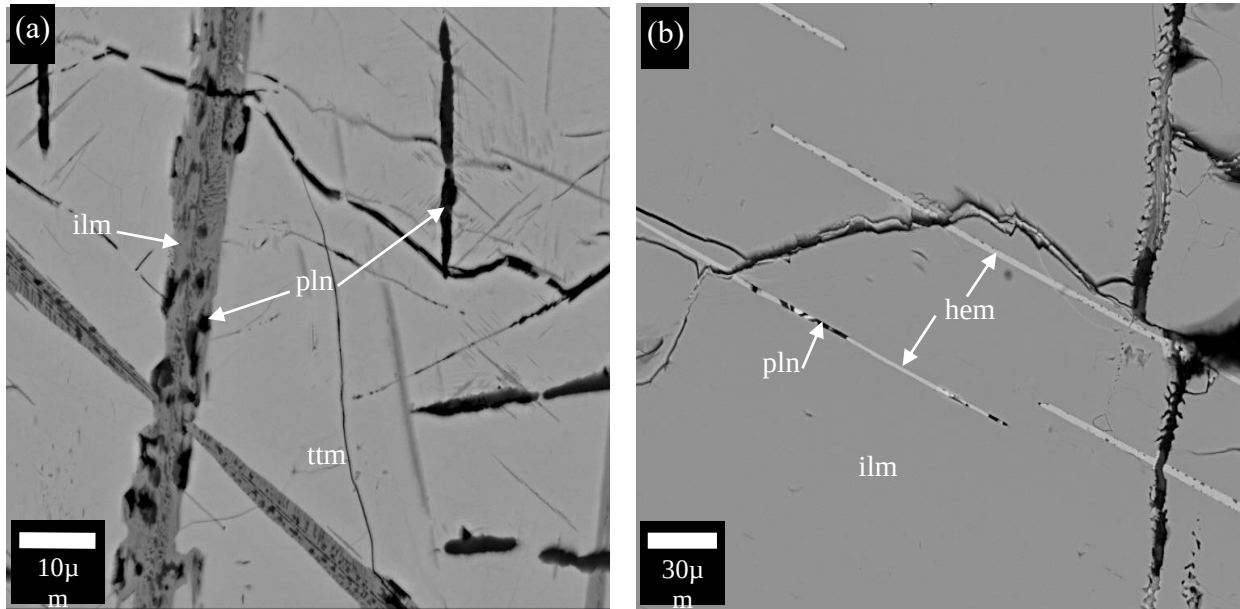


Figure 2 – BSE images of finer exsolution textures from Titac. In (a), ilmenite oxyexsolution bands contain vermicular pleonaste symplectites while titanomagnetite contains pleonaste exsolution lamellae. In (b), the presence of hematite lamellae that exsolved during cooling through decomposition of an original ilmenite-hematite_{ss} below 750–675°C. Ilmenite – ilm; titanomagnetite – ttm; pleonaste – pln, hematite – hem.

Major and minor element compositions of titanomagnetite and ilmenite are broadly similar between Longnose and Titac, with the possibility of remobilization and distribution of V and Co during alteration in Titac. The initial results of this study point towards a similar complex cooling history for Fe-Ti oxide liquids in both the Longnose and Titac OUIs, despite being emplaced in different rock types and hosted in different intrusions. Future work will involve measuring stable Fe and Ti isotopes of the ilmenite and titanomagnetite to fingerprint the metal sources and directly assess whether assimilation of the Biwabik Iron Formation is necessary to form the OUIs. Another avenue for future work involves using stable O isotopes to test whether volatiles released during the assimilation of Virginia Formation footwall were responsible for transporting metals and the serpentinization of olivine.

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Identifying the genesis of Fe-Ti oxide- and sulfide-bearing ultramafic intrusions in the Duluth Complex through sulfide geochemical analysis

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During the formation of the 1.1 Ga Midcontinent Rift System, a series of massive mafic intrusions were emplaced in northeast Minnesota and are referred to as the Duluth Complex. Rock types include a series of gabbroic, troctolitic and anorthositic intrusions that protruded into the Archean and Paleoproterozoic footwall, which comprises banded iron formation and other metasedimentary rocks. The western margin of the complex is home to 14 different Fe-Ti oxide-bearing bodies containing ilmenite, magnetite and titanomagnetite. While these oxide-bearing ultramafic intrusions (OUIs) have been identified in field studies, their exact genesis is unknown. Three hypotheses have emerged that attempt to explain the origin of the OUIs, none of which has been rigorously tested. To investigate the origin of the OUIs, we studied the sulfide geochemistry of two spatially distant OUIs: Longnose, which is located in the Partridge River Intrusion, and Titac (sec. 34), which is located in the Western Margin Intrusion. Published compositional data for sulfides from these OUIs is sparse, with most studies reporting a very brief overview of the sulfide abundances, mineralogies and stable sulfur isotopes. One study, for instance, reports modal abundances of sulfides within Longnose ranging from 0.2-5%, 99% of which being chalcopyrite (Linscheid 1991). Our petrographic study of samples from Titac and Longnose revealed a greater abundance and variety of sulfides in samples from *both* deposits. As the first systematic geochemical comparison of sulfides between OUIs, our research began with scanning electron microscopy (SEM) to image the sulfide grains, followed by energy dispersive spectroscopy (EDS) to identify a range of different sulfides present within the OUI, and finally electron probe microanalysis (EPMA) to quantitatively determine the elemental makeup of the sulfides.

Initial analysis of these data demonstrates that chalcopyrite is the modally dominant sulfide in both Titac and Longnose, with trace bornite, sphalerite and millerite found in both deposits as well. Pyrite was found only in the Titac samples, whereas chalcocite was found only at Longnose. Using the electron probe data, metal/sulfur ratio plots can be produced, such as in figure 1, to visualize the full spectrum of data including non-stoichiometric points that do not distribute into the expected mineral phases. As seen in this figure, which takes the ratio of moles of Fe and Ni to moles of S, the data indicates areas of points consistent with the Fe+Ni values for sulfides of interest, such as chalcopyrite around the value of 0.5 and bornite around 0.25. Many points were present that did not match any known mineral elemental compositions, suggesting points of exsolution, mixing or inclusions. Some Co-rich data points were also present that we were unable to characterize, so further analysis will be required to identify, if any, Co-sulfides within the deposits.

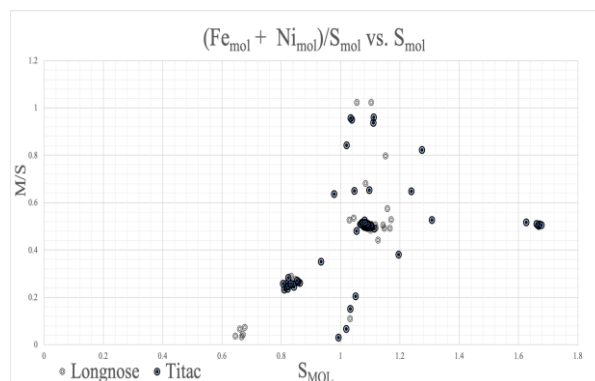


Figure 1: $(\text{Fe}_{\text{mol}} + \text{Ni}_{\text{mol}})/\text{S}_{\text{mol}}$ vs. S_{mol} ratio plot demonstrating the distribution of electron probe microanalysis data for both deposits

With similar bulk sulfide content across the two deposits, these initial results suggest a consequently similar genesis across both of the OUIs. Future work regarding the stable sulfur isotopes will be necessary to identify the origin of the sulfur content to determine whether it is magmatic or through assimilation from the nearby Virginia Formation. Due to the heavier footprint of the Virginia Formation sulfur, an increase in the sulfur isotope ratio in the deposits would indicate some form of assimilation rather than solely a magmatic origin. Furthermore, a complete study on trace elements, such as the Pt group elements, will be necessary to further this project.

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Archean Orogenesis to Proterozoic Rifting: A structural history of Pass Lake, Thunder Bay, Ontario

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New roadside outcrops along the Trans-Canada Highway 11/17 near Pass Lake, ON, expose the basal unconformity between Archean basement rock and the Proterozoic Gunflint Formation. Shear fractures, joints, and the Blende Lake Fault damage zone seen in these two outcrops record the brittle deformation history of the area before and after the Gunflint Formation was deposited. The unconformity represents a temporal gap in the stratigraphic sequence of at least 800 million years. The Archean rock belongs to the Wawa subprovince of the Superior province, in close proximity to the Wawa-Quetico subprovince boundary. Structural measurements, stereographic projections, and qualitative observations have allowed deeper insight and analysis of how structural controls have changed over an approximately 2.7 billion year-old geological history. The Archean basement unit underneath the unconformity is a coarse-grained amphibolite that contains accessory epidote and biotite, and is homogeneous throughout the length of both high-standing outcrops. This is interpreted to be a mafic pluton that has undergone amphibolite-facies metamorphism. The amphibolite records a scatter in orientation of joints and shear fractures, but some trends align well with data from Mackenzie River granite plutons, including an overall east-northeast and west-southwest strike. Later post-Proterozoic features, including the Blende Lake fault, have a common strike of east-northeast, which closely align with the orientation of the 1.1 Ga Mid-Continent Rift in Thunder Bay. This similarity is further reflected by the Blende Lake fault being oriented subparallel to the Mid-Continent Rift related silver veins. Similarities between trends in the amphibolite and Gunflint Formation suggest that the Mid-Continent Rift in Thunder Bay may have reactivated some Archean-aged orogenic-related faults and shear fractures. Minor folding in the Gunflint Formation directly adjacent to the Blende Lake Fault may be evidence of compression during the later stage of the Mid-Continent Rift.

Characterization of Hydrothermal Alteration and Sulfide Ores at the Lynne Zn-Cu-Pb Deposit, Oneida Co. WI.

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The volcanogenic massive sulfide (VMS) Lynne Zn-Cu-Pb deposit was discovered by Noranda Exploration in 1990 within Oneida County, WI (DeMatties, 1994; Adams, 1996). The Lynne deposit is one of many of VMS deposits across northern Wisconsin found in the Pembine-Wausau terrane. The Pembine-Wausau terrane is an accreted volcanic arc that formed during the Paleoproterozoic Penokean Orogeny. VMS deposits form from metallic-rich fluid exhalting on or near the ocean floor during extensional submarine volcanism (Galley et al., 2007). Interestingly, the hydrothermal alteration at the Lynne deposit contains talc-carbonate and calc-silicate mineral assemblages (Adams, 1996) and is unique compared to other deposits in Wisconsin (DeMatties, 1994). In addition, the sulfide ores contain more Pb than other deposits (DeMatties, 1994). The purpose of this study is to better characterize these unique hydrothermal rocks to improve our knowledge of the ore-forming environment at the Lynne deposit.

The drill core from the Lynne deposit was obtained from the Natural Resources Research Institute in Duluth, Minnesota, and brought to Eau Claire where it was re-logged and sampled. Samples taken from the hydrothermal alteration and mineralized zones were cut into thin sections for petrographic analyses using transmitted- and reflected-light microscopes and scanning electron microscope (SEM) to determine the paragenetic sequence of ore minerals. Major and trace element geochemistry of altered rocks were determined using X-Ray Fluorescence (XRF) at UW-Eau Claire to characterize the element mobility during alteration and to determine the nature of the protoliths.

The main sulfide mineralization within the Lynne deposit with abundance in decreasing order includes sphalerite, pyrrhotite, pyrite, galena, and chalcopyrite. Gold, silver, and copper are also found but in more localized sections within the Lynne deposit (Adams, 1996). The mineralization can be further divided into units A, B, and C, based on their stratigraphic position and compositional differences (Adams, 1996). Sphalerite is formed early on and is replaced by other minerals over time. In the deeper ore zones, pyrite tends to form relatively early and is replaced over time but in the ore zones closer to the surface, pyrite forms later. Chalcopyrite forms later in the ore zones replacing other minerals as it grows. Galena, pyrrhotite, and magnetite form in the middle replacing some minerals such as sphalerite and getting replaced by others such as pyrrhotite over time.

The main alteration types found within the Lynne contain are carbonate and talc alteration. The unusually high amounts of carbonate material - unique to VMS deposits - found within the alteration zones are credited to CO₂-rich hydrothermal vent fluid (Adams, 1996). The talc alteration is highly variable throughout the deposit but is largely found within two major zones. There is also unique skarn-type alteration is noted by chloritized diopside and garnet. A brecciated alteration texture is also notable as it shows progressive replacement of volcanic rocks with alteration minerals. Major chemistry indicates Mg-metasomatism with MgO values up to 30 wt% and five times that of the hosting volcanic rocks. Trace element chemistry reveals that these unique alteration assemblages had felsic protoliths with similar trace element abundances as the host rhyolites.

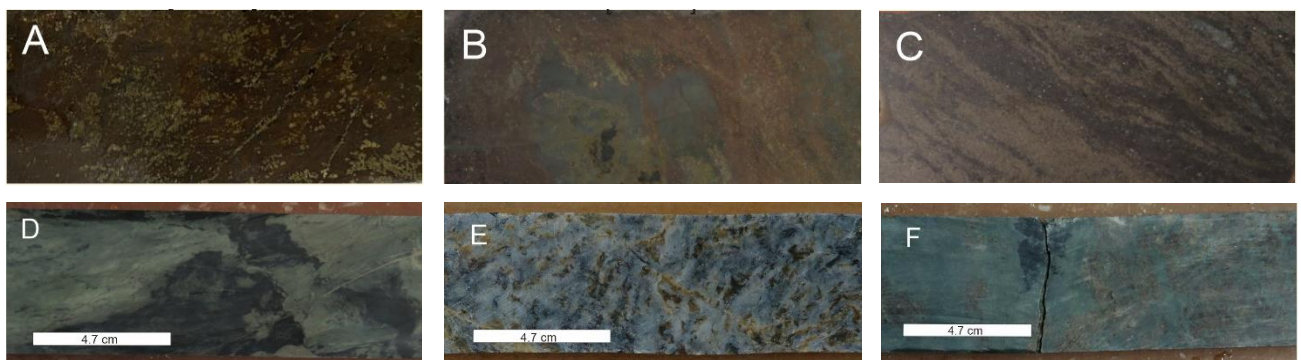
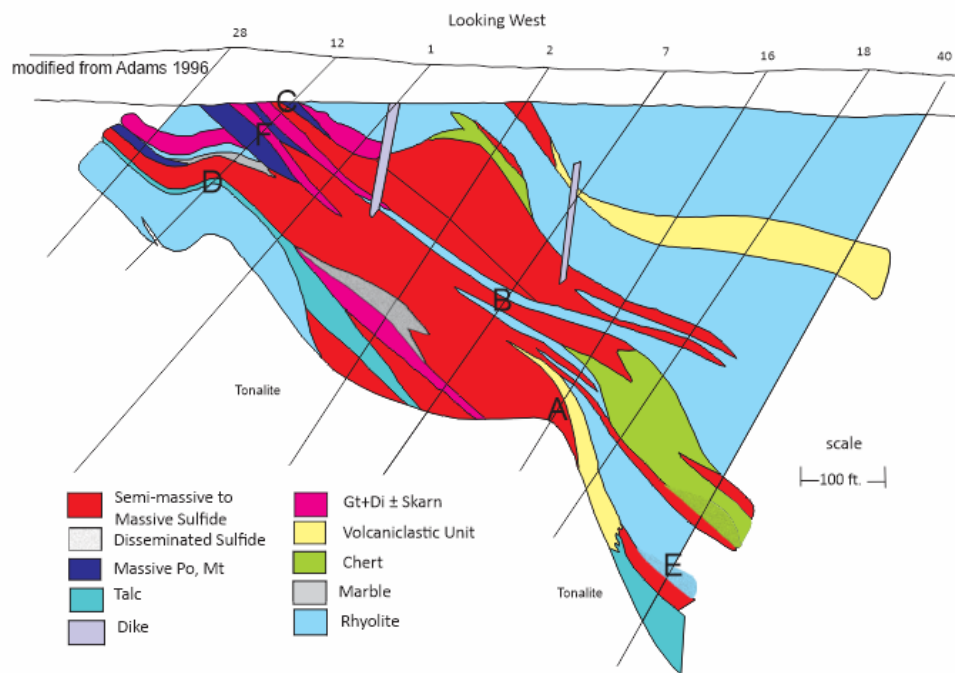


Figure 1: A cross section of the Lynne deposit shows the distinct sulfide units. A) massive sphalerite and pyrite, B) disseminated sphalerite in carbonate host rock, C) massive sphalerite with semi-massive pyrite and disseminated galena, D) talc alteration, E) carbonate alteration, and F) skarn alteration (Adams, 1996).

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Island of Hawaii Field Trip, February 11-21, 2020

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Between February 11 and 21, 2020 the Institute on Lake Superior Geology facilitated a field trip to the Island of Hawai‘i. This 10-day trip was led by Allan MacTavish and Peter Hinz, and consisted of 11 participants that included 4 professional geologists and 7 members of the Minnesota Geological Society. The trip circumnavigated the entirety of the Big Island of Hawai‘i (Figures 1 and 2) and visited all 5 exposed volcanoes on the island. The aims of the field trip were to observe the characteristics of modern volcanoes in an intra-plate, non-rift environment (see) and to provide contrast and comparison to modern and ancient rift environments (i.e. the MCR and Iceland; Figure 3). The Big Island is made up of five distinct volcanoes: Kohala, Hualālai, Mauna Kea, Mauna Loa and Kīlauea. A sixth volcano associated with the Big Island, Lo‘ihi, is an active undersea volcano located approximately 20 km (12mi) south of Kīlauea. Stops were made at all five (5) extinct, dormant, or active volcanoes with the intent to focus on volcanology, igneous petrology, and geomorphology as well as a few stops at Hawai‘ian cultural and historical locations

The 9 main islands comprising the Hawai‘ian islands are part of a chain of over 100 individual volcanoes in various states of formation and erosion (Lockwood and Hazlett, 2010). The Hawai‘ian-Emperor Chain is composed of eighteen islands, atolls, and seamounts stretching for greater than 6000km from the Island of Hawai‘i and Loihi Seamount, in the east, northwestward and then north-northwestward across the Pacific Ocean to the Aleutian Trench (Lockwood and Hazlett, 2010; Best, 2003). It is postulated that this chain of islands was formed over a greater than 65 million year period as the Pacific Ocean plate migrated over a mantle “hotspot” initially in a north-northwest direction (Emperor Chain) and later in a northwesterly direction (Hawai‘ian Chain) (Barker, 1983). The volcanism creating the islands was, and is, primarily basaltic in chemistry with the occurrence of both effusive (dominant) and explosive eruptions (Lockwood and Hazlett, 2010). Explosive activity is primarily due to the interaction between basaltic magma and ground or sea water.

This presentation will summarize the highlights of our trip and provide comparisons of Hawai‘ian geology, the Midcontinent rift, and Iceland (?). Featured highlights will include historical eruptive features from the eruptions of Kohala (100,000BP), Hualālai (1801 To 1802), Mauna Kea, and the 2018 Kīlauea Lower East Rift Zone eruption (Fissures 8 and 9). The presentation will also display local features such as the Koa‘e fault zone, Hōlei Pali (cliff), Mauna Ulu, the Pu‘u ‘Ō‘ō eruption lava field, Kīlauea Iki, fossil footprints in 18th century Kīlauea ash, the 2018 Kīlauea caldera collapse (Halema‘ūma‘u), and the Papakōlea Green Sand Beach.

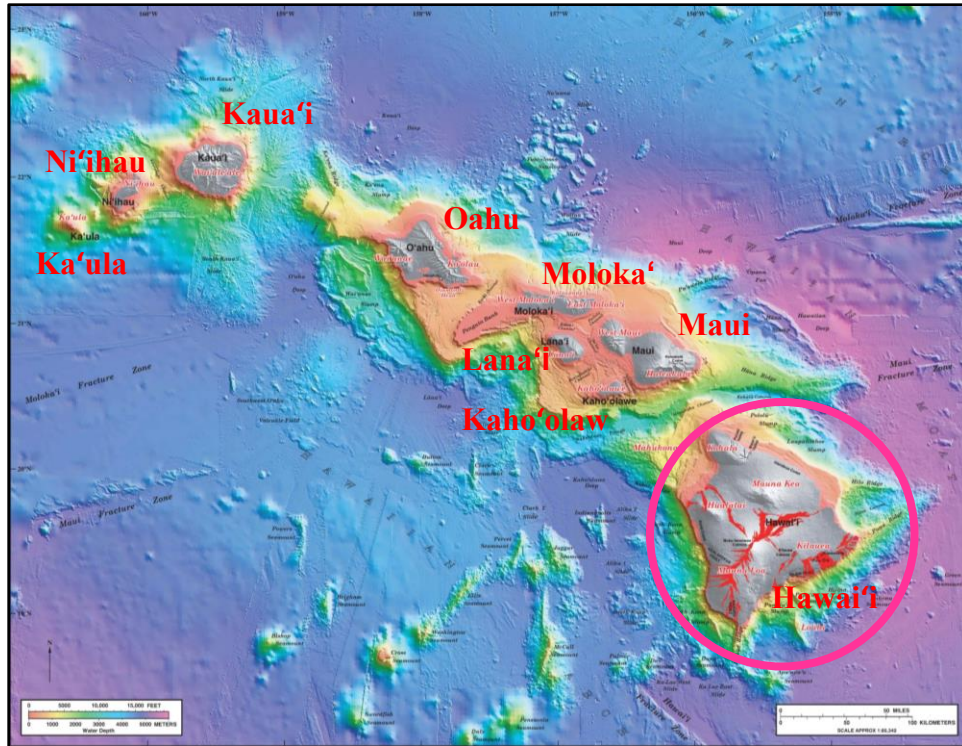


Figure 1: Topographic relief and bathymetric map of the nine Hawai'ian Islands. Modified from Eakins et al., 2003.

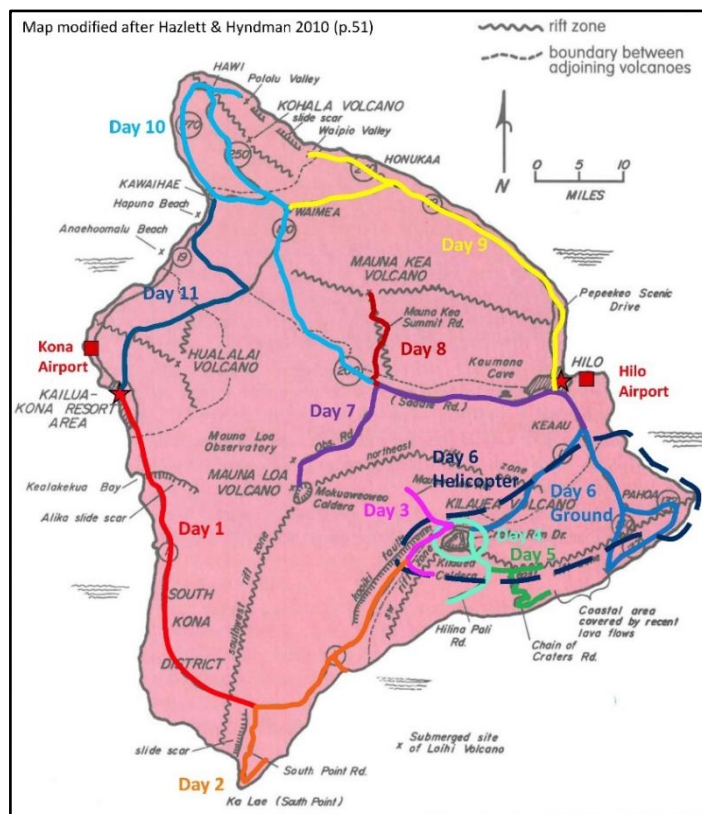


Figure 2: Daily ILSG 2020 Field Trip routes, Island of Hawai'i. Modified from Hazlett and Hyndman, 1996.

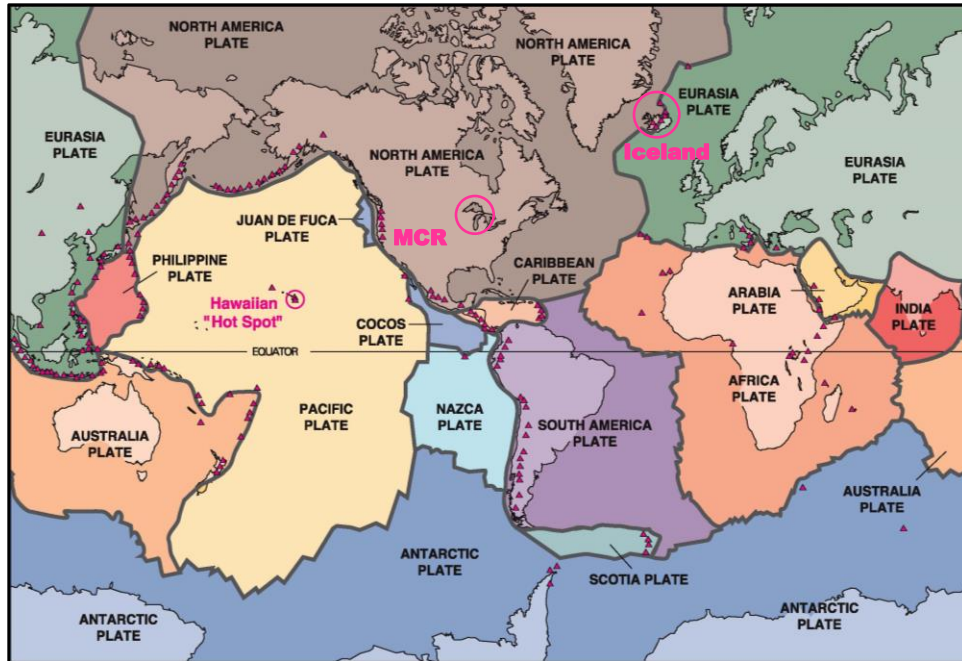


Figure 3: Location of the Hawai'ian Islands with respect to world tectonic plates, the MCR, and Iceland. Modified after Tilling et al., 2010.

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Chemostratigraphy of the western Schreiber-Hemlo Greenstone Belt, Results and Regional Implications

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The Neoproterozoic Schreiber-Hemlo greenstone belt is located within the Wawa-Abitibi terrane of the Superior Province. The western (Schreiber) and eastern (Hemlo) parts of the belt are separated by the cross-cutting Mesoproterozoic Coldwell Alkalic Complex. Recent mapping by the Ontario Geological Survey in the western part of the belt was conducted to produce an updated genetic model for the western part of the greenstone belt and to better understand its relationship with the rocks in the Hemlo area and surrounding greenstone belts (Hastie and Magnus, 2021a; Magnus 2021a, 2019a, 2017). New geochemical and geochronological data (Hastie and Magnus, 2021b; Magnus 2021b, 2019b, 2018) have changed the model presented by the author in a field trip guide for the 2019 ILSG conference (Magnus, 2019c).

The supracrustal rocks in the western Schreiber-Hemlo greenstone belt are arranged in 4 depositional packages composed of metavolcanic and metasedimentary rocks with distinct petrographic and geochemical characteristics. Chemical and clastic metasedimentary rocks mark major unconformities between the depositional packages. For the sake of brevity, the clastic and chemical metasedimentary rocks of the greenstone belt will not be discussed in this presentation.

The oldest recognized supracrustal rocks are exposed south of the Town of Schreiber, west of the Terrace Bay Pluton. In this package, predominantly tholeiitic mafic flows are interbedded with plagioclase porphyritic felsic flows and volcanoclastic breccias, wackes and mudstones. One mafic flow has major and trace element concentrations that are transitional between tholeiitic and calc-alkalic mafic volcanic rocks. Felsic volcanoclastic rocks near the top of this package are cross-cut by a quartz porphyritic felsic intrusive rock west of Worthington Bay, dated at 2722.6 ± 1.1 Ma by zircon (Kamo, 2019), which constrains this depositional package to >2720 Ma.

Quartz porphyritic felsic volcanic and volcanoclastic rocks with U-Pb zircon ages of *circa* 2720 Ma occur along the entire length of the greenstone belt and along the shores of Lake Superior in Tuuri and Walsh townships (Hastie and Magnus, 2021; Magnus, 2021a, 2019a, 2017). These felsic rocks are closely associated with mafic flows that commonly contain an abundance of both equant plagioclase phenocrysts and coarse amygdules. These flows contain major and trace element concentrations that are transitional between tholeiitic and calc-alkalic volcanic rocks. Unlike the single flow of “transitional” mafic rock in the older package, the transitional mafic rocks in this package are the overwhelming majority.

No contacts between the >2720 Ma and the *circa* 2720 Ma depositional packages have been observed. Both packages are unconformably overlain by an extensive package of tholeiitic mafic flows with distinct variolitic textures and trace element geochemistry consistent with a back-arc-basin volcanic environment. These rocks are cross-cut by quartz and feldspar porphyritic felsic dikes dated 2698.1 ± 4.5 Ma (Sutcliffe and Davis, 2019), constraining their deposition to between *circa* 2720 Ma and *circa* 2700 Ma.

The unconformity between the younger tholeiitic rocks and the older transitional mafic rocks is not easily distinguishable by geophysics or by field observations, especially where the rocks are deformed. The distribution of geochemical samples in this study area has helped trace this unconformity and locate cryptic folds along that contact that otherwise would not have been identified. This geochemical mapping technique may be helpful for delineating the stratigraphy in the nearby greenstone belts, it could be critical for reconciling the stratigraphy between the east

and west parts of the Schreiber–Hemlo greenstone belt, and it may be applicable to other nearby greenstone belts in the western Wawa–Abitibi Terrane.

In addition to the major and trace element geochemical analyses, 27 samples of mafic, intermediate and felsic metavolcanic rocks from the previously described packages and 12 samples of the varied granitoid plutons that cross-cut and surround the greenstone belt were submitted for Sm-Nd isotope analysis (Magnus, 2021b). ϵNd values for all of the volcanic and intrusive rocks cluster around the value of the depleted mantle at *circa* 2700 Ma, which supports the model that the volcanic rocks of the Wawa–Abitibi Terrane were generated in a juvenile arc magmatic system.

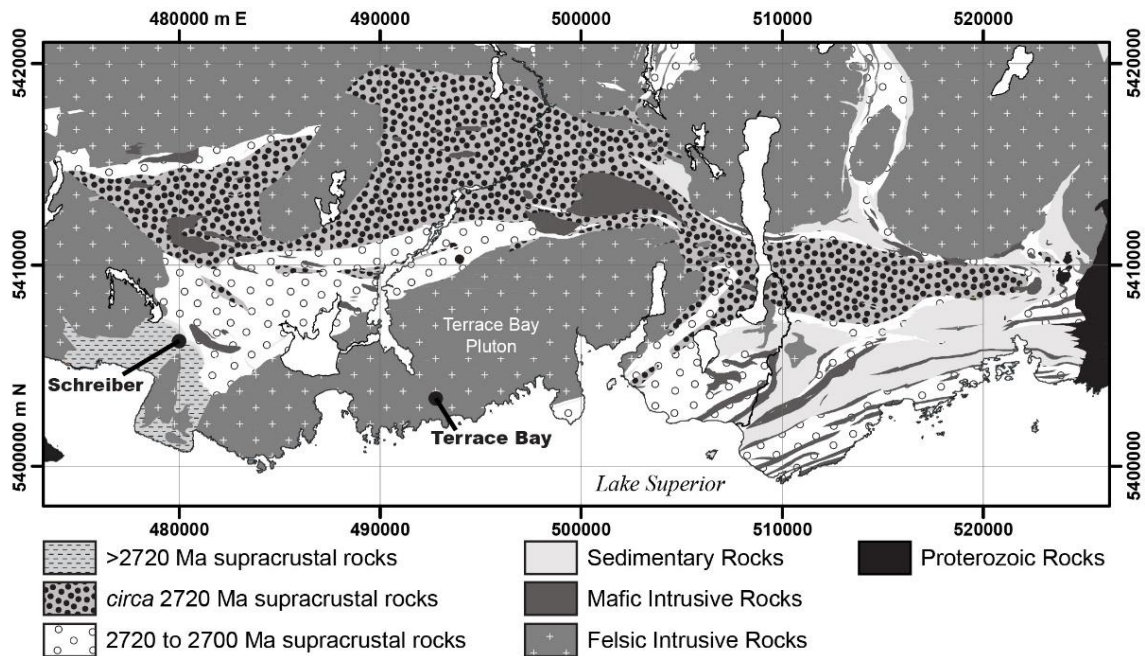


Figure 1. Simplified geological map of the western Schreiber–Hemlo greenstone belt, highlighting the three metavolcanic packages described in this abstract

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Proterozoic Geology of the Schreiber–Terrace Bay Area

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The Mesoproterozoic Keweenawan Midcontinent Rift event emplaced a multitude of intrusive and volcanic igneous rocks around present-day Lake Superior. Previous work on these rocks along the north shore of Lake Superior has mainly focused on the Thunder Bay, Lake Nipigon and Marathon areas. Recent mapping by the Ontario Geological Survey along the north shore in the Schreiber–Terrace Bay area was conducted, in part, to bridge this gap (Hastie and Magnus, 2021a; Magnus, 2017, 2019a, 2021a).

Dikes with orientations and geochemical and geophysical signatures consistent with known Paleoproterozoic dike swarms, including the Matachewan, Biscotasing and Marathon dike swarms, have been identified in the Schreiber–Terrace Bay area. Similarly, dikes with other orientations and geochemical and geophysical signatures, assumed to be Mesoproterozoic and belong to the Midcontinent Rift event. A total of 156 samples of Mesoproterozoic diabase and lamprophyre dikes were submitted for whole rock geochemical analysis throughout this project (Hastie and Magnus, 2021b; Magnus, 2018, 2021b).

The results of mapping and geochemical analysis suggest potential correlation between several smaller populations of dikes and known Keweenawan units. East-northeast trending dikes in the study area are parallel to, along strike with (separated by 200 km), and share similar whole-rock geochemistry with the Pigeon River dikes of the Thunder Bay area (Cundari et al. 2021). Dikes of varied orientation share similar whole-rock geochemistry with Osler Group I and Group II volcanic rocks (Hollings et al., 2007). A newly recognized, circular intrusion north of the town of Terrace Bay, dated 1107.9 ± 1.4 Ma by baddeleyite (Kamo, 2019), also shares similar geochemistry with Osler Group II volcanic rocks.

The results of mapping and geochemical analysis have revealed one new and significant population of diabase dikes. These west-northwest trending dikes with reversely polarized aeromagnetic signature cross-cut the entire study area. In the east, they were observed cross-cutting, and being cross-cut by, syenite at the western edge of the *circa* 1108 Ma Coldwell Alkalic Complex, which constrains them to emplacement at around the same time. The dikes consist of an ophitic to sub-ophitic textured olivine gabbro composed of augite, plagioclase and generally fayalitic olivine (average composition Fo₃₀, as low as Fo₁₀, up to Fo₇₀), which is an expected composition of olivine for an alkalic rock. The dikes have alkalic major element concentrations and enriched, “ocean island basalt”-like trace element concentrations and chondritic to slightly depleted Sm-Nd and Sr-Rb isotopic values. There are two small subsets of these dikes – one that is plagioclase megacrystic and is geochemically indistinguishable from the main population; and one that is heavily depleted in calcium, strontium, barium and phosphorous, consistent with apatite fractionation, and which displays a “trachytic” texture with abundant plagioclase laths.

South of the town of Schreiber a parallel set of alkalic dikes with normally-polarized aeromagnetic signature cross-cut the peninsula between the Schreiber Channel and Worthington Bay. Geophysical data, air photos and previous maps indicate that these dikes continue along strike westward, cross-cutting the islands in Schreiber Channel and south of Nipigon Bay. A targeted

sampling program in these islands would be helpful to study the extent of these normally-polarized alkalic dikes.

The petrographic and geochemical characteristics of the alkalic diabase are similar to the Wolfcamp Lake alkalic basalts that overlie the Coldwell Alkalic Complex (Davis et al., 2017), the Geordie Lake gabbro, which cross-cuts the complex (Meghji, 2016), and a subset of dikes that crop out south of the complex in Pukaskwa National Park (Cundari et al., 2021). Altogether, the mafic alkalic magmatism in the northeast part of Lake Superior represents an emergent and potentially important part of the Keweenawan geological history (Good et al., in review).

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Structural Analysis and Interpretation of Deformation along the Keweenaw Fault System West of Lake Gratiot, Keweenaw County, Michigan

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The Keweenaw fault extends along the southern margin of the Midcontinent Rift System from northwest Wisconsin to near Keweenaw Point in Michigan, making it longest known fault associated with the rift. Reverse movement on the NW-dipping fault has thrust Portage Lake Volcanics (PLV, 1.1 Ga) over younger, mostly flat-lying Jacobsville Sandstone (JS) (Fig. 1), regionally tilting PLV strata northwestward on the southeast limb of the Lake Superior syncline (1). Published geologic maps from the 1950s (2-4) depict the fault as a single sinuous trace parallel to strike of hanging-wall PLV strata that are juxtaposed against JS nearly everywhere. Published cross-sections generally show hanging-wall strata facing northwest with a simple listric geometry and footwall strata tilted steeply southeast near the fault. The maps and cross-sections show a few complications along the fault trace (anomalous sinuosity) and in its hanging-wall (lesser faults, folds), hints of deformation complexity that may reveal the nature and cause of faulting. Midway along the Keweenaw Peninsula, published maps show a prominent reentrant of JS into PLV along the fault and hint at a major splay in the Keweenaw fault's hanging wall (3-4).

New mapping near Lake Gratiot and Lac La Belle, combined with drill core logs, suggests that the postulated splay in the Keweenaw fault's hanging wall is instead the main fault of an orderly fault system (Fig. 2). The Keweenaw fault system here consists of: 1) segments striking east-northeast with steep northerly dip (main trend), 2) segments striking east-southeast also dipping steeply north, and 3) segments striking north-northeast with moderate-to-shallow westerly dip. Members of these fault sets define a multistranded fault system and several, large, PLV blocks southeast of the main fault. Set 2 faults have a left-stepping arrangement similar to analogous faults mapped in a previous project to the east along Bête Grise Bay (5). Mapping also has revealed folding in hanging-wall Portage Lake Volcanics and has resolved fold geometry in footwall Jacobsville Sandstone. Fold axes are generally subparallel to adjacent faults and therefore are probably related to fault movement. A Set 3 fault crossing Bruneau Creek is associated with a faulted anticline in hanging-wall PLV and multiple anticlines and synclines in the footwall JS, indicating significant shortening across a west-dipping thrust fault. A Set 2 fault crossing a Snake Creek tributary has an anticline-syncline pair in hanging-wall PLV and a single asymmetric syncline in footwall JS, resulting from mostly right-lateral strike slip and lesser north-side-up reverse slip on a steeply dipping fault. Shortening across this ESE-trending fault is relatively minor because of its inferred steep dip and dominant strike slip motion.

The pattern and relationships of faults and folds suggest a fault system dominated by dextral shear rather than by reverse movement as in the conventional model. Indicators of slip direction and sense measured on 55 small faults demonstrate that the fault system here is in fact dominated by strike slip, with a 2.5:1 ratio of strike-to-dip slip. Inversion of fault-slip data yields a maximum shortening direction of 285°-105° during faulting, which implies overall dextral shear on the fault system and differences in slip kinematics between fault sets. Set 1 faults defining the overall trend of the Keweenaw fault system in this area have strike slip > dip slip; Set 2 faults with ESE-trend have strike slip >> dip slip; Set 3 faults with N to NE trends have dip slip >> strike slip.

New mapping and structural analyses in this area have revealed a multistranded Keweenaw fault system that is transpressional in nature, dominated by dextral strike slip, and has lesser reverse slip with north side up. Fault-bounded blocks with ENE-oriented long dimensions generally moved eastward along set 1 and 2 faults, as thrusting of Portage Lake Volcanics over Jacobsville Sandstone occurred on set 3 faults. The estimated WNW-ESE maximum shortening direction associated with fault movement strongly suggests that the Grenville Orogeny was primarily responsible for movement of the Keweenaw fault system, with possible reactivation occurring during the Appalachian Orogeny.

Acknowledgements: We appreciate primary funding by the USGS EDMAP program, sponsorship by the Michigan Geological Survey, a Michigan Space Grant Consortium award to the lead author, and a generous donation by the Keweenaw Community Forest Company.

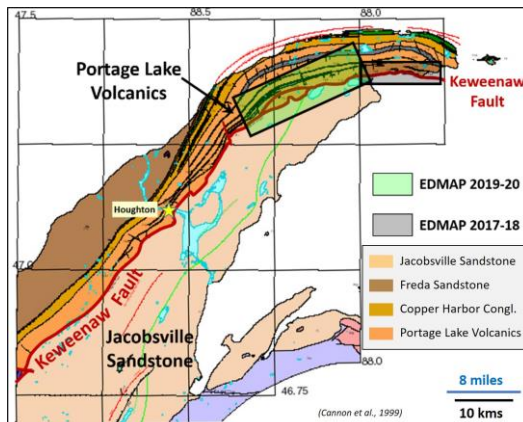
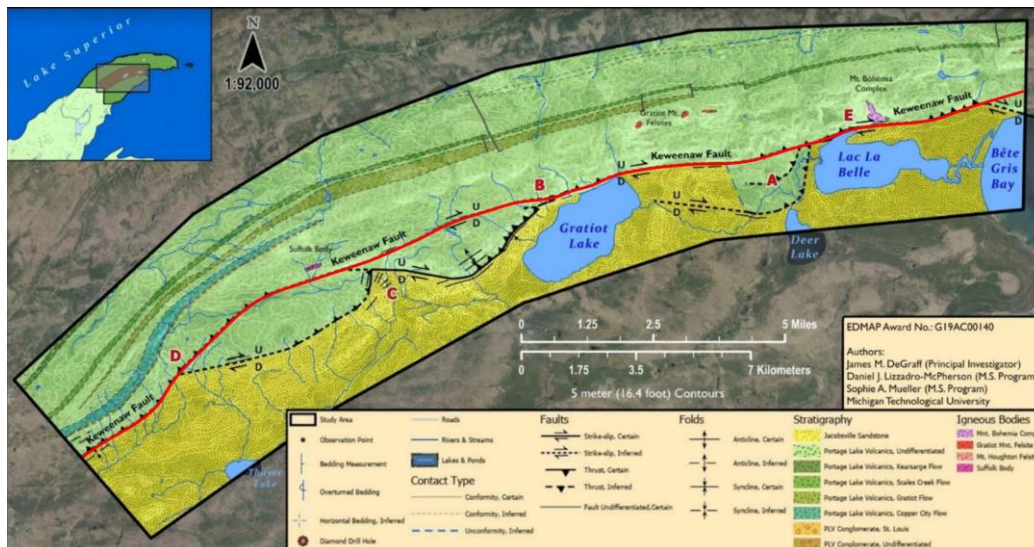


Figure 1 (left): Keweenaw Peninsula where Portage Lake Volcanics are thrust over Jacobsville Sandstone. Green rectangle near middle of peninsula marks area of **Figure 2**. (adapted from 1).

Figure 2 (below): Study area along Keweenaw fault between Mohawk and Bête Grise Bay. Main units: PLV mafic = greens; PLV felsic = reds; JS = yellow. Red line marks newly interpreted main trace of the Keweenaw fault system. Other major faults as black solid and dashed lines.



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U-Pb geochronology and zircon trace-element geochemistry from granitoid plutons in the Neoarchean Sturgeon Lake greenstone belt, Ontario, Canada

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The Sturgeon Lake granite-greenstone belt is in the eastern portion of the Western Wabigoon subprovince of the Superior province and is bordered to the north, east, and south by the Winnipeg River terrane. The belt is comprised of felsic to mafic volcanic successions, syn-orogenic sedimentary assemblages, and calc-alkaline to alkalic plutons (Sanborn-Barrie and Skulski, 2005; Lodge et al., 2019). The emplacement of granitoid plutons in the Sturgeon greenstone belt can provide a more complete magmatic and deformational history than volcanic assemblages and sedimentary rocks. The origin and timing of their melts, mantle-crust interaction, and subsequent magmatic-hydrothermal activity record important tectonic events throughout the petrogenetic history of Sturgeon Lake greenstone belt and the western Superior Province. The primary objective of this project is to better constrain the magmatic and tectonic history of the Sturgeon Lake greenstone belt through U-Pb geochronology and trace element geochemistry of zircons from the granitoid plutons.

Previous mapping in the Sturgeon Lake greenstone belt (Sanborn-Barrie and Skulski, 2005) constrained spatial and temporal relationships between plutonic rock and supracrustal assemblages largely by describing the geometry of plutons through aeromagnetic surveys and their relationship with regional foliations in the surrounding rocks. However, geochronologic data was largely constrained to the volcanic and sedimentary assemblages and the timing of plutonic events were mostly estimated. Plutons were broadly characterized into three categories based on these relationships: synvolcanic, early- to syntectonic, and late- to post-tectonic (Sanborn-Barrie and Skulski, 2005).

This study obtained representative samples from the different plutons along the Metal Earth Sturgeon transect. After petrographic and whole-rock geochemical characterization (Nelson et al., 2020), zircons were separated for further analyses. Zircon grains were analyzed using Laser Ablation Split Stream Inductively Coupled Plasma Mass Spectrometry (LASS-ICP-MS) at Laurentian University for simultaneous collection of U-Pb isotopic abundances and trace-element geochemistry.

The interpreted U-Pb ages of the sampled plutons allowed for refinement of the prior tectonic classifications. Some plutons were re-assigned to refined classifications based on the interpreted age: those that formed at the same time as the greenstone belt volcanic assemblages (syn-volcanic), those that formed during major deformation events (syn-tectonic), and those that post-date most deformation events (post-tectonic) (Figure 1). Trace-element geochemistry of the zircons not only supports the updated plutonic classifications, but also reveals a temporal evolution in the petrogenesis of granitoid plutons from anhydrous melting of mantle-derived sources to hydrous, oxidized melts that have significant interaction with the evolved crust. (Figure 1, *inset*).

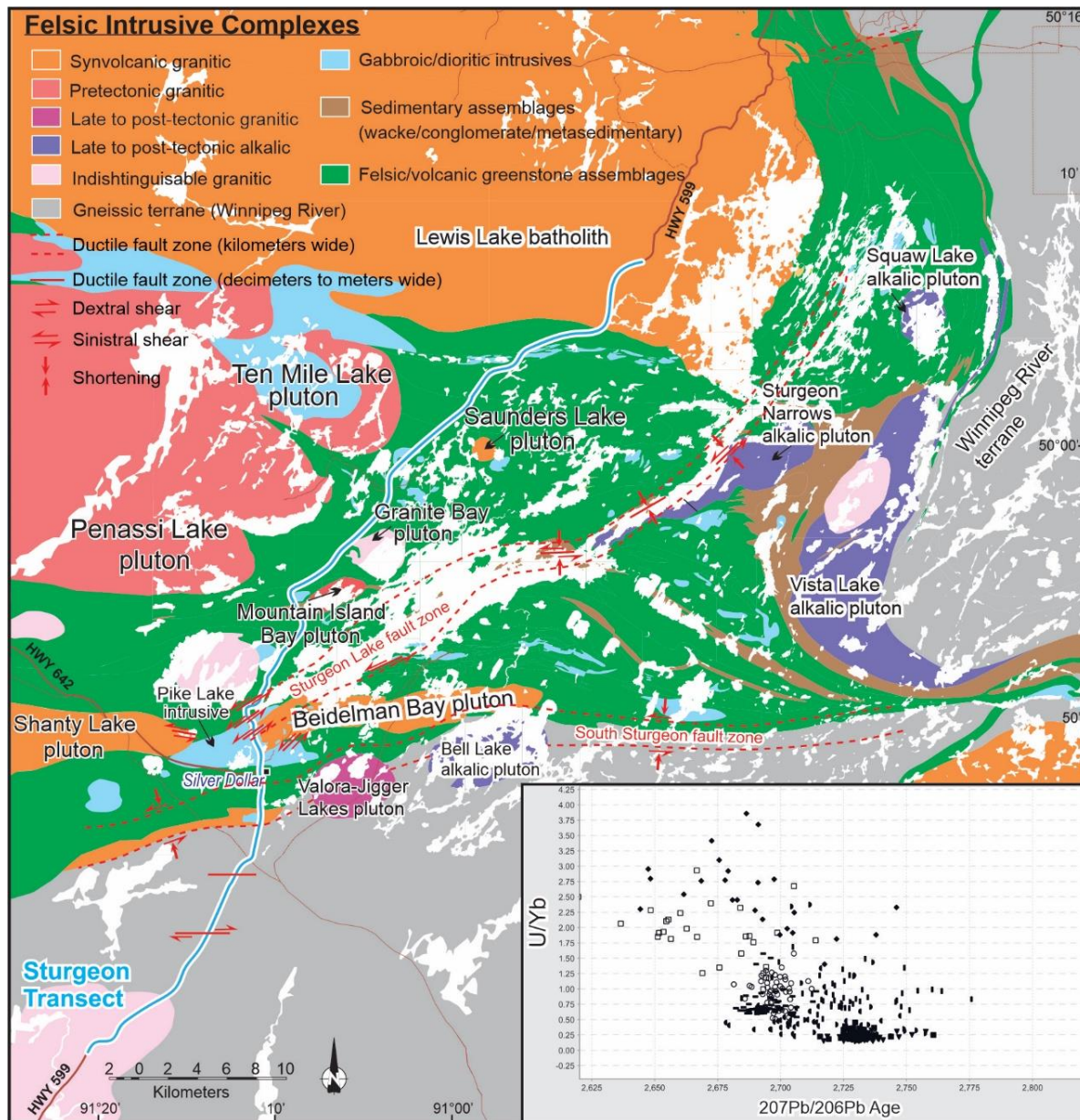


Figure 1: Regional geology of Sturgeon Lake granite-greenstone belt modified from Sanborn-Barrie and Skulski (2005) with new U-Pb ages of granitoid plutons and their timing relative to major tectonic events. Inset diagram displays U/Yb versus $^{207}\text{Pb}/^{206}\text{Pb}$ age displaying increasing role of evolved crust in the genesis of felsic melts over time.

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3-D Modeling of the Duluth Complex from geophysical data

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The Mesoproterozoic Duluth Complex in northeastern Minnesota is one of the major plutonic components of the Midcontinent Rift System and hosts a variety of copper-nickel sulfide and platinum-group element deposits. The Duluth Complex is composed of a series of individual mafic and felsic intrusions emplaced 1110-1098 Ma within Paleoproterozoic sedimentary rocks of the Animikie basin and volcanic flows of the Midcontinent Rift. Prior work has included 2-D modeling and qualitative geologic interpretations of gravity and magnetic data (e.g., Chandler, 1990; Chandler and Ferderer, 1989), much of which is still preliminary (V. Chandler, written commun., 2020). Three-dimensional modeling has been limited, with only one 3-D model created using Bouguer gravity data constrained by seismic-reflection interpretations as part of a PhD thesis (Allen, 1994). Given the complex geology of the area, 3-D modeling is useful for providing a complete picture of the variable densities, susceptibilities, and electrical resistivities throughout the Duluth Complex and associated volcanic rocks as well as their depth extent beneath sedimentary cover. Models of these geophysical properties at depth enable more accurate geologic mapping in the subsurface which can lead to an improved understanding of the formation history of the Duluth Complex.

In this study, we use aeromagnetic data acquired between 1979-1991 (Chandler, 2007), Bouguer gravity data collected since 1950 (Chandler and Lively, 2019), and magnetotelluric data collected in 2019 to create new 2-D and 3-D geophysical models of the Duluth Complex constrained by seismic reflection, geologic, and rock property data. An inversion of the Bouguer gravity data for thickness of the Duluth Complex using constant densities of 3110 kg/m^3 and 2670 kg/m^3 for the Duluth Complex and surrounding crustal rocks, respectively, results in thicknesses ranging from ~3-28 km for the Duluth Complex and related intrusions and volcanic rocks (Figure 1A). A 3-D model of the magnetotelluric data reveals low resistivity anomalies at ~5-10 km depth below the northern margin of the Duluth Complex and below the Greenwood Lake intrusion (Figure 1B). We expect to encounter low resistivities at depth associated with the Paleoproterozoic Animikie basin, which makes up the floor of the Duluth Complex, and therefore interpret these anomalies as either the base of the complex or as fragments of Animikie sediments interfingering with igneous intrusive rocks. Finally, 3-D voxel models of density and susceptibility illuminate the subsurface distribution of rock properties below the Duluth Complex which, in combination with resistivity and thickness models, can be used to create a 3-D geologic map of this area.

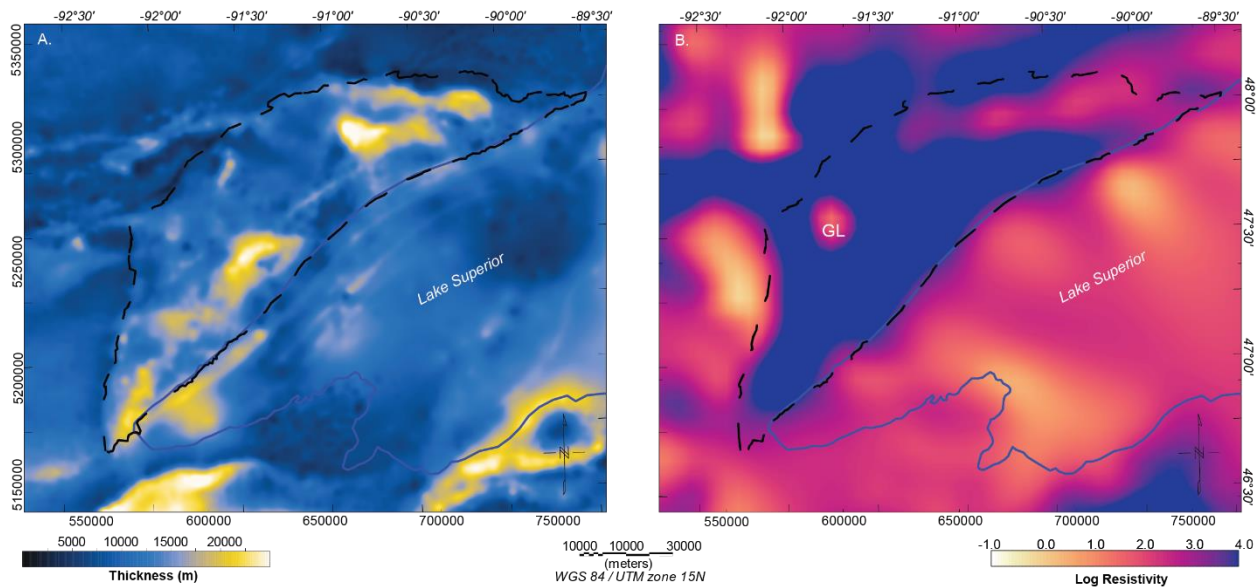


Figure 1. Geophysical models of the Duluth Complex. A) Modeled thickness of the Duluth Complex and associated igneous rocks (dashed black outline in A and B) resulting from constant density inversion of Bouguer gravity data. B) Depth slice through 3-D resistivity model at 5 km below the surface. GL=Greenwood Lake intrusion.

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Negative Carbon Dioxide Emissions through Enhanced Silicate Weathering and the Lake Superior Region

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Carbon capture is now widely recognized as necessary to stabilize atmospheric carbon dioxide to keep global warming below 1.5°C, a temperature threshold mandated by the 2015 Paris Agreement. The Intergovernmental Panel on Climate Change (IPCC) projects significant degradation of livelihoods, food security, and water supply, if this threshold is exceeded. There are multiple proposed mitigation approaches that could curb climate catastrophe. Although no one carbon capture approach is perfect, all are on the table by necessity. Each has specific capture potential in terms of uptake rate, storage capacity, and storage longevity. I will give an overview of work determining whether adding basalt to agricultural lands is an effective, low-risk carbon capture strategy—and make a case that Lake Superior region is great place to implement this means of climate change mitigation.

The idea behind this carbon dioxide removal (CDR) strategy is simple. Carbon dioxide in the atmosphere chemically reacts with silicates minerals—and reacts especially rapidly with mafic minerals. The byproducts of this reaction lead to marine carbonate precipitation, which transfers carbon from the atmosphere into the rock record. This is, on geologic timescales, how Earth has sequestered almost all the carbon continuously sourced to the atmosphere from Earth's interior (e.g., volcanic carbon dioxide outgassing). In principle, carbon capture through mineral weathering involves enhancing the rate of a process that the Earth does naturally. In practice, the overriding controls on this process are complex. Carbon capture rates are highly variable and dependent on local conditions and implementation strategy. Nonetheless it is clear that capture through weathering can be greatly accelerated by milling of mafic minerals to increase its surface exposure. This approach holds great potential and is certain to be carbon negative.

IPCC estimates are that the agricultural sector contributes about 25 percent of total greenhouse gas emissions worldwide. I will present modeling work and empirical studies that suggests addition of mafic rocks to agricultural lands has the potential to simultaneously offset a significant component of this anthropogenic greenhouse gas source and increase agricultural yields and pest resistance. If subsidized, this process could provide a stable source of income for farmers increasingly vulnerable to climate extremes and promote regional economic growth. The Lake Superior region is the ideal area to carry out this carbon capture process and widespread implementation could revitalize the economy of Lake Superior region towns that are (or were formerly) heavily dependent on mining. Compilations of the extensive knowledge of Lake Superior Region geology are essential to support that enhanced silicate weathering is a viable means climate change mitigation, sway policy makers, and foster investment in case studies of this process.

A newly discovered orbicular occurrence within the Good Hope carbonatite, north of Marathon, Ontario

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The Good Hope carbonatite is emplaced within Archean gneisses of the Wawa Subprovince. This occurrence is located along the northwest margin of the Prairie Lake carbonatite complex (1160 Ma, Wu et al. 2017), although their genetic relationship remains speculative (Mitchell et al. 2020). The Good Hope carbonatite is a niobium occurrence with the niobium primarily occurring within pyrochlore-group minerals, minor niobium in ferrocolumbite, and consists of multiple generations of carbonatite that include calcite-, dolomite-, ferrodolomite-, and quartz fluorite-carbonatite (Mitchell et al. 2020). The purpose of this study is to characterize the orbicular occurrence and suggest a possible petrogenesis for this rare textural occurrence.

The orbicular occurrence was first identified from the drill core, where it occurs as narrow bands or possible clasts within the carbonatite groundmass. These orbicules are mm-scale, oblate to spherical in shape with variable degrees of monomineralic shell development ranging from well-developed shells to spherical aggregates of the minerals which define the orbs (Figure 1). The orbicules consist of biotite, Ti-bearing aegirine, and magnetite with ilmenite lamellae within an allotriomorphic calcite carbonatite groundmass that contains some Fe-dolomite. The orbicules commonly consist of a ‘core’ of magnetite + biotite followed by a shell of aegirine and one or more outer shells of monomineralic biotite and/or magnetite. Within these orbicules there are variable amounts of calcite and Fe-dolomite, which can occur both as monomineralic shells, commonly associated with the outer shells, as well as entrained within the ‘core’ of the orbicules.

This type of texture has been observed within other carbonatites (eg. Haggerty and Fung, 2006), but is more commonly observed within granitic and dioritic compositions (eg. Smillie and Turnbull, 2013). It is largely accepted that the orbicular textures are of magmatic origin, however a variety of genetic models exist, due to the unique nature of each occurrence. In general, these models broadly fit into three groups with orbicular formation controlled by (1) liquid immiscibility (eg. Ai et al. 2020) (2) superheating of the magma that lowers the nucleation rate and increases the growth rate (eg. Lindh and Näsström, 2006) or (3) quenched recrystallization following the injection of magma (eg. Zurevinski and Mitchell, 2015). Orbicular textures within carbonatites are commonly modelled by liquid immiscibility, given this model lends itself to the orbicules having a different composition than the groundmass. The second group has variations in the compositions of the shells and groundmass that lead to variability between the models in the source of the ‘orbicular magma’, the cause of the increased temperature within the magma, and the process of crystallization of the orbicule shells. The third group also has variability, with the orbicule and groundmass being either the same composition (Zurevinski and Mitchell, 2015) or different compositions (Zhang and Lee, 2020) due to the composition of the initial magma and the latter injected magma. The Prairie Lake orbicular occurrence mimics ‘contact metamorphism-type’ recrystallization of the orbicules within a compositionally identical groundmass (Zurevinski and Mitchell, 2015). The Good Hope occurrence differs significantly from the Prairie Lake occurrence; the composition of the orbicules and the groundmass are distinctly different, the orbicules are variably oblate indicating soft-shell deformation, and they do not exhibit quenched or recrystallization textures.

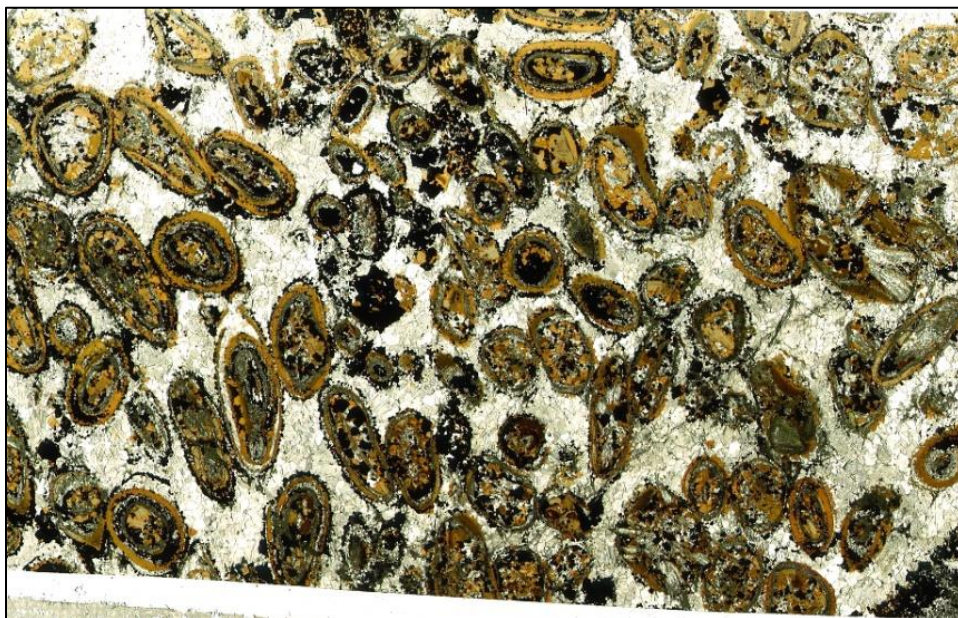


Figure 1: Scan of the standard polished petrographic thin section of the orbicular occurrence of the Good Hope carbonatite, highlighting the predominantly oblate, mm-sized orbicules.

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Preliminary pXRF results from Precambrian rocks of northern Minnesota

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Precambrian iron-rich chemical sedimentary rocks are an important archive of early seawater chemistry (Konhauser et al., 2017). Interpreting the origin of these iron-rich rocks is complicated because they can form at the intersection of sedimentary and hydrothermal activity. One tool that can be used to identify signatures of past seawater and hydrothermal fluids are major-, trace-, and rare-earth-elements. Drawbacks to laboratory-based geochemical approaches include extensive sample preparation and destruction of the material. Advances in XRF technology have led to the development of portable x-ray fluorescence (pXRF) instruments capable of producing laboratory-quality element analyses in the field when used with a custom-built, rock-type-specific calibration (Steiner et al., 2017; Al-Musawi and Kaczmarek, 2020). With the ability to create a custom calibration, it is possible to measure major- and trace- elements in the field or in drill core. One goal of this project is to create a customized, rock-type specific calibration for the Bruker 5g Tracer pXRF instrument to analyze iron-rich rocks that outcrop near Soudan, MN. Field and drill-core geochemical analysis can help identify units of unknown origin, while aiding in the identification of key samples for additional destructive analyses.

To create the custom iron formation calibration for the pXRF instrument, we first need an internal reference material. We analyzed select iron formation samples from the Soudan iron formation for a suite of 46 major-, trace-, and rare-earth-elements using inductively coupled plasma optical emission spectrometry (ICP-OES) and inductively coupled plasma mass spectrometry (ICP-MS) methods following the procedures outlined in Brengman et al. (2020). We can directly compare elements analyzed using ICP-OES and ICP-MS to the pXRF data (Figure 1A). The pXRF instrument was set up in tabletop working mode, and powdered samples were analyzed in standard XRF mount cups. To test the effect of pressing the sample into the mount cup, we performed a comparison test on one sample (PL-19-3c; Figure 1B) using the internal mudrock calibration. First, the un-pressed powder was run, then the pressed powder was run 1.5 hr. later, with five minutes between each analysis to allow for cooling. Measurements for the element silicon (Si) in the three un-pressed powers ranged from 23.075 wt. % (± 0.083) to 23.197 (± 0.083) wt. % (Figure 1B). The same three powders were pressed, and measurements were repeated using the same analytical setup. Measurements for the element silicon (Si) in the three samples (now pressed powders) ranged from 23.733 (± 0.084) to 23.891 (± 0.0847) wt. %. We observe a difference of ~ 0.7 wt. % between Si measured in the un-pressed and pressed powders and recommend pressing powders to ensure uniform measurements. Previous studies identified a “warm-up” period in which the pXRF instrument took roughly 1 hour to stabilize. To test whether the Bruker Tracer 5g instrument also required this “warm-up” period, we conducted continuous acquisition of one sample (V-19-05A) for 21 consecutive runs, with 5 minute-spacing between analyses. At this point, a second “split” of the same initial powder (V-19-05B) was analyzed in the same way to determine if there was a measurable difference between the two splits of the same sample (V-19-05A and V-19-05B). Data for Si (wt. %) and Ca (wt. %) from sample V-19-05A and B are reported in Figure 1C, and D. We identified a steady increase (Figure 1C, D) until the instrument stabilized (run #110 for Si and #102 for Ca). We determined the instrument requires a significant “warm-up” period to ensure consistency between analytical runs. Future work will focus on comparison of ICP-OES and ICP-MS data to pXRF data to build the custom-calibration for powdered, and non-powdered sample materials.

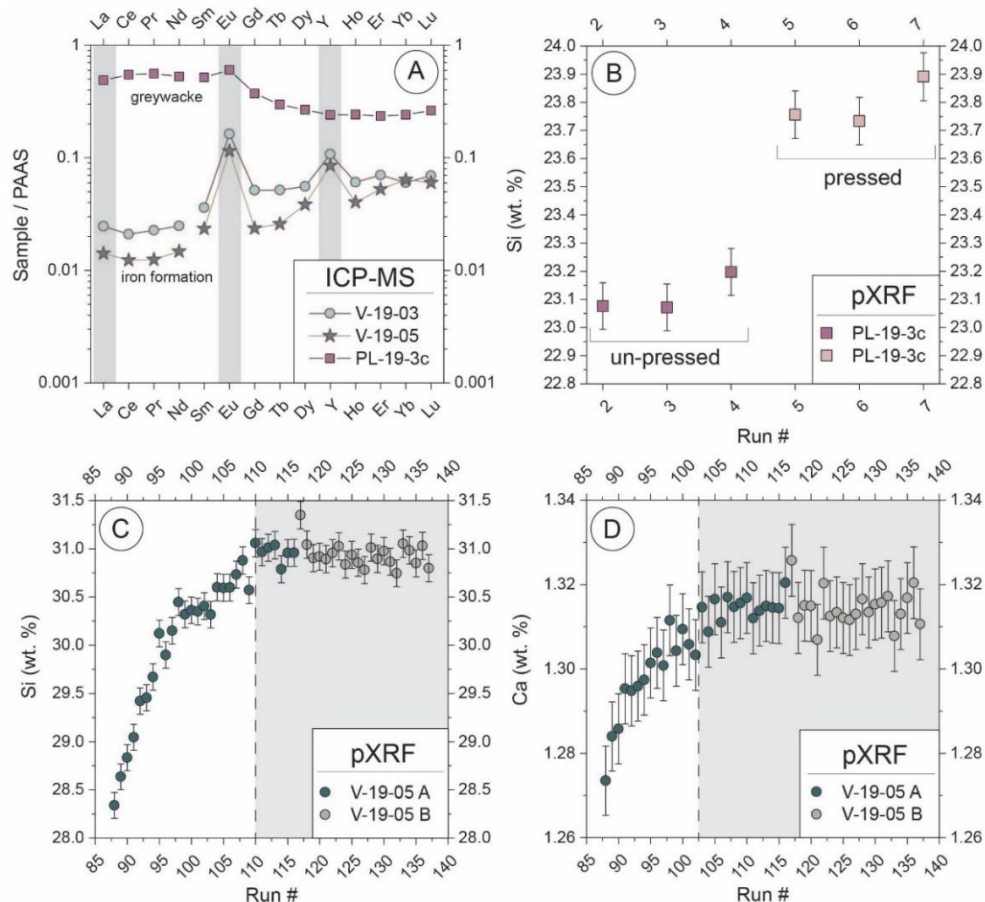


Figure 1: Preliminary geochemical data from iron-rich rocks near Soudan, MN. (A) Rare-earth-element data for iron formation (V-19-05) and regional greywacke (PL-19-3c). (B) Initial test run of pressed versus un-pressed powders using the pXRF instrument. (C, D) Consecutive pXRF analyses of iron formation sample V-19-05 to determine the duration of the “warm-up” period for the instrument.

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Critical Minerals Exploration and Development Potential in Ontario

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On March 10, 2021, Ontario released a discussion paper that outlines the province's proposal to develop a critical minerals strategy (Ministry of Energy, Northern Development and Mines 2021). The discussion paper is focused on:

1. Supporting partnership opportunities with Indigenous peoples;
2. Finalizing an Ontario critical minerals list;
3. Enhancing investment in mineral exploration and development;
4. Regulatory and policy reform; and,
5. Supply chain and manufacturing opportunities.

Public consultation is underway, with the strategy scheduled for release by the end of 2021.

While there is no universal definition of critical minerals and various jurisdictions define them differently, the term generally applies to minerals that have specific industrial, technological and strategic applications for which there are few viable substitutions. These minerals are also at higher supply risk due to geopolitical considerations and market demand. Ontario is uniquely positioned to meet rising global demand for critical minerals and can attract potential investment opportunities by creating a provincial critical minerals list to guide mineral exploration and development. An Ontario critical minerals list will be of interest to jurisdictions that are seeking to secure a reliable supply of raw materials for their own domestic markets, such as the United States, the European Union, Japan and South Korea.

Ontario has created a draft list of critical minerals that includes commodities that are currently being produced commercially at existing mines, commodities that have a reasonable prospect of being developed in the near term (i.e., advanced projects that could produce within 5 years), commodities that have demonstrated exploration potential, and commodities that were not originally mined in Ontario, but are being smelted or refined here. The entire list is provided in Table 1, with the critical minerals that are in common with the United States draft list (Fortier et al. 2018) indicated in bold type.

Ontario's current critical mineral production is derived from magmatic copper-nickel-cobalt-platinum group element (Cu-Ni-Co-PGE) deposits (8 Sudbury mines and Lac des Iles) and volcanogenic massive sulphide zinc-copper (Kidd Creek) deposits. The Sudbury mines also produce selenium and tellurium as by-products, while indium is a by-product at Kidd Creek. Due to current high prices for platinum group elements (most notably palladium) and battery metals (which include nickel and cobalt), current exploration interest in magmatic Cu-Ni-Co-PGE deposits is strong in Ontario, with numerous active projects. These include several in the Midcontinent Rift area that are primarily targeting PGEs, including the Clean Air Metals Inc. Thunder Bay North project, where the Escape Lake deposit is currently being delineated, and Generation Mining Limited's Marathon project, which is undergoing an Environmental Assessment to support future mine development. Another notable advanced-stage magmatic sulphide project is Canada Nickel Company's Crawford Nickel-Cobalt project near Timmins, where a high-tonnage low-grade resource has been defined in an Archean ultramafic intrusion.

Strong interest in battery metals has also fuelled significant exploration interest in lithium and cobalt in recent years. Numerous areas in the Superior Province of northwestern Ontario are known to host lithium-bearing rare element pegmatites. These deposits are associated with fertile peraluminous granites (Breaks et al. 2003), with notable examples currently moving toward

development in the Pakeagama Lake (Frontier Lithium Inc.), Separation Rapids (Avalon Advanced Materials Inc.) and Georgia Lake (Rock Tech Lithium Inc.) areas. Recent cobalt exploration has largely been focussed on the Proterozoic 5-element vein systems of the Cobalt Embayment, where First Cobalt Corp. is developing a refinery to produce battery-grade cobalt sulphate.

Some cobalt exploration has also occurred in the Thunder Bay area, where Honey Badger Exploration Inc. recently discovered a new style of disseminated cobalt mineralization in close proximity to silver-bearing veins at the Beaver Mine, near the contact between the Rove Formation and a diabase sill (Puumala et al. 2019). Another previously unrecognized style of cobalt-copper-nickel mineralization that has been described as a possible skarn or IOCG occurrence is hosted in altered calcareous sedimentary rocks of the Rossport Formation north of Thunder Bay, near Disraeli Lake (Ontario Geological Survey 2019). Both deposit types present new critical mineral research and exploration opportunities in Ontario.

Table 1. Ontario’s draft list of critical minerals. Asterisk indicates commodity also processed in Ontario. Critical minerals listed in bold type are also found on the United States draft list (Fortier et al. 2018).

Producing	Advanced Projects	Exploration Potential		Processing Only
Cobalt * Copper * Indium Nickel * Platinum Group Elements * Selenium * Tellurium * Zinc	Barite Chromite Graphite Lithium Magnesium Niobium	Antimony Beryllium Bismuth Cesium Fluorspar Manganese Molybdenum Phosphate	Rare Earth Elements Tantalum Tin Titanium Tungsten Vanadium Zirconium	Uranium

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Environmental Control of Seawater Geochemistry in a Mesoarchean Peritidal System, Woman Lake, Superior Province

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The 2.857±5 Ga (this study) carbonate platform at Woman Lake, Ontario, Canada, presents a unique opportunity to fill a 130 million year knowledge gap on early carbonate sedimentology and ocean chemistry between similar platform occurrences at Steep Rock Lake (2.80Ga)(Fralick & Riding, 2015) and Red Lake (2.93Ga)(MacIntyre & Fralick (2017). Woman Lake carbonates are among the few very early and thick carbonate platforms to develop in the Mesoarchean. Field, petrographic, and geochemical investigations were performed on the limestone sequence to better understand the paleoenvironmental context of this understudied, 90-meter-thick succession.

At the base of the carbonate platform, lying atop felsic subaerial Archean tuff, are stratiform stromatolites interbedded with thin beds of massive carbonate grainstone, followed by laterally linked low domal stromatolites, which gradually become larger domes, then bioherms with walled pseudocolumnar stromatolites. They are overlain by cross-stratified and parallel laminated carbonate grainstones and more pseudocolumnar stromatolites. A variety of fenestral microbialites overly this unit, including thrombolites, stromatactis-bearing low domal stromatolites, and narrow isolated columnar stromatolites. This is followed by a cyclic succession of low domal stromatolites alternating with microbial carbonate and carbonate grainstone. Three main stromatolitic morphologies exist and represent a range of low to moderate current energies from upper intertidal to subtidal environments. They are: 1) low relief stratiform to undulating stromatolites 2) laterally linked low domal and pseudocolumnar stromatolites, and 3) isolated to locally isolated domes and narrow columnar stromatolites. Evidence here supports mainly peritidal environments on a carbonate platform with fluctuating sea-level and water energies in an overall deepening succession.

The diverse carbonate facies are comprised of geochemical features reminiscent of both Archean and modern signatures in shale normalized REE patterns. Trace elements indicate that the carbonates precipitated from a mixture of two different fluids: anoxic seawater that carried a positive Eu anomaly, and oxygenated waters that imparted significant negative Ce anomalies. On a microscopic scale, using LA-ICP-MS, there is less compositional contrast between carbonate phases, which indicates that dissolution and precipitation on a small spatial scale homogenized localized areas, but did not affect changes on a metric scale. Geochemical trends paired with stratigraphic depth show decameter cycles of gradual declines in Mg, Fe, Mn, Ba and Sr substitution into the calcite lattice followed by sharp increases throughout the platform's deposition, possibly reflecting changing accommodation space effecting precipitation rate (Fig. 1). Typical Archean values for $\delta^{13}\text{C}$ ranging from -3.83‰ to 1.30‰, with an average of 0.53‰ (± 0.59 , $n=31$) occur with Y/Ho ratios ranging from 27 to 117 and $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic values from 0.700346 to 0.711313 (± 0.00098 (1σ)). The observed trends suggest that the precipitating carbonates were able to record and retain the effects of an evolving water column had in the local environment. Importantly, the Woman Lake carbonate platform provides context for, and evidence of, free oxygen approximately 500 million years before the Great Oxygenation Event, during a relatively undocumented period in time.

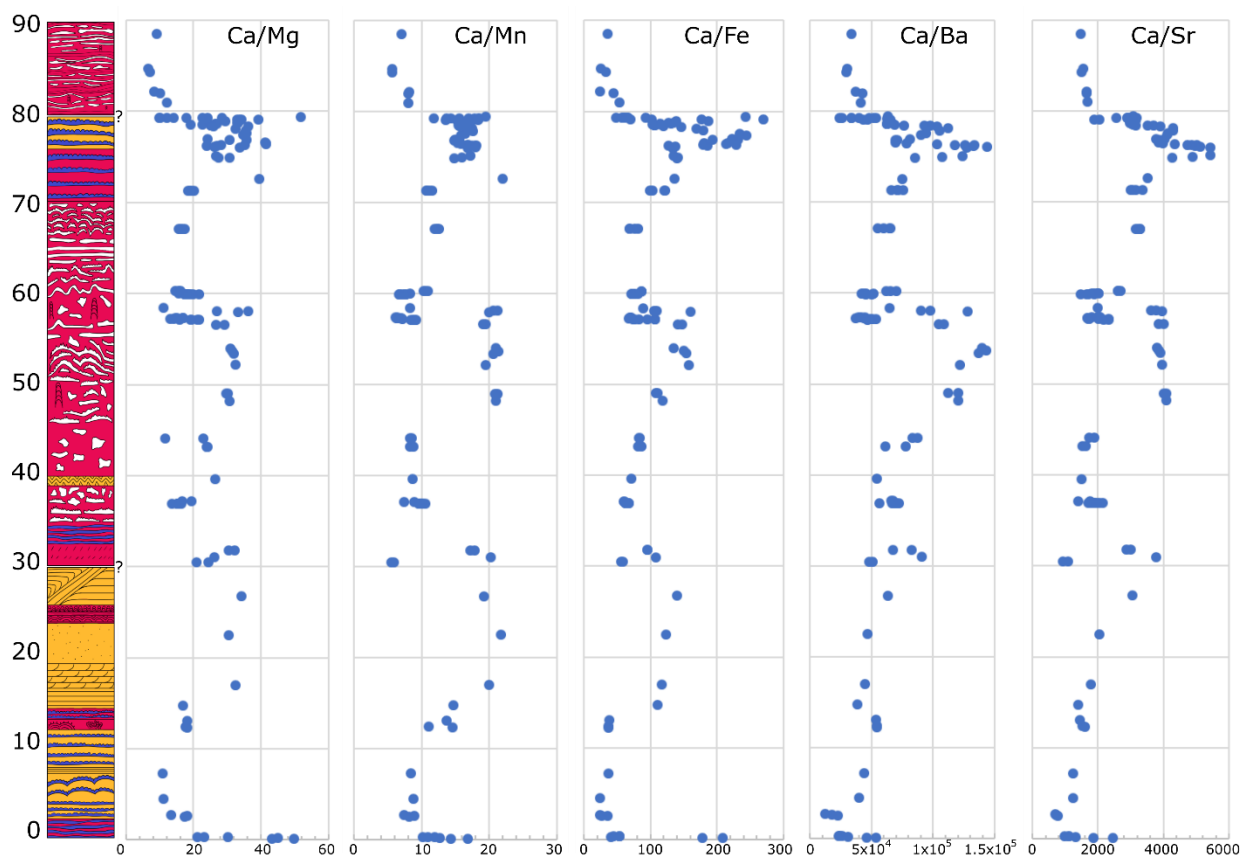


Fig. 1. Five meter moving averages of molar weight ratios normalized to Ca are plotted against stratigraphic depth. Ratios are of common carbonate group elements that substitute into various carbonate minerals. Three cycles of increasing and decreasing concentrations are evident. Decreasing trends represent times of higher substitution rates and an increase represents lower substitution rates relative to Ca (numerator).

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Geochemistry and Petrography of Volcanic and Intrusive Rocks Hosting the Lynne Cu-Zn-Pb Deposit, Oneida County, WI

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The Lynne Zn-Cu-Pb deposit was first discovered in 1990 by Noranda Exploration in Oneida County, WI and is one many volcanogenic massive sulfide (VMS) deposits in northern Wisconsin (DeMatties, 1994). These deposits formed 1.8 to 1.9 Ga when the Pembine-Wausau Terrane collided and accreted onto the Superior Craton during the Paleoproterozoic Penokean Orogeny. VMS deposits are created in extensional submarine environments that are preserved in the rock record in a variety of tectonic settings. The VMS-forming environment in Wisconsin has previously been interpreted to be back-arc rifting in a continental setting during the collision of the Archean Marshfield Terrane onto the Pembine-Wausau Terrane and the rest of the Superior Craton (Schulz and Cannon, 2007). However, studies at other deposits throughout Wisconsin have highlighted variable volcanic and tectonic settings (e.g. Jackson et al, 2016; Jacobson and Lodge, 2018). The purpose of this study is to better constrain the volcanic and tectonic setting at the Lynne deposit and improve tectonic and metallogenic models across the Penokean Orogen.

Research on Penokean VMS systems depends on drill core as outcrop exposure in the region is limited due to a thick cover of glacial deposits and Paleozoic Sedimentary strata (Dematties, 1994; Adams, 1996). The Noranda drill cores from the Lynne deposit were obtained from the archives at the Natural Resources Research Institute of Duluth, Minnesota and re-logged and sampled at an off-campus lab associated with UW-Eau Claire. Core samples from the least-altered felsic host rocks and various intrusive rocks were then processed for petrographic and geochemical analyses. Major and trace elements were analyzed using X-ray Fluorescence at the Materials Science Center at UW-Eau Claire. Interpretations from this new geochemical data yielded an improved volcanic stratigraphy and tectonic model that describes the volcanic system forming the Lynne VMS deposit.

The stratigraphy of the Lynne deposit was described by Adams (1996) based on drilling during the exploration program. The stratigraphy consists of the Upper Rhyolite, Upper Dacite, Upper Volcaniclastic (VCS), Lower Rhyolite, Lower Dacite, and Lower Volcaniclastic based on their relative position to the ore horizon (Adams, 1996). After a geochemical analysis of the felsic volcanic units was conducted, it revealed that there are no chemical distinction between the upper and lower horizons. Therefore, unit descriptions are constrained by composition and not stratigraphy. Rhyolites are crystal rich lapilli tuff to ash with plagioclase being the most abundant crystal. The VCS unit is greywackes and siltstones with some bedding and localized alteration. The Dacite unit is a crystal to crystal-lithic lapilli tuff with plagioclase crystals.

The Lynne drill core also intersects felsic and mafic dykes, along with a large granophyre/granodiorite pluton at the bottom of the deposit which is geochemically indistinguishable from intersecting felsic dykes. The felsic dykes are fine grained and light to medium grey in color and contain plagioclase and quartz veins. The mafic dykes appear fine grained, dark grey in color, and contain plagioclase phenocrysts. The granodiorite/granophyre contains medium- to coarse-grained quartz and feldspars which vary between the phenocrystic granophyre near the contact to equigranular away from the contact region. The geochemical signature of the intrusive units of the Lynne deposit indicate that they are derived from two distinct

sources that formed in a volcanic arc setting much like the extrusive volcanic stratigraphy. Therefore, it is likely that they are genetically related.

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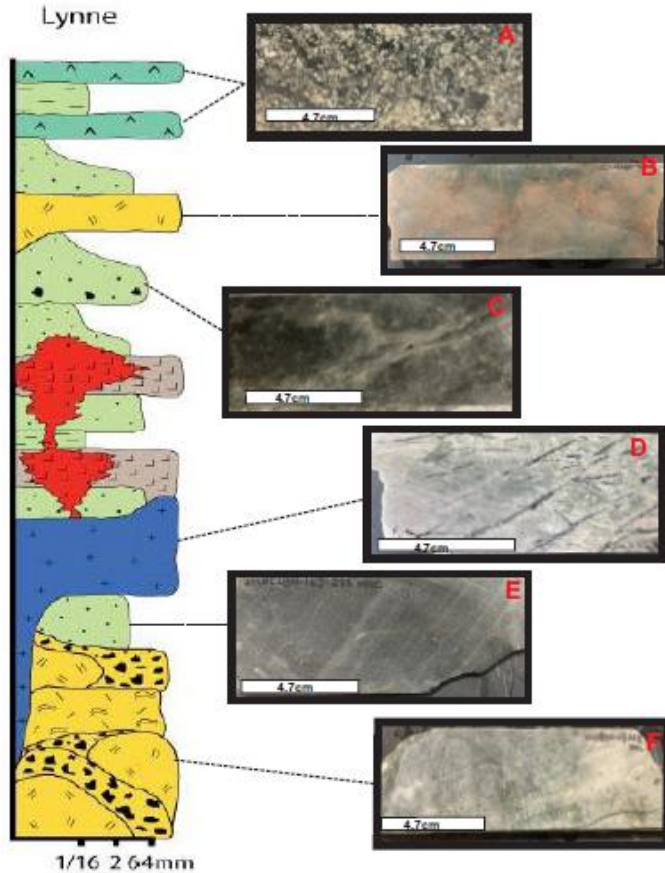


Figure 1: Generalized stratigraphic column of the Lynne Deposit (from Quigley, 2016) with core pictures from representative volcanic and intrusive units. **A.** Upper Dacite **B.** Upper Rhyolite **C.** Upper VCS **D.** Felsic Dyke **E.** Lower VCS **F.** Lower Rhyolite

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Geologic mapping identifies bedrock folds that may be significant for increased probability of arsenic detection in water wells

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Recently completed bedrock mapping of Dodge County, southeast Wisconsin, provides an improved geologic framework that informs the region's geologic history and adds to our understanding of groundwater resources (Stewart, E.D. et al., 2021; Stewart, E.K. 2021). Dodge County is underlain by glacial sediments, Precambrian Quartzite, and Cambrian through Silurian siliciclastics and carbonates and is situated proximal to the WI Arch, a basement high that influenced Paleozoic basin development. We identify bedrock folds that likely increase the probability of arsenic (As) detection in groundwater wells. New petrographic observations constrain the As host and suggest processes that resulted in As mineralization.

Mapping indicates episodic movement along the WI Arch influenced deposition of Paleozoic strata. Most significant deformation during early Ordovician time resulted in localized uplift and erosion of the dolomitic Prairie du Chien Group prior to deposition of the overlying siliciclastic Ancell Group. Continued deformation is associated with folding of the overlying Sinnipee Group, fracture development, and mineralization. Marcasite and carbonate-filled fractures in one locality along an anticlinal axis show well developed cataclasis evidencing deformation during and after formation of trace MVT occurrences. Most elevated hydraulic conductivity (K) estimates from the Ancell Group are within 2 km of mapped folds, indicating fractures associated with folds locally increases groundwater flow (Stewart, E.D. et al., 2021).

Water wells completed in the Ancell Group in Dodge County have increased likelihood of detecting As close to folds, suggesting fold induced fractures promoted a focus or change in As host minerals that increased the probability of arsenic release. No As was detected in SEM-EDS analysis of oxide phases, while two sulfide As hosts were identified in mineralized core samples: (1) Small (10-20 μm), cubic, Ni-Co-Fe sulfides with up to 3 wt.% As are scattered within marcasite that infills localized fractures and sulfide cement in Cambrian Elk Mound Group sandstone. These crystals are similar in morphology, size, and chemistry to Ni-Co-Fe sulfides identified as Vaesite-Bravoite from trace MVT-mineralized samples in Brown and Oconto Counties reported by Luczaj et al., 2016. (2) Tiny (3-5 μm), circular, rimmed Fe-sulfides with 1.4-2.2 wt.% As are only present within thin clay rims on quartz grains in the Ancell Group sandstone, in contrast to all other sulfides observed from the same sample, which lack detectable As. Rimmed grains may be the mineralized remains of specialized microbacterial colonies that metabolically reduced dissolved arsenate and sulfate to produce As-bearing Fe-sulfide (e.g. Stolz et al., 2006). Observation of Fe-sulfide frambroids supports a biologic control on sulfide mineralization. High-resolution SEM-BSE imaging reveals common As-poor, Fe-sulfides present as hexagonal, small to large, euhedral marcasite plates and subordinate framboidal clusters of tiny Fe-sulfide crystals. Frambroids are common as isolated clusters encased within larger euhedral sulfide or as nucleation points for single grains of euhedral sulfide. Framboidal sulfide clusters are commonly interpreted as mineralized remains of sulfate-reducing microbacterial colonies (e.g. Folk, 2005), and sulfate-reducing bacterial colonies are known to seed adjacent areas with reduced sulfur allowing for inorganic precipitation of larger volumes of sulfide cement (Schieber, 2002). Bacterial reduction

of sulfate sourced from regionally migrating hydrothermal brines coming out of the Michigan Basin is proposed as a broader mechanism that drove precipitation of Fe-sulfides forming the bulk of mineralization within the trace MVT occurrences of Dodge County.

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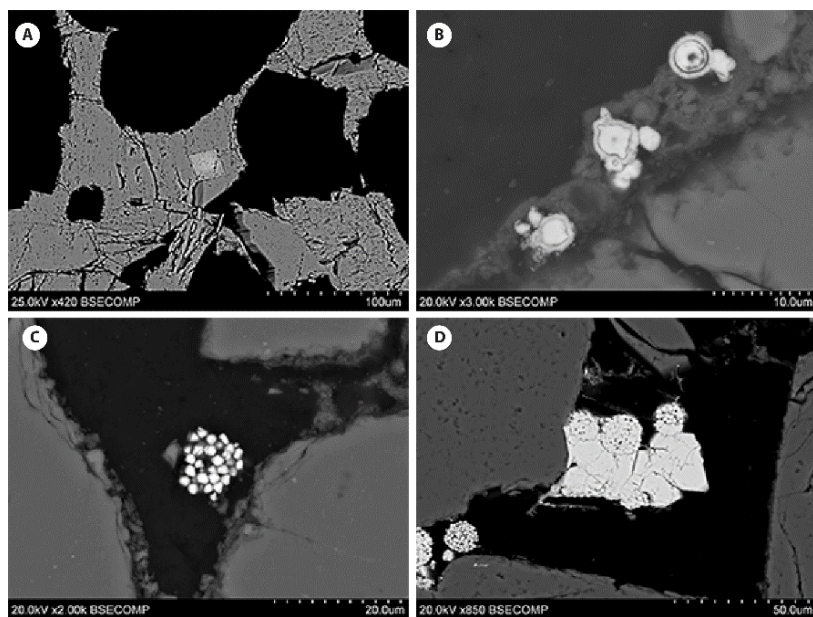


Figure 1: (A) Electron backscatter image of marcasite-cemented vertical zone within Elk Mound group. Frame is centered on an unusual cubic Fe-Ni-Co-As sulfide grain. (B) Electron backscatter image of unusual rimmed, circular As-bearing Fe-sulfides from Tonti Member of the St. Peter Formation, Ancell Group. Smaller, unrimmed grains outboard of main rimmed sulfides contain detectable As but at reduced concentration relative to main rimmed grain (<.5 wt%). Platy medium gray matrix enclosing sulfides is a thin rim of kaolinitic clays. Light gray at bottom right of image is edge of detrital quartz grain. (C) Electron backscatter image of single framboidal cluster at high magnification illustrating tiny individual grains making up structure. (D) Electron backscatter image of cluster of sulfide grains within Tonti Member of St. Peter. Note how framboidal clusters appear to be serving as nucleation points for larger, euhedral hexagonal sulfide grains.

The paleogeography of Laurentia in its early years: new constraints from the Paleoproterozoic East-Central Minnesota batholith

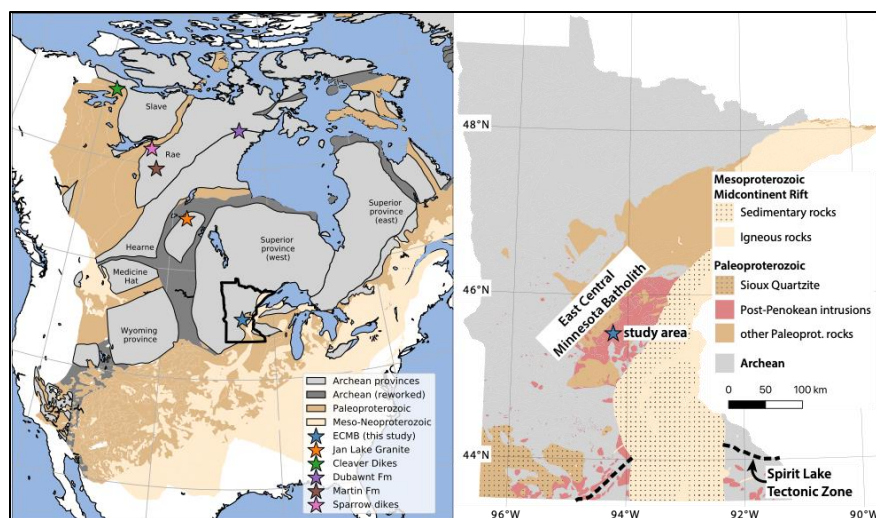
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The ca. 1.83 Ga Trans-Hudson orogeny resulted from collision of an upper plate consisting of the Hearne, Rae, and Slave provinces with a lower plate consisting of the Superior province. While the geologic record of ca. 1.83 Ga peak metamorphism within the orogen suggests that these provinces were a single amalgamated craton from this time onward, a lack of paleomagnetic poles from the Superior province following Trans-Hudson orogenesis has made this coherency difficult to test.



We develop a high-quality paleomagnetic pole for northeast-trending diabase dikes of the post-Penokean orogen East-Central Minnesota Batholith (Holm et al., whose age we constrain to be 1779.1 ± 2.3 Ma (95% CI) with new U-Pb dates. Demagnetization and low-temperature magnetometry experiments establish dike remanence be held by low-Ti titanomagnetite. Thermochronology data constrain the intrusions to have cooled below magnetite blocking temperatures upon initial emplacement with a mild subsequent thermal history within the stable craton. The similarity of this new Superior province pole with poles from the Slave and Rae provinces establishes the coherency of Laurentia following Trans-Hudson orogenesis. This consistency supports interpretations that older discrepant 2.22 to 1.87 Ga pole positions between the provinces are the result of differential motion through mobile-lid plate tectonics. The new pole supports the NENA connection between the Laurentia and Fennoscandia cratons. The pole can be used to jointly reconstruct these cratons ca. 1780 Ma thereby strengthening the paleogeographic position of these major constituents of the hypothesized late Paleoproterozoic supercontinent Nuna.

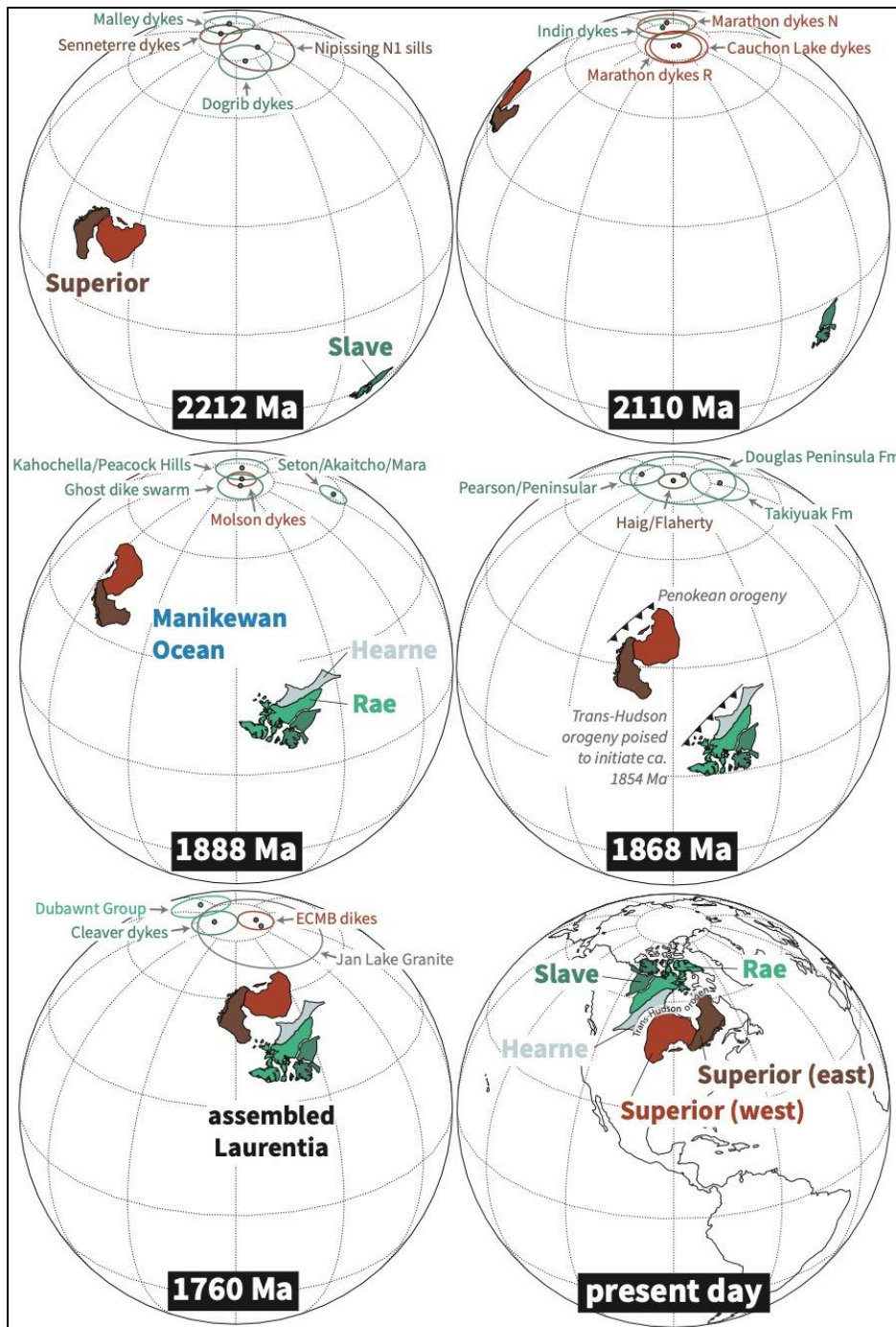


Figure 2: Paleogeographic reconstructions at five different times in the Paleoproterozoic and the position of the provinces at present. Paleomagnetic poles within 20 Myr of the given time (10 Myr for 1888 and 1868 Ma) are shown from the compilation of Evans et al. (2021) as well as the new ECMB pole. These data illustrate differential plate motion between the Superior and Slave Provinces that is required by the data leading up to the closure of the Manikewan Ocean and the assembly of Laurentia during the Trans-Hudson orogeny. The ECMB pole is consistent with an assembled Laurentia following the Trans-Hudson orogeny which contrasts with the disparate orientations and paleolatitudes between Laurentia's constituent provinces prior to the orogeny.

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The provenance, depositional environment and metallogenic implications of the Ament Bay Metasedimentary Assemblage, Sturgeon Lake Greenstone Belt, Northwest Ontario

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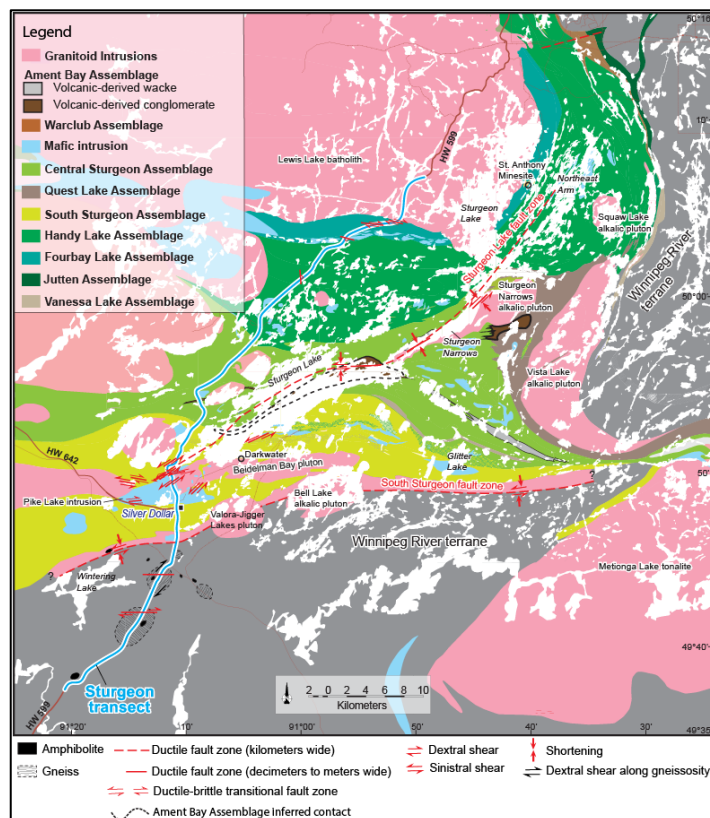
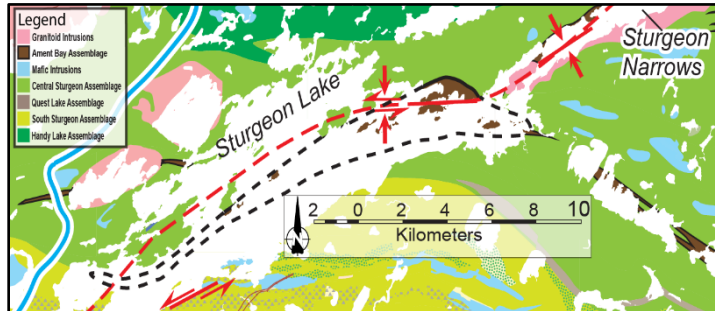


Figure 1. Regional geology of the Sturgeon Lake greenstone belt. Modified after Sanborn-Barrie and Skulski (2005). Inset map showing close-up view of central portion of ABMA (outlined).

The Ament Bay Metasedimentary Assemblage (ABMA) is the youngest supracrustal assemblage in the Savant Lake-Sturgeon Lake greenstone belt (SSGB), and has previously been interpreted to have alluvial-fluvial origin (Sanborn-Barrie and Skulski, 2005). However, its timing, tectonic setting, and metallogenic significance is unclear. The SSGB makes up the easternmost part of the Western Wabigoon terrane of the Superior Province. The supracrustal assemblages in this belt form a regional-scale syncline, with the ABMA exposed along the hinge, and is intersected by the Sturgeon Lake fault zone (fig. 1). The ABMA is surrounded by felsic and mafic volcanic rocks that compose the Central and South Sturgeon Assemblages, however its contact relationships are poorly understood (Sanborn-Barrie and Skulski, 2005).

The goal of this study is to determine if the ABMA represents a Timiskaming-type basin. Timiskaming-type basins are found in various Neoproterozoic greenstone belts throughout the Superior. These are synorogenic basins which consist of clastic rocks with fluvial and marine

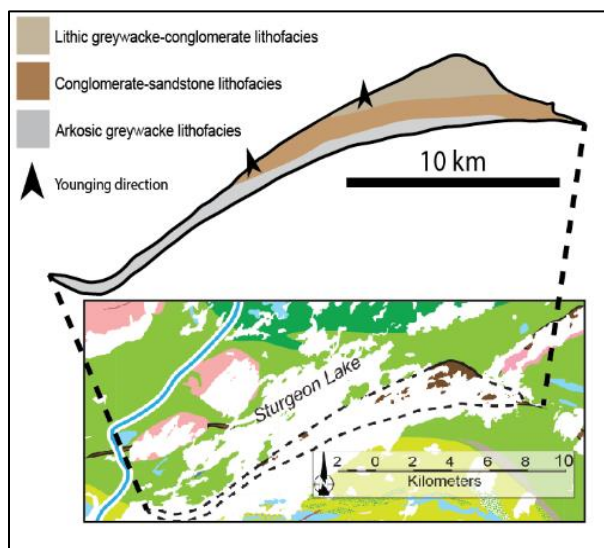


Figure 2. Close-up view of central portion of the ABMA and its interpreted lithofacies.

The ABMA consists of mostly weakly foliated, massive- to- planar bedded polymictic conglomerates and arkosic- to- lithic-rich arenites and greywackes. Based on petrographic analysis and lithology distribution, three lithofacies have been attributed to the ABMA: (i) arkosic greywacke lithofacies; (ii) polymictic conglomerate-sandstone lithofacies; (iii) lithic greywacke-mafic-rich conglomerate lithofacies (fig. 2). These are comparable to some lithofacies which make up other molasse basin-fill successions, some of which are Timiskaming-type (Corcoran and Mueller, 2007).

Despite having similar characteristics with Timiskaming-type basins, the ABMA is poorly endowed relative to some of the gold-rich Timiskaming Group sediments in the Abitibi greenstone belt. This study explores possible factors which hindered gold mineralization in the Sturgeon Lake greenstone belt.

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Possible implications of a non-Archean Grand Marais Ridge, western Lake Superior

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The Grand Marais Ridge (GMR) is a gravity low but a structural high hidden beneath the waters of western Lake Superior. It has been interpreted as a preserved basement block of low-density Archean granite that remained a positive topographic high as adjacent volcanic basins subsided (Allen et al., 1997). Recent geophysical analysis (Grauch and Heller, 2021, this volume), however, suggests that the GMR likely comprises a significant volume of anorthosite, possibly mixed with felsic rocks. This part of the Midcontinent Rift System (MRS) in western Lake Superior is an area where many unusual features occur, including extraordinarily large concentrations of rapidly intruded mafic intrusions of the Duluth and Beaver Bay Complexes (DC and BBC), and a high percentage of felsic rocks in the North Shore Volcanic Group (NSVG) compared to other MRS volcanic sections. The thick basalt and overlying sedimentary packages in western Lake Superior also occur in a series of sag basins rather than the graben-like basins that characterize the MRS in the nearby St. Croix horst and the western arm extending away from Lake Superior. Here we address implications of recent modeling results and speculate on the potential significance of a GMR composed of anorthosite and felsic rocks, as well as the evolution of the MRS in this unique part of the Lake Superior region. Perhaps the most challenging aspect of this new compositional interpretation is how the GMR came to be a topographic high if it is not a block of remnant Archean basement.

1) What is the origin of anorthosite in the GMR?

Option 1. Anorthosite represents pre-MRS basement rocks (e.g., Allen et al., 1997). This age is possible but unlikely as the regional Archean basement is granite-greenstone with little reported major units of anorthosite, and thus does not match the observed geophysical characteristics.

Option 2. Anorthosite is part of the large complex suite of plagioclase-rich cumulate intrusions of the DC. Anorthosite intrusions are widespread throughout the DC, from the exposed western margin to where it disappears under the younger BBC and the NSVG. It is plausible that anorthosite in the GMR is an eastern extension of the DC, although it is challenging to determine how an older, deeper DC anorthosite pluton would now represent a high structural block.

Option 3. The striking presence of abundant and, in places, very large anorthosite inclusions in the BBC Beaver River gabbro has been attributed to incorporation at depth of older DC anorthosite (Miller and Chandler, 1997). A recent paleomagnetic intensity study by Zhang (2020) found that anorthosite inclusions and host Beaver River diabase have similar paleomagnetic poles, which suggests that inclusions could be related to the BBC rather than the slightly older DC. Thus, anorthosite in the GMR could be products of BBC igneous events. In either case, anorthosite inclusions appear to be related to the MRS rather than pre-MRS basement and may be evidence of significant anorthosite accumulation at some depth near the GMR.

2) What is the origin of the felsic component in the GMR?

Option 1. Archean granitic rocks that were intruded by plagioclase-rich magma during MRS time.

Option 2. Partial melting of older basement rocks caused by staging of mafic magmas at depth during MRS time would lead to large accumulations of felsic magma (Vervoort and Green, 1997). Felsic magma could have been incorporated into an anorthosite cumulate melt and intruded higher in the crust.

Option 3. The GMR is located just offshore of two of the largest rhyolite lava or ash flows in the NSVG (Green and Fitz, 1993), all temporally related to the DC. Nicholson et al. (1997) suggested that the proximity of large felsic flows on land and the GMR was not coincidental. It is possible that the GMR was a felsic volcanic center during DC time that erupted these large lava flows along with other regional felsic volcanics.

3) What dynamic processes could have created the GMR anorthosite/felsic structural high?

Option 1. Anorthosite and layered troctolite-gabbro plutons were intruded as inclined sheets between a footwall of Paleoproterozoic Animikie Group sedimentary rocks and Archean granites and a hanging-wall of the NSVG (Miller et al., 2002). Thus, an Archean GMR would have to have been a topographic block within the Animikie Basin, as suggested by Allen et al. (1997). This basement structure could have been intruded by one of the many anorthositic igneous bodies generated during DC magmatic events as well as by felsic magmas derived from partial melting of some basement rocks.

Option 2. Recent high precision $^{206}\text{Pb}/^{238}\text{U}$ zircon dates show that multiple intrusions of DC were emplaced together around 1096 Ma within less than 1 million years (Swanson-Hysell et al., 2020), suggesting that magma supply from deep crustal chambers for both intrusions and overlying volcanics was effectively continuous. Rapid, repetitive magmatic pulses would have elevated crustal temperatures around DC feeder zones and crustal magma chambers. Vervoort and Green (1997) suggested that the large rhyolite flows of the NSVG were products of crustal melting produced by the large thermal flux of DC magmatism. Perhaps remnants of a felsic volcanic center are located above a now crystallized plagioclase-rich magma chamber in the GMR, although the relative geometry of a middle-crust anorthosite intrusion, an upper crust felsic center, and a resulting GMR topographic high is perplexing.

Option 3. A large volcanic sag basin just offshore from the BBC is bounded on the northeast by the GMR and on the southwest by the Archean (probable) structural block of White's Ridge. The ~14 km-thick basalt section that fills this bowl-shaped basin, which is not fault-bounded as shown by Grant-Norpac legacy seismic profiles, was likely erupted from the curvilinear Beaver River diabase dike and related sheets that acted as major conduits for igneous activity (Miller and Chandler, 1997). Loading by a rapid succession of relatively dense basalt flows into an initially thermally subsiding basin could create an unstable environment (e.g., Mukherjee et al., 2020) where less dense underlying plagioclase-rich cumulates could be forced upward into a zone of weakness created by earlier high temperature felsic volcanism. This scenario, however, would require ductile behavior relatively high in the crust, but could explain how MRS anorthosite and felsic rocks became a topographic high as adjacent volcanic basins subsided. Perhaps localization of magmatic events over a short duration in this area created this seemingly implausible scenario.

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