70th Annual Meeting

Institute on Lake Superior Geology

Houghton, Michigan May 15-18, 2024



Proceedings Volume 70
Part 1 - Program and Abstracts



70th Annual Meeting
Institute on Lake Superior Geology

Houghton, Michigan
May 15-18, 2024

Sponsored by:

A. E. Seaman Mineral Museum
Great Lakes Research Center
Department of Geological and Mining Engineering and Sciences
Michigan Technological University

Meeting Co-Chairs

Theodore J. Bornhorst, Erika C. Vye, Patrice Cobin, and James DeGraff

Proceedings Volume 70
Part 1: Program and Abstracts

Edited by Theodore J. Bornhorst and Erika C. Vye

Cover Photo: The only known color photograph of in situ colorless calcite crystals with inclusions of native copper. Vug is about 15 cm across and 30 cm deep; located at the top of the Knowlton basalt lava flow at the 4th level, 850 ft stope, of the Caledonia Mine, Michigan. Photo taken in 1994 soon after the vug was blasted open. Native copper in the calcite crystals has not been visibly altered despite being about 1 billion years old.

Photograph by Theodore J. Bornhorst

70th Institute on Lake Superior Geology

Volume 70 consists of:

Part 1: Program and Abstracts

Part 2: Field Trip Guidebook

- **Trip 1:** *Mesoproterozoic Midcontinent Rift-filling Strata and Native Copper Deposits of the Keweenaw Peninsula, Michigan*
- **Trip 2:** *Mining History and Geology of the Quincy Mine, Keweenaw Peninsula Native Copper District, Michigan*
- **Trip 3:** *Geoheritage of Buffalo Reef: Industrial Impact on Land, Culture, and Fish Sovereignty*
- **Trip 4:** *Keweenaw Fault System Geometry and Kinematics: Clues to Its Nature and Origin*
- **Trip 5:** *Geology and History of a Native Copper Mine: Adventure Mine, Ontonagon County, Michigan*
- **Trip 6:** *Southern Complex Granitoids, Gneisses, and Migmatites: New Data, Discoveries, and Perspectives*
- **Trip 7:** *Landslides on the Ontonagon River at Military Hill*

Reference to material in Part 2 should follow the example below:

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Some figures in this volume were submitted by authors in color but are printed black and white. Full color imagery will appear in the digital version of the volume when it is available on-line at:

http://www.lakesuperiorgeology.org

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Part 1: Program and Abstracts

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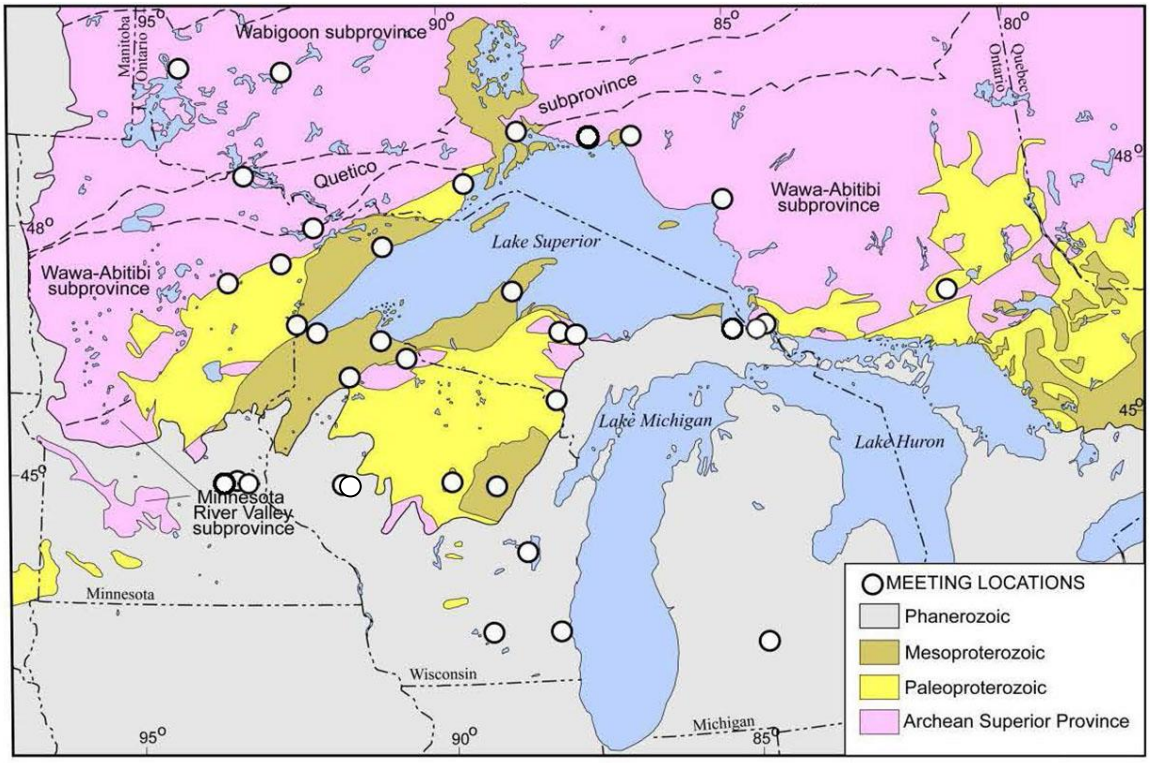
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Institutes on Lake Superior Geology, 1955-2024



#	Date	Place	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

#	Date	Place	Chairs
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	Meeting cancelled	Cancelled by the COVID-19 pandemic
67	2021	Virtual meeting	M. Jirsa, M. Smyk & P. Hollings
68	2022	Sudbury, Ontario	R.M. Easton & W. Bleeker
69	2023	Eau Claire, Wisconsin	R. Lodge, E.K. Stewart, & C. Ames

#	Date	Place	Chairs
70	2024	Houghton, Michigan	T.J. Bornhorst, E. Vye, P. Cobin, & J. DeGraff

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 1970s, 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 MEDAL

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 medalists 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 medalist, 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 in 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
1980 *not awarded*
1981 Carl E. Dutton, Jr
1982 Ralph W. Marsden
1983 Burton Boyum
1984 Richard W. Ojakangas
1985 Paul K. Sims
1986 G.B. Morey
1987 Henry H. Halls
1988 Walter S. White
1989 Jorma Kalliokoski
1990 Kenneth C. Card
1991 William Hinze
1992 William F. Cannon
1993 Donald W. Davis
1994 Cedric Iverson
1995 Gene La Berge
1996 David L. Southwick
1997 Ronald P. Sage
1998 Zell Peterman
1999 Tsu-Ming Han
2000 John C. Green
2001 John S. Klasner
2002 Ernest K. Lehmann
2003 Klaus J. Schulz
2004 Paul Weiblen
2005 Mark Smyk
2006 Michael G. Mudrey
2007 Joseph Mancuso
2008 Theodore J. Bornhorst
2009 L. Gordon Medaris, Jr
2010 William D. Addison & Gregory R. Brumpton
2011 Dean M. Rossell
2012 James D. Miller
2013 Tom Waggoner
2014 Laurel Woodruff
2015 Rodney J. Ikola
2016 Mark A. Jirsa
2017 Philip Fralick
2018 Val W. Chandler
2019 Mark Severson
2020 *not awarded*
2021 Alan MacTavish
2022 Terrence J. Boerboom
2023 Peter Hollings
2024 Suzanne W. Nicholson

2024 GOLDICH MEDAL RECIPIENT

Suzanne W. Nicholson

Goldich Medal Committee

Serving through the meeting year shown in parentheses.

Dorothy Campbell (2019-2024) Ontario Geological Survey, Government Member (Committee Chair)

Dean Peterson (2022-2025) Big Rock Exploration, Industry Member

Marcia Bjornerud (2023-2026) Lakehead University, Academic Member

Citation for the 2024 Goldich Medal Recipient
Suzanne W. Nicholson



It is a pleasure and honor to present the 2024 Goldich Medal to our close friend and colleague, Suzanne Nicholson, recently retired from a long and fruitful career at the U.S. Geological Survey.

Suzanne began working for the USGS as a student field assistant in 1978, and then, after completing a master's degree at the University of Massachusetts, was hired as a full-time employee in 1981. Suzanne's interest in the geology of the Lake Superior region began with her dissertation work with Paul Weiblen at the University of Minnesota on felsic magmatism in the Portage Lake Volcanics in Michigan, part of the Mesoproterozoic Midcontinent Rift System (MRS). This study included detailed mapping and sampling (typically big samples that had to be carried long distances) followed by major and trace element whole rock analysis and determination of a suite of radiogenic isotopes (Sr, Nd, Pb). Using modern petrologic methods, her research documented the presence of two distinct felsic magma types, one derived by partial melting of felsic basement and the other related to rift basalts through partial melting and/or fractional crystallization. Suzanne also was one of the first to provide comprehensive radiogenic isotope analyses of host basalts, documenting their distinctive isotopic character and that of their mantle sources. Her 1990 seminal publication (Nicholson, S.W., and Shirey, S.B., 1990, *Midcontinent Rift volcanism in the Lake Superior region: Sr, Nd, and Pb isotopic evidence for a mantle plume origin*: Journal of Geophysical Research, v. 95, p. 10,851-10,868) described the unique geochemical character of rift magmatism around the Lake Superior region. Her on-going interest in MRS geochemistry culminated in the 1997 paper that established a rift-wide correlation of MRS basalts (Nicholson, S.W., Schulz, K.J., Shirey, S.B., and Green, J.B., 1997, *Rift-wide correlation of 1.1 Ga Midcontinent Rift System basalts: multiple mantle sources during rift development*: Canadian Journal of Earth Sciences, v. 34, p. 504-520), providing a foundation for future interpretations of MRS-related volcanic rock geochemistry. Suzanne was also a leader in advancing an understanding of the spatial-temporal evolution of MRS metallogeny (Nicholson, S.W., Cannon, W.F., and Schulz, K.J., 1992, *Metallogeny of the Midcontinent Rift System of North America*: Precambrian Research, v. 58, p. 355-386), further refined in a 2020 paper (Woodruff, L.G., Schulz, K.J., Nicholson, S.W., and Dicken, C.L., 2020, *Mineral deposits of the Mesoproterozoic Midcontinent Rift system in the Lake Superior region - A space and time classification*: Ore Geology Reviews, 103716).

Along with colleagues from the USGS, Suzanne helped produce a series of 1:100,000-scale geologic maps for the MRS and adjacent rocks from the Keweenaw Peninsula, extending through Michigan into northern Wisconsin to the Minnesota state line. These maps summarized legacy mapping and, along with new fieldwork, resulted in interpretations and correlations that

are the current standard for understanding the distribution and origin of the MRS volcanic and intrusive rocks of that area. Suzanne also initiated and continues to lead an on-going cooperative government/academia effort to compile and digitize existing MRS geology, geochemistry, isotope data, and age dates that will promote and direct future research of the region. Throughout her career, Suzanne was a careful and meticulous researcher who held her own results to a very high standard for accuracy, completeness, and thoroughly documented interpretations.

Through the years, Suzanne has been a strong supporter of the Institute on Lake Superior Geology. She was a first or co-author on 17 abstracts presented at ILSG meetings from 1990 through 2019, a co-leader for two ILSG field trips, and co-editor for the 1996 Proceedings, Part 1- Program and Abstracts volume. Suzanne also was always willing and able to help with anything needed at ILSG meetings (a common trait among ILSG participants), such as acting as a session chair or serving on the student paper committee.

In 2015, Suzanne moved into increasingly responsible managerial positions within the USGS, which curtailed her direct involvement with research in the Lake Superior region. In 2020, she received the U.S. Department of Interior's second highest honorary award—the Meritorious Service Award— in recognition of her scientific leadership and noteworthy contributions to the USGS Mineral Resources Program. Suzanne retired from her position as Associate Program Coordinator for the USGS Mineral Resources Program in 2021 but was retained for 2 years as an annuitant to keep the Program on budgetary track during a time of transition. Her qualities as a scientist transferred to her administrative duties, demonstrating the same dedication and skills she brought to her research.

Now that Suzanne's service to the Program has ended, we look forward to her return to MRS-related research as a USGS Emeritus scientist. Throughout her managerial tenure, Suzanne never lost her attachment to the Lake Superior region and was able to promote and maintain funding for ongoing regional project work for her USGS colleagues. This support resulted in many new and exciting discoveries, such as tracing the extent and nature of the Sudbury ejecta layer across Michigan and Wisconsin, and tackling legacy seismic data to help understand the tectonic-magmatic evolution of the MRS. Through her thoughtful discussions, critical reviews, cheerful field assistance, and friendship for the past 40-some years, Suzanne helped enrich the lives and careers of many people, including those of her fellow USGS MRS aficionados. We remain a convivial group and all of us look back fondly on the times we spent together in the field. Who could forget death marches across Isle Royale, or raccoons swiping rhyolite samples in the Porcupine Mountains, or six long weeks at the Hurley Holiday Inn, among our many other adventures? So now, the three of us, all former recipients of the Goldich Medal, are joined by Suzanne in that honor. In recognition of her decades of accomplishments and dedication to the geology of the Lake Superior region and to the Institute on Lake Superior Geology, it is our pleasure to present the 2024 Goldich Medal to its second female recipient, Suzanne Nicholson.

Citation by:

Laurel G. Woodruff, USGS, Goldich Medal Winner, 2014
Klaus J. Schulz, USGS, retired, Goldich Medal Winner, 2003
William F. Cannon, USGS, Emeritus, Goldich Medal Winner, 1992

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 the inception of the Institute in 1955. Biographical sketches of those pioneers will be presented at future annual meetings so that all may 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 summarize the contribution of the nominee.
2) The Organizing 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)

2018-20 *not presented*

2021 Newton Horace Winchell (1839-1914)

2022 Thomas Leslie Tanton (1890-1971)

2023 Thomas Benton Brooks (1836-1900)

2024 Roland Duer Irving (1847-1888)

2024 Citation for the Roland Duer Irving
Pioneer of Lake Superior Geology

It is my great honor to nominate and promote Roland Duer Irving (1847-1888) as the 2024 Pioneer of Lake Superior Geology.



Roland Duer Irving
(1847 – 1888)

I suspect that many ILSG members are unfamiliar with Dr. Irving and his many truly pioneering contributions to our understanding of various aspects of Lake Superior geology. Were it not for his premature death at the age of 41, I have no doubt that his continued work on the Precambrian geology of the Lake Superior region would have ranked him as one of the greatest Lake Superior geologists of his time. As it stands, his nearly two decades of mapping, petrography, and geochemical studies and mentoring of students at the University of Wisconsin provided a firm and rational foundation for our further understanding of Lake Superior geology.

Roland Duer Irving was born in New York City on April 29th, 1847 as grand-nephew to the classic American novelist-essayist Washington Irving and the New York State Supreme Court Justice, John Duer. John Wesley Powell (2nd USGS Director 1881-1894) noted in his memoriam of Dr. Irving (Powell, 1891) that in his youth, "Roland was subject to frequent and alarming attacks of illness, also to a weakness of sight, which proved to be his greatest obstacle through life" and as such "his early education was at home, his sisters and his father being his instructor". Ultimately, he enrolled at Columbia College School of Mines in 1863, and with the continued help of his sisters, he graduated in 1868 with a degree in mining engineering. During and after his time at Columbia, he worked for coal mines and smelters in Pennsylvania and New Jersey. In 1870, he was offered a mining and metallurgy chair position at the University of Wisconsin.

Irving's arrival at the University of Wisconsin in 1870 marked the emergence of the "Wisconsin School of Precambrian Geology" (Dott, 2001). He quickly gained prominence within the university as a faculty leader and outside the university as a research investigator (Curti and Carstenson, 1949). Soon after his arrival, the Wisconsin Geological Survey was established by the legislature in 1873 with Irving, T.C. Chamberlain, and Moses Strong serving assistant geologists. By 1876, Chamberlin took the reins as chief geologist of the survey, a position he would hold until its legislative termination in 1879. In 1880, Clarence King, first director of the US Geological Survey, recruited both Chamberlin and Irving to join the USGS in an effort to develop a geologic map of the entire United States. In 1881, Chamberlin was appointed director of the Glacial Division of the USGS. In 1882, Irving was appointed to head the USGS's Lake Superior Precambrian Division, all the while continuing as head of the Department of Mineralogy and Geology at the University of Wisconsin.

During Roland Irving's teaching and research time with the University of Wisconsin, the Wisconsin Geological Survey and the USGS, he came to mentor and collaborate with several notable geologists who would make their own mark on Lake Superior geology (Dott, 2001). Charles Van Hise arrived at UW as a geology student under Irving's supervision in 1874. He completed his BS in 1879, his MS in 1882, and his PhD in 1892 (1st PhD at UW). With the passing of Dr. Irving in 1888, Van Hise became not only the principal geologist for the USGS's Lake Superior Division, but also the head of Wisconsin's geology department. Another notable student of Roland Irving's at Wisconsin was Florence Bascom. She conducted a petrographic study of the Mellen Complex under the supervision of Irving and Van Hise and received the second ever MS degree in geology from UW in 1887. She later earned her doctorate degree from Johns Hopkins in 1893, the first woman in the US to be awarded a PhD in geology.

Irving's work with the Wisconsin Geological Survey (1873-1879) involved many aspects of Wisconsin geology. In Volume 1 (actually published last in 1883), which was intended to be a general summary of the geology, natural history and economic geology of the state for the general education of the public, Irving contributed chapters on the minerals, rock types, and iron ores of the state. In Volume 2 (1877), Irving reported on the Precambrian, Paleozoic, and Quaternary geology of central Wisconsin. His descriptions of the general structure and lithologic attributes of the Baraboo Quartzite and its unconformable relationship with adjacent "Silurian" (Paleozoic) rocks is particularly noteworthy. Volume 3 (1880), which focussed on the geology of Northern Wisconsin, included Irving's summary report on the general geology of the Lake Superior region (Part 1) and a more detailed report on the geology of the eastern Lake Superior District (Part III). This work, which was based on field studies conducted between 1875 and 1878, formed the basis of his subsequent USGS work detailing the overall geology and structure of the Keweenawan System in the Lake Superior region. It is noteworthy that the renown petrographer, Raphel Pumpelly, contributed a chapter on the petrography of Keweenawan rocks (Part II) collected by Irving and others. Irving relied heavily on petrographic examination of field samples in his subsequent USGS work. In the final volume (#4, 1882) devoted to the geology, paleontology, natural history, and glacial geology of the southern half of the state Irving's contribution focussed on the field and petrographic attributes of crystalline rocks of the Wisconsin River valley. He recruited his MS student, Charles Van Hise, to carry out most of the petrographic descriptions.

Joining the US Geological Survey in 1880 as head of the Lake Superior Precambrian Division, Irving took advantage of being able to explore beyond the confines of Wisconsin and immediately embarked on his long-standing desire to produce a "resume of the results obtained in the Lake Superior country by other geologists up to the present" (Geology of Wisconsin, Volume III (1880) Part 1, p. 3). Building on his own studies of the Keweenawan System in northern Wisconsin, he reviewed and, where appropriate, integrated all former geologic studies in the Lake Superior dating back to the Michigan surveys of Douglass Houghton (1831-1844), the surveys of Upper Canada starting with Logan (1846), and the work of Joseph Norwood in northeastern Minnesota as part of the D.D. Owen US Survey (1847-1852). Between July 1880 and March 1882, Irving conducted reconnaissance mapping, along with a crew of five assistant geologists, in several poorly understood areas throughout the Lake Superior basin.

In 1880, the Minnesota Geological Survey, headed by N.H. Winchell, was in its 9th year of existence, but had only just begun to map the Precambrian geology of the state. As such, Irving decided to spend much of his mapping efforts on the north shore of Lake Superior between Duluth and Nipigon Bay to ascertain how it correlated with the south shore. This occurred at a time when many frontier states were developing their own geologic surveys with the expressed purpose of excluding the federal survey. The USGS already had a strong foothold in Michigan and after the ending of the Wisconsin survey in 1879, developed a strong presence there as well. Suffice it to say that Irving's work in Minnesota was not well received or valued by the Winchell's Minnesota Survey.

Notwithstanding Winchell objections, Irving's publication of USGS Monograph 5 - *The Copper-bearing Rocks of Lake Superior* (Irving, 1883) proved to be a remarkably complete and accurate picture of the geology and structure of Keweenawan System (Figure 1). The many important observations and interpretations about Keweenawan geology put forth by Irving include:

- formalizing the lithostratigraphy of the Keweenawan System
- defining the synclinal structure of the lavas in the Lake Superior area
- recognizing that eruptive rocks consist of basic, intermediate, and felsic types
- noting no obvious relation of volcanic type to stratigraphic position
- interpreting that basic lavas were erupted subaerially from fissures, not ash-generating volcanoes
- recognizing that amygdaloidal zones capping basalts are themselves volcanic (not sedimentary)
- accurately estimating the thickness of the North Shore Volcanics to be about 18,000'
- interpreting gabbroic and granitic rocks to be intrusive into the volcanic rocks (thus younger) and likely formed in staging chambers that fed surface eruptions

Following on the publication of Monograph 5, Irving continued to apply his geologic and petrographic expertise to studies of other Precambrian systems (greenstones, quartzites, and iron formations) in collaboration with students and USGS colleagues. When Roland Irving unexpectedly died (from "paralysis", perhaps a stroke) on May 30, 1888, he was engaged with Van Hise on another USGS monograph (#19) on the Gogebic Iron Range, which was published posthumously (Irvine and Van Hise, 1892). This monograph launched Charles Van Hise on a career path to becoming an internationally recognized expert on Lake Superior iron formations. While Van Hise will ultimately be recognized as pioneer of Lake Superior geology, it is fitting that we first acknowledge the remarkable accomplishments of his advisor and mentor, Roland Duer Irving. One can only imagine the professional stature he would have attained were he not struck down at the peak of his creativity and expertise.

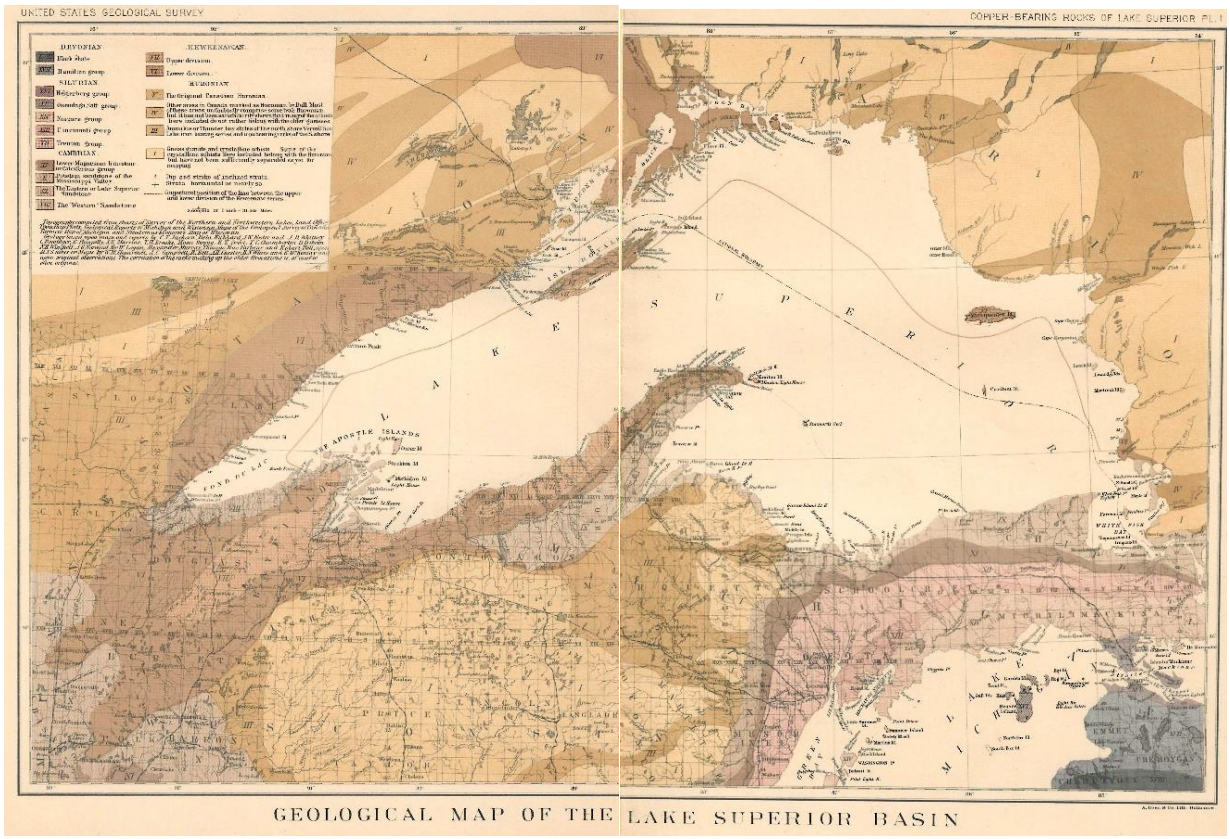


Figure 1: Plate 1 of USGS Monograph 5 by R.D. Irving, 1883

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Citation by:

James Miller
University of Minnesota-Duluth

In Memoriam
Louis Mattson



Obituary 12/31/2023

Louis A. Mattson, 89, of Pengilly, MN. passed away December 31, 2023, in Grand Rapids, MN. He was a long-time member of the Institute on Lake Superior Geology.

The son of commercial fishermen, Lou was the last surviving member of the Mattson Tobin Harbor Fishery on Michigan's Isle Royale. The fishery on Isle Royale, and family homesteads settled in the 1890's at Larsmont, and the French River on Minnesota's North Shore were part of Lou's DNA. If you knew Lou, you knew about the family legacy on Lake Superior.

The landscape of northern Minnesota inspired Lou to pursue a BS in Geology from the University of Minnesota Duluth and an MS in Geology from the University of Minnesota and the Colorado School of Mines. This education would lead to a 30-year career highlighted by travel around the world while working for M.A. Hanna's Minerals Research Laboratory in Nashwauk.

Lou's sharp mind did not rest in retirement. He extensively researched family genealogy culminating in connections with relatives in Larsmo, Finland, enhanced his boat collection at the home he and Peggy built on Swan Lake, supported the Isle Royale Friends and Family Association (IRFFA).

Eisenbrey Student Travel Awards

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 end of the annual meeting.

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. "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 2023, the ILSG Board of Directors selected two students to be granted research funding of $500 each from the Joe Mancuso Student Research Fund. The awardees were:

Adrian Perez Avila
Lakehead University
TOPIC*: Characterization of the host rocks to mineralization in the Shebandowan greenstone belt in the vicinity of the Moss Lake deposit, NW Ontario*

Zsuzsanna P. Allerton
University of Minnesota- Twinn Cities
TOPIC*: Investigate the timing and genesis of massive and semi-massive hematite ore bodies located in the Neoarchean (~2.7 Ga) Lake Vermilion/Soudan Underground Mine State Park (SSP)*

Braxton Murphy
Michigan Technological University
Department of Geological and Mining Engineering and Sciences
TOPIC*: Determine the relative paleostress state and tectonic conditions that resulted in formation and* movement of faults making up *the Keweenaw fault system near Houghton, Michigan, USA.*

Farhan Ahmed Bhuiyan
University of Minnesota- Duluth
TOPIC*: Evaluating post-depositional mineral reactions in the 1.71 – 1.47 Ga Freedom Formation, Baraboo, WI*

Doug Duskin Student Paper Awards

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.

2024 Student Paper Awards Committee

Stacy Saari – Minnesota Department of Natural Resources (Committee Chair)

Paula Leier-Englehardt – HydroGeo Solutions LLC, Wisconsin

Dan Hirvi – Consulting Geologist, Michigan

Allison Severson – Minnesota Geological Survey

Board of Directors

Theodore J. Bornhorst, Chair (2024-2027) — Michigan Technological University

Carysn Ames (2023-2026) — Wisconsin Geological and Natural History Survey

Mike Easton (2022-2025) — Ontario Geological Survey

Mark Smyk (2019-2024) — Lakehead University

Peter Hollings Secretary (2019-2024) — Lakehead University

Mark A. Jirsa Treasurer (2022-2025) — Minnesota Geological Survey

Board member through the close of the meeting year shown in parentheses.

2024 ILSG Meeting Michigan Tech Volunteers

Great Lakes Research Center

Daniel J. Lizzadro-McPherson

Student Volunteers: Affiliated with Michigan Tech

Jhuleyssy Liesseth Sánchez Aguilar

Gabriel Ahrendt

Katherine Langfield

Marie, Lansbery

Braxton Murphy

Abe Stone

2024 ILSG Meeting Session Chairs

Allan Blaske, GEI Consultants

Amy Radakovich Block, Minnesota Geological Survey

Patty Cobin, A. E. Seaman Mineral Museum, Michigan Tech

Mary Louise Hill, Lakehead University

Allan MacTavish, AGC GeoConsulting

Ashley Quigley, Michigan Geological Survey

Bernie Saini-Eidukat, North Dakota State University

Mark Smyk, Lakehead University

Field Trip Leaders and Guidebook Authors

Field trips have been the mainstay of the ILSG since its inception 70 years ago. We give special thanks to the field trip leaders and guidebook authors who volunteered their time and talent in carrying that tradition forward.

Trip 1: *Mesoproterozoic Midcontinent Rift-filling Strata and Native Copper Deposits of the Keweenaw Peninsula, Michigan*

Ted Bornhorst (Michigan Tech)

Trip 2: *Mining History and Geology of the Quincy Mine, Keweenaw Peninsula Native Copper District, Michigan*

Tom Wright (Quincy Mine Hoist Association)

Jim DeGraff and Ted Bornhorst (Michigan Tech)

Trip 3: *Geoheritage of Buffalo Reef: Industrial Impact on Land, Culture, and Fish Sovereignty*

Erika Vye, Charlie Kerfoot (Michigan Tech)

Stephanie Swart (Michigan Department of Environmental Quality)

Dione Price and Evelyn Ravindran (Keweenaw Bay Indian Community)

Trip 4: *Keweenaw Fault Geometry and Kinematics: Clues to Its Nature and Origin*

Jim DeGraff, Katherine Langfield, and Dan Lizzadro-McPherson (Michigan Tech)

Trip 5: *Adventure Mine, Ontonagon County, Michigan: Geology and History of a Native Copper Mine*

Matt Portfleet (Adventure Mining Company)

Ted Bornhorst (Michigan Tech)

Trip 6: *Southern Complex Granitoids, Gneisses and Migmatites: New Data, Discoveries, and Perspectives*

Chad Deering (Michigan Tech)

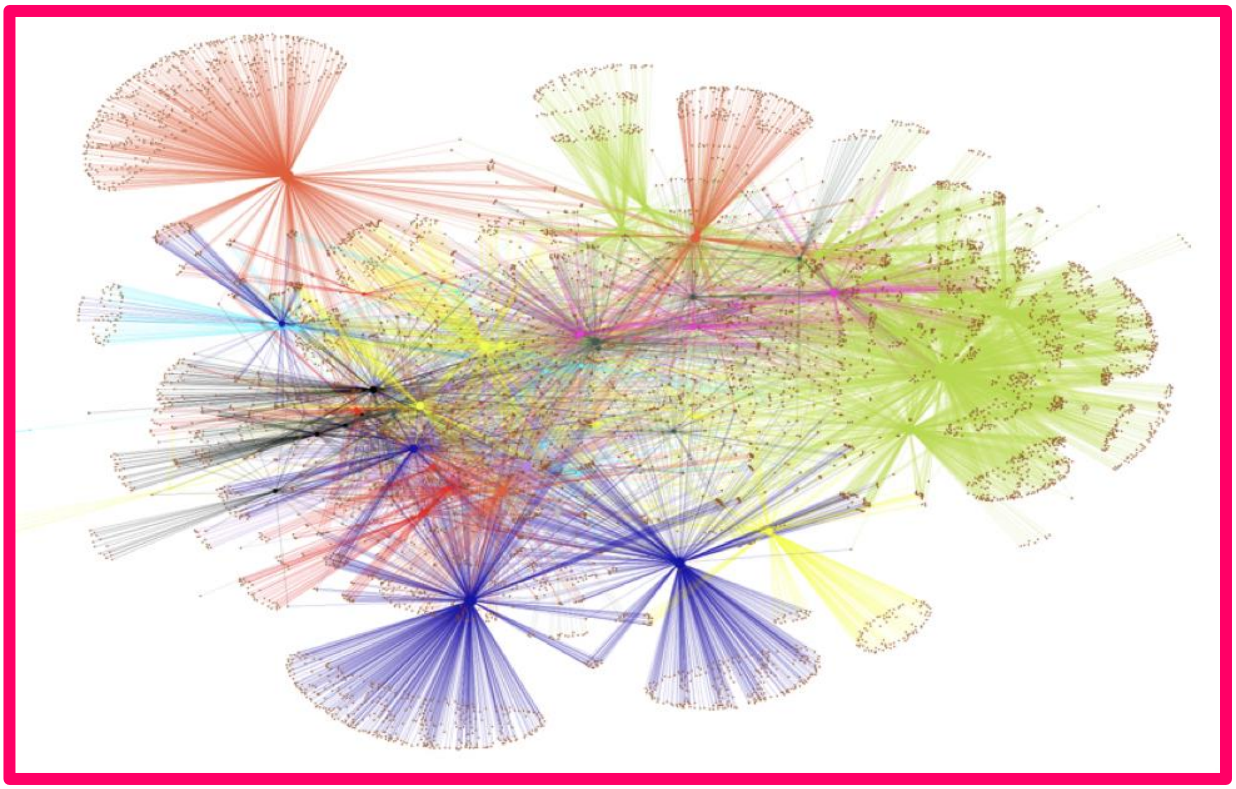
Trip 7: *Landslides in the Glacial Lake Ontonagon Sediments*
Stan Vitton and Mohammad Sadeghi (Michigan Technological University)

Mineral Informatics: A New Frontier in Understanding Earth

Robert M. Hazen

Banquet Speaker
Senior Staff Scientist, Earth and Planets Laboratory
Carnegie Institution for Science, Washington, DC 20015
Email: rhazen@carnegiescience.edu

The story of Earth is a 4.5-billion-year saga of dramatic transformations, driven by physical, chemical, and biological processes. The co-evolution of life and rocks unfolded in an irreversible sequence of evolutionary stages. Each stage re-sculpted our planet's surface, while introducing new planetary processes and phenomena. This grand and intertwined tale of Earth's living and non-living spheres is coming into ever-sharper focus, thanks to advances in "mineral informatics" - a field that employs large and growing mineral data resources to tell the deep-time stories of our evolving planet. Minerals are remarkably information rich, holding dozens of trace and minor elements, scores of stable isotopes, solid and fluid inclusions, chemical zoning, twinning, exsolution, countless defects, and a host of optical, magnetic, electrical, and other properties. Every mineral specimen is a time capsule waiting to be opened—waiting to tell its story. This lecture will explore some of the advanced data analytical and visualization methods that are shining new light on the old field of mineralogy, while revealing in ever greater clarity the co-evolution of the geosphere and biosphere.



A network diagram of all known minerals colored by the way the minerals form. For example, red indicates high-temperature igneous minerals, while green indicates minerals formed by life.

REPORT OF THE 69th ANNUAL MEETING OF THE INSTITUTE ON LAKE SUPERIOR GEOLOGY

Robert Lodge (University of Wisconsin-Eau Claire), Esther Stewart, and Carsyn Ames (Wisconsin Geologic and Natural History Survey) hosted the 69th Annual Institute on Lake Superior Geology on April 23 – 26, 2023 at the Lismore Hotel and Conference Center in Eau Claire, Wisconsin. The meeting consisted of two days of technical sessions with pre- and post-technical session field trips.

First, we would like to thank the meeting sponsors for their generous support, either through direct funding or in-kind support, namely: Talon Metals, American Institute of Professional Geologists, Geological Society of Minnesota, Crystal Cave, and Visit Eau Claire. We also thank the Individual Contributors to the Student Travel Scholarship fund: Val Chandler, Jim DeGraff, Thomas Erickson, Tom Fitz, Dave Good, Bob Mahin, Gordon Medaris Jr., Jim Miller, Steven Pinta, Tod Roush, and Gerry White.

The 2023 meeting was the first conference held in the US since the 2018 Iron Mountain meeting, the first in Wisconsin since the 2011 Ashland meeting, and the first meeting in Eau Claire since 1991. Total meeting registration was 126, including 19 students. Attendance from both Canadian and United States was excellent despite other conferences in the Lake Superior region in April and May (GAC-MAC, Sudbury; Northcentral GSA, Grand Rapids). The technical program was nevertheless excellent with a good array of topics from Archean and Paleoproterozoic geology, to Midcontinent Rift geology and mineralization, to Quaternary Geology, Geoscience Education and Geoheritage. In addition, a student-industry networking lunch was held at the Riverview Room in the Eau Claire Public Library and an evening social was held at Reboot Social.

Proceedings Volume 69 was published in two parts. Part 1 – Program and Abstracts, compiled and edited by Carsyn Ames (WGNHS) contains 54 published abstracts for 34 oral and 19 poster presentations. Students presented 8 oral and 10 poster presentations. Part 2 – Field Trip Guidebooks, was compiled and edited by Robert Lodge (UWEC). It contains descriptions of two pre-meeting and two post-meeting field trips. Hard copies of the Abstract Volume and Field Trip Guidebooks for trip participants were printed by University Printing at the University of Wisconsin-Eau Claire. Both volumes are available for download from the Institute on Lake Superior Geology website.

The 69th ILSG marked only the third time in the Institute's long history that its annual meeting was held in Eau Claire, the last time being in 1991. Plans for another Wisconsin-based ILSG meeting had been discussed for a while. With recent work in the Paleoproterozoic geology and mineralization in the Penokean orogen in northwestern Wisconsin and the central location of Eau Claire, it seemed appropriate to host the meeting there. Eau Claire sits on the boundary between Precambrian Shield, Paleozoic Platform, and the terminus of the continental ice sheet and allowed organizers to host four field trips examining billions of years of geologic history. Two field trips focused on the Precambrian geology of the Penokean orogen exposed in the Chippewa and Eau Claire River Valleys. While the preconference field trip got to see historic flooding on the Chippewa River (there are not many days when a bunch of Precambrian geologists are

looking at the river rather than the rocks), waters receded for the post-conference field trip. Field stops on this trip were originally (in some cases, exclusively) described in previous ILSG meetings (Eau Claire, 1980; 1991) but benefitted from new research and analyses and new viewpoints on the tectonics and metallogeny of the region. One fieldtrip visited classic exposures Paleozoic stratigraphy around the Eau Claire and Menominee regions and enjoyed lunch in an ancient meteorite impact structure. One field trip visited Quaternary geology and fluvial geomorphology of the Chippewa River valley. All the field trips, and the meeting itself, were blessed with good weather. Total field trip participation was 116 (excluding leaders and volunteer drivers). A list of field trips is provided below:

<u>Pre-meeting field trips (and leaders) on Tuesday, April 23.</u>

1) Precambrian Geology of the Chippewa River valley: A Transect through the Marshfield Terrane
   (Robert Lodge, Bob Hooper, UW-Eau Claire)
2) Wisconsin's Paleozoic stratigraphy and tour of Crystal Cave
   (Carsyn Ames, Esther Stewart, Bill Batten, Eric Stewart, Ian Orland, WGNHS)

<u>Post-meeting field trips (and leaders) on Friday, April 26.</u>

3) Precambrian Geology of the Eau Claire River valley: Re-discovering the Eau Claire Volcanic Complex
   (Robert Lodge, Evan Weber, Bob Hooper, UW-Eau Claire)
4) Quaternary Geology and Geomorphology of the Eau Claire Region
   (Doug Faulker, UW-Eau Claire; Elmo Rawling, WGNHS; Phil Larson, Minnesota State University, Mankato)

Many registrants attended the welcoming reception on Tuesday evening. Furthermore, 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 2023 annual meeting, or in the previous 4 years!

As always, a highlight of the post-banquet activities was presentation of the 2023 Goldich Medal. This year's very deserving recipient was Dr. Pete Hollings. The Goldich Medal citation was presented by Mark Smyk, his colleague for many years. Mark described Pete's many contributions to the ILSG, to the greater understanding of Archean and Proterozoic geology of the Lake Superior region, and his commitment to students. Pete is indeed a worthy recipient of this prestigious award.

The 69th ILSG continued the post-banquet guest speaker tradition. Curt Meine, a conservation biologist, historian, and writer from the Aldo Leopold Foundation and Center for Humans and Nature, gave a presentation entitled *Imagining "Conservation Geology": Lessons from the Driftless Area*. His talk provided an insightful viewpoint of how geology and landscapes integrate with history and culture in the Driftless Area of central Wisconsin.

In 2023, the student paper committee remarked on the high quality of student research across all participants and had a difficult time of selecting the best among the excellent oral and poster presentations. The committee awarded four prizes for the best oral and poster presentations by

both undergraduate and graduate students. The best graduate oral presentation was awarded to Justin Jonsson and his talk on "*Petrogenesis of the mineralized horizons in the Offset and Creek zones, Lac des Iles Complex, N. Ontario"*. The best undergraduate oral presentation was awarded to Blaize Briggs for his talk on "*Quetico-Wabigoon Subprovince Boundary in the Superior Province north of Thunder Bay, Ontario, Canada*". The best graduate poster presentation was awarded to Fransisca Nunez Ferreira for her poster on "*Morphometry and formation process of eskers developed under the Chippewa Lobe of the Laurentide Ice Sheet".* The best undergraduate poster presentation was awarded to Lillian Glodowski for her poster on "*Characterizing volcanic host stratigraphy and syn-volcanic intrusions at the Lynne Zn-Pb-Cu deposit, Oneida Co., Wisconsin".* Eisenbrey Student Travel Grants were given to twelve students: Zsuzsanna Allerton, Ryan Barkley, Blaize Briggs, Tianna Groeneveld, Justin Jonsson, Daniel Lizzardo-McPherson, Francisca Nunez Ferreira, Jordan Peterzon, Sam Ghantous, Madeline Taylor, BJ Itai, and Katherine Langfield.

The Institute's Board of Directors met on Thursday, April 25, 2023, and a brief overview of the meeting notes is provided below:

1. Accepted report of the Chairs for the 68th ILSG, as published in the Proceedings volume, and minutes of last Board meeting, May, 2022 (Hollings)
2. Received, discussed, and accepted 2022-2023 ILSG Financial Summary (Jirsa).
3. Received, discussed, and accepted 2022-2023 report of the Secretary (Hollings).
4. Approved Carsyn Ames as on-going ILSG Board member
5. Discussed and approved Amy Radakovich Block as Assistant Treasurer in a non-voting role (end of term 2026).
6. Discussed and approved replacing Steve Kissin as the "member from academia" on Goldich Committee (end of term 2023) with Marcia Bjornerud
7. Approved Houghton as the site for the 70th annual ILSG meeting. The meeting will be hosted by Ted Bornhorst.
8. Discussed the role of the Michigan Tech archives as the host of hard copies of the publications of the Institute. A formal agreement has been signed with the Archives who will request financial support as needed rather than the previous model of providing a donation of $1 per attendee.
9. A number of future meeting locations were discussed. Peter Hinz has offered Kenora as a future site and Mark Jirsa is keen to host the Mountain Iron meeting that was cancelled due to the pandemic. Bernie Saini-Eidukat to be approached to see if he is still interested in organizing a meeting in St Cloud.
10. The cost of insurance was again discussed and it was agreed that the Board of Directors insurance should be maintained and that the costs would be included in the cost of each meeting. Given the high costs quoted for field trip insurance the Board to investigate field trip insurance options. Hollings to approach GAC. Amy to approach GSA and Carsyn to approach a risk advisor. The Board discussed embedding a Liability waiver in the registration process.
11. The Board discussed embedding a photo release in the meeting and/or field trip registration process such that anyone registering for the field trip is aware they are agreeing to be photographed and have their image used in ILSG publications/website etc. It was agreed that the Institute does not want to turn anyone away from the meeting/trips simply because

they do not want to be photographed, and the result is that before any photos are uploaded to the website, someone on the Board (or a future social media position) will need to go through the photos and make sure that no one who has NOT signed a photo release is shown in a shot where they are identifiable.

The 69th ILSG meeting was a great success, and we wish to thank all the people who contributed to that success, field trip leaders and drivers, UWEC student volunteers, and businesses and organizations in downtown Eau Claire that hosted and entertained visitors. Patty Cobin and Ted Bornhorst (A.E. Seaman Mineral Museum, Michigan Technological University) handled the pre-meeting registration and supplied the poster boards. Thanks also go to the staff at Lismore Hotel and Conference Center who helped the meeting and banquet run smoothly and providing lunches and snacks during the technical sessions. Thanks to Eau Claire Public Library for hosting our student-industry luncheon, Reboot Social for hosting our post-meeting evening social, Eau Claire Cheese and Deli for field trip lunches, and Eau Claire Student Transit for bus transportation for fieldtrips.

Robert Lodge (UWEC), Carsyn Ames (WGNHS), and Esther Stewart (WGHNS)

Co-Chairs, 69th Institute on Lake Superior Geology

Donations to Support Student Participation at the Annual Meeting of the Institute on Lake Superior Geology

Eagle Mine
lundin mining

A SPECIAL THANK YOU TO OUR INDIVIDUAL CONTRIBUTORS

Roger Anderson

Wouter Bleeker

Terry Boerboom

Ted Bornhorst

Alex Brown

Michael Carr

Val Chandler

Kate Clover

Abraham Drost

Thomas Erickson

Annia Fayon

Mary Louise Hill

Aaron Hirsch

Allan MacTavish

Bob Mahin

Gordon Medaris Jr.

Jim Miller

Rick Sandri

Isabel Serrano

Mark Severson

Jim Small

Gerry White

Graham Wilson

TECHNICAL PROGRAM

Wednesday May 15, 2024

All field trips begin and end at the Michigan Tech Memorial Union Building

Parking tickets are given between 7 am to 4 pm weekdays.

Between ticketing hours all vehicles need a parking pass; these will be available from trip leaders.

Pre-meeting Field Trips May 15, 2024

8:00 am - 5:00 pm **PRE-MEETING FIELD TRIPS**

Trip 1: *Mesoproterozoic Midcontinent Rift-filling Strata and Native Copper Deposits of the Keweenaw Peninsula, Michigan*
Ted Bornhorst (Michigan Tech University)

Trip 2: *Mining History and Geology of the Quincy Mine, Keweenaw Peninsula Native Copper District, Michigan*
Tom Wright (Quincy Mine Hoist Association),
Jim DeGraff, Katherine Langfield, and Ted Bornhorst (Michigan Tech)

Trip 3: *Geoheritage of Buffalo Reef: Industrial Impact on Land, Culture, and Fish Sovereignty*
Erika Vye and ***Charlie Kerfoot*** (Michigan Tech)
Stephanie Swart (Michigan Department of Environmental Quality)
Dione Price and Evelyn Ravindran (Keweenaw Bay Indian Community)

Wednesday evening May 15, 2024

4:00 pm - 8:00 pm **Registration** (2nd floor, Michigan Tech Memorial Union)

6:30 pm - 8:30 pm **Poster Setup and Viewing** (2nd floor, Michigan Tech Memorial Union)

6:30 pm - 8:30 pm **Welcoming Reception** (2nd floor, Michigan Tech Memorial Union)

* Denotes a student eligible for Best Student Paper Award. To be eligible students must have graduated no more than one month before the ILSG meeting, be first author, and present the paper at the meeting
+ Denotes author that will present the paper if different than the first author.

Thursday - May 16, 2024

All vehicles need a parking pass between 7am to 4pm weekdays; these will be available from registration

7:15 am - noon **Registration** (2nd floor, Michigan Tech Memorial Union)

8:15 am **OPENING REMARKS** (2nd floor, Michigan Tech Memorial Union)
Ted Bornhorst, Erika Vye, Patty Cobin, and Jim DeGraff
Co-Chairs, 2024 ILSG

TECHNICAL SESSION I – ORAL PRESENTATIONS

***Session Chair:** Mark Smyk*

8:20 **Jim MILLER**
Roland Duer Irving - Pioneer of Lake Superior geology

8:35 **Graham WILSON, Charles BUTT, Robert GARRETT and Heather ROBINSON**
R.W. Boyle's History of Geochemistry and Cosmochemistry

8:55 **James DeGRAFF, Nolan GAMET, Katherine LANGFIELD, Daniel LIZZADRO-McPHERSON, Sophie MUELLER, and Colin TYRRELL**
Transpressional Nature of the Keweenaw Fault System, Lake Superior Region, and Its Relationship to Grenville Orogenesis

9:15 **Alex BROWN**
Re-interpretation of hydrothermal alteration, mineralization and host-rock oxidation to form the Keweenaw native copper lodes, northern Michigan

9:35 **Esther STEWART, Michael TAPPA, Ann BAUER, Anthony PRAVE, and Latisha BRENGMAN**
Geochemical fingerprints from the late Mesoproterozoic epeiric seaway of the Nonesuch Formation, Wisconsin and Michigan, USA

9:55 **END OF TECHNICAL SESSION I**

9:55-10:10 COFFEE BREAK

TECHNICAL SESSION II – ORAL PRESENTATIONS

Session Chair: Ashley Quigley

10:10 **Sarah GORDEE, Madison RIAN, Stacy SAARI, and Matthew CARTER**
Description and application of the Consolidated Minerals Database to support geological investigations: an example from the Cuyuna Range, central Minnesota

10:30 **Stacy SAARI, Sarah GORDEE, Madison RIAN, and Matt CARTER**
Compiled historical drillhole and geochemical data from the Cuyuna Range, Minnesota, provides powerful new insights for geological and mineral potential investigations.

10:50 **Bob MAHIN, Ashley QUIGLEY, John YELLICH, John ESCH, and Nolan GAMET**
Critical Mineral Systems in the Upper Peninsula of Michigan, A Cooperative Effort Between the USGS and the Michigan Geological Survey

11:10 **Paul BEDROSIAN, Dana PETERSON, and Bennett HOOGENBOOM**
Geophysical imaging of the Paleoproterozoic Animikie basin in Minnesota

11:30 **Dan HOLLIS**
Use of Ambient Noise Tomography for Mineral Exploration in the Lake Superior Region

11:50 **END OF TECHNICAL SESSION II**

11:50-1:10 LUNCH BREAK and ILSG BOARD OF DIRECTORS MEETING
- lunches not provided to conference attendees-

TECHNICAL SESSION III- ORAL PRESENTATIONS

Session Chair: Mary Louise Hill

1:10 ***Demily THIBODEAU-BELLO, Mary Louise HILL, Andrew CONLY,**
An evaluation of structural and mineralogical controls on gold mineralization on the GoldRich property in the Abbie Lake area, Wawa, Ontario

1:30 **Dean PETERSON and Alex STEINER**
The geology and ore deposit model of the high-grade Emily Manganese Deposit, Cuyuna Range, Minnesota: Results from the 2023 drilling program

1:50 ***Gabriel AHRENDT and Aleksey SMIRNOV**
Rock magnetic investigation of the Vulcan Iron Formation: Unveiling Paleoproterozoic Paleoenvironments

2:10 ***Zsuzsanna ALLERTON, George HUDAK, Christian TEYSSIER, Annia FAYON, Martin DANIŠIK, Liam COURTNEY-DAVIES, and Phillip LARSON**
Geochronology and geochemistry of hematite ore in northeastern Minnesota

2:30 **Joyashish THAKURTA and Beau HAAG**
Sulfur-isotope ratios in Paleoproterozoic Michigamme Formation at the Lake Superior Region: Implications on basin evolution and ambient seawater composition in the Greater Animikie Basin

2:50 ***Jordan PETERZON, Noah PHILLIPS, Pete HOLLINGS, and Lionnel DJON**
Deformation conditions, micromechanics, and fault zone development in mafic protoliths at the Lac des Iles mine, northwestern Ontario

3:10 **END OF TECHNICAL SESSION III**

3:10-3:30 COFFEE BREAK

TECHNICAL SESSION IV – POSTER PRESENTATIONS

Session Chair: Allan Blaske and Patty Cobin

3:30-5:00 **AUTHORS PRESENT AT THEIR POSTERS**

5:00 **END OF TECHNICAL SESSION IV**

Thursday evening May 15, 2024

6:00 pm **RECEPTION AND CASH BAR** (2nd floor, Michigan Tech Memorial Union)

7:00 pm **ANNUAL BANQUET** (2nd floor, Michigan Tech Memorial Union)

2024 Goldich Medal Recipient: Suzanne W. Nicholson

Banquet Speaker: Robert M. Hazen, Carnegie Institution for Science

"Mineral Informatics: A New Frontier in Understanding Earth"

Friday - May 17, 2024

All vehicles need a parking pass available from co-chairs

8:15 **INTRODUCTORY REMARKS AND UPDATES** (2nd floor, Michigan Tech Memorial Union)
Ted Bornhorst, Erika Vye, Patty Cobin, and Jim DeGraff
Co-Chairs, 2024 ILSG

TECHNICAL SESSION V – ORAL PRESENTATIONS

Session Chair: Bernie Saini-Eidukat

8:20 ***Farhan Ahmed BHUIYAN, Latisha BRENGMAN, and Esther STEWART**
Assessing depositional and post-depositional mineral associations in the <1.71 Ga Freedom Formation, Baraboo, WI, USA.

8:40 **Jack MALONE, Ryan CLARK, Amira HARRIS-BOMMARITO, and David MALONE**
Baraboo Interval Quartzites in Iowa: Reassessing the Origin and Provenance of the Washington County Quartzite, SE Iowa

9:00 **Gordon MEDARIS, Chloe BONAMICI, Phil BROWN, Laurel GOODWIN, Brian JICHA, Brad SINGER, Michael SPICUZZA and John VALLEY,**
The Evolution of Baraboo Interval Sedimentary Rocks: Deposition at 1.63 Ga and Metamorphism at 1.47 Ga

9:20 **Amy Radakovich BLOCK, George HUDAK, and Kate SOUDERS**
Insights into the southwestern Superior Province: New igneous geochronology and geochemistry in northwestern Minnesota, USA

9:40 **Ryan CLARK, David PEATE, Allison KUSICK, Kenny HORKLEY, and Chris MACFARLANE**
*Baddeleyite age reveals timing of the Northeast Iowa Intrusive Complex (NEIIC***)**

10:00 **END OF TECHNICAL SESSION V**

10:00-10:20 COFFEE BREAK

TECHNICAL SESSION VI – POSTER PRESENTATIONS

Session Chair: Allan Blaske and Patty Cobin

10:20-11:40 **AUTHORS PRESENT AT THEIR POSTERS**

11:40 **END OF TECHNICAL SESSION VI**

11:40-1:00 LUNCH BREAK

TECHNICAL SESSION VII – ORAL PRESENTATIONS

Session Chair: Allan MacTavish

1:00 **Jim MILLER and John GREEN**
Two decades of teaching the geologic heritage of Minnesota's North Shore at the North House Folk School, Grand Marais

1:20 **Erika VYE, Daniel LIZZADRO-MCPHERSON, and James JUIP**
The Keweenaw Geoheritage Summer Internship Experience

1:40 **Eric NOWARIAK, S, Allison SEVERSON, and Amy Radakovich BLOCK**
Lithostratigraphy and Geochronology of the Lower Northeast Sequence of the North Shore Volcanic Group, Cook County, MN, USA

2:00 **Pete HOLLINGS and Mark SMYK**
New Insights into the Geology and Geochemistry of the Osler Group and Related Rocks, Midcontinent Rift System, Northern Lake Superior, Ontario

2:20 **David GOOD**
MCR Synthesis 1. Characterizing the MCR mantle plume

2:40 **END OF TECHNICAL SESSION VII**

2:40-3:00 COFFEE BREAK and TAKE DOWN POSTERS

TECHNICAL SESSION VIII – ORAL PRESENTATIONS

Session Chair: Amy Radakovich Block

3:00 **Bill ROSE and James DeGRAFF**
Lidar Topography: Bright opportunity for reading Keweenaw Landscapes

3:20 **Wouter BLEEKER, Natasha WODICKA, Sandra KAMO, Michael HAMILTON, Quinn EMON, and Jennifer SMITH**
The Lake Superior area "event layer": Testing the connection with the Sudbury impact

3:40 **Tien GRAUCH, S. HELLER, Laurel WOODRUFF, and Esther STEWART**
Revisiting geophysical interpretations of the Midcontinent Rift below Lake Superior—Insights from GLIMPCE seismic-reflection line C

4:00 **Aaron HIRSCH**
Recent developments on the use of the Horizontal-to-Vertical Spectral Ratio (HVSR) passive seismic method to determine depth to bedrock in Minnesota

4:20 **END OF TECHNICAL SESSION VIII**

4:20 **Presentation of Student Awards**

Best Student Paper Awards – Stacy Saari
Student Travel/Participation Awards – Ted Bornhorst

4:40 **Concluding Remarks and Field Trips**

Ted Bornhorst, Erika Vye, Patty Cobin, and Jim DeGraff
Co-Chairs, 2024 ILSG

END OF TECHNICAL SESSIONS OF THE 70th ANNUAL MEETING

Friday Evening May 17, 2024

7 pm ATDC Building across the parking lot from the A.E. Seaman Mineral Museum

2024 Edith D. and E. Wm. Heinrich Lecture

"Mineral Evolution: A Case Study of a New Natural Law" by Robert M. Hazen

Sponsored by the Edith D. and E. Wm. Heinrich Mineralogical Research Foundation and the A. E. Seaman Mineral Museum

Saturday May 18, 2024

Field trips begin and end at the Michigan Tech Memorial Union

Parking pass not needed on weekend.

8:00 am – 5:00 pm **POST-MEETING FIELD TRIPS**

Trip 4: *Keweenaw Fault Geometry and Kinematics: Clues to Its Nature and Origin*
Jim DeGraff, Katherine Langfield, and Dan Lizzadro-McPherson (Michigan Tech)

Trip 5: *Adventure Mine, Ontonagon County, Michigan: Geology and History of a Native Copper Mine*
Matt Portfleet (Adventure Mining Company), ***Ted Bornhorst*** (Michigan Tech)

Trip 6: *Southern Complex Granitoids, Gneisses and Migmatites: New Data, Discoveries, and Perspectives*
Chad Deering (Michigan Tech)

Trip 7: *Landslides in the Glacial Lake Ontonagon Sediments*
Stan Vitton (Michigan Tech)

POSTER PRESENTATIONS

* Denotes a student eligible for Best Student Paper Award. To be eligible students must have graduated no more than one month before the ILSG meeting, be first author, and present the paper at the meeting
+ Denotes author that will present the paper if different than the first author.

Numbered Posters and Abstracts are in sequential order

Poster Number

1. ~~**Sheree HINZ**~~
withdrawn ~~*GeologyOntario: a powerful search tool for Ontario explorationists*~~

2. ~~**Therese PETTIGREW, Robert CUNDARI, Rebecca PRICE, and Manuel DUGUET**~~
withdrawn ~~*Identification of Fertile Parent Granitoid Units in the Superior Province of Ontario*~~

3. **Mia MORSON and + Shannon ZUREVINSKI**
Quartz trace element chemistry: Exploring the link between a fertile parental granite and a mineralized pegmatite

4. ***Kevin MEXIA, Pete HOLLINGS**
Geochemistry of Midcontinent Rift-related intrusive rocks of the Sunday Lake intrusion

5. ~~**Justin JONSSON, Paul MALEGUS, Sophie CHURCHLEY, and Rebecca PRICE**~~
withdrawn ~~*Characterizing the geochemistry and nickel-copper-platinum group elements potential of mafic and ultramafic intrusions in northwestern Ontario*~~

6. ***Andrea Paola CORREDOR BRAVO, Pete HOLLINGS, Matthew BRZOZOWSKI, and Geoff HEGGIE**
Magmatic and hydrothermal evolution of the Mesoproterozoic Current ultramafic PGE-Cu-Ni deposit within the Thunder Bay North Intrusive Complex: insights from trace elements, Nd, Sr, O, and H isotopes

7. **Max LAXER and + David GOOD**
Building a 3D model for Cu/Pd inflection points throughout the Marathon PGE-Cu Deposit

8. ***Vlad SHESHNEV, Pete HOLLINGS, Noah PHILLIPS, Ryan WESTON, Matt DELLER, and Dana CAMPBELL**
Geochemistry and Petrology of the Eagle's Nest Intrusion, McFaulds Lake Greenstone Belt, Northern Ontario

9. ***Yiruo XU and Robert HOLDER**
Cooling of an Archean metamorphic terrane: garnet diffusion study of the Quetico Subprovince, Canada

10. ***Clare BEAUDRY, Madelyn HESS, Cristian PEREIRA, and Bernhardt SAINI-EIDUKAT**
Petrology and geochemistry of Precambrian basement rocks in Walsh County, North Dakota

11. ***Cristian PEREIRA, Timothy NESHEIM, Jeffrey D. VERVOORT, and Bernhardt SAINI-EIDUKAT**
Major element geochemistry and first zircon U-Pb age dates of Precambrian basement rocks in eastern North Dakota

12. **Jamey JONES, Bill CANNON, Ben DRENTH,** and **Paul O'SULLIVAN**
Geologic and tectonic implications of detrital zircon U-Pb ages from the Dickinson Group in the western Upper Peninsula of Michigan, USA

13. **Bill CANNON, A. SOUDERS, Ben DRENTH, and Robert AYUSO**
The Sacred Heart Orogeny in Michigan: Latest Archean Granites and the Great Lakes Tectonic Zone

14. **A. SOUDERS, W. CANNON, B. DRENTH, R. SALERNO, J. THOMPSON, and P. SYLVESTER**
New LA-ICP-MS U-Pb geochronology of Archean rocks, central Upper Peninsula, Michigan, USA: a step toward refining the final assembly of the Superior craton

15. ***Zsuzsanna ALLERTON, Annia FAYON, George HUDAK, Christian TEYSSIER, Liam COURTNEY-DAVIES, and Martin DANIŠIK**
Geochronology campaign in northeastern Minnesota

16. **Ross SALERNO, Bill CANNON, Amanda SOUDERS, Jay THOMPSON**
Understanding the evolution of the upper Midwest Archean gneiss dome corridor using apatite, titanite, and monazite LA-ICP-MS U-Pb geochronology and microstructural analyses

17. ***Trent EDIGER and Marcia BJØRNERUD**
Glimpses of a Paleoproterozoic landscape: Analysis of exhumed topography on Archean basement rocks northwest of Marquette, Michigan

18. **Rebecca STOKES, Bill CANNON, and Ross SALERNO**
Characteristics of graphitization across a metamorphic gradient in the Michigamme Formation of the Marquette Trough and Baraga Basin, MI

19. **Tom BUCHHOLZ, Alexander FALSTER, and Wm. SIMMONS**
Preliminary mineralogy of a pegmatite in the pyroxene syenites of the Stettin Complex, Wausau Complex, Marathon County, Wisconsin

20. ***Katherine LANGFIELD, Nolan GAMET, James DeGRAFF**
*Cross-sectional Geometry of the Keweenaw Fault System between Hancock and Mohawk, Upper Peninsula of Michiga*n

21. ***Braxton MURPHY, Katherine LANGFIELD, and James DeGRAFF**
Geometry, Slip Kinematics, and Deformation along the Hancock Fault in the Quincy Mine Workings, Upper Peninsula of Michigan

22. ***Kenz CARLTON, Basil TIKOFF, and Esther STEWART**
The Honey Creek Structure, Sauk County, Wisconsin: Asymmetric Faulting Associated with Seismic-Induced Fluid Escape

23. ***Alex LAWRENCE, Adam VANDERKIN, and Robert LODGE**
Volcanic and Hydrothermal Reconstruction of the Paleoproterozoic Butler Zn-Cu occurrence, Clark County, Wisconsin

24. ***Lyndsie VICKERS, and Robert LODGE**
Petrology and Geochemistry of Felsic Magmatism in the Paleoproterzoic Eau Claire Volcanic Complex, Northcentral Wisconsin

25. ***Dan SHAKKED, Lucas ROBARGE, and Robert LODGE**
Analysis of deformation-related structures in the Eau Claire Volcanic Complex, Wisconsin

26. ***Gwendolyn MARTIN and Marcia BJØRNERUD**
Investigating the origin of pervasive breccias in the Paleoproterozoic Saunders Formation in northern Wisconsin

27. **Aaron HIRSCH, Emma SCHNEIDER**
Lithostratigraphic discrimination of Quaternary core in Minnesota using magnetic susceptibility

28. **Bill ROSE and Erika VYE**
Michigan Coastal Path: A Social Commitment to Geoeducation

29. **Bill ROSE and Erika VYE**
Jacobsville geoheritage is globally celebrated and locally loved

30. ***Alice MARTIN, Zsuzsanna ALLERTON, Emma JOHNSON, Annia FAYON, Jim ESSIG, Sarah GUY-LEVAR,George HUDAK**
The Soudan Geology Trail Project: Let's talk about rocks in northeastern Minnesota

A tribute to Jean Peterman Kemp Zimmer and Jeanne Seaman Farnum by the A.E. Seaman Mineral Museum: Trailblazers for Women in Geology

ABSTRACTS

Rock magnetic investigation of the Vulcan Iron Formation: Unveiling Paleoproterozoic Paleoenvironments

AHRENDT, Gabriel[1] and SMIRNOV, Aleksey[1,2]

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The Paleoproterozoic (~1.88 Ga) Vulcan Iron Formation, located in the Southwestern Upper Peninsula of Michigan, is a significant Superior-type Banded Iron Formation, comprising four main members. The lower, Traders Member is characterized by banded ferruginous-siliciclastic layers with distinct alternating layers of ferric iron. The middle, Brier Member is a fissile slate with varying concentrations of magnetite from low to locally enriched. The upper, Curry Member, is an oolitic iron formation enriched with specular hematite and lacking noticeable banding. In some locations, the Curry Member is overlain by the ferric slate referred to as the Loretto Member. We conducted comprehensive rock magnetic investigations of three lower formation members, using thermal demagnetization of natural remanent magnetization, magnetic hysteresis and first-order reversal curve measurements, and thermomagnetic analyses. Our findings suggest that the members may be genetically distinct, reflecting shifts in depositional regimes that dramatically affected their texture and mineralogy. The Traders Member, characterized by abundant small paramagnetic grains, likely formed during a period of rapid subsidence and soluble transport of ferrous iron into a euxinic basin, followed by alternating periods of CO2 fixing and sulphide-oxidizing cyanobacteria. The subsequent transition to a shallow, foreshortened basin as the Pembine-Wasau terrane accreted led to the increased silica saturation and local concentration of superparamagnetic ferrous iron mud, forming the Brier slate. A further evolution due to the flooding of a shallow sea inducing high turbidity and increased oxygenation in the water column, resulted in the formation of the Curry Member, marked by a mix of magnetically hard minerals, including specular hematite. We speculate that, subsequently, a decrease in sea level, associated with the basin's contraction, created conditions conducive to high silica input from continental margins and a change in the biotic regime which reduced the formation of granules and led to the creation of the Lorretto slate member.

Geochronology campaign in northeastern Minnesota

ALLERTON, Zsuzsanna[1], FAYON, Annia[1], HUDAK, George[1], TEYSSIER, Christian[1], COURTNEY-DAVIES, Liam[2], and DANIŠIK, Martin[3]

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[2] Geological Sciences, University of Colorado, Thermochronology Research and Instrumentation Lab, Boulder, CO 80309-0399, USA
[3] School of Earth and Planetary Sciences Department, John de Laeter Centre, Curtin University, Perth, WA 6845. Australia

Northeastern Minnesota is known from volcanic rocks along the north shore of Lake Superior and the intrusive suit of the Duluth Igneous Complex (DC) to its west with associated Ni-Cu-PGE mineralization (Leu, 2015; Miller, 2002). These lithologic units are part of the ~1100 Ma Midcontinent Rift System (MRS). During the rifting event, the hot (~1000°C) DC was emplaced into the "cold" Neoarchean (~2700 Ma) monzo-granitic Giants Range Batholith (GRB) footwall, resulting in contact metamorphism, sulfide mineralization (Benko et al., 2015), and hydrothermal activity. The focus of this project is to constrain the hydrothermal effect of DC emplacement and other regional events by tracking isotopic, chemical, and textural changes in accessory minerals zircon and apatite along a transect from the DC/GRB contact westward into the Archean basement.

Samples in this study are collected from the GRB and the Purvis Lake tonalite. Six of the GRB samples were analyzed for U-Pb dating of *in-situ* apatite, and twelve GRB samples and one Purvis Lake tonalite sample were disaggregated to isolate individual zircon grains to acquire U-Pb radiometric dates (Figure 1). U-Pb data were obtained by Laser Ablation-Inductively Coupled

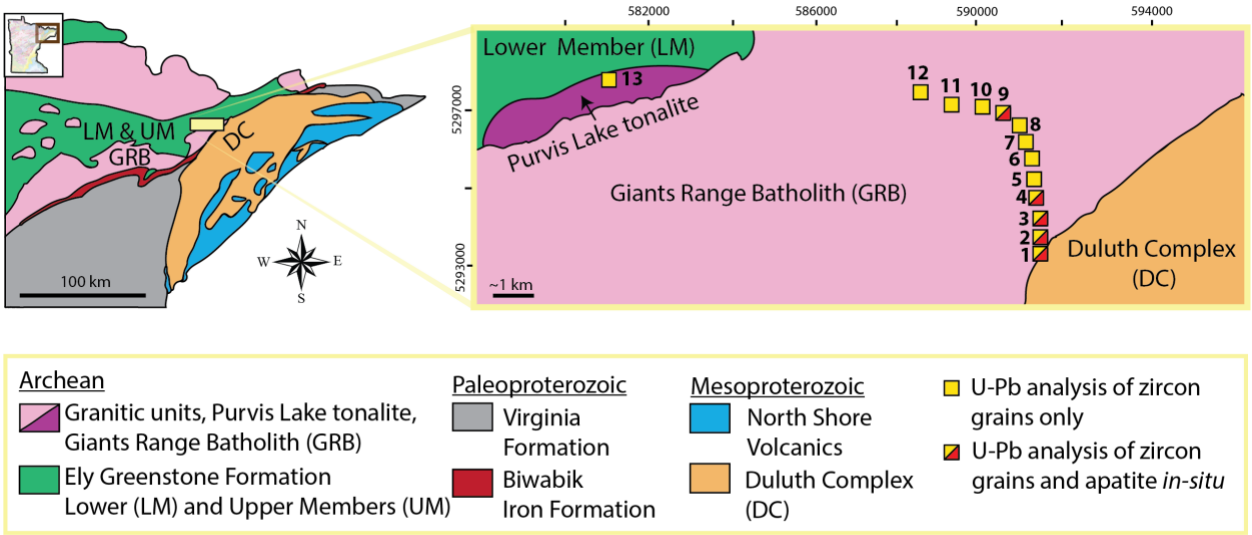


Figure 1: Simplified geologic map of Minnesota's arrowhead region showing the study area (yellow inset). Samples are numbered within lithological units of the Giants Range Batholith (GRB) and Purvis Lake tonalite. Maps are modified from Griffin and Morey (1969) and Peterson and Jirsa (1999).

Plasma Mass Spectrometry (LA-ICP-MS) at laboratories of University of Santa Barbara (*in-situ* apatite) and University of Colorado, Boulder (zircon separates).

Results show bimodal dates signifying crystallization age and the timing of hydrothermal alteration. *In-situ* apatite U-Pb yields 2594.3 ± 30.8 Ma ages at ~ 2 km from the contact, and the rest of the apatite U-Pb dates suggest Pb-loss as a function of hydrothermal alteration from ~1067.24 ± 7.64 Ma to ~1084.89 ± 9.23 Ma within ~1 km of the contact. Zircons separated from twelve samples yield U-Pb crystallization ages ranging from ~2640 to 2700 Ma, and lower intercepts ranging from ~700 to 1200 Ma with uncertainties of ~4-200 Ma. The average lower intercept is ~1150 Ma, and we interpret these ages to record hydrothermal activity-induced Pb-loss. Crystallization age and error increase, and the timing of hydrothermally driven Pb-loss becomes more elusive with distance from the contact. The tonalite ~20 km from the DC/GRB contact yields a crystallization age of 2708 ± 25 Ma and displays Pb-loss at 1140 ± 116 Ma. The large uncertainty associated with Pb-loss might be suggestive of multiple hydrothermal events.

These data are consistent with hematite (U-Th)/He dates of the massive hematite ore bodies of Soudan Iron Mine, ~40 km (map distance) from the DC/GRB contact, that record hydrothermal alteration at ~ 1100 Ma (see Allerton at al., 2024 *"Geochemistry and geochronology of hematite ore in northeastern Minnesota", ILSG 2024)*.

References

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Geochronology and geochemistry of hematite ore in northeastern Minnesota

ALLERTON, Zsuzsanna[1], HUDAK, George[1], TEYSSIER, Christian[1], FAYON, Annia[1], DANIŠIK, Martin[2], COURTNEY-DAVIES, Liam[3], and LARSON, Phillip[4]

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[2] School of Earth and Planetary Sciences, John de Laeter Centre, Curtin University, Perth, WA 6845, Australia
[3] Geological Sciences, University of Colorado Boulder, Thermochronology Research and Instrumentation Lab, Boulder, CO 80309-0399, USA
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The Neoarchean Lake Vermilion-Soudan Underground Mine State Park is known for its Algoma-type banded iron formation (BIF). The BIF encloses lens-shape high-grade (63-65% Fe) iron ore locally. The well-established view is that massive to semi-massive hematite ore bodies are the product of hydrothermal alteration of BIF, during which process hydrothermal fluids leached silica, resulting in volume reduction (production of vug spaces) and Fe-replacement (Gruner 1930; Klinger, 1960; Thompson, 2015). Studies have postulated that ore mineralization was syn- or post-depositional with BIF (Gruner, 1926; Thompson, 2015), but the absolute timing of hematite ore had not been established until now.

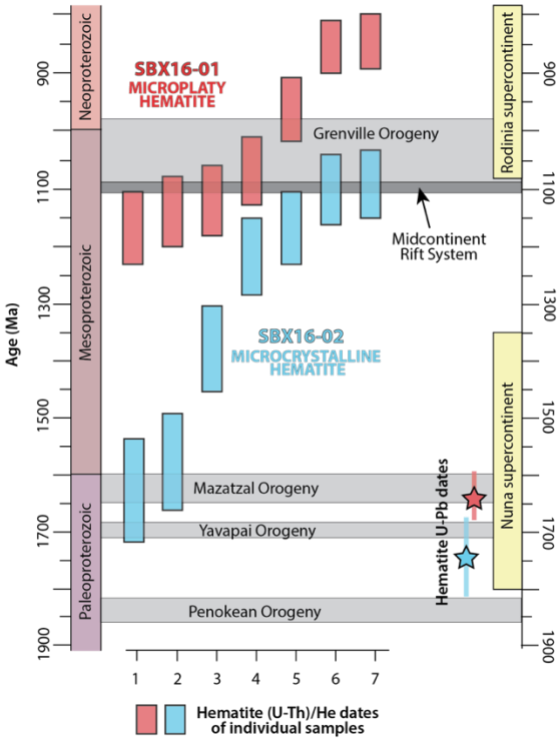


Figure 1: The diagram illustrates hematite mineralization consistent with the timing of Yavapai and Mazatzal orogenies based on U-Pb ages, and Midcontinent Rift System signatures overprint mineralization ages with (U-Th)/He analysis.

Presented is a novel technique based on coupled U-Pb and (U-Th)/He hematite radiometric dating (Courtney-Davies et al., 2022) to determine the formation age and thermal history recorded by hematite. Initial electron probe microanalyses (EPMA) allowed for hematite characterization (microcrystalline and microplaty) that helped locating inclusion-free mineral surfaces for radiometric age dating. U-Pb Laser Ablation-Inductively Coupled-Plasma Mass Spectrometry results suggest Paleoproterozoic mineralization at 1740.4±72.5 Ma and 1640.8±47.2 Ma and (U-Th)/He ages clustered at 1093.1±16.4 Ma, the latter indicating a hydrothermal overprint of the original mineralization event (Figure 1).

We propose a regional scale model that describes the hydrothermal alteration of Archean BIF at ~1700-1600 Ma with the formation of hematite ore including the growth of microcrystalline then microplaty textures, followed

by a thermal overprint at ~1100 Ma associated with the development of the Midcontinent Rift System (Figure 2).

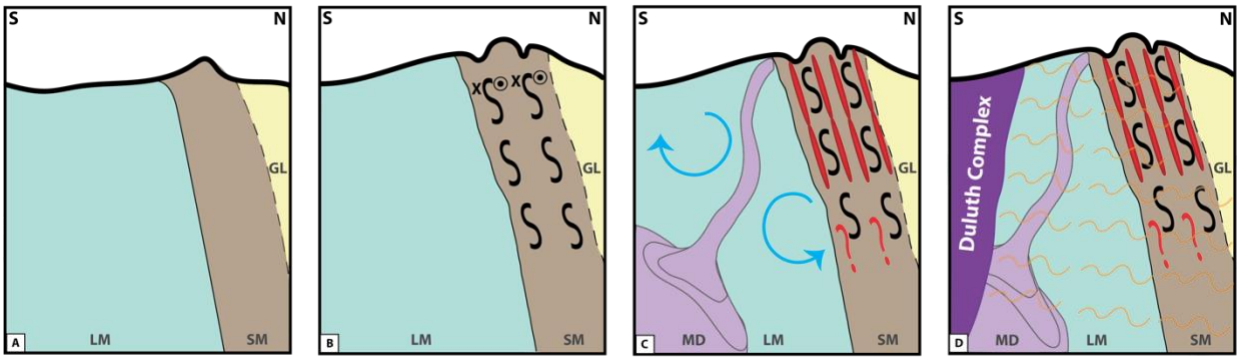


Figure 2: Schematic diagrams display S-N cross-section starting with A) pre-D_2, showing Gafvert Lake sequence (GL) unconformably above the Soudan Member (SM) that is stratigraphically above the Lower Member (LM) of Ely Formation. B) D_2 regional transpression resulting in right lateral shear zones within SM, constrained to 2685-2674 Ma from dating of regional metamorphic fabrics (Lodge et al., 2013). C) Orogenic magmatism—depicted by a mafic dike (MD) at 1700-1600 Ma—generates hydrothermal fluids, and shear zones are utilized for fluid flow and facilitate a 2-stage hematite ore mineralization (microcrystalline and microplaty). D) The Midcontinent Rift System at ~1100 Ma results in hydrothermal overprint of original mineralization recorded in hematite (U-Th)/He ages.

Whole-rock — including major, trace and rare earth elements—lithogeochemical analysis has been performed on four iron formation and ore samples, and results are currently being processed. Klinger (1969) proposed a volume-to-volume replacement mineralization, while Thomson (2015) calculated 39% volume loss by silica leaching and 9% Fe mass gain with Fe replacement. Additionally, isocon analysis (Grant, 2005) is underway to better understand the relationship between mobile and immobile elements during ore mineralization and the paragenesis of hematite.

References

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Petrology and geochemistry of Precambrian basement rocks in Walsh County, North Dakota

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In 1977, thirty-two cores were drilled in eastern North Dakota and western Minnesota along the Red River, for the purpose of evaluating uranium potential (Figure 1). The project was funded by the Department of Energy and overseen by Bendix Corporation. A technical report (Moore, 1978), a M.S. thesis that focused on the weathered horizon at the top of the Precambrian bedrock (Kelley, 1980), and several ILSG abstracts were published.

For this study, three cores from Walsh County, North Dakota were sampled at the North Dakota Geological Survey Drill Core Library (Grand Forks, ND). Samples were taken from RRVD #17, RRVD #18, and RRVD #19A to focus the study to Walsh County, ND. Figure 2 shows the lithology of the three cores and outlines sample locations.

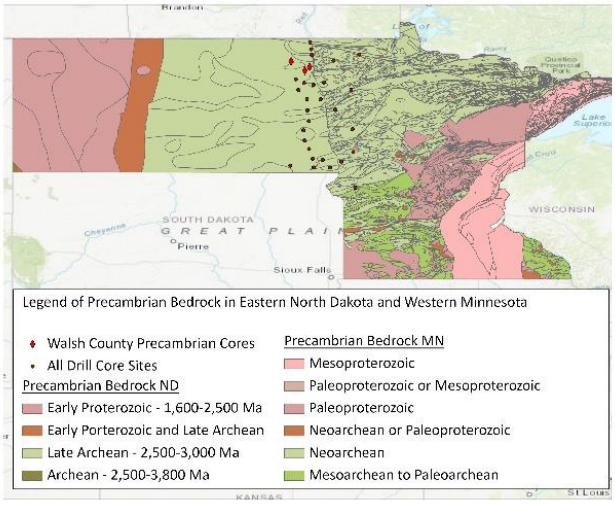


Figure 1: Location map of Eastern North Dakota and Western Minnesota. Era of Precambrian Bedrock is outlined. Red River Valley Drill Cores are outlined.

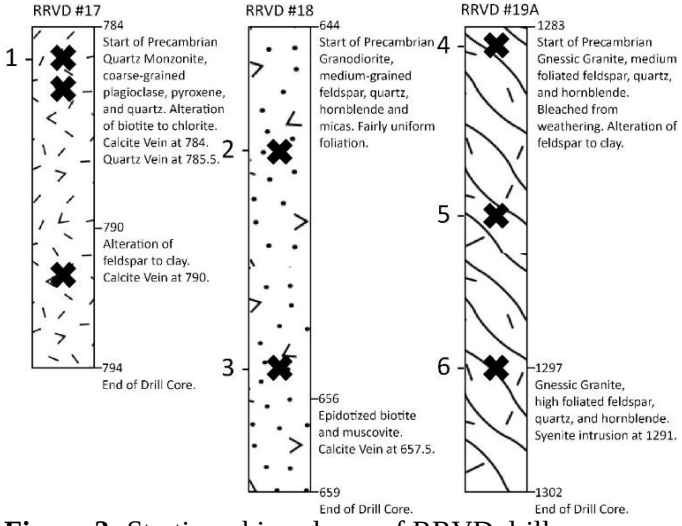


Figure 2: Stratigraphic column of RRVD drill core Precambrian layers. Black Xs indicate sample locations. Numbers to the left correspond to the XRF analysis in Table 1. Data taken from Moore (1979) and optical observations.

Petrography and whole rock geochemical analyses (Table 1) were carried out on Precambrian layers. Precambrian sediments are buried under younger layers in Eastern North Dakota, the sampled areas are underlain by Archean gneiss, (Klasner and King, 1986). RRVD #17 was characterized as quartz monzonite with heavier alterations of biotite and feldspar farther up in the core. The alterations may be due to stronger weathering agents on the paleoweathered horizon. RRVD #18 was characterized as a granodiorite with uniform foliation and mineral percentages throughout the drill core. RRVD #19A was characterized as a gneissic granite with

higher foliation as the sample increases in depth. The top of the cores is bleached, likely an effect of paleoweathering processes. Analyses were plotted on AFM and TAS diagrams (Figure 3).

Table 1: RRVD #17-785, 2: RRVD #18-645.5, 3: RRVD #18-655.5, 4: RRVD #19A-1284.5, 5: #19A-1291, 6: #19A-1296.5. Chemical data from NDSU XRF analysis.

wt%	1	2	3	4	5	6
SiO_2	59.1	69.2	71	68.2	73.5	73.6
TiO_2	0.58	0.39	0.32	0.31	0.21	0.22
Al_2O_3	23.6	14.7	13.8	20.4	13.5	13.1
Fe_2O_3	6.77	3.55	3.06	3.53	2.54	2.57
MnO	0.07	0.05	0.04	0.03	0.03	0.03
MgO	2.25	1.19	1.04	0.87	0.44	0.44
CaO	3.44	3.83	3.44	N.D.	3.12	2.8
Na_2O	5.32	5.23	5.51	N.D.	4.82	4.32
K_2O	1.84	1.46	1.32	6.4	1.36	2.47
P_2O_5	0.20	0.15	0.13	0.07	0.09	0.07
Total	103.1	99.75	99.66	99.81	99.61	99.62

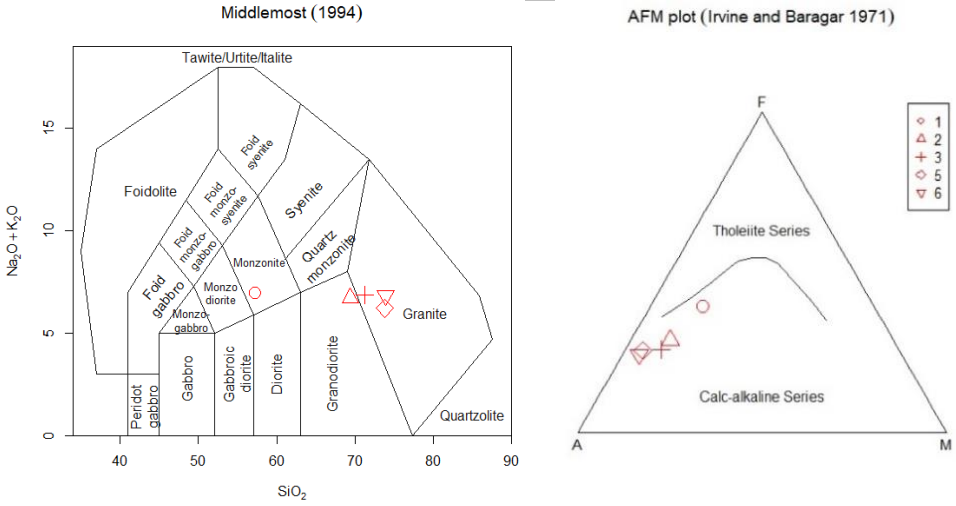


Figure 3: Classification diagrams for measured samples.

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Geophysical imaging of the Paleoproterozoic Animikie basin in Minnesota

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The 1.88-1.83 Ga Penokean orogen is preserved as a discontinuous fold belt stretching nearly 1500 km from central Minnesota to eastern Ontario. In Minnesota, the supracrustal sequence occupies a NW-facing salient broadly divided into a southern fold-and-thrust belt and a northern tectonic foredeep. The former consists of volcanic and sedimentary rocks in several structural panels while the latter - the 'main bowl' Animikie basin (AB) - consists of thick sedimentary sequences and is one of the least deformed remnants of this former continental-margin. Metasedimentary rocks of the AB include chemical sedimentary rocks (e.g., iron formation of the Mesabi iron range) and turbidites of the Virginia and Thomson Formations. The latter are an important source of sulfur for Ni-Cu mineralization within the intruding Duluth Complex and satellite intrusions.

The USGS has been collecting geophysical data in the AB and surrounding areas, including airborne electromagnetic, broadband and nodal seismic, and magnetotelluric data. These data and resulting models reveal the main bowl AB to be more complex than suggested from surface geological mapping. High-electrical conductivity is mapped throughout the basin, including along its northern edge where it is linked to the gently dipping bedded-pyrrhotite-unit and along the steeply dipping SW edge of the Duluth Complex, where it may reflect a hornfels zone formed during contact metamorphism. At the basin scale, a discontinuous bowl-shaped high conductivity zone extends to ~5 km depth. This intra-basin conductor shows some relation to deformation boundaries, such as a demarcation between rocks exhibiting folding and cleavage and those that do not.

Some deep (>5 km) geophysical variations are likely related to structural variations within the Archean basement or within thrust panels inferred to project some distance beneath the basin. Where exposed, strong conductors within some of the adjacent thrust belts suggest a correlation with metamorphic grade. Elevated conductivity can, in most cases, be related to a combination of metallic sulfides and graphite. A 9-20 km deep, steeply dipping conductive band is also imaged internal to the Duluth Complex and adjacent to modeled high-density bodies interpreted as magmatic feeder zones. We interpret this conductor as a remnant of AB metasediments preserved within the complex and speculate that the AB played an important control on magma emplacement.

Assessing depositional and post-depositional mineral associations in the <1.71 Ga Freedom Formation, Baraboo, WI, USA.

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Some geochemical proxy records suggest that the period following Earth's initial rise in atmospheric oxygen ~2.4 billion years ago was marked by low, fluctuating oxygen levels (Lyons et al., 2014; 2021). Such conditions would likely have made the ocean's photic zone inhospitable to multicellular life forms that require oxygen (e.g. Krause et al., 2022). Interpreting the trajectory of Earth's oxygenation is complicated due to uncertainties in the diagenetic effects on redox proxy records and limited preservation, especially across the late Paleoproterozoic and early Mesoproterozoic (e.g. Slotznick et al., 2022). To fill in critical knowledge gaps in surface redox conditions and geochemical characteristics of Mid-Proterozoic depositional environments, we investigated the Freedom Formation, a <1.71 Ga and >1.47 Ga iron-rich chemical sedimentary unit preserved in historic drill cores near Baraboo, WI, USA (Stewart et al., 2021). Our goal is to decipher primary redox information that links back to the depositing fluid. To accomplish this goal, and separate primary depositional signatures from post-depositional overprinting, we integrate core observations, mineral, petrographic, and geochemical datasets.

The Freedom Formation includes a lower unit composed of thin-bedded, interlaminated, fine-grained clastic and chemical sediments and an upper unit composed of dolomite. We document a coarsening upward sequence in the lower Freedom Formation, accompanied by mineralogical changes in three drill cores (H122, H22, and H23). Two of the cores (H122 and H22) show a transition in mineralogy from a base assembly of chamosite, quartz, and magnetite to a Mn-carbonate and hematite-dominant assembly towards the top of the sections. This mineralogical transition is accompanied by an increase in the proportion of sand-sized material, a decrease in mud-sized material, and a noticeable transition to carbonate. Veining and disrupted beds occur throughout all the cores. Whole rock geochemical samples targeting carbonate-rich beds across the lower Freedom Formation indicate a decline in clastic contamination up section, marked by falling Al_2O_3 concentrations and reduced Zr/Hf ratios. Positive shale normalized Eu/Eu^*_{SN} anomalies indicate a role for hydrothermal fluids in precipitation of the authigenic mineral phases. Throughout the lower units, anoxic conditions are dominant, indicated by positive shale-normalized cerium (Ce/Ce^*_{SN}) anomalies.

Interpreting the observed mineralogical transition in drill cores and the geochemical dataset requires detailed, systematic petrographic observation to distinguish the relative order of events and develop a paragenetic sequence. We identify texturally early minerals based on criteria outlined in LaBerge (1964) and separate those from post-depositional phases to interpret the history of the unit. To classify as a texturally-early phase, minerals must meet the following criteria: 1) be very fine-grained (where no grain size reduction can be attributed to metamorphism); 2) form even and consistent grain size distributions throughout the sample; 3) form the main component of granules or mud-sized particles in fine-grained layers characterized by a granular or particulate textural pattern; and 4) be associated with sedimentary features like

bedding. From this work, we identified quartz and chamosite as the texturally earliest phases in the lowermost Freedom Formation. Towards the top of the lower Freedom Formation, carbonate phases were most commonly identified as texturally earliest. Additionally, the following key observations were made: (1) if quartz is not present, chamosite is the texturally earliest phase; (2) if chamosite is not present, then carbonate is the texturally earliest phase; (3) nano-scale hematite exists at boundaries of chamosite, quartz, carbonate, and stilpnomelane crystals, and within veinlets; (4) euhedral magnetite cross-cuts all other phases, and is often associated directly with chamosite; and (5) large hematite sometimes crosscuts small magnetite, or forms oxidized rims on euhedral magnetite crystals; (6) multiple generations of quartz and oxides exist; and (7) at least two types of carbonate are present (Fe- and Mn-rich and poor). Combining core and mineral datasets, we note that because multiple generations of oxides are present (Fig. 1), post-formational fluid flow may directly connect to observed redox changes in oxide phases. The most critical of these post-depositional observations is the oxidation of magnetite rims (Fig. 1).

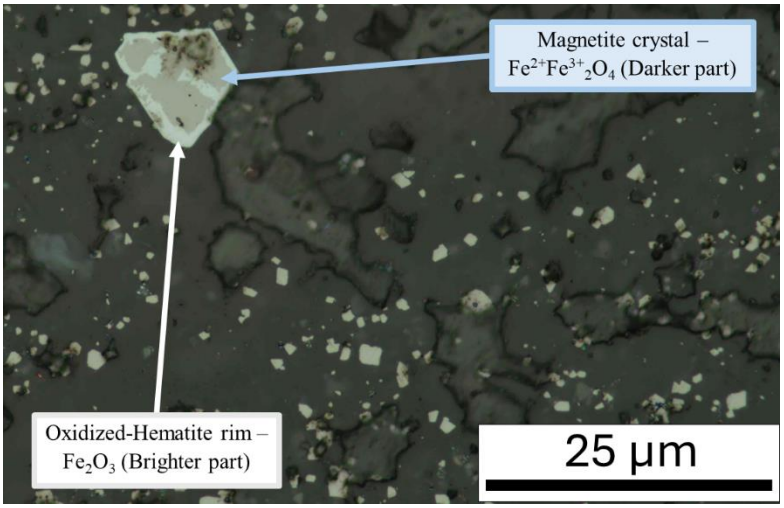


Figure 1: Reflected light photomicrograph of slide no: H122 538 FF (50X) documenting oxidized hematite rims on magnetite

Overall, across all the cores, independent of redox changes observed in oxide phases, we note a transition in texturally early phases from reduced fine-grained, Fe^{2+}- containing minerals to Mn-Carbonate. This mineralogical transition is marked by anoxic geochemical signatures and possibly indicates minor variations in oxygen conditions during the formation of the mineral phases preserved in the Freedom Formation.

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The Lake Superior area "event layer": Testing the connection with the Sudbury impact

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Following the initial publication of Addison et al. (2005) [1], there has been growing recognition of a major "event layer" near the top of the Gunflint Formation in the Thunder Bay area [e.g. 2,3,4], and at equivalent stratigraphic levels in the Marquette Range Supergroup of Michigan and Wisconsin [5,6]. Despite some initial hesitation [7,8], a consensus quickly emerged that this event layer represents the local manifestations, in the Lake Superior area, of the 1850 Ma Sudbury impact event that, ~600 km to the east, formed a multi-ring impact crater centered on the Sudbury area (see [9,10] for a recent review). The deformed and partially preserved remnants of this crater are known as the "Sudbury Structure" and, with a reconstructed final crater diameter of ~300 km, it represents the largest terrestrial impact crater known in the geological record [9]. As such, it would have had far-reaching effects extending out to several crater diameters from "ground zero", in addition to a global fall-out layer of impact material (cf. the global K-Pg ejecta layer).

A curious question, raised in Bleeker & Kamo (2022) [10], is why then this event layer is not more widely recognized in Canada, in places where ca. 1850 Ma basinal stratigraphy is reasonably well preserved (e.g., Mistassini Basin, Fox River Belt, Belcher Islands, Labrador Trough etc.)? Some of these localities are not much farther away from a "ground zero" near Sudbury. This has prompted us to undertake further tests of the putative link between the Lake Superior area event layer and the Sudbury impact structure.

Our first test is to more precisely date, by CA-ID-TIMS, felsic ash layers in the lowermost Rove Formation, i.e. the first well-defined and well-preserved tuff layers overlying the event layer. Currently our results suggest the oldest of these tuff layers is ca. 1842 Ma, thus tightening the permissible time interval for the event layer to 1856-1842 Ma [cf. 1,2].

Our second test (in progress) is to attempt a precise CA-ID-TIMS zircon date of the ca. 1850 Ma Peavy Pond Granodiorite (which currently has a SHRIMP age with ±11 Myr uncertainty, see [11]). This granodiorite is known to intrude the lower Michigamme Slates, Baraga Group, in Michigan (W. Cannon, pers. comm. 2023), thus constraining a minimum age for the event layer.

Our third and potentially most definitive test is to identify "tracers" in the event layer of the Lake Superior area that can be uniquely tied to target rocks of the Sudbury area. One such tracer would be 2460 Ma zircons from the Copper Cliff Rhyolite and its subvolcanic intrusions (Creighton and Murray granites) that are unique to the area and represent the final felsic rift volcanism/magmatism of the lowermost Huronian Supergroup [12,9,10]. For this test we processed a large bulk sample (~7.5 kg) of the event layer, with its diagnostic grey accretionary lapilli, from the HWY 588 locality west of Thunder Bay. Zircons were separated and mounted for SHRIMP U-Pb analysis at the Geological Survey of Canada, Ottawa. Eighty three zircon grains were spot dated, of which 71 returned high-quality results (Figure 1).

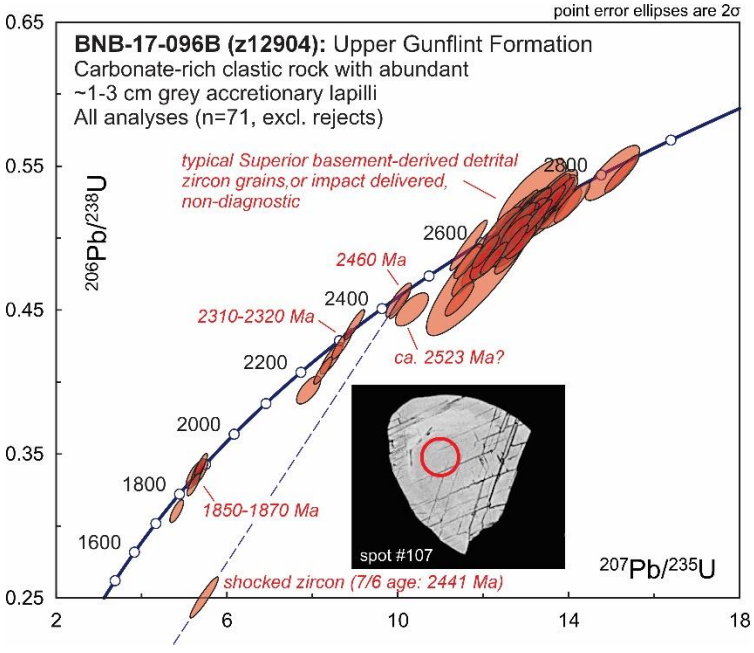


Figure 1: U-Pb concordia plot for spot dates by SHRIMP on 71 zircon grains from the Gunflint event layer, HWY 588 roadside outcrop.

The age distribution shows several well-defined clusters with 2(3) of the dated zircons defining a small but discrete subpopulation at ca. 2460 Ma. One of these zircons shows possible shock features (PDFs, planar deformation features; see Figure 1 inset) identified during picking. Although this particular grain is likely ca. 2460 Ma in origin, its result shows considerable discordance and should thus be treated with caution. Nevertheless, we think the 2460 Ma subpopulation uniquely ties fall-out material in the event layer, including rare shocked quartz grains [e.g. 2], to the Sudbury crater and its target rocks. In addition to the conclusive result of the 2460 Ma zircons, the data also identify a distinct ca. 2310-2320 Ma subpopulation of zircon grains that are known to first show up (in a regional stratigraphic sense) in the Gordon Lake Formation of the upper Huronian Supergroup. These zircon grains could have been delivered to the Thunder Bay area either as 1) ejecta from the Sudbury impact event, or perhaps more likely 2) as reworked detrital zircons from widespread felsic ash material that was deposited across the wider Superior craton at 2310-2320 Ma. Finding shock features in these grains would favour the first scenario, whereas a total absence of shock features would favour the second scenario.

To further constrain the impact event, we also subsampled the large sample from the HWY 588 event layer into 6 small slabs with varying abundances of 1–3 cm accretionary lapilli (i.e. from ~5 to ~95 vol% lapilli) and analyzed these for major and trace elements, and for low-level PGE abundances. Results show a negative correlation between siderophile elements such as Ir (also Ru, Ni, Cr etc.) and lapilli abundance, indicating that the lapilli consist largely of diluting material and are not the optimum target for identifying the nature of the impactor [e.g. 13]. The highest Ir content of 0.3–0.4 ppb, i.e. ~1–2 orders of magnitude above average crustal values, actually occurs in laminated, dark, fine sand- to silt-size sediments that overlie the lapilli-rich horizon fall-out material (~0.5–1.0 m above). Future work will entail more detailed sampling of this overlying stratigraphy to identify the Ir peak and define the detailed mineralogy and Ir deportment in this material. Incidentally, values of 0.3–0.5 ppb Ir are also the maximum recorded values in the upper Onaping Formation filling the Sudbury crater and overlying its melt sheet [14]. From our initial results it appears that a maximum of impactor material condensed relatively late and was least diluted in fine grained fall-out material near the top of the event layer, well above the accretionary lapilli.

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Insights into the southwestern Superior Province: New igneous geochronology and geochemistry in northwestern Minnesota, USA

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The U.S. Geological Survey Earth Mapping Resources Initiative (Earth MRI) program recently funded acquisition of new airborne geophysical (Allen Langhans and Drenth, 2023), geochronologic, and geochemical data in a part of the Superior Province in northwest Minnesota that is prospective for numerous Archean critical-mineral-producing systems. The study area comprises three subprovinces of the Archean Superior Province (Fig. 1). Previous work in the area (Jirsa et al., 2012; Jirsa et al., 1999) has been severely limited by an absence of outcrop, sparse drill hole data, and the existence of only one geochronologic age. These new ages and geochemical analyses, obtained through the Earth MRI program, represent the first high-resolution geologic data in the Neoarchean subprovinces of the southwestern Superior Province.

Seven new U-Pb zircon LA-ICP-MS magmatic ages (Souders, in review) establish the timing of intrusive activity in the southwestern extent of both the Wawa and Wabigoon subprovinces. A biotite-hornblende tonalite in the Red Lake Falls pluton ($^{207}Pb/^{206}Pb$ weighted mean age of 2701 ± 4 Ma, 2s), a biotite tonalite in the Snake River batholith ($^{207}Pb/^{206}Pb$ weighted mean age of 2738 ± 12 Ma, 2s), and a diorite in the Grygla pluton ($^{207}Pb/^{206}Pb$ weighted mean age of 2771 Ma ± 8 Ma, 2s) define three distinct Neoarchean episodes of intermediate intrusive activity near the present-day southern margin of the Wabigoon subprovince. A preliminary magmatic age from a small hornblende monzodiorite stock in the Wabigoon indicates ca. 2727 intermediate-mafic intrusive activity. In the Wawa subprovince, a $^{207}Pb/^{206}Pb$ weighted mean age of 2702 ± 6.5 Ma age (2s) from the Fertile pluton biotite granodiorite indicates Neoarchean intermediate intrusive activity at the northern margin of the Wawa subprovince coincident with similar activity in the Wabigoon. A small mafic body that intrudes a mafic volcanic sequence in the Wawa yields a preliminary age of ca. 2690 Ma. Finally, a combined $^{207}Pb/^{206}Pb$ weighted mean age from two closely spaced anorthosite samples confirms a Neoarchean (2737 ± 4.5 Ma, 2s) age for the Mentor Anorthosite Intrusive Complex (MAIC).

High-precision CA-TIMS U-Pb zircon analyses provide age constraints on supracrustal rocks in both subprovinces. Two trachyandesite lapilli tuff samples from the Wabigoon subprovince yield $^{207}Pb/^{206}Pb$ weighted mean ages of ca. 2730 Ma and ca. 2733 Ma (Block et al., in prep. b), >25 Ma older than the few other volcanic ages from the Wabigoon in Minnesota. Two feldspathic wackes in the Wawa subprovince are still being processed for ages.

Newly dated intermediate intrusions are LREE enriched and have arc-like trace element patterns. Discrimination diagrams indicate that these intrusions are generally I-type, calc-alkaline, volcanic arc-granites. Samples from the MAIC exhibit complex REE patterns, and their interpretation is less straightforward. The newly dated intermediate volcanic samples from the Wabigoon are also calc-alkaline and exhibit arc-like signatures. In combination with ~130 additional geochemical analyses and detailed petrography, results presented here provide significant insight into the tectonic evolution of the southwestern Superior Province and invite comparison with well-studied rock packages in the Wabigoon and Abitibi provinces in Canada.

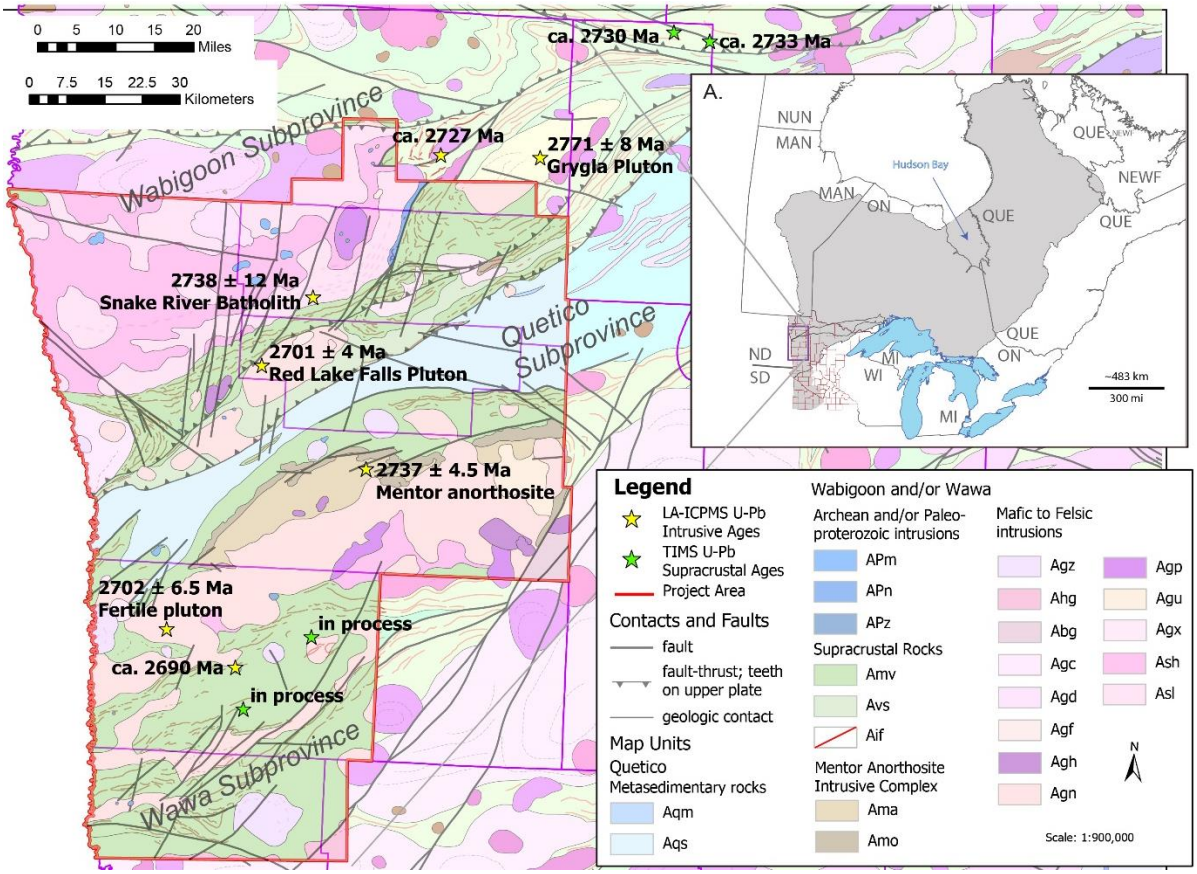


Figure 1. Bedrock geology map of northwestern MN, USA. Units within the project area (Block et al., in prep. a) are shown in the legend. Units outside the map area are from Jirsa et al. (2012). Newly obtained LA-ICP-MS U-Pb ages are shown as yellow stars, and newly obtained TIMS U-Pb ages are shown as green stars.

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Magmatic and hydrothermal evolution of the Mesoproterozoic Current ultramafic PGE-Cu-Ni deposit within the Thunder Bay North Intrusive Complex: insights from trace elements, Nd, Sr, O, and H isotopes

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The Mesoproterozoic PGE-Cu-Ni enriched Current intrusion, part of the Thunder Bay North Intrusive Complex, is located 50 km northeast of Thunder Bay, Ontario. The northwest-trending intrusion is a 3.4 km long conduit-type that intruded the rocks of the Quetico Basin during the early stages of the Midcontinent Rift System (MRS; Woodruff et al, 2020). The intrusion has four mineralized zones; the Current and Bridge Zone in the northwest are characterized by shallow and thin features; in the middle lies the Beaver-Cloud Zone, characterized by its substantial thickness, while the southeast is the deepest 437-Southeast Anomaly (SEA) Zone (Kuntz et al., 2022).

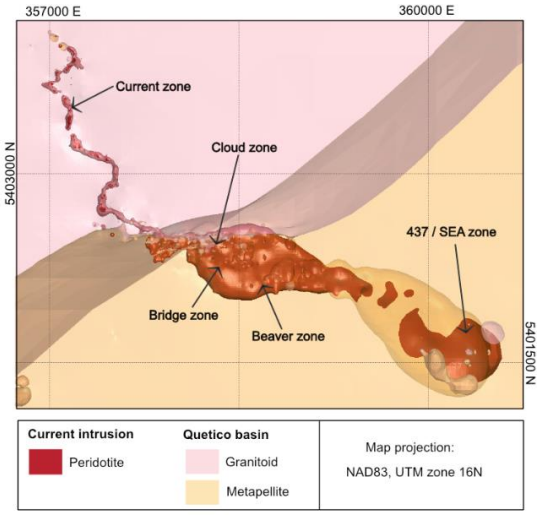


Figure 1. Schematic model of the Current intrusion and the Quetico country rock. Illustration compiled in Leapfrog using data provided by Clean Air Metals Inc.

The intrusion exhibits a primitive mantle-normalized pattern resembling ocean island basalt, characterized by LREE enrichment and small positive anomalies in Nb, La, and Ce, consistent with minimal continental crust contamination. The La/Sm_n values in the Current intrusion samples, ranging from 1.8 to 2.6, align with previous studies, indicating a basaltic magma derived from an enriched mantle plume. The enriched nature of the magma in the Current intrusion is consistent with other mineralized and unmineralized intrusions associated with the MRS (Escape, Seagull, Lone Island intrusion, and Nipigon Embayment; Heggie, 2005; Hollings et al., 2007b; Caglioti, 2023; Yahia, 2023). The intrusion has slightly lower Sr_i (0.7021 to 0.7043) and ε_{Nd} (-1.18 to -4.02) values compared to typical the mantle source at 1100 Ma. Therefore, it is suggested that the plume-derived magma interacted with an enriched subcontinental lithospheric mantle, which may have contributed to the slightly negative ε_{Nd} values of the intrusion.The stable isotope analysis data from the Current intrusion indicates an interaction between magmatic mantle-derived fluids (δ^2H from −40 to −80‰, $\delta^{18}O$ from 5.5 to 7.0‰), meteoric fluids (δ^2H <-80‰, $\delta^{18}O$ <5.5‰), and devolatilization/ dehydration fluids of the Quetico country rocks ($\delta^{18}O$ >7‰).

Three distinct domains within the intrusion were identified based on alteration intensity and micro-textural observations and each showing varying secondary mineral assemblages Domain A consists of antigorite, tremolite, clinochlore, epidote, pyrite, cubanite, millerite, secondary pyrrhotite ± chamosite ± sericite, and ± secondary magnetite, Domain B consists of

lizardite-chrysotile, tremolite, clinochlore, epidote, pyrite, cubanite, millerite ± sericite, and ± secondary magnetite Domain C consists of talc and carbonates. Domain A and B have characteristics of interaction with meteoric, mantle, and/or subcontinental lithospheric mantle -derived fluids, whereas Domain C is associated with fluids from devolatilization of the country rock and is overprinted on Domains A and B. The alteration processes in the different domains involved two distinct fluid types at varying temperatures, Domain A likely involved higher temperatures (>300°C) and fluids rich in H_2O. In contrast, domain B was altered by fluids at lower temperatures (<300°C). Later CO_2-bearing fluids of Domain C overprinted earlier alteration at temperatures below 50°C.

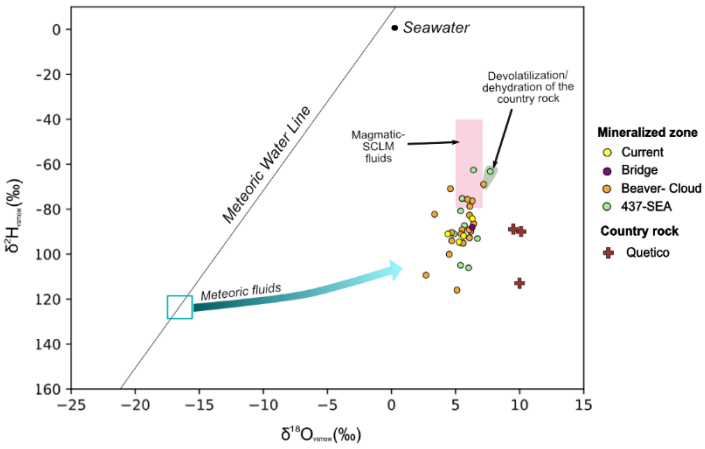


Figure 2. $\delta^{18}O$ and $\delta^{2}H$ values of bulk rock in the four mineralized zones of the Current intrusion (Current, Bridge, Beaver-Cloud, and 437-SEA) and the surrounding country rock of the Quetico basin.

The alteration of the intrusion also resulted in significant volume reduction of primary sulfides and oxides that have been replaced by secondary minerals, such as chalcopyrite and pyrrhotite were replaced by secondary magnetite and pyrite and primary magnetite was replaced by pyrite and chamosite.

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Re-interpretation of hydrothermal alteration, mineralization and host-rock oxidation to form the Keweenaw native copper lodes, northern Michigan

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The sandstone/conglomerate-hosted portions of the native copper ores of northern Michigan (e.g., the Calumet and Hecla Conglomerate ores) occur mostly in deeply reddish sediments. In the immediate vicinity of native copper ores, the reddish sediments appear to have been hydrothermally bleached to salmon-red colors (Butler and Burbank, 1929; Cornwall, 1956; White, 1968; Weege and Pollock, 1972). This communication notes that fine-grained salmon-colored clastic sediments may host fine-grained disseminations of native copper enclosed by salmon-red aureoles, not unlike grey reduction halos commonly found in red sandstones (Figs. 1, 2). If the interpreted origin and preservation of reduction halos in red sandstones is applied to the native copper-hosting aureoles in the Calumet and Hecla Conglomerate, the deep reddening of the conglomerates hosting native copper of the Keweenaw Peninsula may be interpreted as a post-ore event.

Redbed sandstones commonly show centimeter-scale reduction spots and blotches, e.g., rift-hosted Carboniferous clastic sediments of eastern Canada (Poll and Sutherland, 1976), the Permian fluvial Abo Formation of New Mexico (Bensing et al., 2005), and the Jacobsville sandstones of northern Michigan. Petrographic and chemical analyses of reduction spots in the Abo Formation indicate that those reduction spots have never been reddened – ferrous clastic grains within the reduction spots are still ferrous while similar grains in the enclosing red sandstone are oxidized (Bensing et al., 2005). Interpretation: wood trash in the cores of reduction spots maintained elliptical reducing conditions in the immediate vicinity of wood trash (i.e., within the grey halos), while oxidizing post-sedimentary water reddened all other portions of the clastic sediments.



Figure 1. Carboniferous redbeds of Dorchester Cape, New Brunswick, Canada, showing abundant centimetric-scale reduction spots with dark-greyish cores centered on fossilized organic matter.



Figure 2. Close view of greyish reduction spots in redbeds of Figure 1 (tip of hammer for scale). Cores of reduction spots contain fossil wood debris and base-metal sulfides e.g., chalcocite, partially oxidized to malachite).

Native copper in the Calumet and Hecla Conglomerate occurs as interstitial fillings in conglomerates and as fine-grained disseminations in finer sandy sediments. Curiously, very fine-grained disseminations of native copper in fine-grained sediments are observed to be surrounded by elliptical salmon-red sediment (Fig. 3). A possible, chemically justified interpretation: native copper was deposited with salmon-red alteration, mostly within highly permeable conglomeratic portions of the sandstone-conglomerates and also as very fine-grains in associated sandy sediments. Subsequently, all sandstone-conglomerates were thoroughly oxidized to their classic deep-red color during post-ore circulations of oxygenated ground water, *except in the finer-grained sediments where local salmon-red alteration was preserved against reddening by reduction-inducing fine grains of native copper*. Post-ore deep-red oxidation of copper in the fine-grained sediment was inhibited by the poor permeability of this fine-grained sediment to late deep-reddening groundwaters, but also *by the reducing property of metallic copper*.

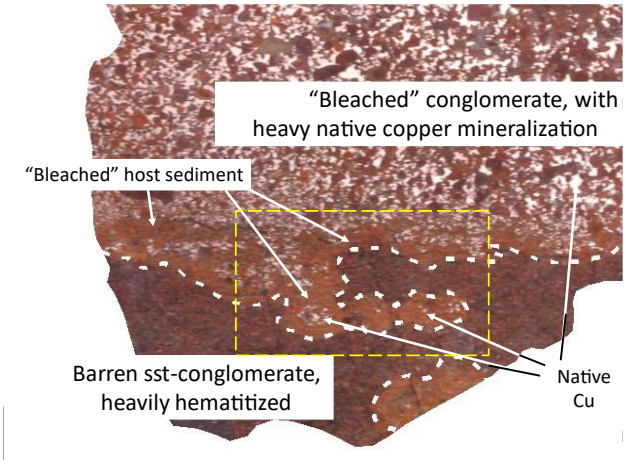


Figure 3. Cut and epoxy-ed sample of Calumet and Hecla Conglomerate native copper ore. Upper half: Deep red, coarse conglomeratic sediment with coarse-grained native copper. Lower half: Fine-grained clastic sediment containing fine-grained native copper enclosed by "bleached" salmon-red alteration halos. Bleached halos and core native copper are equated here to reduction spots with fossil wood debris common in redbed sandstones (see text for explanation).

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Preliminary mineralogy of a pegmatite in the pyroxene syenites of the Stettin Complex, Wausau Complex, Marathon County, Wisconsin

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The Stettin Complex is the oldest (1565 +3-5 Ma, Van Wyck 1994) and most alkalic of the four intrusions that comprise the Wausau Syenite Complex, and is composed of various syenite phases. Recently an opportunity arose to examine the mineralogy of a pegmatite located in the pyroxene syenites of the Stettin Complex.

Upper portions of the roughly horizontal pegmatite are below tilled soils but in-situ, are weathered, and fragments are coated with Fe-oxides and clays. Excavations over the last several years has exposed somewhat fresher material at depth and allowed better study. The pegmatite is zoned, but numerous included syenite screens complicate evaluation. Pegmatite-host syenite contacts are often sharp with no notable contact zones, suggesting relatively minor temperature contrast between the two phases, but thin 2-3 cm reaction zones are also common, with minor coarsening of feldspar and arfvedsonite compared to host syenite, small miaroles, scattered patches of abundant, tiny pink zircons and yet unidentified minerals, and in the freshest material, fluorite. The upper weathered portions of the dike, probably corresponding to border and intermediate zones, consist of anorthoclase (often showing "moonstone" visual effects; the recovery of these feldspars is the objective of those working the dike), highly altered former pyroxenes(?) with-sparse remnant hedenbergite, arfvedsonite, quartz, abundant clear pink to orange zircons and other accessory phases, including small miarolitic cavities. Per Medaris & Koellner (2010), pyroxenes in the Stettin complex range from Fe-rich diopside, to hedenbergite and aegirine. In this pegmatite pyroxenes appear to have been affected by late-stage oxidizing fluids, altering Fe^{2+}-rich pyroxenes to Fe^{3+} rich smectite-group clays ± Fe-oxyhydroxides with sparse remnants of hedenbergite, while aegirine is absent from the dike. Ca released by pyroxene alteration may have contributed to the formation of various late-stage Ca-rich species.

Deeper interior zones are mostly anorthoclase with arfvedsonite and other accessory minerals, with contact zones (or lack thereof) repeated around included syenite fragments. Graphic quartz-anorthoclase intergrowths "graphic syenite" are locally common, as are small miarolitic cavities. Several small-volume pegmatite units are: rare irregular patches of granular albite +- larger anorthoclase crystals, with abundant pyrochlore(?) crystals and possibly other species; and enigmatic thin 2-5 cm thick irregular veins or pods, mainly quartz, albite and anorthoclase: these are confined to the pegmatite and do not enter the host syenite, and includes sparse arfvedsonite, abundant cassiterite grains (≈2-4 μm), fergusonite, metamict zircons (some showing Hf-enrichment), sparse microlite (Ta-dominant pyrochlore group), sparse tantalite-(Mn) (Ta-Mn dominant columbite-group species), tiny grains of barite, and other yet-unidentified species. These anomalous pods or veins may be derived from highly fractionated late-stage differentiates. Perhaps high F activity supported unusual enrichment of HFSE in late-crystallizing melt.

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Other accessory mineralogy of the main dike includes: Aeschynite-(Ce): Elongated, dark grey-black crystals in anorthoclase. Synchysite/Parisite: Small red to pinkish hexagonal crystals. High Ca contents suggest they are either synchysite or parisite. Bavenite(?): Small white bladed crystals included in clear quartz crystals; tentative ID based on their morphology and presence of Ca, Si and O (EDS). Calcite: White crusts and masses in vugs from lower portions of the excavation. Chevkinite-group(?): Dark grains with white borders; often heavily altered to soft, chalky, fine-grained niobian Ti-oxides with minor Th, Ca, LREE ± Si and Al. Columbite-group: Sparse columbite-(Fe) noted as inclusions in a porous fergusonite-(Y) grain. Fayalite: Uncommon gray radiating acicular crystals and glassy brown grains associated with arfvedsonite. Fergusonite-(Y): Small yellowish to reddish-brown tapering crystals in anorthoclase, arfvedsonite and miaroles. Ferro-anthophyllite: Uncommon, patches of white acicular crystals in smectite-rich altered pyroxenes. Fluorapatite: Sparse crystals in vugs with arfvedsonite. Fluorite: Late in vugs and isolated grains, likely often removed by weathering. Graphite: Sparse Thin hexagonal platy crystals, typically showing thin hexagonal overgrowths. Ilmenite: Common; thin black metallic plates with a pyrophanite component in anorthoclase and miaroles. Kainosite-(Y)(?): One off-white crystal in pegmatite, appears to be a Ca-Y-LREE silicate, may be kainosite-(Y). Magnetite: Common as irregular masses, rarely as well-formed octahedral crystals. Molybdenite: Sparse as thin soft hexagonal plates. Monazite-(Ce): Uncommon, small brick-red crystals in feldspar and in vugs. Niocalite(?): Yellow to pale yellow-brown elongated crystals in anorthoclase. Very sparse. Some compositions strongly suggest niocalite, others are yet-unidentified species. Pyrochlore: Rare: yellow-brown octahedral crystals. Quartz: Common, generally as a later-stage mineral. Siderite: now absent, but goethite pseudomorphs after probable siderite are common in small vugs. Thorite: Rare; red to red-black grains associated with fergusonite-(Y). Titanite: Uncommon, as brown to red-brown grains. Zircon: Abundant in upper intermediate zone, less so in coarse interior zones.

As work continues, it is likely that additional phases will be identified, as there are a number of unknowns awaiting further work, and much material awaits cleaning and study. Thanks are due to Austin Gausmann, Bill Schoenfuss, and Trent and Shana Rebeck for access to the pegmatite.

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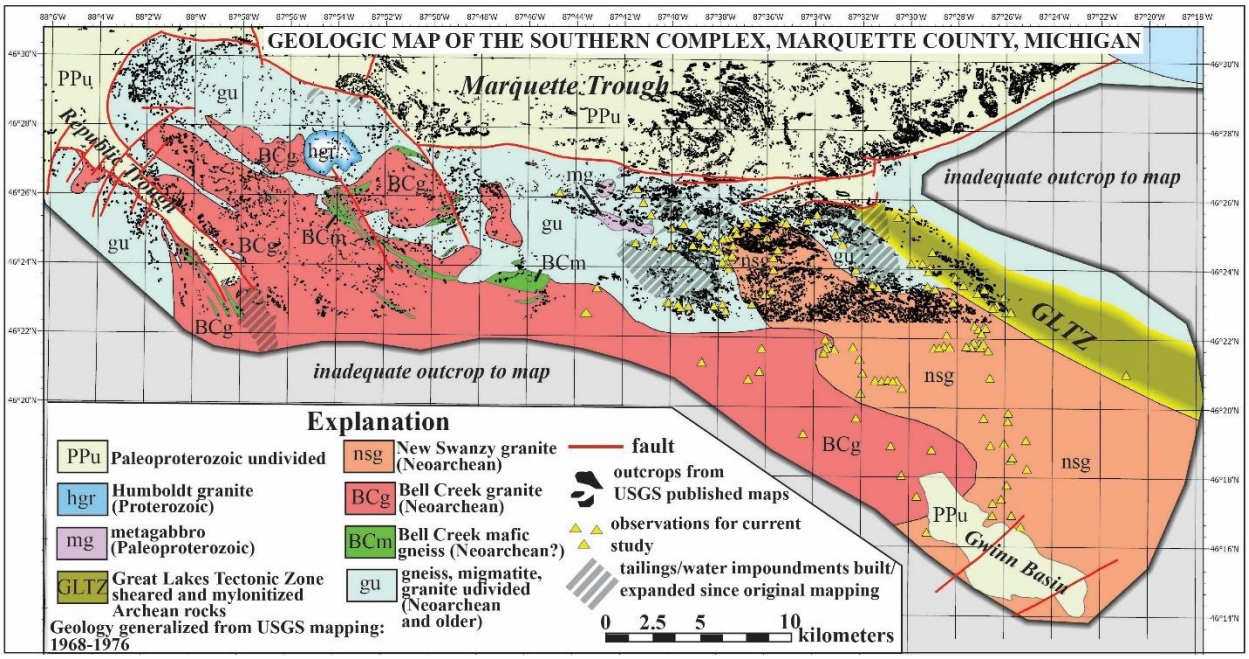
The Sacred Heart Orogeny in Michigan: Latest Archean Granites and the Great Lakes Tectonic Zone

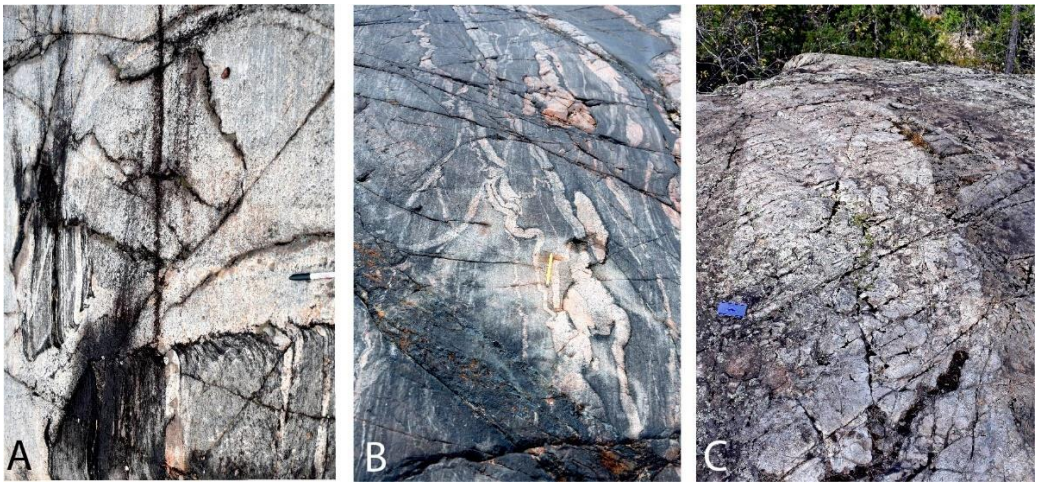
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The Sacred Heart Orogeny, as defined in Minnesota (Schmitz, et al., 2018), is the terminal Archean contractional and magmatic event during which the Minnesota River Valley Subprovince (MRVS) was sutured to the southern edge of the Superior craton along the Great Lakes Tectonic Zone (GLTZ), accompanied by voluminous granitic magmatism. The ages of those granites are tightly clustered from 2.58-2.6 Ga. In Michigan's Upper Peninsula voluminous granites of the Southern Complex, the eastern extension of the MRVS, have ages very similar to those in Minnesota and were emplaced near and within the GLTZ during suturing. The granitic phase of the Bell Creek Gneiss (Cannon and Simmons, 1973), a coarse-grained, K-spar megacrystic granite, is well dated (Petryk, 2019; Barth, 2023). The average of ten dates is 2.56 Ga. An additional age from SHRIMP analyses (Ayuso, presented here) is 2584+5.3/-2.79 Ma, fully consistent with previous determinations. We have recently recognized and dated a batholithic-scale intrusion of medium-grained, massive, K-rich granite, informally the New Swanzy granite, that borders the granitic phase of the Bell Creek Gneiss to the east and is adjacent to and interacted with the GLTZ during suturing. A regionally extensive negative gravity anomaly south and southeast of the exposed granite suggests that the batholith is substantially larger than its exposed portion (see map below). Both granites intruded an older gneiss complex with ages ranging from 2.6-2.9 Ga. The Bell Creek granite has an internal foliation defined by alignment of K-spar megacrysts broadly conformable with trends of adjacent gneisses, and contains no angular xenoliths. In contrast, the New Swanzy granite, although compositionally uniform as judged in outcrop, has numerous pegmatitic segregations and dikes. It has sharp cross-cutting contacts with older gneisses and contains many xenoliths. These characteristics and several instances of dikes of New Swanzy-like granites cutting the Bell Creek, suggests that the New Swanzy granite post-dates the Bell Creek Gneiss, at least slightly, and has an intrusive contact with it.

The New Swanzy granite has a complex interaction with sheared rocks of the GLTZ. The GLTZ is a 2.5 km-wide, SW-dipping zone of dextral shear-thrusting where rocks of the MRVS were thrust northward over the Superior craton (Sims, 1991). The age of suturing was suggested to be about 2.69 Ga. Close to the GLTZ, the New Swanzy granite has a shear foliation parallel to the GLTZ. Within the GLTZ areas of granite are enveloped in intensely sheared rocks whose protolith is uncertain. Many dikes and stringers of granite cut mylonitic foliation. These show varying intensity of deformation, but all were emplaced after the most intense shearing. An undeformed granite dike was intruded across shear foliation at 2559±19.5 Ma (U-Pb apatite). We consider this to set a minimum age for deformation in the GLTZ in this region. Thus, the New Swanzy seems best interpreted as a syntectonic granite emplaced adjacent to the active suture late in development of the GLTZ

The data summarized here indicate the latest Archean tectonic and intrusive events in northern Michigan and Minnesota are correlative. Thus, we deem it appropriate to extend the Minnesota-derived term "Sacred Heart Orogeny" to the culminating phase of development of the Southern Complex in Michigan. Because rocks of the Southern Complex are exposed in direct contact with the GLTZ, they present a unique opportunity to study the interaction of intrusion and suturing of the MRVS to the Wawa-Abitibi terrane.





A-Massive New Swanzy granite cutting country rock gneiss. B- GLTZ mylonite cut by granitic stringers with varying degrees of deformation. C- undeformed 2.56 Ga granite dike cutting foliation of GLTZ.

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The Honey Creek Structure, Sauk County, Wisconsin:
Asymmetric Faulting Associated with Seismic-Induced Fluid Escape

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The Honey Creek structure occurs in the Balfanz quarry in Sauk County, Wisconsin. It is south of the Baraboo syncline and in the vicinity of the Denzer syncline. The Honey Creek structure is dominantly a N dipping fault (striking ~250 and dipping ~30 using right hand rule) that deforms the Ordovician Oneota Formation and underlying Cambrian Jordan Formation. The hanging wall contains units that are stratigraphically younger than those immediately adjacent across the fault; this geometry requires that the Honey Creek structure contains a normal fault. The footwall side of the fault was deformed, such that the beds were rotated to a nearly vertical orientation and occasionally overturned next to the fault. The folding in the footwall is consistent with drag on a reverse fault, which is opposite to the direction of inferred stratigraphic offset. Soft sediment deformation, interpreted as sand injection emanating from the Jordan Formation, is prevalent alongside the fault on the footwall side, although a sand lens crosscuts the fault in one place. A smaller-scale structure is located less than 30 m S of the Honey Creek structure. This feature has a similar strike and dip, normal sense of offset, and folding of the footwall. It differs from the Honey Creek structure insofar as there is brecciation but no sand injection along the fault. Finally, there appears to be a recumbent fold located less than 40 m S from the main Honey Creek structure, with a vergence away from the Honey Creek structure. We interpret this recumbent fold to have formed in the same deformational event.

We consider two possible interpretations for this structure, both of which invoke significant ground shaking. First, the deformation could result from intracratonic seismicity. The timing of deformation (Early Ordovician) is broadly consistent with that of the Taconic orogeny, although the orientation of the fault is at a high angle to the inferred regional shortening direction (EW). Its location, directly south of the Baraboo syncline, could be consistent with reactivation of a Proterozoic fault. Second, the deformation could result from a distant (<200 km) meteor impact. The timing of deformation is consistent with a swarm of meteorites that occurred at the same time in the upper Midwest, and resulted in a number of craters (e.g., Decorah, Elm Creek, etc.). This interpretation is consistent with regional soft-sediment deformation in the Oneota Formation.

Baddeleyite age reveals timing of the Northeast Iowa Intrusive Complex (NEIIC)

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Recent geophysical surveys over portions of the entirely concealed Northeast Iowa Intrusive Complex (NEIIC) have provided a clearer picture of the region's Precambrian basement geology (Drenth et al., 2015 and 2020). High amplitude magnetic and gravity anomalies remain the focus of further research into their mineral resource potential, due in part to the likelihood that the NEIIC is related to the ~1,100 Ma Midcontinent Rift System (MRS). A core drilled into the northeast-trending Osborne Anomaly in Clayton County, Iowa provides the only samples in the vicinity of the NEIIC. The Osborne core encountered 722 feet (220 m) of mafic-ultramafic rocks that has been previously described as olivine-plagioclase cumulate. Recent screening using a portable X-ray fluorescence (pXRF) spectrometer revealed elevated concentrations of zirconium (Figure 1) as well as aluminum and potassium in several discrete zones of late stage melt (Clark et al., 2019). Datable minerals in the form of zirconolite and baddeleyite have been identified in samples from these zones.

Obtaining a reliable age from the Osborne core has been paramount to making the argument that the NEIIC is Keweenawan and thus possibly related to other magmatic intrusive terranes in the Lake Superior Region. A recent study (Drenth et al, 2020) obtained an age of ~1,170 Ma from LA-ICP-MS analyses of apatite crystals from the Osborne core. However, accurate U-Pb ages on apatites are often limited by the need for a precise correction for the common Pb component. Here, we present new U-Pb ages on baddeleyite crystals from a depth of 2,416.3 feet (736.5 m) that were analyzed by LA-ICP-MS at the University of New Brunswick. The U-Pb crystallization age of 1,148 ± 14 Ma (weighted average of six concordant baddeleyite analyses) stands as the first reliable date to come from the NEIIC region. This age is comparable with other intrusions outboard of the MRS, such as the Corson Diabase in eastern South Dakota (1,149 ± 7 Ma), the Great Abitibi dike (1,141 ± 2 Ma), and the Inspiration diabase (1,159 ± 33 Ma) (McCormick et al., 2017 and references therein), and indicate a wider regional magmatic event that pre-dated initiation of the MRS by ~50 Ma.

The general age of these intrusions has been interpreted as early stage magmatism related to the onset of the MRS. The latest geophysical survey over the majority of the southern portion of the NEIIC shows that the Osborne Anomaly is cut by NEIIC intrusions (Drenth et al., 2020), thus providing a maximum emplacement age of ~1,150 Ma.

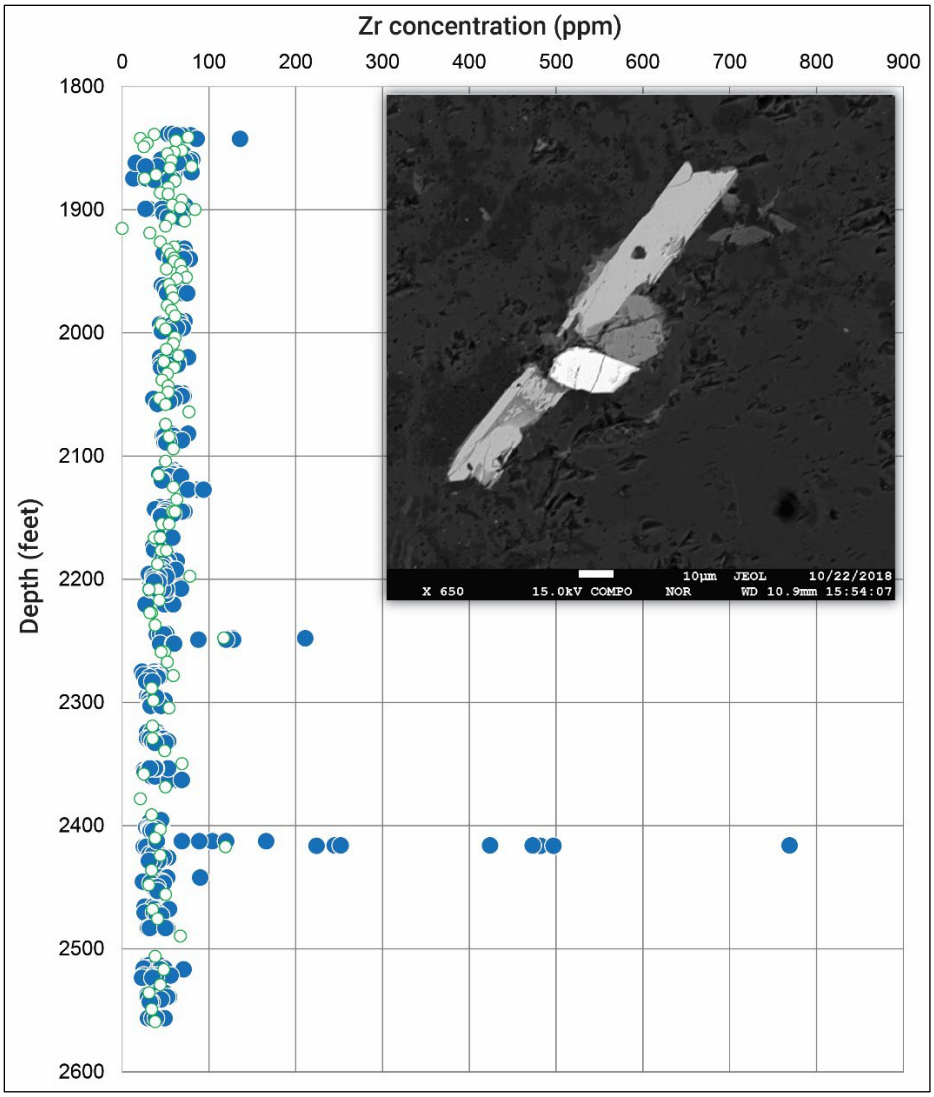


Figure 1. Graph of Zr concentration by depth from two separate rounds of pXRF analyses illustrates two distinct zones of Zr-enrichment. Inset backscattered electron image shows an elongated zirconolite crystal (gray) with inter-grown baddeyelite crystal (white) from a sample at 2,614.3 feet depth.

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Transpressional Nature of the Keweenaw Fault System, Lake Superior Region, and Its Relationship to Grenville Orogenesis

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The Keweenaw fault system (KFS) is a connected set of faults that extends along the southern margin of the Midcontinent Rift System from northwest Wisconsin to near Keweenaw Point in Michigan. A component of reverse slip has thrust Portage Lake Volcanics (PLV, 1.1 Ga) southeastward over younger, mostly flat-lying Jacobsville Sandstone (JS) on some faults in the system (Fig. 1). This motion enhanced a regional northwesterly tilt to PLV strata, produced counter-regional tilt near major fault segments, and locally tilted footwall JS strata to vertical and overturned attitudes (**1, 2**). Regionally, the KFS azimuth changes by 65° from 35° near Houghton to 100° at Big Bay, as does the strike of PLV layers. Locally, the Keweenaw fault on published maps changes azimuth by up to 85° at unusual bends, some of which have been attributed to offsets on transverse faults. These changes in fault azimuth are important clues to the geometry of faults making up the KFS and to their individual and collective slip behavior. If opposing rock masses across the KFS are relatively rigid, a reasonable assumption, the fault system cannot be pure dip slip everywhere along its curved path, which inference also applies to its component faults.

Mapping along the KFS since 2017 reveals that the sinuous, mostly single fault trace on published maps oversimplifies important structural relationships. In any part of the system, three directional fault sets are recognized: (1) a dominant set that defines the KFS trend and locally separates steeper dipping PLV layers to the northwest from shallower dipping PLV layers to the southeast; (2) splay faults angled 15-30° clockwise from set 1; and (3) connector faults angled 35-75° counterclockwise from set 1 that join footwall splays to the main fault trend (Fig. 1). The three fault sets maintain these angular relationships as the curved KFS changes direction from near Houghton to the tip of the peninsula. Interconnections between faults define fault-bounded blocks with long dimensions roughly parallel to the local KFS trend. The fault-bounded blocks and footwall splay faults defining their southeastern and southern edges are arrayed in a left-stepping pattern along the KFS, suggesting a component of right-lateral strike slip.

Analysis of fault-slip data, i.e. slickenlines and slip-sense indicators, from the fault population along the KFS indicates that the system's slip characteristics change between Houghton and the tip of the Keweenaw Peninsula. Near Houghton where the KFS trends northeasterly, the ratio of strike slip to dip slip is about 1:1 and is bimodal, whereas the ratio is more than 2:1 and is unimodal near Bête Grise Bay where the KFS trends easterly. Geologic relationships across some faults are consistent with their northwest and north sides sliding to the right and upward relative to opposing sides. Inversion of fault-slip data indicates that a strike-slip regime existed near Keweenaw Point with an azimuth of maximum shortening of about 100°, which favors a component of right-lateral slip on the KFS. Folding within and adjacent to the fault-bounded blocks exhibits two styles. Multiple folds subparallel to shorter northeast and east ends of fault-bounded blocks (i.e. NE- to N-trending axes) formed by shortening across such boundaries. In contrast, single folds subparallel to longer sides of the blocks in footwall JS strata (i.e. NE- to ESE-trending axes) formed by drape

of JS strata over steeply dipping, mostly strike-slip faults with little to no shortening across them. Based on this evidence, we infer that oblique slip on the KFS becomes mostly right-lateral strike slip near Keweenaw Point and that crustal shortening is along a line roughly perpendicular to the Grenville front about 550 kilometers to the east-southeast (Fig. 1).

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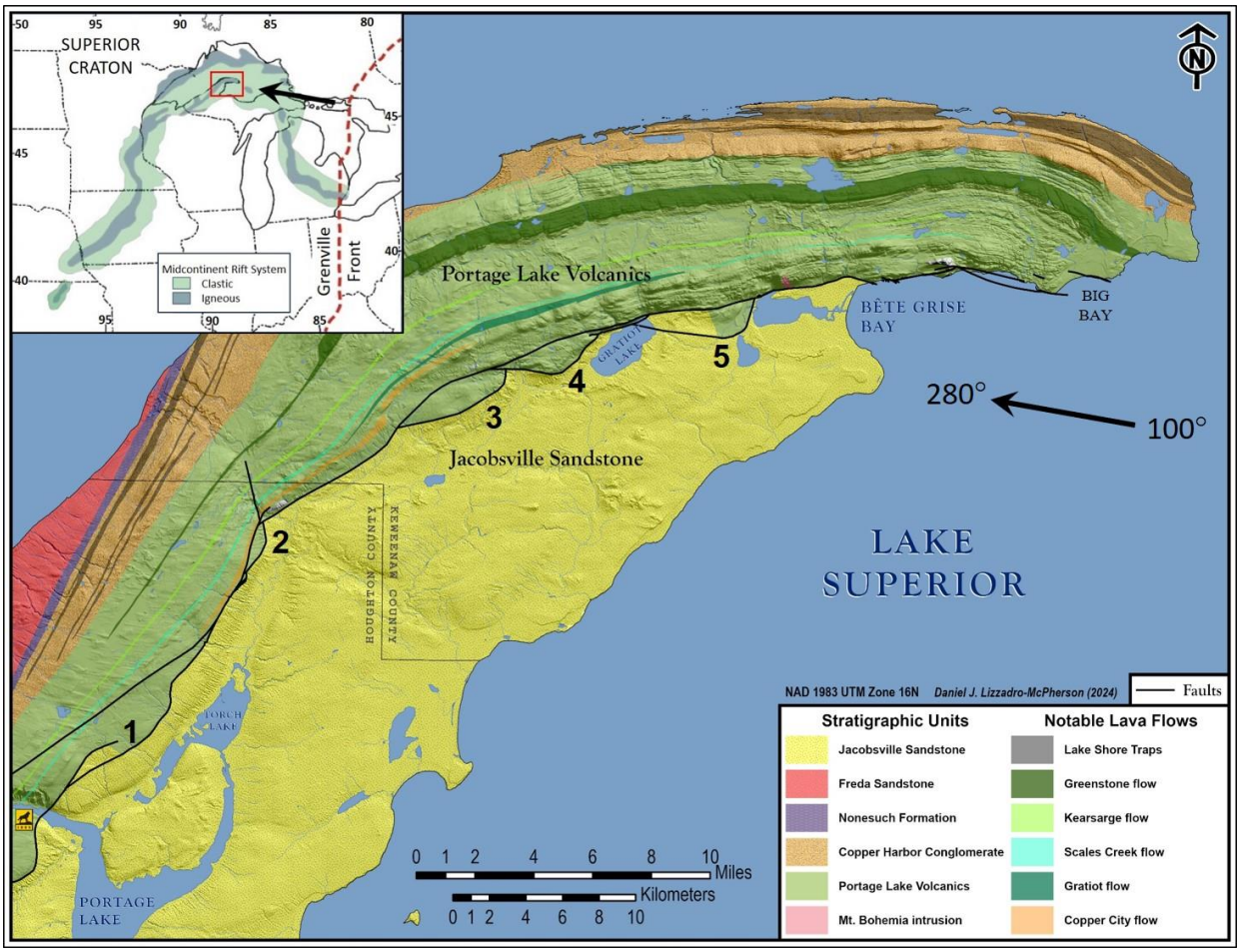


Figure 1: *Keweenaw fault system (black lines) north of Portage Lake, Michigan. Five largest fault-bounded blocks numbered 1 – 5. Black arrows show inferred maximum shortening direction. Inset map modified from Northwestern University maps online (https://www.earth.northwestern.edu/spree/Maps.html).*

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Glimpses of a Paleoproterozoic landscape: Analysis of exhumed topography on Archean basement rocks northwest of Marquette, Michigan

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Background and purpose: Northwest of Marquette, MI, between the Yellow Dog River on the north, and Silver Lake and the Little Garlic River on the south, the modern land surface lies close to the nonconformity between an Archean granite-greenstone complex (the ~2.7 Ga Compeau Creek Gneiss and Mona Schist) and Paleoproterozoic metasedimentary rocks (the ~1.85 Ga Michigamme Formation). High areas are underlain by Archean rocks, while lower ones are underlain by the Michigamme Fm., suggesting that Michigamme sediments accumulated on an ancient land surface of hills and valleys with up to 70 m of relief. Although the Archean and Proterozoic rocks are locally in fault contact, good exposures of the nonconformity, together with systematic fining of grain size in the Michigamme with distance from Archean highs, support the interpretation that much of this area is an ancient exhumed landscape. Further evidence for a regional Paleoproterozoic landscape with significant relief comes from observations that the Sudbury ejecta layer in the region occurs at a wide range of stratigraphic heights above the base of the Michigamme Formation, and locally directly on Archean rocks (Cannon et al., 2010).

The modern topography of this region is also qualitatively different - more rugged – than that seen on Archean rocks exposed only 25 km to the south, along the Black River east of Republic, even though the two areas share the same glacial history. In the study area, we suspect that the primary effect of glacial erosion was to remove the soft Michigamme Fm. from high spots, re-exposing the sub-Michigamme surface. In the southern area, either the Michigamme Formation was never deposited or the pre-glacial landscape had been already been eroded to a level below the nonconformity. We believe, therefore, that the study area preserves a low-fidelity version of a Paleoproterozoic landscape and can provide insight into patterns of erosion and weathering at a time before land plants and modern atmospheric conditions. On an Earth with no vegetation and little to no soil, eroded sediments would have had a shorter residence time on landscapes and in river systems. Bedrock rivers would have been more common than they are today, and the primary mechanisms of landscape evolution would have been corrosion (chemical weathering) in a CO_2-rich atmosphere, corrasion (abrasion of bedrock by entrained sediment), and cavitation (pitting of bedrock surfaces by bubble implosion in turbulent waters). Faults, joints, and other bedrock features would have been the primary influences on river channel location and potholes would have played an important role in channel development (Wohl, 1998). The goal of the study was to develop quantitative metrics to characterize the exhumed ancient landscape and contrast these with modern topography in areas with similar bedrock in order to gain a better understanding of geomorphologic processes in Paleoproterozoic time.

Methods: The boundaries of the 165 km^2 study area -- the extent of the exposed Archean nonconformity surface -- were drawn based on the provisional geologic map by Klasner *et al.* (1979) in combination with field observations and visual assessment of the topography. The rocks in the southern comparison area along the Black River are not a granite-greenstone complex like those in the study area, but they do include a mix of felsic and mafic lithologies (Archean gneisses and Paleoproterozoic dikes; Cannon, 1975) and thus serve as a reasonable analog. In order to understand the role of climate in generating relief in granite-greenstone complexes, we also analyzed the topography of two other granite-greenstone terranes: the Pilbara craton in the desert of northwestern Australia (ca. 3.5-3.2 Ga) and the Umburanas complex in the rainforest of Bahia

Province, Brazil (ca. 3.4-3.1 Ga). In both areas, the bedrock lies close to the surface and the regions have been tectonically stable since at least Mesoproterozoic time.

Digital Elevation Models (DEMs) for the study site and comparison site came from LiDAR data collected by the USGS 3D Elevation Program and were accessed via OpenTopography's data map. DEMs for the Bahia province in Brazil and the Pilbara craton in Australia were generated by the Shuttle Radio Topography Mission and accessed through USGS EarthExplorer, and Geoscience Australia's data map, respectively. When necessary, DEMs were merged into a single feature layer in Esri ArcGIS Pro 3.2.0 and clipped to the areas of interest. Roughness visualizations were calculated by determining the difference between the highest and lowest elevation cell in each 3x3 rectangular pixel neighborhood (Wilson *et al*. 2007). In ArcGIS Pro, focal statistics (statistical operations on each pixel based on specified neighboring pixels), were used to generate maximum and minimum elevation rasters. These intermediary rasters were then used to quantify roughness and create visualizations using the raster calculator tool.

Results: By several measures, the topography of the study area is significantly more rugged than that of both the Black River comparison site and the Pilbara Craton. The roughest 90 m^2 parcel in the study area has 73 m of relief compared with 27 m for the Black River and 46 m for the Pilbara. The study site also has a greater percent of land area in the highest roughness classes (>16 m of relief within 90 m^2 parcels). The Black River area and Pilbara craton are surprisingly similar in the distribution of elevations, despite representing very different erosional conditions (glacial scouring and desert exposure, respectively). However, along the Black River, lithology seems to have little control on topography while in the Pilbara craton, contacts between Archean batholiths and volcanogenic sediments are the roughest areas. The Umbaranas site is much rougher than the other three, with up to 392 m of local relief where greenstones are exposed, possibly reflecting the wide range of volcanic and sedimentary lithologies in the Umburanas complex (Barbosa & Sabaté, 2002). In the study site NW of Marquette, topographic roughness is concentrated along linear zones – presumably erosion-enhanced faults or fractures in the Archean bedrock. These straight paleochannels differ from the meandering shapes typical of alluvial (sediment-dominated) river systems. Moreover, some of these channels have scalloped edges, a possible record of their evolution through linkage of bedrock potholes (Wohl, 1998). In summary, the topography of the study area differs not only from that of the nearby Black River site, which shared the same recent glacial history, but also from both the desert and rainforest sites. We suggest, therefore, that the region northwest of Marquette represents a Paleoproterozoic bedrock landscape that may have developed under warm, wet conditions in the absence of vegetation, a combination that does not occur on Earth today.

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MCR Synthesis 1. Characterizing the MCR mantle plume

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The Midcontinent Rift (Keweenawan Large Igneous Province) contains the most diverse assemblage of mafic rock types for any LIP on earth with 9 distinct basalt groups and more than 15 major Ni-Cu-PGE occurrences or deposits. The main objective of the MCR synthesis is to build a coherent model to explain the vast array of observations, geochemical data and interpretations presented by numerous researchers over the past four decades. The project is subdivided into 4 related objectives: 1) Recognition of the key geochemical features of global rift/LIP settings that we should see in the MCR; 2) Build a classification scheme for all basalts, gabbros and ultramafic rocks using high-precision incompatible trace elements; 3) Apply analytical tools and modelling to unravel petrogenesis of recognized groupings; and 4) Represent the results in a model for the MCR that highlights spatial and temporal relationships in the rift. This project was inspired by several key events over the past decade, each of which indicate the project is feasible at this time. Proof of concept tests for objectives 2, 3 and 4 were presented in 2023 indicating a high degree of confidence for the success of this 4-to-5-year project.

A few researchers have identified various stratigraphic units in the MCR to have originated by partial melting in the mantle plume and used their inherent isotopic or trace element compositions to model melt-crustal interaction and the petrogenesis of various intrusions that host Cu-Ni-PGE deposits. These plume-related basalt units include the lower Siemens Creek and Kallander Creek basalt in Michigan and the lower Osler and Mamainse Point basalt in Ontario. But these units each present slightly different trace element characteristics, so the question arises as to what criteria are useful for distinguishing mantle plume magmas from those generated in the upper mantle or at different depths within the plume. The main criteria for identifying plume magmas are based on ocean island basalt-like trace element characteristics. In this study, two MCR plume basalt types are identified (Groups 1 and 5) using the combination of $\lambda 1$-$\lambda 2$ REE coefficients, TiO_2/Yb, and Gd/Yb diagrams. The differences between groups 1 and 5 are best explained by partial melting at different depths, based on differences between majorite (>~300 km) and pyrope garnet fractionation, respectively. Group 1 includes basalts from the Lower Osler and lower Kallander creek groups and the highly fractionated Devon volcanic unit. Group 5 includes basalts from the lower series A and B units at Mamainse Point, Central Osler Volcanic Group and the lower Siemens Creek basalt located at the Skinny, Bluff and Bond Falls sites in Michigan.

A well-understood and fundamental characteristic of highly incompatible trace element ratios is their use to correlate basalt and intrusive rocks. These typically unique trace element signatures can be used in a manner like finger printing. However, in all cases, care must be taken, particularly for TiO_2, to evaluate clinopyroxene or spinel fractionation, as is the case for basalt and intrusions in Group 1. Based on these comparisons, the Bovine, Current Lake, Disraeli, Haystack, Hele, Kitto, Riverdale Sill, Seagull, Shillabeer, and Thunder Intrusions belong to Group 1, whereas the McIntyre, Jackfish, and Logan sills belong to Group 5.

Description and application of the Consolidated Minerals Database to support geological investigations: an example from the Cuyuna Range, central Minnesota

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Over the past ~50 years, the Minnesota Department of Natural Resources (DNR) Lands and Minerals Division has amassed numerous collections of mineral exploration-related documents, amounting to well over 10,000 hardcopy materials containing geoscience and related land data. Curating these collections has proven to be challenging given the sheer volume of documents from multitudinous sources, necessitating a concerted solution to manage these materials. The Consolidated Minerals Database (CMD) is under development by the DNR to support the initiative to bring the agency's collections of historical and contemporary documents into digital format and to make them readily available for public use. It is a database of unique collections containing cross-referenced documents with linkages to other internal and external databases, including the Hibbing Drill Core Library (DCL) database, and a web map, where geospatially linked documents can be retrieved from specific localities or regions.

The various collections comprising the CMD are designated by project, company, or other relevant shared interest(s). Documents are individually entered into a particular collection and assigned a unique numerical identifier, which is used to cross-reference to different databases. Metadata (e.g., title, date, source) are recorded in a series of entries, and attributes of the document (e.g., scope, subject, content, methods, materials, discipline) are classified in a series of dropdown menus, enabling users to search and find documents meeting specific criteria relating to documents' contents and origin.

In the current initiative, the DNR utilizes the CMD intake application to produce digital records of documents from the Cuyuna Range in central Minnesota, where exploration and mining for iron and manganese ores was active throughout much of the early-middle 20th century. The objective is to curate mineral exploration documents and compile geological data from these records in a large database. A synthesis of these data will help to better understand the geological architecture and extent of historical exploration in the region, and the compiled datasets will help to evaluate the potential for additional iron, manganese, and other resources.

Historical documents from the Cuyuna mining district are stored in the Hibbing Lands and Minerals office. Dozens of different exploration companies drilled at least 12,000 boreholes and created thousands of documents spanning multiple decades of mineral exploration and mining in this district. Relevant documents in this collection range from 1905 to the 1970s, and include geological maps, surface maps with drillhole collars and associated metadata, mine maps (surface, subsurface, infrastructure), tables with geochemical data, drillhole profiles with tabular geochemical data, geological information and interpretations, geological cross-sections, field notes, and notes and correspondences regarding property ownership, exploration results and resource estimates. Because of the number of companies involved and diversity in the presentation of data it is necessary to address certain challenges before curation into CMD.

Documents are first sorted by company and locality in the Public Land Survey System, which allows for the identification and removal of duplicate maps and other documents shared

among and across different companies. Once sorted, all relevant documents with clear datasets and sufficient metadata to identify the source and locality are curated into the CMD. Following curation, plan-view maps are converted to picture format and brought into ArcGIS, where they are spatially located using georeferencing methods. This method helps to resolve problematic drillhole locations, and to identify less obvious duplicate documents and datasets, including drillholes that were renamed over time as operators changed hands. Drillhole collar locations can then be added to a database of known drillholes in the region, and integrated and compared to cores from the DCL database. Once correctly positioned, individual geospatial datasets, such as geological logs, and geochemical and geophysical data, are extracted from each document.

Extracting and compiling geologic data such as geologic logs and assays into tabular format has been a challenging endeavor. These data were hand-written or typed using a typewriter, and utilizing optical character recognition technology to extract text is not straightforward. However, transcribing the data by hand is a cumbersome and protracted process, and potentially introduces errors that must be checked for quality assurance. With the advance of artificial intelligence (AI) and machine learning, it is now possible to train an AI model to extract data into tables. Training the AI data extraction model is an efficient process. First, pages (10 minimum) containing example data listed in an internally consistent format are imported; then table(s) are delineated using the associated headers, labels, and rows per each page. Once the model is trained, numerous documents or pages of the same format are uploaded and the data are auto-extracted, and the output reflects the model's specified number of tables, columns, and rows. Before the outputted data are extracted, they are enhanced within the model workflow to account for spelling errors, incorrect symbols, etc., so that it is unnecessary to resolve errors individually by hand. Once a model is trained for a specific table format, thousands of pages of tabular data can be extracted into a tabular database *en masse* in a matter of minutes. Using MircoMine modeling software, the tabulated data are visualized in a 3D model, where any remaining tabulation errors are identified and corrected.

This process is ongoing, as many still-uncurated documents remain in the Cuyuna collection. To date, nearly 2,000 documents totalling over 20,000 pages have been scanned, georeferenced and lodged in the CMD, and the drillhole database contains over 4,000 individual drillholes with assay data totaling over 60,000 lines. Incompleteness notwithstanding, the current database is a growing and ever-refining, data compilation from thousands of geological investigations. Together, the newly compiled data are sufficiently expansive to make new observations and interpretations pertaining to the geology and distribution and style of iron and manganese resources, as well as the potential for other base and precious metal resources, in the Cuyuna Range.

Revisiting geophysical interpretations of the Midcontinent Rift below Lake Superior—Insights from GLIMPCE seismic-reflection line C

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The 1.1 Ga Midcontinent Rift System (MRS) has been investigated in the Lake Superior region for more than a century, driven by mineral exploration, academic study, and, for a brief time, oil and gas exploration. Limited outcrops on land and the extent of MRS rocks under the lake have motivated many workers to use geophysical methods to investigate the nature and extent of the rift. The most influential geophysical data for modern paradigms has come from seismic-reflection profiles collected by the Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE) in the late 1980s. Notably, many previous workers have used interpretations of GLIMPCE line C (Fig. 1, inset) to demonstrate the architecture of the MRS in western Lake Superior. A recurring theme from the previous work is that syn-extensional basalt flows accumulated in half-grabens bounded by normal growth faults, which then reactivated as reverse faults in response to later compression (e.g., Cannon et al., 1989; Hinze et al., 1992; Dickas and Mudrey, 1997; Stein et al., 2015).

We are revisiting GLIMPCE line C by constructing a detailed velocity model for conversion of the seismic data measured in two-way travel time to a section plotted versus depth (Grauch et al., 2023). This approach allows for digital verification of the modeled velocities and more accurate depiction of thicknesses and dips of units to tie to geology onshore. We have constructed an analogous gravity model along line C that provides independent evaluation of our velocity model using velocity-density relations developed from analysis of region-wide rock property compilations (Grauch, 2023).

Preliminary results from the velocity modeling, depth conversion, and ties to onshore geology have led to a significantly different view of Line C as primarily a sag basin rather than a half-graben, showing both syn- and post-magmatic subsidence (Fig. 1; Grauch et al., 2023). Narrow intervals of high velocities, which indicate a composition of gabbro (Grauch, 2023), emanate upwards along both sides of the sag basin from an inferred mantle bulge. The intervals are associated with strong linear reflections that truncate sub-horizontal layers in the sag basin and may obscure any minor faulting that occurred before or after intrusion. Cross-cutting mafic intrusions provide an alternate explanation for the termination of layers that was previously thought to indicate major faulting. This new view of line C implies that basin subsidence was the dominant process in the development of rift stage troughs rather than major half-graben structures.

Other important interpretations include the following.

- Portage Lake Volcanics show syn-magmatic basin subsidence
- The Lower Oronto Group section shows post-magmatic basin subsidence
- Onlap of Upper Oronto Group onto tilted Porcupine Volcanics suggest the deformation pre-dated deposition of Oronto Group sediments

- Rocks of the lower northeast sequence of the North Shore Group may connect to rocks of similar age from the south shore that lie underneath the sag basin.

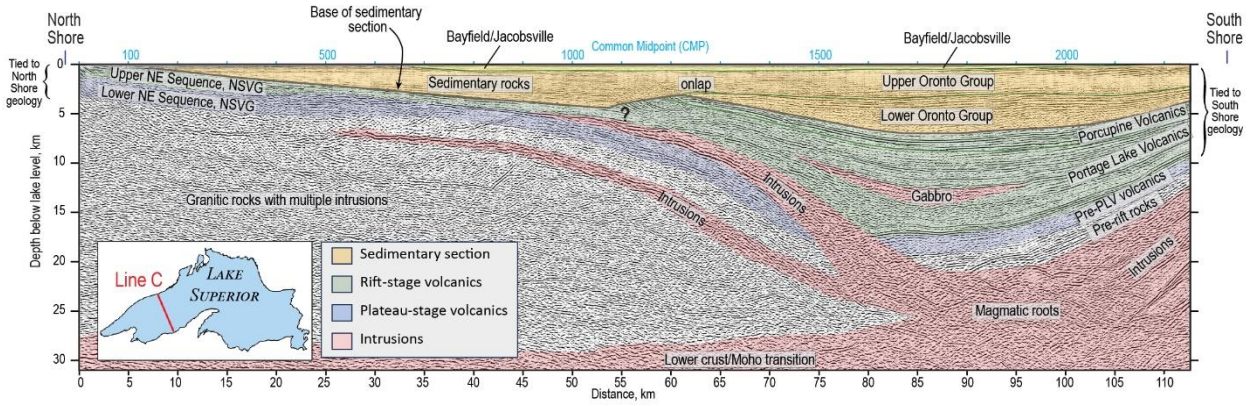


Figure 1. Interpreted depth section for GLIMPCE Line C. No vertical exaggeration. NSVG, North Shore Volcanic Group. PLV, Portage Lake Volcanics.

The new rendition of the Line C seismic data also raises several questions.

- How do the sedimentary sections correlate from north to south?
- What caused the truncation of volcanic layers at the volcanic-sedimentary contact in the middle of the seismic section and was reverse faulting involved?
- What is the tectonic process that drove the syn-magmatic subsidence?
- Where does the reverse Keweenaw fault extend into the section from the south shore and what was its influence?

These and other questions can be addressed through the construction of velocity models and depth conversions of other seismic lines in the lake. Future insights will benefit from a three-dimensional view that these additional seismic lines will provide.

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GeologyOntario: a powerful search tool for Ontario explorationists

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In March of 2023, the Ministry of Mines released a new online platform to search and query Ontario Geological Survey data. The Ontario Geological Survey maintains and provides public access to a wealth of geological information including maps, publications, assessment files, mineral inventory points, miscellaneous data releases, geophysical data, abandoned mine site information, and more. Though this information has been available online for many years, the previous iteration of GeologyOntario had significant constraints, including a lack of spatial search abilities, and users experienced challenges in finding relevant information. The new GeologyOntario consists of separate text (Figure 1) and spatial search (Figures 2 and 3) tools which provides ample opportunities to discover information. Geological information is often dependent on spatial data, and the new spatial search tool runs on a powerful Esri-based system, allowing clients to build queries to focus on the types of data relevant to their interests, within the geographical areas they are working. The new GeologyOntario Search Hub is located at https://geology-ontario-en-mndm.hub.arcgis.com/.

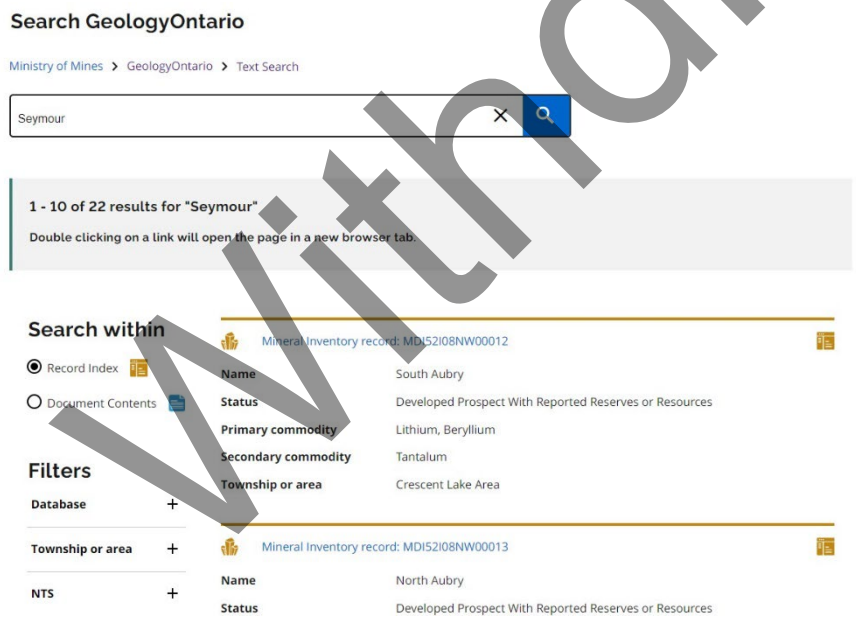


Figure 1. GeologyOntario text search page (https://www.geologyontario.mines.gov.on.ca/).

Withdrawn



Figure 2. GeologyOntario spatial search page showing regional geology, mineral inventory, and the results of a search for mineral inventory points listing lithium as a primary commodity in the area of the Separation Rapids pluton(https://mndm.maps.arcgis.com/apps/webappviewer/index.html?id=66ee0efe4d3c4816963737dbdb890708).

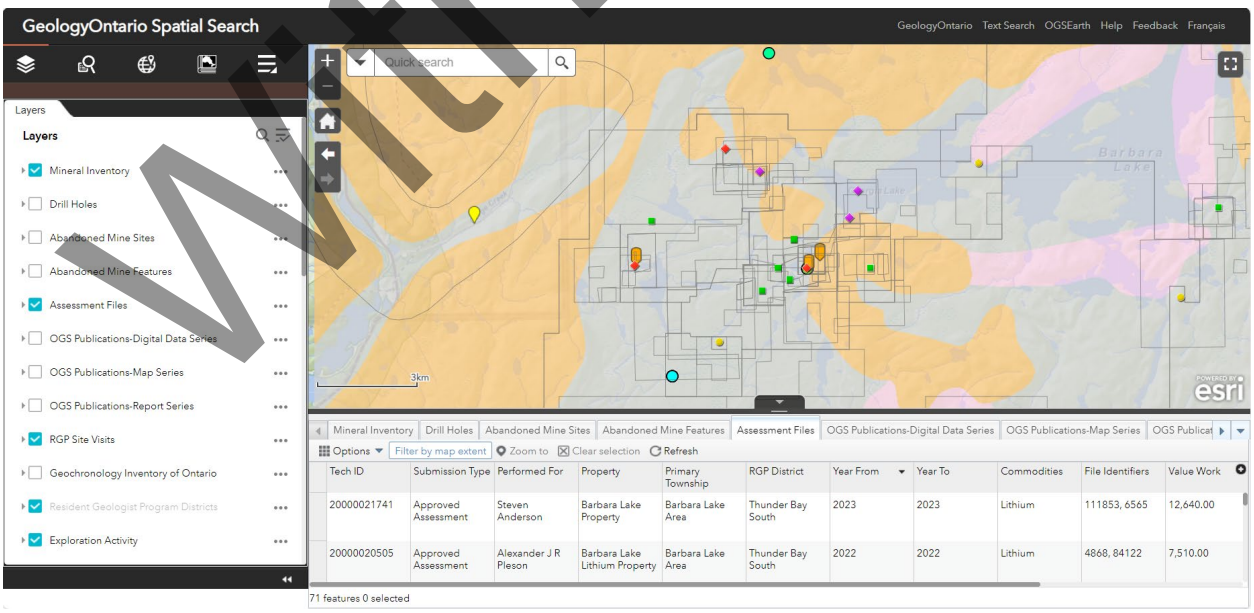


Figure 3. GeologyOntario spatial search page with regional geology, mineral inventory, assessment files, Resident Geologist Program (RGP) site visits, and exploration activity layers active.

Withdrawn

Recent developments on the use of the Horizontal-to-Vertical Spectral Ratio (HVSR) passive seismic method to determine depth to bedrock in Minnesota

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Bedrock depth is an important dataset for water resource management, hydrological studies, mineral exploration, and general well planning. In Minnesota, bedrock depth is highly variable; thin to nonexistent in the northeast, up to 250m+ in areas to the west, and irregular elsewhere. In areas where bedrock depth is not known from existing water, exploration, or scientific drilling, various geophysical techniques can be used. One of these methods is the Horizontal-to-Vertical Spectral Ratio (HVSR) (Nogoshi and Igarashi, 1971; Nakamura, 1989) which utilizes horizontal ambient noise surface wave frequencies that are excited and amplified dependent on the depth to the basement bedrock below a less dense and seismically slower velocity upper layer (i.e. unconsolidated glacial sediments).

The HVSR method has been utilized in Minnesota to estimate the depth to bedrock since the late 2000's (Chandler and Lively, 2014) and has become a standard measurement in the MN County Geological Atlas program (e.g. Bauer et al., 2023; Mayer et al., 2023). The initial HVSR dataset used 1647 passive seismic measurements with 303 locations with a known bedrock depth, also known as control points, to develop parameters to accurately estimate the depth to bedrock across Minnesota (Chandler and Lively, 2016). The Minnesota Geological Survey has now collected a total of over 6000 HVSR measurements and 480 control points resulting in a new assessment from the larger and more geographically and geologically widespread dataset. Analyses has included a new quantitative data quality ranking using international HVSR guidelines (SESAME, 2004) and new control parameters have been investigated. The shape of the HVSR curve is now being captured in a passive seismic database due to its relationship with bedrock depth topography, bedrock weathering, and the underlying velocity structure. Ongoing evaluation of this database will help refine the HVSR depth to bedrock estimation and more accurately identify potential bedrock valleys while future work will include measuring densities and ultrasonic velocities of Quaternary cores to constrain the control point parameters more accurately.

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Lithostratigraphic discrimination of Quaternary core in Minnesota using magnetic susceptibility

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Most of Minnesota is covered by Quaternary sediments deposited during multiple glaciation events. This Quaternary stratigraphy is highly complex due to multiple glacial events in which ice lobes emanated from differing locations north of Minnesota and deposited sediment (diamict, till) of variable thicknesses (up to 250m), provenance, and morphology across the state (Johnson et al., 2016). The Minnesota Geological Survey uses grain counts, color, sedimentary structures, and composition to establish Quaternary lithostratigraphic units that distinguish these deposits by lithology, stratigraphy, and geomorphology. Nine lithostratigraphic regions were identified using cuttings, outcrops, and rotary sonic core (Johnson et al., 2016). Magnetic susceptibility measurements were taken at 1-2 meter intervals from many of these rotary sonic cores during core analysis by applying a magnetic field to the core and recording the magnetic response. This study was conducted to determine if magnetic susceptibility measurements from cores can aid unit correlation across Minnesota regions as part of a USGS funded data preservation project. Over 11,000 measurements were recorded in a newly established Quaternary magnetic susceptibility database with over 7,000 measurements assigned to a lithostratigraphic formation and unit interpretation. Magnetic susceptibility logs were generated for each measured core and statistics calculated for each unit. Analysis of this database has identified lithostratigraphic units with distinctive magnetic susceptibility ranges as compared to nearby and similarly aged units. Due to these results, this newly established database functions as another tool for lithostratigraphic identification of Quaternary sediments and local and regional correlations.

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New Insights into the Geology and Geochemistry of the Osler Group and Related Rocks, Midcontinent Rift System, Northern Lake Superior, Ontario

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Ongoing geological reconnaissance and lithogeochemical sampling were undertaken on parts of the Black Bay Peninsula, St. Ignace Island and neighbouring islands in 2022 and 2023. New field and geochemical data have helped to both distinguish lithostratigraphic units and suggest common magmatic histories in developing a model for the Midcontinent Rift System (MRS)-related Osler Volcanic Group and related intrusive rocks.

The Osler Group (1108-1105 Ma), a ~3 km-thick succession of predominantly basaltic flows and clastic sedimentary rocks on the north shore of Lake Superior, represents some of the earliest MRS magmatism. Previous studies have largely focused on the paleomagnetism (e.g. Swanson-Hysell et al., 2019; Halls, 1974) and geochemistry (e.g. Hollings et al., 2007; Keays and Lightfoot, 2015) of the flood basalts in developing a stratigraphic sequence. However, only basic mapping and some initial studies had been conducted on felsic extrusive and intrusive rocks (e.g. St. Ignace Island Complex, Hollings et al., 2023, Smyk et al., 2006; geochronology, Swanson-Hysell et al., 2019 and references therein). Sampling efforts were most recently focused on these felsic rocks in order to determine their geochemical affinity and to suggest how they, and related mafic igneous rocks, may fit in with the provisional tectono-magmatic model for the Osler Group.

Felsic rocks include the Agate Point rhyolite flows (1105.15 Ma); thin felsic fragmental units; aphanitic felsite; and massive, subvolcanic(?), quartz-feldspar-phyric rocks (*aka* "quartz-feldspar porphyry"/QFP). These red, brown or gray rocks occur predominantly on St. Ignace Island (including in the core of the St. Ignace Island Complex (SIC)) and on smaller islands, south to Agate Point. Rhyolites tend to be LREE-enriched (La/Sm_n= 5.20-5.47), have higher total REE than the QFPs and more pronounced negative Ti anomalies. The majority of QFPs, including those in the core of the SIC, tend to display a coherent, tightly grouped REE trend, characterized by moderate LREE enrichment (La/Sm_n= 2.34-4.71, averaging 3.50), relatively flat HREE patterns and pronounced negative Nb anomalies. This similarity in the REE distribution of both extrusive and subvolcanic felsic rocks suggests that they may share a common magmatic and fractionation history.

In contrast, the basaltic flows into which felsic rocks have been emplaced have flatter REE distribution patterns (La/Sm_n= 1.61-3.51) than those of the felsic rocks, with less-pronounced negative Ti anomalies. Mafic and felsic flows situated above an unconformity/conglomerate at Bullers Bay, St. Ignace Island, display pronounced negative Nb anomalies whereas those below do not. This suggests that the lower flows are part of the more primitive Lower Formation of the Osler Group, while the flows above the unconformity resemble those of the more crustally contaminated Central Formation (cf. Keays and Lightfoot 2015; Hollings et al. 2007) as delineated on nearby Simpson Island.

Gabbroic rocks occur at the margin of the SIC, in the Moss Lake Intrusion and as numerous diabase sills and dykes with various orientations which intrude the supracrustal rocks. SIC and Moss Lake gabbro samples display similar REE patterns, characterized by moderate LREE enrichment (La/Sm_n= 2.59-3.23), moderate negative Ti anomalies and pronounced negative Nb anomalies. By comparison, smaller, diabasic dykes and sills have relatively flat REE distribution and less-pronounced negative Ti anomalies. Prominent, regional-scale mafic dykes (i.e. McEachan, Shesheeb, Paps) display lower total REE and lack negative Sm anomalies.

Hollings et al. (2023) suggested that the rocks of the SIC likely formed as the result of emplacement of a large mafic magma chamber at the base of the Osler volcanic pile that triggered partial melting to generate felsic end members which then ascended to shallower levels in the crust. The SIC QFPs are geochemically similar to both the massive, subvolcanic(?) QFPs elsewhere on St. Ignace Island and nearby islands, as well as to the rhyolites at Agate Point, suggesting a similar origin for all of these felsic rocks.

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Use of Ambient Noise Tomography for Mineral Exploration in the Lake Superior Region

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Abstract

Ambient noise tomography (ANT) is a relatively new passive seismic tool used in mineral exploration. The method has been successfully used in the Lake Superior region in mapping subsurface structure and rock properties. This presentation will provide a brief introduction to the ANT method and review recent ANT work done in the Lake Superior region.

Introduction

Exploration for mineral resources uses a variety of geophysical methods to detect and delineate mineral deposits and systems in order to optimize core drilling programs: gravity, magnetics, active-source reflection seismic and electromagnetics methods to name a few. Ambient noise tomography is a relatively new seismic geophysical tool that has seen increasing use in the past couple of years for mineral resource exploration. ANT uses natural earth vibrations and human-generated seismic vibrations to image subsurface structure and map physical properties of the subsurface. Four ANT surveys for mineral resources in the Lake Superior region have been completed: three surveys within the Coldwell Complex near the town of Marathon, Ontario, and one in the Duluth Complex in northeastern Minnesota.

Ambient Noise Tomography Method

The Earth is constantly vibrating. For the ANT exploration method, useful vibrations, sometimes referred to as “ambient seismic noise”, are generated by hydrosphere-lithosphere interaction such as the oceanic microseism caused by swell (a similar microseism is caused by swell in Lake Superior and the other Great Lakes), and anthropogenic sources such as vehicular traffic, industrial sites, railroads, and other human activity.

An ANT survey uses continuous passive seismic data collected with an array of nodal seismometers (“nodes”) and uses surface waves to image the subsurface. The data recording duration is usually between 1 to 4 weeks. Surface waves are dispersive with different frequencies propagating at different velocities related to the seismic velocities of subsurface lithology. Frequency-velocity dispersion curves are picked for all receiver pairs. These dispersion curves serve as input for a tomographic process resulting in an array of frequency-velocity points for each cell in a grid. All cells within the grid are inverted to produce depth-velocity profiles and the result is a 3D shear wave velocity (V_s) cube where velocity is the seismic velocity of the lithology and subsurface structure interpreted from the velocity model.

Case Studies

<u>Coldwell Complex, Marathon Area, Ontario</u>

The first Marathon ANT survey was collected in October 2017 in the Marathon area over a VMS target. This first survey was intended as a noise test using 31one-component (vertical) 10 Hz nodes. The purpose of the noise test was to characterize the spectral power, temporal variation and azimuthal distribution of the local ambient noise. The collected data was also used to cross-correlate all receiver pairs to assess the signal-to-noise ratio of surface waves in the virtual source gathers and processed to produce a crude 3D velocity model which showed agreement with available core hole data. The positive results of the noise test led to the go-ahead for an expanded survey over the target.

An 8.6 km^2 expanded ANT survey over the Marathon target was collected in November-December 2017 using 91 one-component (vertical) 10 Hz nodes. The resulting 3D velocity volume had usable imaging down to 1500 meters and imaged the gabbro intrusion slab target. Details about the noise test and expanded ANT survey and its interpretation can be found in Hollis et al.

In July-August 2018, the Sally ANT survey was conducted over an exploration target several kilometers to the northwest of the Marathon surveys. The Sally survey was collected using 196 three-component 5 Hz nodes. This survey demonstrated the effectiveness of using three-component data to produce a more accurate velocity model. Details of the Sally survey can be found in Lavoué et al.

With the good results of the expanded Marathon survey, funding was obtained through the European Union Horizon 2020 program to conduct larger, higher resolution survey again over the Marathon target in order to test the limits of the ANT method and to test other potential ANT analyses and passive seismic methods. This survey was acquired in September-October 2018 using 983 one-component (vertical) 10 Hz nodes. This third Marathon ANT survey generated several publications on its results some of which are listed in the Reference section.

Duluth Complex, Northeast Minnesota

In September 2023, a 32 km^2 survey was collected over a helium exploration target in Lake County, Minnesota. This survey used 183 three-component seismic nodes. Logging of a post-survey confirmation well has helium shows between 533 – 671 meters which agrees with the interpreted reservoir depth range from the ANT 3D data (Pulsar Helium).

Conclusion

Past work in the Lake Superior region has shown the ambient noise tomography is an effective tool for mineral exploration in the area.

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Geologic and tectonic implications of detrital zircon U-Pb ages from the Dickinson Group in the western Upper Peninsula of Michigan, USA

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In the Lake Superior region of the northern United States and southern Canada, Paleoproterozoic metasedimentary successions record the breakup of southern Superia (in present coordinates) that began ca. 2.3 Ga and the eventual transition to long-lived accretionary orogenesis along the southern Laurentia margin ca. 1.90–1.85 Ga. These successions are difficult to correlate for reasons that include contrasts in thickness and facies at multiple scales, similarities in depositional environment through hundreds of millions of years of sedimentation, and polyphase tectonism that variably produced intense deformational and metamorphic overprints. Detrital zircon U-Pb geochronology is useful for correlating siliciclastic strata that are widespread throughout the successions and for identifying provenance patterns in space and time. We present new data for samples collected from ca. 2.3–1.8 Ga strata across the western Upper Peninsula of Michigan and northern Wisconsin that provide a baseline for regional geologic mapping and correlations with similar strata regionally to globally. Our findings provide new insights into stratigraphic relationships of the ca. 2.1 Ga Dickinson Group and require revision of the depositional history, tectonic evolution, and regional significance of the succession.

The Dickinson Group is a distinctive succession of metasedimentary and metavolcanic rocks exposed only in the Felch trough area of the western Upper Peninsula. The strata are bounded by the Randville Dolomite of the Chocolay Group to the north and Archean banded gneiss to the south. These bounding contacts are mostly interpreted to be structural. The lowermost unit of the Dickinson Group is the East Branch Arkose, a coarse cobble to boulder conglomerate that contains rounded clasts of granite and quartzite in a matrix of feldspathic to lithic wacke. The conglomerate is moderately sorted and generally matrix-supported. At a few localities, the East Branch appears in unconformable contact with coarse-grained granite, interpreted as one of the ca. 2.6 Ga batholiths that are common in the southern Superior Province. At these basal localities, cobbles are strongly flattened and the entire unit contains a well-developed foliation defined by the flattened cobbles and aligned biotite in the sedimentary matrix. The East Branch Arkose is overlain by the Solberg Schist, the lower part of which contains fine-grained mafic schist and amphibolite together with discontinuous calc-silicate horizons up to 15 cm thick. Compositional layering in the Solberg is isoclinally folded with a consistent foliation defined by fine-grained chlorite and amphibole. The middle Solberg contains a ~100-ft-thick bed of iron-formation called the Skunk Creek Member that includes biotite-hornblende schist and thinly bedded metachert with magnetite layers (James, 1958). The upper Solberg is made up of interlayered biotite quartzite, massive gray quartz-mica schist, and staurolite-biotite schist. The Solberg Schist is overlain by the Six-Mile Lake Amphibolite, which is made up of fine- to medium-grained amphibolite with a strong tectonic foliation defined by hornblende. As originally mapped, the Dickinson Group defines a subvertical, south-facing homocline and was previously thought to be Archean based on an inferred gradational contact between the Six-Mile Lake Amphibolite and the Archean banded gneiss (James, 1958; James et

al., 1961). However, detrital zircon data published by Craddock et al. (2013) showed that the East Branch arkose was deposited ca. 2.1 Ga or later, thus implying a Paleoproterozoic age for the entire succession.

Our detrital zircon U-Pb data from the East Branch Arkose match previously published data from Craddock et al. (2013) and are dominated by ca. 2.6 Ga grains interpreted to reflect local granitic sources that are also observed as cobbles. Rare, but statistically significant ca. 2.1 Ga populations, confirm the Paleoproterozoic maximum depositional age. Mafic Solberg Schist that overlies the arkose does not contain abundant zircon, although some small grains that were recovered show a mix of ages ranging from ca. 3.1 to 2.6 Ga and a small ca. 2.1 Ga population. Detrital zircon age spectra from upper Solberg exposures are distinctly different, though. Samples of biotite quartzite and staurolite schist both contain prominent ca. 1.86–1.84 Ga age populations together with more minor ca 2.5 and 2.3 Ga age populations. The upper Solberg age spectra closely match samples of the Michigamme Formation from throughout the surrounding region, suggesting that the upper siliciclastic component of the Solberg schist should, instead, be mapped as Baraga Group. This revised interpretation raises the possibility that the mafic volcanic rocks and iron formation of the lower and middle Solberg Schist could also correlate with the lower Baraga and(or) Menominee Groups, though additional data are required to test these possibilities. Furthermore, it raises questions about the age of the Six-Mile Lake Amphibolite, the uppermost unit of James' (1958) Dickinson Group. We suggest that the Six-Mile Lake may be Archean as previously inferred by James (1958), in which case its concealed contact with the upper Solberg or Michigamme Formation would be tectonic rather than depositional. We are presently working to test this revised hypothesis through new geochronology and $^{40}Ar/^{39}Ar$ thermochronology across the contact. The actual depositional age of the East Branch Arkose remains uncertain, as it can be younger than the ca. 2.1 Ga detrital zircon age populations that it contains. This age population overlaps with the ca. 2.1 Ga porphyritic red granite that crops out among the western exposures of Dickinson Group strata, though cross-cutting relationships between the Dickinson and porphyritic red granite are not observed. A ca. 2.1 Ga depositional age for the arkose would require rapid unroofing of the coeval granite in a manner not presently observed elsewhere in the region.

In summary, prior interpretations of a continuous ca. 2.1–2.0 Ga Dickinson Group succession in the western Upper Peninsula of Michigan are not consistent with new detrital zircon ages from siliciclastic strata previously mapped as the upper Solberg Schist. These units correlate with the Michigamme Formation instead and raise new questions about the age, setting, and tectonic evolution of multiple Archean and Paleoproterozoic units in the region.

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Characterizing the geochemistry and nickel-copper-platinum group elements potential of mafic and ultramafic intrusions in northwestern Ontario

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Globally, magmatic sulphide deposits host significant resources of nickel, copper, cobalt and platinum group elements (PGE). These deposits occur as concentrations of sulphide minerals hosted within mafic to ultramafic intrusive rocks and are widespread across Ontario, occurring in every Precambrian geologic terrane. Ontario is home to 10 operating mines in magmatic sulphide deposits: 9 within the Paleoproterozoic Sudbury Igneous Complex and one within the Neoarchean Lac des Iles Complex.

In 1999, Operation Treasure Hunt was initiated by the Ontario Government to stimulate mineral exploration by acquiring new airborne geophysical data, surficial and bedrock geochemical data, and development of new methods. In 2003, following completion of the Operation Treasure Hunt project, the Ontario Geological Survey published a report (Vaillancourt et al. 2003) that assessed 109 mafic to ultramafic intrusions across Ontario. The purpose of this part of Operation Treasure Hunt was to characterize and publish data for intrusions known to be prospective for PGE-dominated magmatic sulphide mineralization. Many of the intrusions studied during Operation Treasure Hunt were host to significant known mineralization, including current and past-producing mines, and several of these intrusions are the focus of ongoing mineral exploration.

Despite the work by Vaillancourt et al. (2003), there are hundreds of mafic to ultramafic intrusions in Ontario that have not been systematically assessed for magmatic sulphide mineralization potential. Many of these intrusions have favourable characteristics for potentially containing magmatic sulphide deposits, including geophysical anomalies (e.g., magnetic, conductivity), overburden geochemical anomalies and known sulphide mineralization.

In 2023, the Resident Geologist Program of the Ontario Geological Survey initiated a project to systematically characterize geochemistry of a subset of mafic-ultramafic intrusions in northwestern Ontario that largely have not been subject to significant historical evaluation by academic researchers, government surveys, or mineral exploration companies. Evaluating the geochemistry of mafic to ultramafic intrusions can provide insight into the magma history, tectonic setting and potential for economic metal endowment. Factors that may influence metal endowment, that can be determined from the examination of geochemical data, include determining magma source characteristics, the timing of sulphur saturation and the degree of interaction of the magma(s) with their country rocks. Careful evaluation of physical characteristics and whole-rock geochemistry can inform future mineral exploration and/or the development of models for the emplacement of mafic to ultramafic intrusions and any hosted mineralization.

Withdrawn

Initial sample collection and analytical work took place during 2023. Areas of interest are shown in Figure 1, and include the Red Lake, Onaman–Tashota, and Heaven Lake greenstone belts. In this display, we provide examples of preliminary results and interpretations from areas targeted in the first year of field work, including the Trout Bay intrusion (Red Lake greenstone belt), Westwood intrusion (northeast of the Lumby Lake greenstone belt), and the Big Ghee Lake intrusion (south of the Shebandowan greenstone belt).

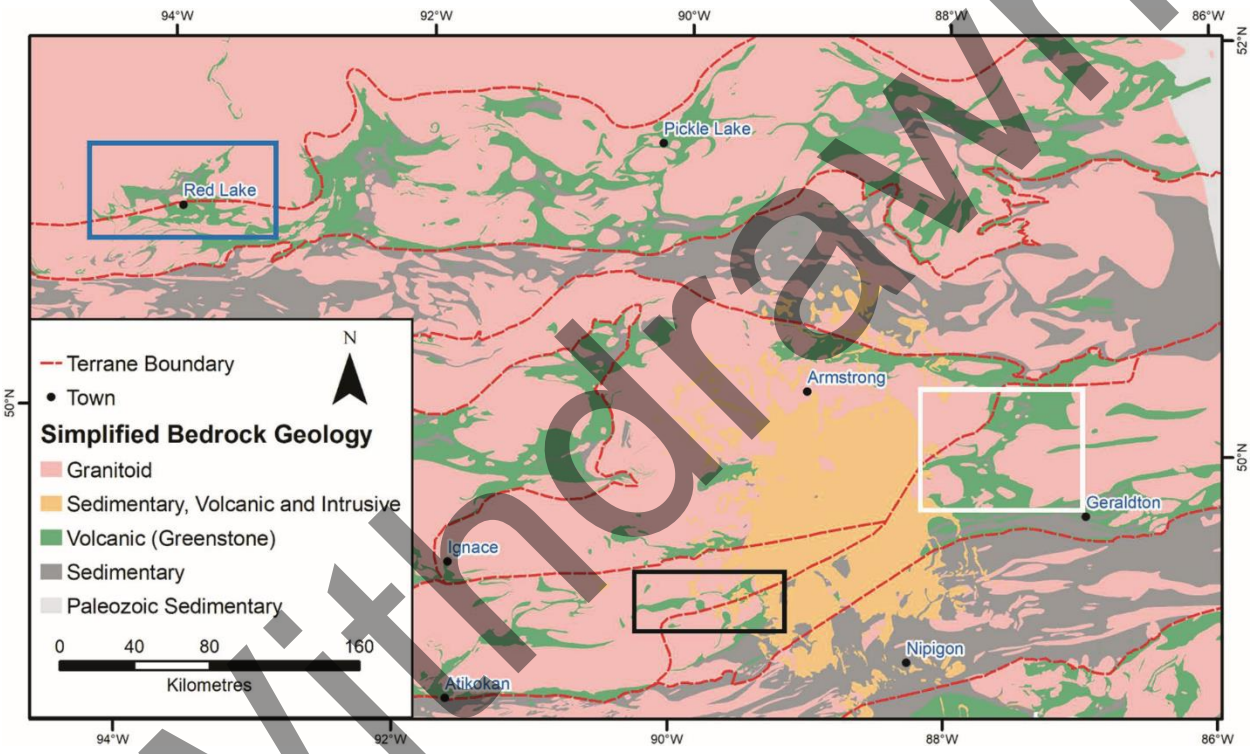


Figure 38.1. Simplified bedrock geology map of a portion of northwestern Ontario, showing project target areas: Red Lake greenstone belt (outlined in blue); Heaven Lake greenstone belt (outlined in black); and Onaman–Tashota greenstone belt (outlined in white). Regional geology *modified from* Ontario Geological Survey (2011).

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Cross-sectional Geometry of the Keweenaw Fault System between Hancock and Mohawk, Upper Peninsula of Michigan

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The Keweenaw fault system (KFS) is a major compressional feature along the Keweenaw Peninsula near the southern edge of the Midcontinent Rift System (MRS). The MRS formed in the Mesoproterozoic when a major extensional event split the ancient North American continent across the Upper Midwest, yielding large volumes of basaltic lava such as the Portage Lake Volcanics (1.1 Ga, PLV). The PLV strata were thrust southeastward over the Jacobsville Sandstone (JS) along the KFS during post-rift compression by the Grenville Orogeny (**1**), and some have postulated an earlier origin by normal faulting during rifting (**2,3**). A recent interpretation based partly on cross-section modeling is that faults making up the KFS are parts of a detached thrust system that formed during the Grenville Orogeny (**4**).

Faults of the KFS have been interpreted to have dip slip – recent reverse slip and possibly earlier normal slip. Since 2017, bedrock mapping and analysis of fault-slip indicators have revealed a significant component of right-lateral strike slip on the KFS, which at its northeast end is inferred to have twice the magnitude of north-side-up reverse slip (**5**). The collective oblique motion across the KFS is accommodated on fault segments with three distinct orientations that overlap and intersect: (1) major segments parallel to the KFS trend, (2) splay faults striking clockwise to major segments by less than 35°, and (3) shorter connector faults striking counter-clockwise to major segments and splays by up to 75° (Fig. 1). The ratio of dip slip to strike slip should vary among faults with such a range of orientations, as should the style of deformation in their hanging walls and footwalls. To help understand these relationships, cross-sections were constructed across various fault components of the KFS using recent mapping data, heritage data from published maps, and drill hole data. Cross-section work employed the dip-domain-bisector method and principles of detached thrust systems and conservation of volume.

The new cross-sections attempt to model the subsurface geometry of the segmented KFS and to build on previous work in the area (**4**). Important unknowns are the JS thickness in the footwall and how JS strata deform adjacent to major faults. A minimum JS thickness of 800 meters was assumed, based on Mayflower drill hole #41 that crosses the Keweenaw fault at 476 meters below sea level (Fig. 2). Ductile deformation of a poorly indurated, mud-prone section near the base of JS was the method used to accommodate flexural slip in the overlying section, but other mechanisms remain to be investigated. A common feature of cross-sections transverse to the KFS trend is a thrust sheet with shallowly dipping PLV strata between a major fault segment and a splay fault. The cross-sections are adding to our understanding of deformation within the KFS and to the tectonic forces that created it.

Acknowledgements
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Wright for access to Quincy Mine; Ian Gannon, Breeanne Heusdens, Jack Hawes, Braxton Murphy, and Dillon Breen for field assistance; and Dan Lizzadro-McPherson for ArcGIS assistance.

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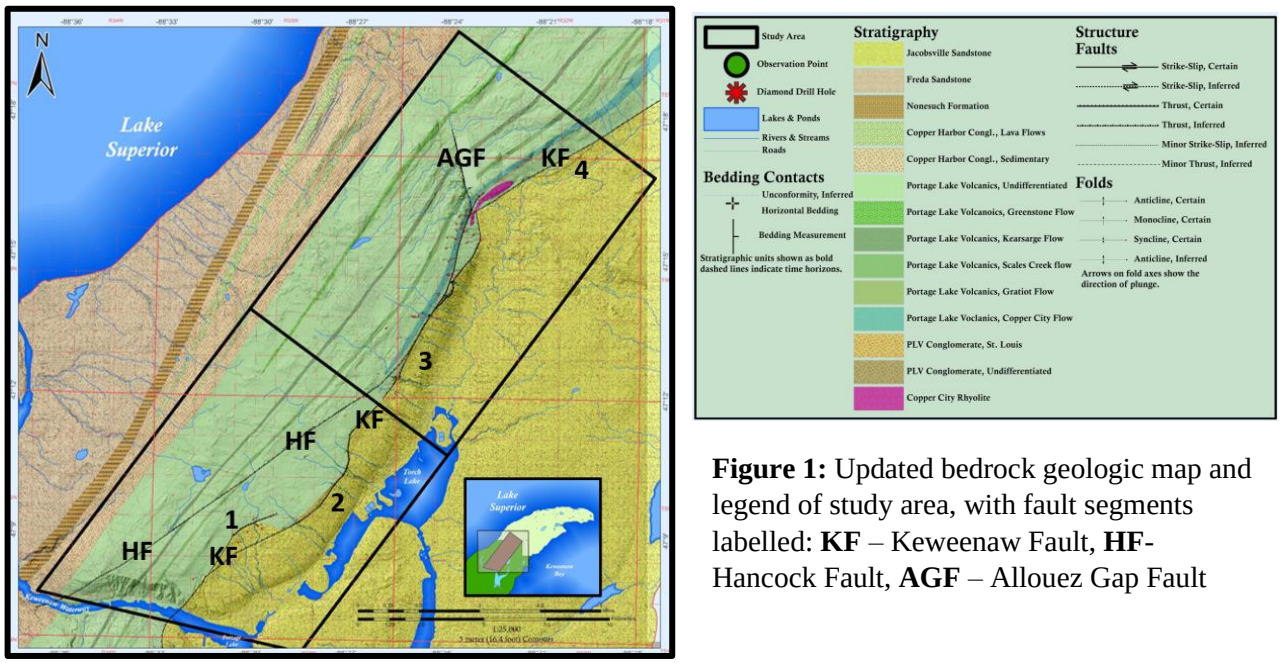


Figure 1: Updated bedrock geologic map and legend of study area, with fault segments labelled: **KF** – Keweenaw Fault, **HF**- Hancock Fault, **AGF** – Allouez Gap Fault

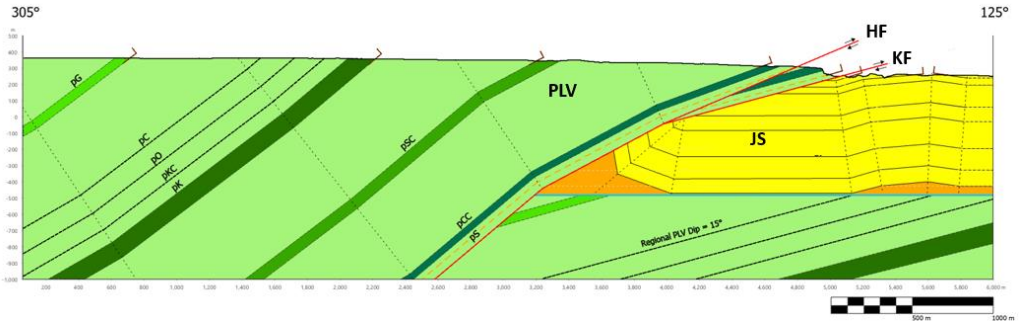


Figure 2: Cross-section showing Keweenaw (**KF**) and Hancock Faults (**HF**) at Douglass-Houghton Falls. Main units: **JS** – Jacobsville Sandstone, **PLV** - Portage Lake Volcanics

Volcanic and Hydrothermal Reconstruction of the Paleoproterozoic Butler Zn-Cu occurrence, Clark County, Wisconsin

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The Butler Zn-Cu occurrence is located in western Clark County, northcentral Wisconsin, and is an example of a volcanogenic massive sulfide (VMS) deposit. These VMS deposits are mined globally for numerous metals including Zn, Cu, Pb, Ag, and Au, and are formed at or near the seafloor in extensional submarine volcanic environments through the discharge of hot, metal-rich hydrothermal fluids (e.g. Franklin et al., 2005). The Butler occurrence is hosted in the Paleoproterozoic Eau Claire Volcanic Complex (1.8-1.9 Ga) within the Marshfield terrane of the Penokean Orogen (Shultz and Cannon, 2007; DeMatties, 2022). Historically, the interpreted setting for Penokean volcanism within the Marshfield terrane was a "continental' setting with younger magmas emplaced within older Archean crust. New data from the Eau Claire Volcanic Complex suggests the absence of Archean crust during Penokean volcanism (Weber et al., 2023).

The goal of this project is to interpret the volcanic and hydrothermal setting of the Butler Zn-Cu deposit and test whether the lithostratigraphic and petrochemical associations fit an oceanic or continental model. Extensional environments that form VMS deposits can exist in both oceanic and continental settings. This imparts unique lithostratigraphic (Franklin et al. 2005) and petrochemical (Piercey, 2011) characteristics on the host stratigraphy and alteration styles. The lithostratigraphy of continental-associated VMS tends to be more felsic in nature with a higher abundance of siliciclastic rocks relative to oceanic-settings. Mafic rocks are much more abundant in ocean environments whereas are rare and largely intrusive in continental settings. Chemically, felsic rocks in continental settings are HFSE- and REE-enriched while mafic rocks are typically alkalic- to MORB-affinities commonly found in continental rift settings.

Approximately 2700 linear feet of drill core from the Butler occurrence were re-logged and sampled for petrographic and geochemical characterization of the host volcanic and hydrothermally-altered rocks. Petrography divided the host strata into three main units: 1) felsic volcanic rocks, 2) amphibolite, and 3) metapelite. The felsic volcanic rocks are fine-grained, foliated quartzofeldspathic schists (Figure 1A) that have layered volcaniclastic textures and local stretched and flattened lapilli fragments. The amphibolite units (Figure 1B) are fine- to medium-grained, homogenous, and largely unaltered suggesting an intrusive origin that post-dates the main VMS-forming event. The metapelite units (Figure 1C) are made up of a micaceous matrix composed of muscovite, chlorite, and biotite. The metapelite units are characterized by large porphyroblasts of garnet, staurolite, and/or cordierite. Hydrothermally-altered rocks that host sulfide mineralization are metamorphosed to biotite±chlorite±talc schists and calc-silicate mineral assemblages. The sulfide mineralization is primarily pyrite with variable amounts of chalcopyrite, and sphalerite. Massive sulfides (Figure 1D) are weakly banded with chloritic gangue while semi-massive vein-type mineralization is found throughout altered rocks.

The relative abundance of the felsic and amphibolite units coupled with an intrusive origin for amphibolite, suggests a bimodal-felsic type VMS, described in the paper *Volcanogenic Massive Sulfide Deposits* that is typical of continental magmatism (Franklin et al., 2005). Mafic units are interpreted to be island arc to MORB-type based on Ti vs. V discrimination plots. Felsic volcanic rocks have an FII-type affinity on Zr/Y vs. Y discrimination diagrams and have within plate affinities on Nb vs. Y discrimination diagrams. Geochemical abundances of the host rocks support a continental petrochemical association.

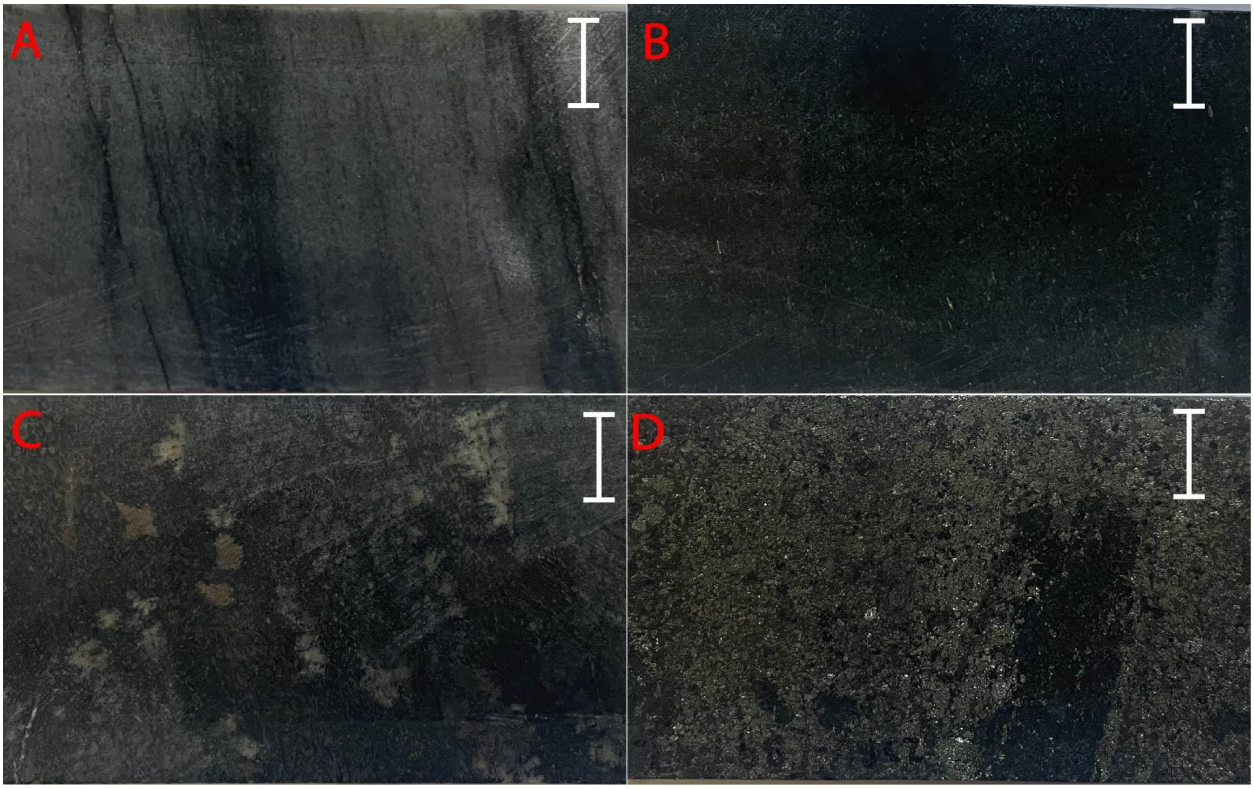


Figure 1. Photographs of core samples from the Butler deposit featuring the host rocks of the VMS. White scale bar equals about 1 cm. (A) Foliated felsic volcanic rock that is the main host rock of the Butler formation. (B) Amphibolite unit, image displays how homogenous the matrix is. (C) Metapelite unit, tan staurolite porphyroblasts along with large purple to grey cordierite porphyroblasts found throughout the matrix. (D) Massive sulfide unit containing pyrite and chalcopyrite.

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Building a 3D model for Cu/Pd inflection points throughout the Marathon PGE-Cu Deposit

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The Marathon PGE-Cu deposit is hosted in the North American Midcontinent rift system, a failed continental rift (Good et al., 2015). Magmatic activity in the area created an optimal environment for the formation of economically significant sulphides (Smith et al., 2022) bearing copper (Cu), and platinum group elements (PGE) at the Marathon deposit. The deposit lies in the Two Duck Lake Gabbro, a subophitic, coarse-grained intrusion located at the eastern margin of the Coldwell Complex. This study explores how Cu/Pd varies in 3D space at the deposit scale and aims to use it as a vectoring tool to guide exploration. The ratio of Cu/Pd is a useful marker of the enrichment of Pd relative to the mantle. Low Pd relative to Cu indicates previous Pd depletion due to the early formation of sulphides in the intruding magma that formed the deposit, whereas a relatively higher Pd concentration implies Pd enrichment (Barnes et al., 1993). The 3D model helps to visualize the positions of the abrupt shifts (inflection points) in Cu/Pd ratio throughout the Marathon deposit. Identifying and modelling Cu/Pd inflection points facilitated the search for trends in mineralization. To create the model, a data filtration process was employed to define wide mineralization intervals containing at least 80 ppm Cu and 0.15 ppm Pd. Zones of continuous mineralization of at least 16 m in length were identified. To identify inflection points the difference in Cu/Pd ratio was evaluated at 10 m intervals. The mineralized zones were searched for points that surpassed the thresholds found to constitute trend reversals in Cu/Pd (ΔCu/Pd >5000 or <-5000). Approximately 1150 inflection points have been identified in 404 drillholes from a dataset of 997 drillholes and 61960 assays.

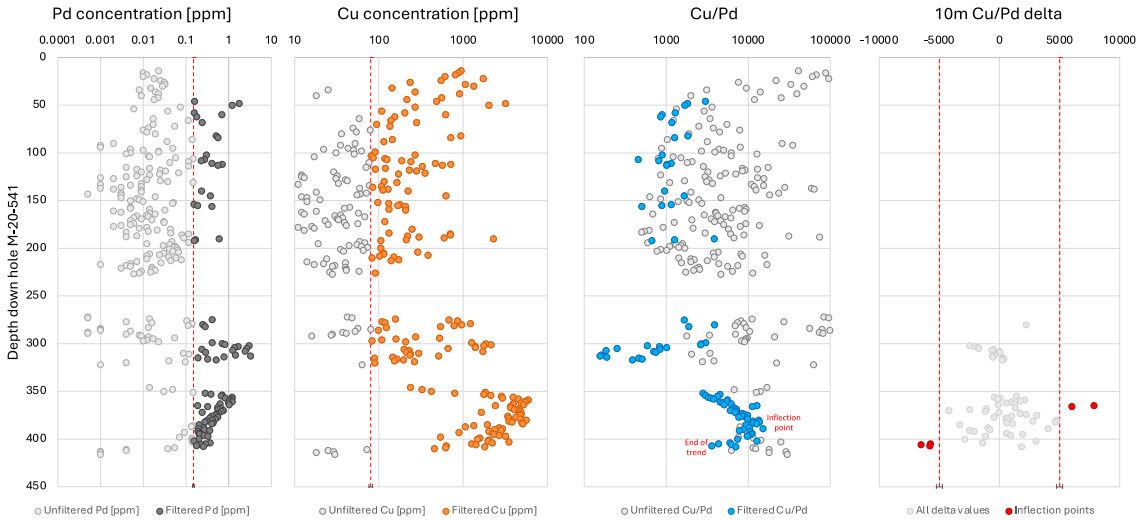


Figure 1. Graphs showing the trends of concentration Cu and Pd in ppm, the ratio of Cu/Pd, and the 10 m difference calculations used to identify inflection points, down drill hole M-20-541 (depth in m) at the Marathon PGE-Cu deposit. The dashed lines indicate filtration cut-offs for Cu (80 ppm) and Pd (0.15 ppm) and the inflection point thresholds in the Cu/Pd graph (at -5000 and 5000).

Three zones of interest were identified within the model of the deposit with distinct trends in the occurrence Cu/Pd ratio inflection points (Fig. 2). Area 1 included zones of high grade Pd mineralization occurring independently of any high-grade copper or any inflection points. In Area 2 the arrangement of inflection points suggests a boundary which aligns with the paleosurface at the contact between the Footwall and the Main Zone. A fault runs through Area 3 (Good et al., 2015), along which there are no Cu/Pd inflection points, indicating that there may be a link between faulting and the consistency of Cu/Pd ratio. The most prominent pattern observed in the 3D model of the inflection points was that Cu/Pd correlates better with lithological changes than with shifts in Cu and Pd grade.

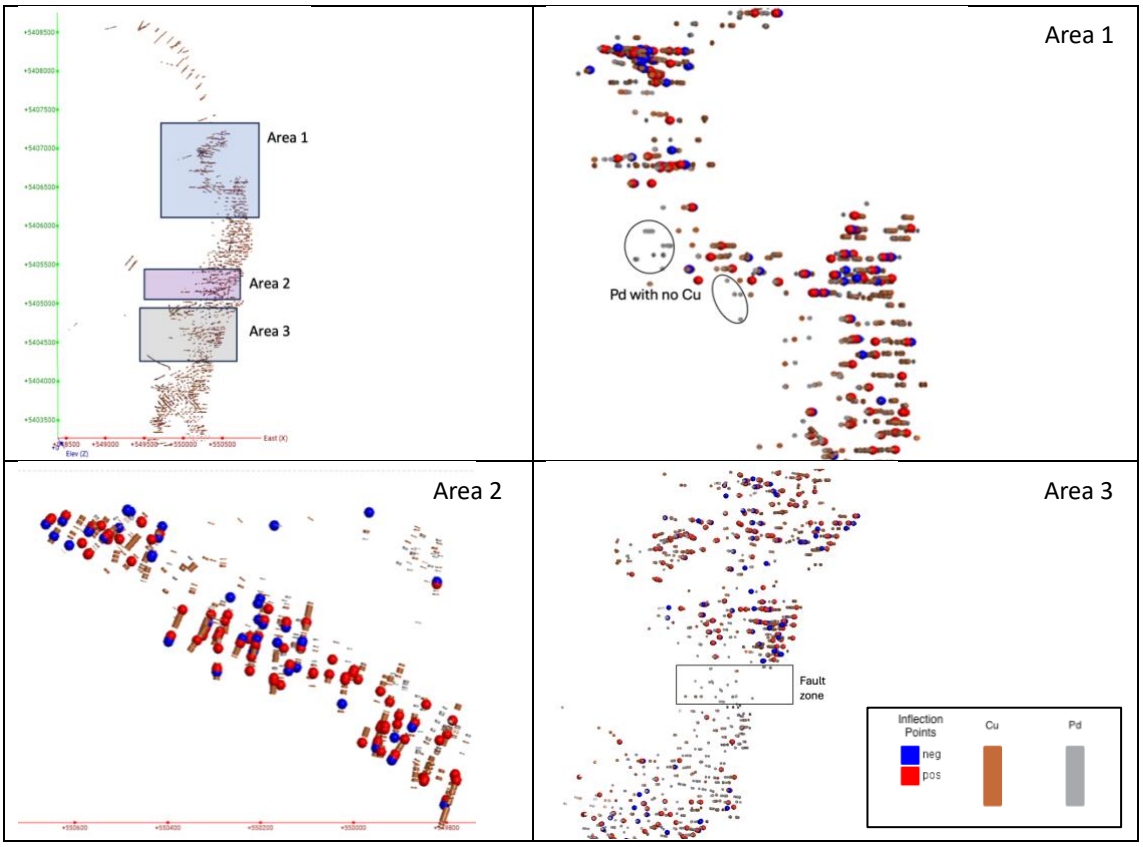


Figure 2. Views of the Leapfrog model of the Marathon deposit, including all Cu and Pd assays and all inflection points. Showing plan views of the whole deposit, Areas 1 and 3 and a cross-section of Area 2.

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Critical Mineral Systems in the Upper Peninsula of Michigan, A Cooperative Effort Between the USGS and the Michigan Geological Survey

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In 2018, the U.S. Geologic Survey (USGS) released a list of critical minerals defined as "non-fuel mineral or mineral material essential to the economic or national security of the U.S., and which has a supply chain vulnerable to disruption" and updated it in 2022 to a total of 50 critical minerals (Burton, 2022). Since 2021, President Biden has made the domestic supply of critical minerals a national priority. With federal funding, the USGS Earth Mapping Resource Initiative (EMRI) is collaborating with State geological surveys on geologic mapping and critical mineral assessments, as well as inventorying and characterizing mine wastes.

The USGS has identified broad focus areas within the United States to target critical minerals (Hammarstrom and others, 2023). These focus areas are based on known mineral occurrences and favorable geologic settings. The Precambrian of the Upper Peninsula (UP) figures in 17 mineral systems. The Michigan Geological Survey (MGS) has narrowed the list to nine systems in the UP to focus our future work (Table 1). With the support of the USGS, forthcoming mapping and geochemical reconnaissance programs by the MGS over the next few years will assess these systems.

Name of focus area	Mineral system	Deposit type(s)	Critical minerals in the deposit types	Critical minerals Identified
Midcontinent Rift magmatic sulfide Ni-Cu-PGE	Mafic magmatic	Nickel-copper-PGE sulfide	Co, Ni, PGE, Te	Nickel, Co, PGE
Manganese (Mn) in iron-formations	Marine chemocline	Iron-manganese	Co, Mn	Manganese
Graphite in black shales	Metamorphic	Graphite (carbonaceous sed)		Graphite
Humboldt Granite	Porphyry Sn (granite-related)	Porphyry/skarn	Be, Nb, Sc, Sn, Ta, W	Trace
Humboldt Granite	Magmatic REE	Peralkaline syenite/granite/rhyolite/ alaskite/pegmatites	Be, Fl, Hf, Nb, REE, Ta, Te, V, Zr	Trace
Southern Complex pegmatites	Porphyry Sn (granite-related)	Pegmatite LCT	Be, Ce, Li, Nb, Sc, Ta, Sn	Trace
Mesoproterozoic Phosphate	Marine chemocline	Phosphate	Co, REE	Phosphate
Peavey Pond Complex	IOA-IOCG	Iron oxide apatite; Iron oxide copper gold	Co, REE	Unknown
Western Upper Peninsula, IOCG	IOA-IOCG	Iron oxide apatite; Iron oxide copper gold	Co, REE	Unknown

Table 1: USGS-MGS Critical Mineral Focus Areas for the UP (modified from Hammarstrom and others, 2023)

The existence of some critical minerals is well-established in the UP, such as magmatic sulfide Ni-Cu-Pt-Pd-Co. Others, such as graphite, manganese, and phosphate have been documented in small occurrences or as accessory minerals in larger deposits (Cannon and Klasner, 1976: Hwang and others, 1986; James and others, 1968; Peterman and others, 1987,

Mancuso, 1975). Evidence for critical minerals such as rare-earth elements, beryllium, and fluorspar in pegmatites, granites, and iron-oxide-copper-gold/oxide apatite deposits (IOCG/IOA) is sparse. A limited number of studies of UP pegmatites and the Humboldt granite have identified trace REE, Be, and Ta minerals (e.g. Buchholz and others, 2014; Johnson and others, 2015; Moss, 1975, Schulz and others, 1988). Mineralization directly tied to IOCG/IOA has not been identified, although the tectonic history and metal endowment suggests the UP is a permissive, if not prospective region for them.

The USGS has also mounted a mine waste characterization program intended to identify potentially recoverable critical minerals in historical mine stockpiles, waste piles and tailings and prioritized by size, potential mineral resources. As part of the effort, the MGS has identified over 80 mine sites in the UP within EMRI critical mineral focus areas that have published references to possible critical mineral content. Future assessments will involve representative sampling of mine waste features and geochemical evaluations.

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Baraboo Interval Quartzites in Iowa: Reassessing the Origin and Provenance of the Washington County Quartzite, SE Iowa

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The Washington County Quartzite (WCQ) in southeastern Iowa is the southernmost occurrence of the Baraboo Interval quartzites in the midcontinent region (Figure 1). Two drill holes encountered poorly sorted quartzite and phyllite at a depth greater than 2,300 feet, likely deposited in a braided fluvial or deltaic environment near the Laurentian continental margin on the Columbia supercontinent. One hundred new LA-ICPMS detrital zircon ages from the WCQ show a prominent 1.78 Ga age peak, representing local Yavapai-aged basement, a secondary peak at 1.8-1.9 Ga representing a distal Penokean source, and minor <2.5 Ga peak derived from distal sources in the Superior Province. Multidimensional scaling of other Baraboo Interval quartzites and potential sources show that the WCQ is indistinguishable from the lower interval of the Baraboo quartzite (Figure 2). Cumulative and stacked probability plots also reflect principal source areas locally derived by erosion of underlying Yavapai-aged crust and distally derived Penokean and older sources from the Pembine-Wausau Terrane or southern Superior Province. The WCQ likely serves as the down slope equivalent during initial Baraboo deposition.

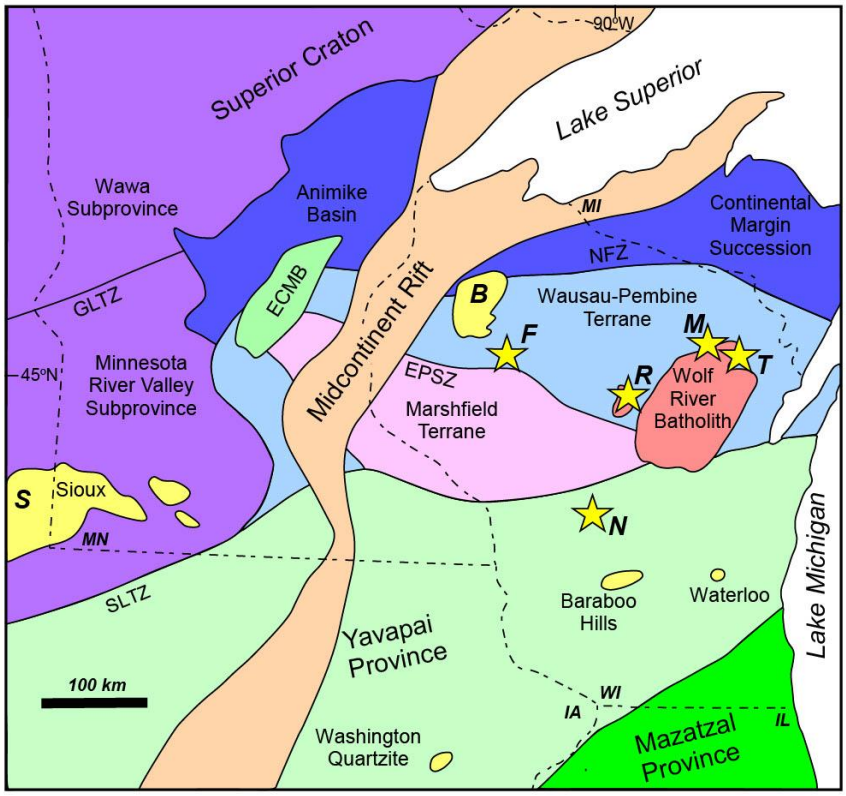


Figure 1. Geological map of Precambrian basement rocks in the northern midcontinent (modified from Medaris et al., 2021). Baraboo Interval Inliers are B = Barron, F = Flambeau, M = McCaslin, T = Thunder Mountain, R = Rib Mountain, and N = Necedah. SLTZ = Spirit Lake Tectonic Zone, ECMP = East-Central Minnesota Batholith, GLTZ= Great Lakes Tectonic Zone, and NFZ = Niagara Fault Zone.

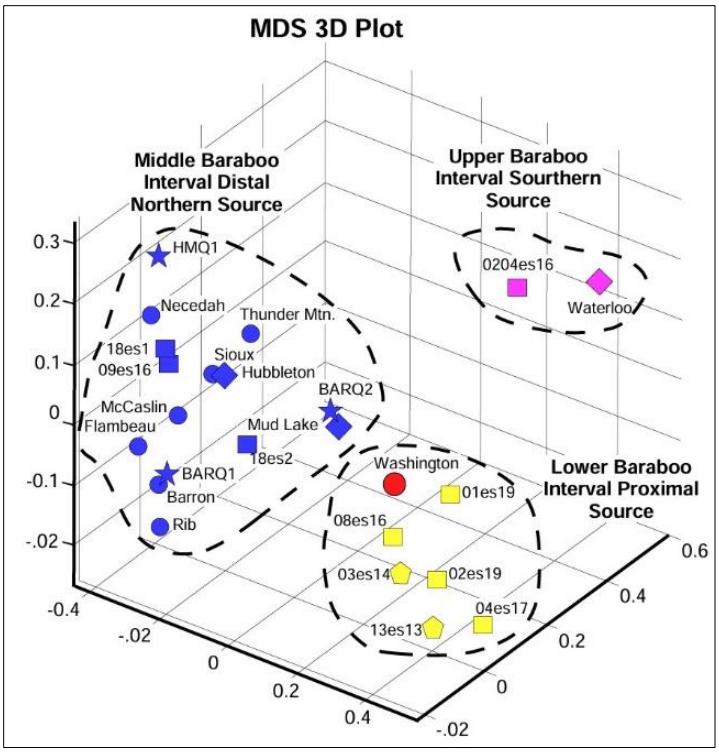


Figure 2. Three-dimensional multi-dimensional scaling plot of Baraboo Interval strata in the northern midcontinent. Included data compiled from Malone et al. (2022), Van Wyck and Norman (2004), Stewart et al. (2018), Stewart et al. (2021), and Medaris et al. (2021). The red circle is the WCQ from this study. The yellow cluster includes samples from the lower members of the Baraboo Quartzite in the Baraboo Hills that are dominated by Yavapai-age zircons. The blue cluster includes the middle members of the Baraboo Quartzite in the Baraboo hills, other quartzites north of the SLTZ, and Necedah reflects a complex sedimentary provenance that includes proximal and distally derived zircons from the Penokean Province, Superior Province, and Trans-Hudson belt. The purple cluster includes the Waterloo Quartzite and the upper members of the Baraboo Quartzite in the Baraboo Hills that are dominated by southerly derived Mazatzal-age zircons.

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The Soudan Geology Trail Project: Let's talk about rocks in northeastern Minnesota

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As part of a larger research endeavor within the Archean terrane of northern MN, we are developing educational outreach content created to engage the public with portions of the important geology of the region. Rocks exposed in the Lake Vermilion-Soudan Underground Mine State Park, located near Tower, MN, record glimpses of environmental and tectonic conditions from 2.7 billion years ago to the present, including mysteries of the early Earth, complexities of modern history, and possibilities of the future. The planned content will be designed to follow outcrops located along a paved trail that runs through the park (Figure 1).

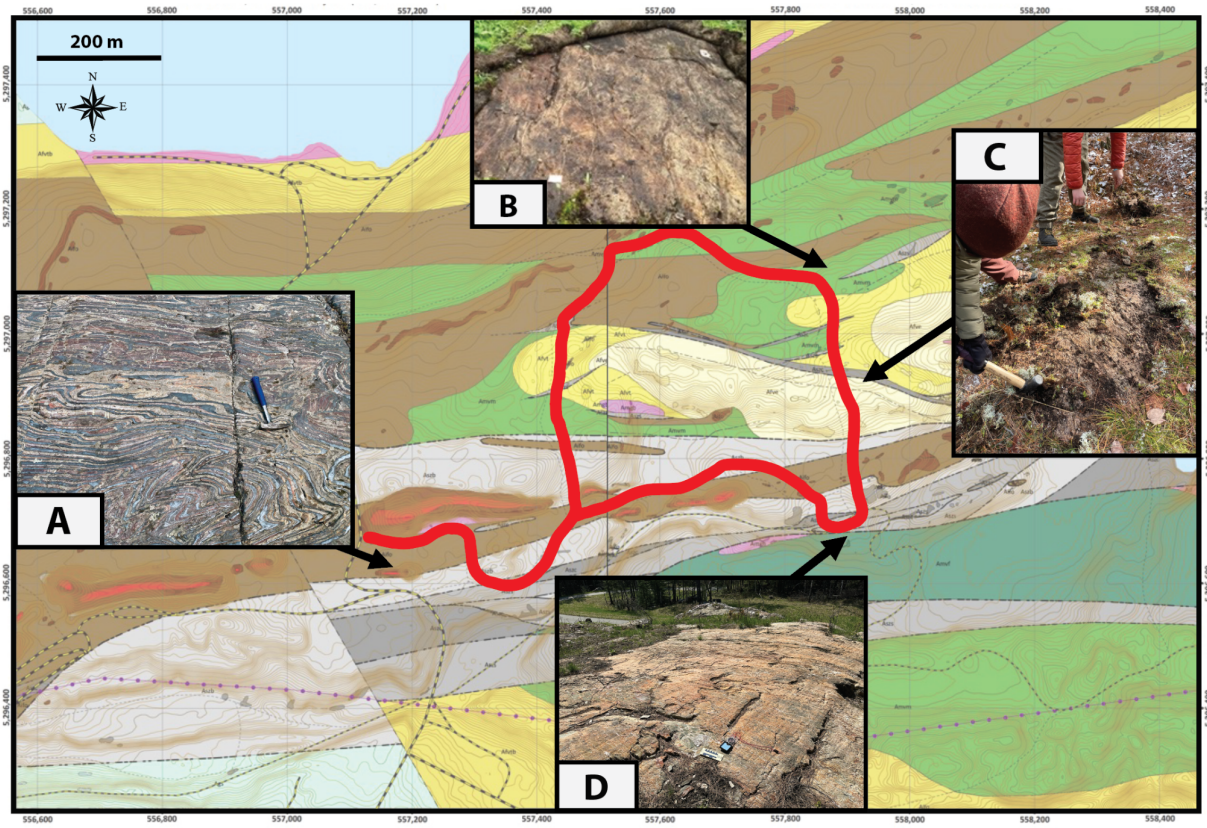


Figure 1: This figure shows recently exposed units along the proposed trail (bold line in center of the figure). Starting at the banded iron formation (A), the trail leads north then east (clockwise) to the next units (B) consisting of pillow basalts and basaltic lava flows, followed by felsic tuff (C) and lastly a large, exposed outcrop along the paved road is chlorite schist with intertwined with banded iron formation (D).

The chosen outcrops consist of well-preserved greenschist-facies metamorphosed igneous, sedimentary, and sheared rocks. Selected rock units along the trail include Neoarchean basaltic lava flows, pillow basalts, felsic tuff, gabbro, oxide-facies banded iron formation, and chlorite- and sericite-dominant schists. These rock units represent an ancient submarine volcanic and hydrothermal environment that was subsequently regionally deformed (Hudak et al., 2016).

The work being done will be included in educational materials designed to communicate the scientific content in digestible ways. Plain language writing, paired with visuals, modern analogues and analogies will present the information in a variety of ways with the intention of supporting a range of learning styles. The materials will be available in physical forms (on paper and/or trail signs) and with QR codes which will link to additional online content. Visual illustrations will be designed in collaboration with a Minnesota high school student. Combining educational material with the hands-on outdoor experience of visiting the trail and highlighted outcrops aims to facilitate cognitive development and understanding of the long history and importance of the regional geology.

This initiative is a collaboration among park officials Jim Essig (Park Manager) and Sarah Guy-Levar (Interpretive Supervisor) from the MN Department of Natural Resources, the University of Minnesota Department of Earth and Environmental Sciences, and local and state educators.

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Investigating the origin of pervasive breccias in the Paleoproterozoic Saunders Formation in northern Wisconsin

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The Paleoproterozoic Saunders Formation is an enigmatic unit with limited exposure along the Brule River, which forms the border between northern Wisconsin and the Upper Peninsula of Michigan. The unit occurs just north of the Niagara Fault zone, the Penokean-age (ca. 1.88 Ga) tectonic suture between the Superior Craton and the Wisconsin Magmatic Terranes (Schulz & Cannon, 2007). Variously described as a "massive dolomite" (Allen 1910), a "silicified dolomite" (Sims, 1992), and a "silica rock" (Cannon, 1986), the Saunders Fm. is thought to be part of the lower Chocolay Group, correlative with the Randville, Bad River, and Kona Dolomites, and possibly also the quartzites underlying these units (Sturgeon River, Sunday, and Mesnard Fms.). Each of these carbonate formations is overlain by a major unconformity, at ca. 2.1 Ga., representing at least 100 million years of erosion.

Every published description of the Saunders Fm. mentions that it tends to be brecciated, yet the nature of these breccias has not been explored in detail. Dutton & Linebaugh (1967) suggested that the Saunders Fm. represents a condensed section of basal Chocolay quartzite and dolomite, related to the formation of the regional unconformity. James *et al.* (1968) similarly hypothesized that "silcretes" within the Saunders had formed by Proterozoic weathering but also pointed out that none of the other Chocolay Group carbonate units displays evidence of such deep weathering. They speculated, therefore, that the Saunders breccias could have had a tectonic origin but did not pursue that hypothesis further. The purpose of this study was to characterize and interpret Saunders breccias in outcrops at Brule River Cliffs State Natural Area in Wisconsin.

At this site, outcrops of the Saunders Formation are of two types: 1) beige to orange-colored dolostone with a 'gritty' but otherwise massive (unveined, unlaminated) texture; and 2) dramatically fragmented dolostone with extensive 'stockwork" quartz veins that constitute most of the rock mass. Immediately southwest of the Natural Area boundary, large boulders of dolomite-matrix breccias with angular chert fragments are common. Although these are not *in situ*, we suspect they come from the Saunders Fm., and were transported ca. 12 km by glacial ice. If so, these chert breccias represent a third, distinct textural type within the Saunders.

The gritty dolomite, which is typically unveined, has a distinctive diamictic, granular texture, with scattered mm-sized, rounded grains set in a much finer matrix. In thin section, the matrix also appears granular, unlike the crystalline texture typical of most carbonate rocks. Similar gritty/ granular dolomites have been observed along a major upper crustal fault zone in Namibia. Rowe *et al*. (2012) interpreted these unusual textures as records of decarbonation and fluidized granular flow caused by rapid frictional heating during seismic slip in rocks that had been at ambient crustal temperatures of around 200°C. (Carbonate rocks typically devolatilize, rather than melt, during seismic slip, so pseudotachylyte is rare along faults cutting through dolostone). The absence of talc or other calc-silicate metamorphic minerals in the Saunders Formation points to sub-greenschist temperatures in an upper crustal setting comparable to the Namibian case.

The veined breccias have an 'exploded' look, with quartz veins in multiple orientations that appear to have increased the volume of the rock mass more than 100%. The isolated fragments of host dolostone have narrow, slab-like shapes that suggest fragmentation occurred partly along bedding planes. In thin section, most of the veins have a coarse, blocky texture with no preferred orientation of crystals. Fluid inclusions arrays are common, particularly in the interiors of the crystals. Some of the vein quartz shows slight undulose extinction. The chert breccia boulders

found southwest (in the down-ice direction) of the Saunders outcrops have the texture of cataclasites. The angular fragments of chert within these breccias appear to represent thin silicified stromatolitic layers that were fractured and dismembered.

We interpret these three textural types of the Saunders Fm. as distinct areas within a major Penokean-age fault zone. The chert breccias may represent the outer part of the fault zone, dominated by non-seismic cataclasis. The gritty dolomite, bearing evidence of co-seismic heating, would have been closer to the fault core, together with the heavily veined dolostone, whose 'exploded' nature points to extreme dilational strain and forceful fluid influx with little cataclasis or grinding. The large amounts of vein material relative to the host rock, as well the blocky texture of the veins, are consistent with the introduction of large volumes of overpressured, silica-supersaturated fluids into the shallow crust during the propagation of a fault rupture upward from depth. Such fluid influx can happen when co-seismic slip breaks the barrier between deep crustal, low-permeability rocks in which fluids are at lithostatic pressures and overlying high-permeability rocks with fluids at hydrostatic pressure (Cox and Munroe, 2016). Silica-rich fluids traveling upwards from below this barrier would be far from chemical equilibrium in the shallow crust, and they would rapidly precipitate their dissolved silica, easily overcoming kinetic quartz growth limits that exist under equilibrium conditions (Williams and Fagereng, 2022). This interpretation of the Saunders breccias is supported by oxygen isotope analyses of seven vein quartz samples, all of which yielded $\delta^{18}O$ values between 15.94 to 17.46 VSMOW.

Although brecciated textures described in previous studies of the Saunders formation may be related to deep weathering and the post-Saunders unconformity, the breccias exposed in the Brule River Cliffs Natural Area are clearly tectonic -- and probably coseismic -- in origin. The Saunders Formation thus provides further evidence for great earthquakes at various crustal depths along major fault zones during the Penokean orogeny (Larson & Bjørnerud, 2017; Taylor & Bjørnerud, 2023).

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The Evolution of Baraboo Interval Sedimentary Rocks: Deposition at 1.63 Ga and Metamorphism at 1.47 Ga

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Supermature siliciclastic sedimentary rocks of the Baraboo Interval (Dott, 1983) were deposited in the southern Lake Superior region following the 1.65-1.63 Ga Mazatzal orogeny and subsequently experienced 1.47 Ga fluid-rock interactions related to the trans-Laurentian Pinware-Baraboo-Picuris orogeny (Daniel et al., 2022). Metamorphic fluid-rock interactions include dehydration and metasomatic varieties, the latter having been promoted by regional-scale advective flow of brines along permeable channels in the various Baraboo Interval occurrences.

In the Baraboo Range, south-central Wisconsin, the supermature sedimentary rocks are composed of five oxides, *viz.* SiO_2, Al_2O_3, Fe_2O_3, TiO_2, and H_2O, with CaO, Na_2O, and K_2O having been largely removed during weathering of the igneous basement. During metamorphism, the original sedimentary mineral assemblage of kaolinite + quartz + hematite + rutile was transformed to one of pyrophyllite + quartz + hematite + rutile through the dehydration reaction,

$$Al_2Si_2O_5(OH)_4\ (kln) + 2SiO_2\ (qtz) = Al_2Si_4O_{10}(OH)_2\ (prl) + H_2O\ (fluid)$$

Note that in shale, which consisted mostly of kaolinite, the appearance of pyrophyllite is accompanied by diaspore, as expressed by the dehydration reaction,

$$2Al_2Si_2O_5(OH)_4\ (kln) = Al_2Si_4O_{10}(OH)_2\ (prl) + 2AlO(OH)\ (dsp) + 2H_2O\ (fluid)$$

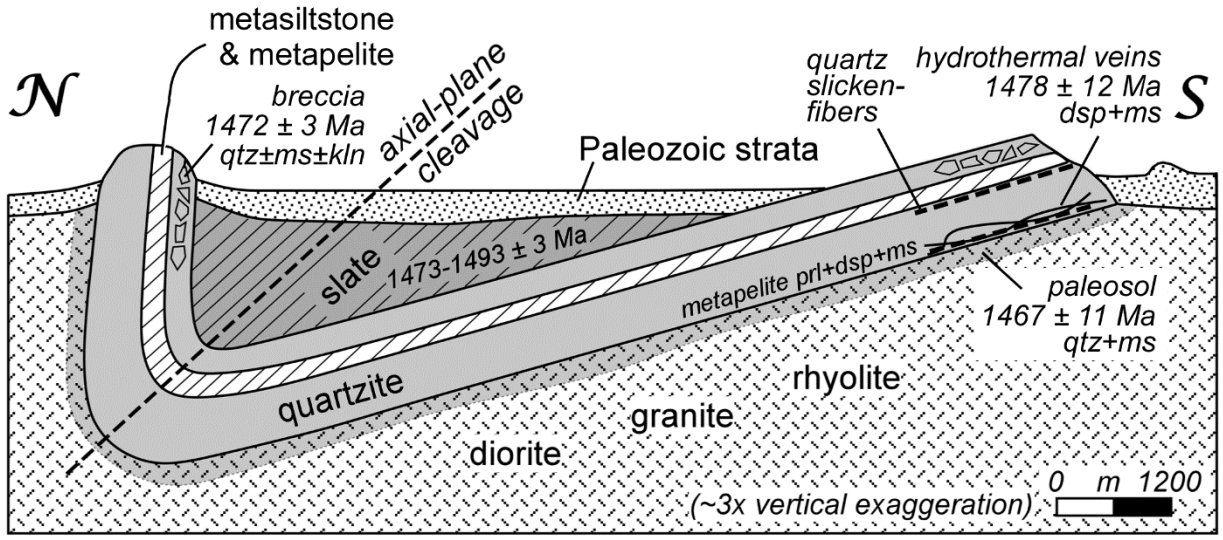


Figure 1. Schematic cross-section of the Baraboo Range, indicating the various metasomatic mineral assemblages; the numbers specify $^{40}Ar/^{39}Ar$ plateau ages for muscovite.

Folding and metamorphism in the Baraboo Range were accompanied by advective flow of brines and potassium metasomatism along the base of the quartzite and in the overlying slate (Fig. 1). At the base of the quartzite, kaolinite was replaced by muscovite in *paleosol*, kaolinite was replaced by pyrophyllite and accompanied by precipitation of muscovite in *metapelite (pipestone)*, and thin diaspore *hydrothermal veins* (bordered by muscovite) intruded quartzite

above the metapelite. Slate that overlies the quartzite consists of muscovite, chlorite, quartz, hematite, and rutile and contains 4.7% to 6.4% K_2O, due to potassium metasomatism, compared to 3.5% K_2O in average shale.

The paleosol at the base of the quartzite in Baxter Hollow (Fig. 1), which is 796 cm thick, experienced a total flux of 0.46 mol cm^{-2} K_2O during metasomatism. Five additional Proterozoic paleosols in the southern Lake Superior region, ranging in thickness from 300 cm to 950 cm, also experienced potassium metasomatism, with K_2O fluxes between 0.22 and 0.73 mol cm^{-2}, respectively; for all six paleosols taken together, $K_2O_{flux} = 0.00066 \times thickness_{cm} + 0.06$, for which $R^2 = 0.82$.

SiO_2 was mobilized high in the quartzite section at the base of the metasiltstone and metapelite horizon in the south limb of the syncline, where quartz was precipitated in several bedding-parallel slickenfiber layers, 3 mm to 8 mm thick (Fig. 1). Individual slickenfibers are cylindrical, having a:b:c fabric ratios of 8:1:1, in which the a-dimension is up to 4 mm in length. Slickenfibers plunge down-dip approximately perpendicular to the fold axis of the syncline, and slickenfiber steps record top-to-the-south shear.

SiO_2 was also mobilized above the metasiltstone/metapelite horizon, where quartz was precipitated in bedding-parallel quartzite breccia zones up to 100 m thick (Fig. 1). The breccia zones consist of angular red quartzite fragments cemented by a stockwork of white quartz veins that consist predominantly of coarse-grained quartz and small amounts of specular hematite and locally, coarse-grained muscovite. Euhedral quartz crystals occur in late-stage vugs, some of which are partly to completely filled by kaolinite. Values of $\delta^{18}O$ (-2‰ to +31‰ VSMOW, SIMS) in euhedral quartz correlate with complex patterns of growth zoning and healed fractures (SEM-CL) to reveal multiple fluid events, including high-T (~300 ^oC) and low-T (50-100 ^oC) exchange with hydrothermal and meteoric fluids (Schranz et al., 2017).

The pyrophyllite + diaspore mineral assemblage in metapelite constrains the temperature of Baraboo recrystallization to between 315 ^oC and 360 ^oC at a pressure of 2.0 kbar. An isochor for fluid inclusions in quartz in a folded quartz vein in metapelite, combined with phase equilibrium considerations, yields T-P conditions between 320 ^oC, 2.7 kbar, and 385 ^oC, 4.0 kbar, corresponding to a thermal gradient of ~30 ^oC/km. Expressed another way, the thermal gradient for metamorphism of the Baraboo quartzite was ~1700 ^oC/GPa, which places Baraboo metamorphism in the high T/P type of metamorphism (775 ^oC/GPa < T/P < 2000 ^oC/GPa), as defined by Brown and Johnson (2019).

$^{40}Ar/^{39}Ar$ plateau ages for muscovite in paleosol (1467 ± 11 Ma), hydrothermal veins (1478 ± 12 Ma), quartzite breccia (1472 ± 3 Ma), and four samples of slate (between 1493 ± 3 and 1473 ± 3 Ma) demonstrate that recrystallization and K-metasomatism in the Baraboo Range were contemporaneous with emplacement of the 1476-1470 Ma Wolf River A-type ferroan granitic batholith in Wisconsin. Such metamorphism and magmatism in Wisconsin represent the local expression of the continental-scale geon 14 Pinware-Baraboo-Picuris orogeny, which is characterized by high T/P metamorphism and A-type ferroan granitic batholiths.

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Geochemistry of Midcontinent Rift-related intrusive rocks of the Sunday Lake intrusion

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The Sunday Lake intrusion is located 25 km north of Thunder Bay, Ontario and hosts Ni-Cu-PGE mineralization. It has an age of 1109.0±1.3 (Bleeker et al., 2020), and is related to the ~1115 to 1106 Ma magmatic event of the Midcontinent Rift System (MRS; Heaman et al. 2007). The intrusion is emplaced in Archean rocks of the Quetico Basin along the Crock Fault (Flank, 2017). It is not exposed at surface but was first identified from airborne magnetic surveys. In 2008, platinum and palladium mineralization was discovered by HTX Minerals Corp. In 2017 Impala Canada Ltd. Partnered on a joint venture with more than 30 holes drilled to date.

The intrusion is funnel-shaped with a width of up to 1.5 kilometers and is 3 kilometers in length. It varies from 350 meters to 1000 meters in thickness. The intrusion consists of mafic-ultramafic layers divided into three series: the Upper Gabbro Series, the Lower Gabbro Series, and the Ultramafic Series (Flank, 2017). Reef-style mineralization present in the lower zones of the intrusion consists of disseminated to blebby chalcopyrite-pyrrhotite-pyrite bearing olivine melagabbro (Fig. 1; Miller, 2020). One hole intersected the basal zones of the intrusion with more than 20 meters of mineralization at 2.11 g/t Pt, 0.95 g/t Pd, 0.16g/t Au, 0.26% Cu, and 0.11% Ni (Flank, 2017). The objectives of this project are to characterize the paragenesis of the Sunday Lake intrusion and the Ni-Cu-PGE mineralization, investigate the effects of crustal contamination on mineralization within the Sunday Lake Intrusion, and to place the Sunday Lake intrusion within the evolution of the MRS.

This project utilizes two representative drill holes from which a total of 71 samples were collected. A total of thirty polished thin sections were generated for petrographic studies. Rocks were classified based on relative proportions of olivine, clinopyroxene, and plagioclase with modal rock names such as melagabbro, olivine melagabbro, and wehrlites. Fifty-five samples were analyzed for major and trace elements. Spider diagrams show different compositions within the layered intrusion, with primitive samples having trends consistent with a plume-like composition (Fig. 2A) while others suggest interaction with and contamination by host rocks (Fig. 2B). Variation in the behavior of trace elements suggest contamination, assimilation, and fractional crystallization processes were involved in the magmatic evolution of the intrusion. Sixteen samples have been sent for Sm-Nd and Rb-Sr isotope studies. The results of this study will be used to assess the source of mineralization and extent of contamination of the Sunday Lake Intrusion.

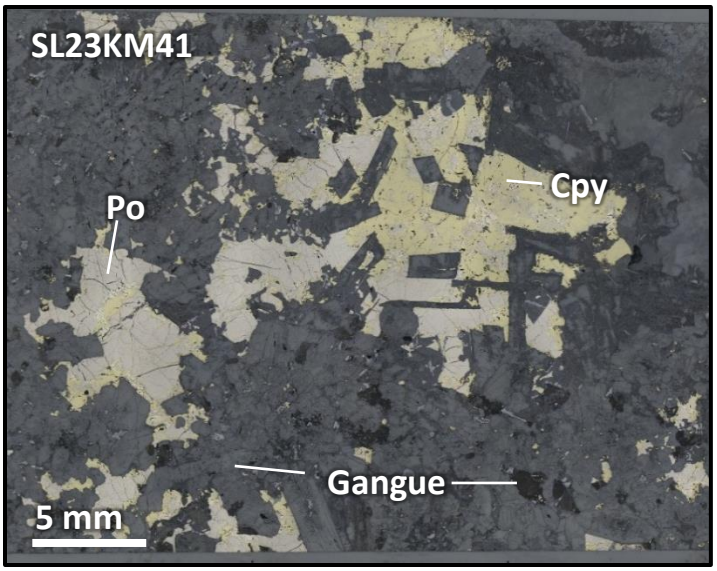


Figure 1. Photomicrograph in reflected natural light (PPL) of a gabbroic sample containing pyrrhotite and chalcopyrite. Polished thin section scanned using a Zeiss microscope.

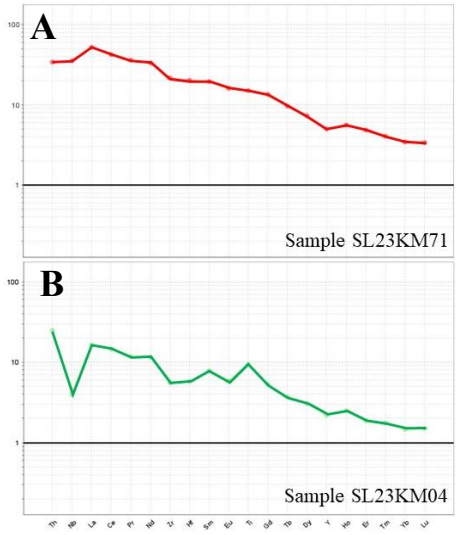


Figure 2. Primitive mantle normalized REE spider diagram of two samples. A: Sample showing a plume-like trend. B: Sample suggesting an interaction with the host rock. Normalising values from Sun and McDonough (1989).

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TWO DECADES OF TEACHING THE GEOLOGIC HERITAGE OF MINNESOTA'S NORTH SHORE AT THE NORTH HOUSE FOLK SCHOOL, GRAND MARAIS

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Since 1997, the North House Folk School, located in Grand Marais, Minnesota, has been promoting lifelong learning in the traditional arts and crafts and in knowledge about our northern culture and environment - present and past. Starting with a dozen courses at its inception, North House currently offers over 350 classes per year to over 3,000 students. From 2004 to 2010, John Green lent his expertise to North House by offering weekend lectures and field courses each year on basic geology and the geology of the North Shore and the Gunflint Trail. As a bonus, he also compiled lists of the native plants seen on these field excursions.

In 2013, Jim Miller revived the course and has come to offer 2-3 courses per year that explore the Midcontinent Rift geology of the North Shore (What's This Rock series) and the diverse geology at the end of the Gunflint Trail (Geology up the Trail series). By 2022, three different North Shore classes are offered (two per year, rotating in May and August) that explore different segments of the shore: *What's this Rock?* – Grand Portage to Grand Marais, *What's this Rock Too?* - Grand Marais to Tettegouche State Park, and *What's this Rock 3?* - Tettegouche to Two Harbors (Fig. 1). From 2014 to 2019, a mid-October weekend field trip at the head of the Gunflint Trail was run out of the Gunflint. We hope to reinstate this course this fall or next, but will run it out of Grand Marais.

Due to the Covid pandemic, no in-person field courses were permitted during 2020 and most of 2021 (one WTR course was run in October 2021, but participants drove their own vehicles). North House opted to host on-line webinars during the winter of 2021-22. Jim presented three webinar series. In January 2021, three lectures were offered on North Shore geology which was virtually attended by 104 students. During March 2022, three lectures were presented on the geology of Minnesota State Parks and Waysides with 83 people logged in. Then, in January 2023, a two-lecture webinar on the geology of the Gunflint Trail was viewed by 50 people. With the lifting of all Covid restrictions in the winter of 2022-23, North House reverted to only offering in-person classes.

As currently taught, the three weekend WTR courses start with an introductory meeting on Friday evening on the North House campus in Grand Marais to discuss trip logistics and provide a geologic overview. Saturday is devoted entirely to a field trip that visits various classic geological exposures along the North Shore. Travel has typically involved carpooling with personal vehicles, but starting in August, 2023, the field trips have used a mini-bus. This or a 15-passenger van will be the preferred method of transport going forward. In the evening, participants have the option to gather for informal discussions or a special lecture on various topics, especially at wood-fired pizza party held either Friday or Saturday evenings at the North

House campus. The weekend concludes with a half-day field trip on Sunday morning, after which the group gathers either on a cobbled beach on Lake Superior to practice their newfound rock identification skills.

Each field course is limited to about 15 registrants. A total of over 400 students have attended the field courses we have taught at North House over the past 20 years. Participants have ranged in age from 10 to 80 and come from all over the US and Canada, though most are from Minnesota, especially the Twin Cities. Their backgrounds range from those who have never heard of plate tectonics, to those who have had a few geology courses in their past. The common denominator among all participants is that they can all be characterized as being "rock curious".

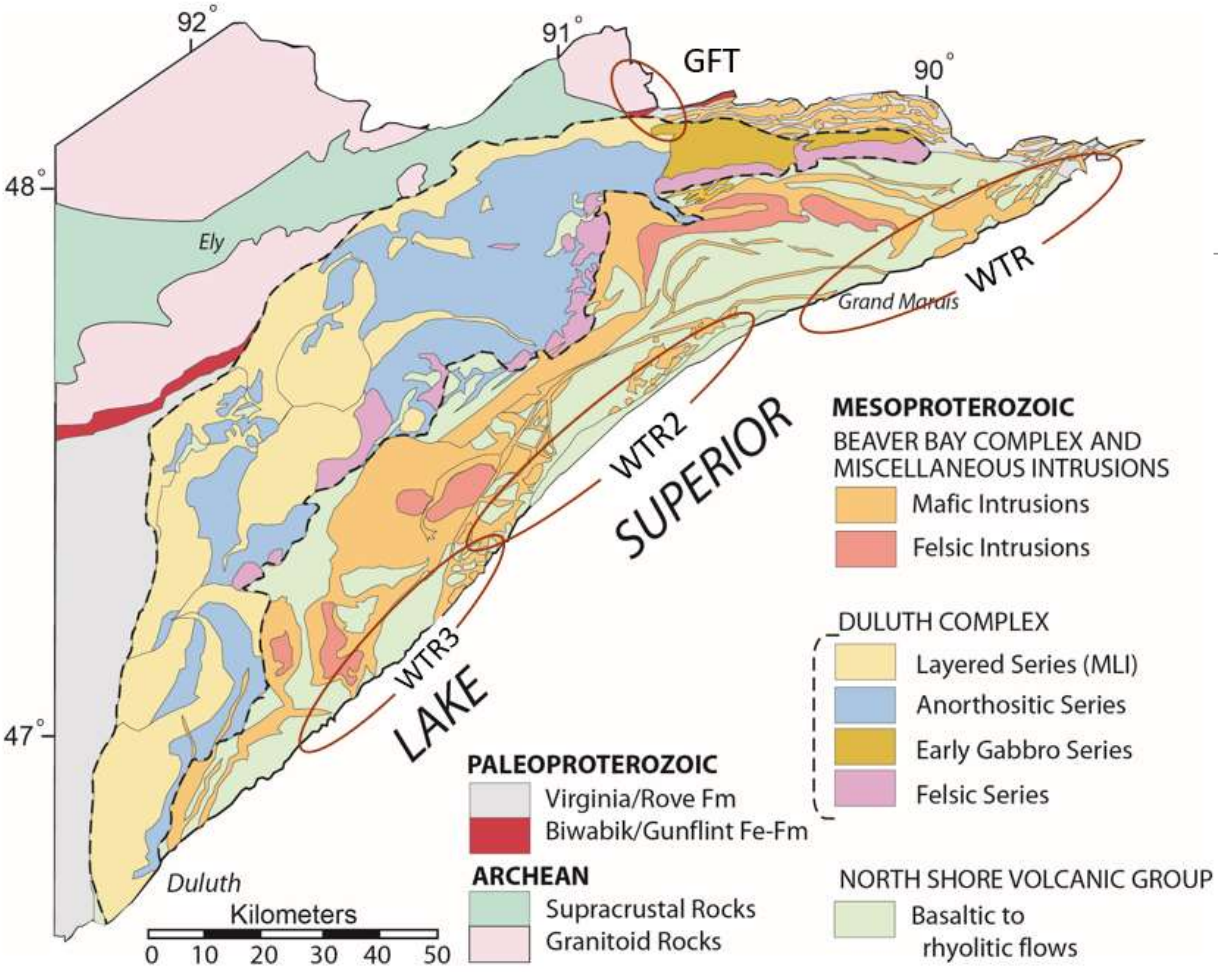


Figure 1: Geology of northeastern Minnesota showing the general locations of geology field courses currently taught at North House Folk School - three "What's this Rock?" courses and a Gunflint Trail (GFT) course.

Quartz trace element chemistry: Exploring the link between a fertile parental granite and a mineralized pegmatite

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Recent studies have proposed the use of pegmatitic quartz trace element chemistry as an indicator to lithium mineralization of potential economic pegmatite deposits (Müller et al., 2021). Using Laser Ablation- Inductively Coupled Mass Spectrometry (LA-ICP MS), the trace elements are determined *in situ* within a single quartz grain. Trace elements such as Al, Ge, Ti, P, B, and Fe^{3+}, can substitute for Si^{4+} at very low concentrations, and the elements H, Li, Na, K, Fe^{2+} can enter the quartz crystal lattice via interstitial lattice positions (Götze et al., 2004). In this study, quartz from the 2685 Ma fertile Ghost Lake granitic batholith (GLB) and related Mavis Lake pegmatites group (Dryden, Ontario) were used to compare trends in quartz trace element concentrations within a single system (Figure 1). The focus of this study was to test the applicability of using quartz to (1) help identify fertile parental granitoid plutons and (2) help decipher any internal fractionation trends in mineralized pegmatites. If trace element concentrations in quartz from the granitic parent show any relationship to the mineralized pegmatites, this would prove beneficial in other exploration programs where potentially enriched Li pegmatites have not yet been identified. It could allow for an early assessment of an S-type granitoid and show indication of a potential nearby mineralized pegmatite, essentially the technique could be deemed a 'fertility indicator'. Furthermore, if the quartz trace element compositions in the pegmatite zones show enrichment trends similar to the proposed model of Černý (1991), the technique would prove powerful in defining potential areas for further investigation (i.e. following the trend of enrichment).

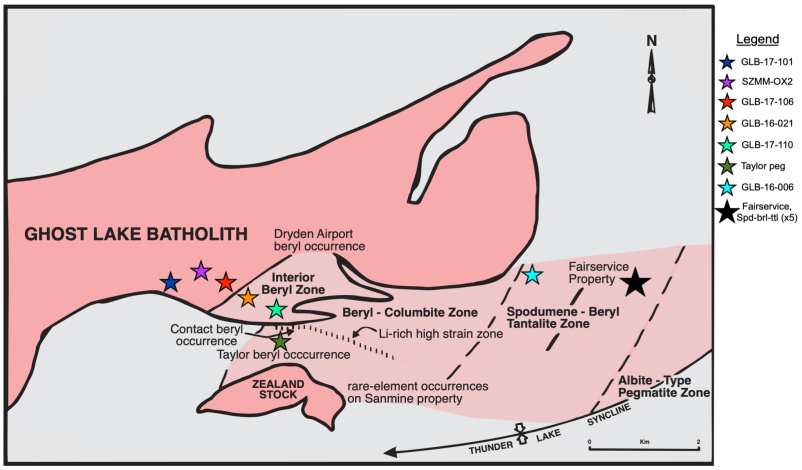


Figure 1: Study sample location through the zones of fractionation and enrichment, from the Ghost Lake Batholith to the Mavis Pegmatites (modified from Breaks and Selway, 1991).

The results show correlations with increasing Li, Al, and Ge, and decreasing Ti from the GLB fertile parent granite to mineralized Mavis Lake pegmatites (Figure 2). The quartz trace elements can be used to form a simple fractionation model, similar to the pegmatite fractionation model of Černý (1991) to show elemental enrichments in a fertile LCT pegmatite system upon evolution (Figure 3). In summary, the quartz chemistry indicates fractionation and enrichment

trends can be identified across the pegmatite zones. It is still unclear whether or not the technique could be applied to granites in order to assess fertility, as more work is required to understand the key differences in the quartz chemistry between a barren granite and a fertile parent granite.

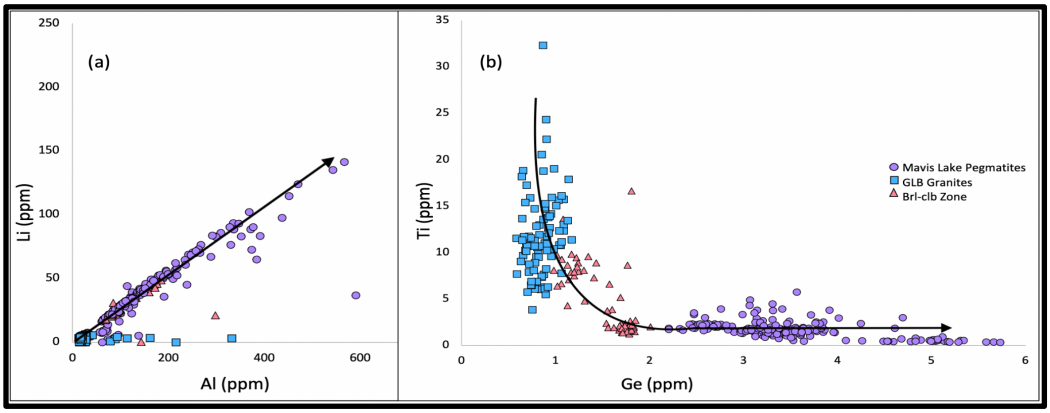


Figure 2: Trends in quartz trace element concentration in the GLB granites, intermediate beryl columbite zone, and mineralized Mavis Lake pegmatites. (a) Al vs Li bivariate plot. (b) Ti vs Ge bivariate plot.

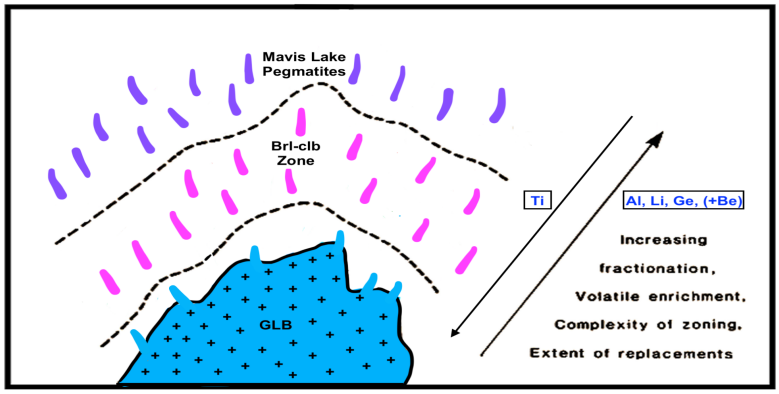


Figure 3: Fractionation model showing quartz trace element trends within the GLB-Mavis Lake system (modified from Černý, 1991).

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Geometry, Slip Kinematics, and Deformation along the Hancock Fault in the Quincy Mine Workings, Upper Peninsula of Michigan

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The Hancock fault is one of several major compressional features along the southern edge of the Midcontinent Rift System. It forms part of the Keweenaw fault system (KFS) whose connected segments follow the spine of Michigan's Keweenaw Peninsula. The Hancock fault is a splay in the hanging wall of the KFS that intersects the main Keweenaw fault zone at an acute angle to define a thrust slice (Fig. 1). It extends along an azimuth of 55° for 17 kilometers from a point west of Houghton to its intersection with the main Keweenaw fault zone between Calumet and Lake Linden. Volcanic and sedimentary layers of the Portage Lake Volcanics (PLV, 1.1 Ga) are shown on bedrock geology maps with left-lateral offset across the Hancock fault (**1, 2**).

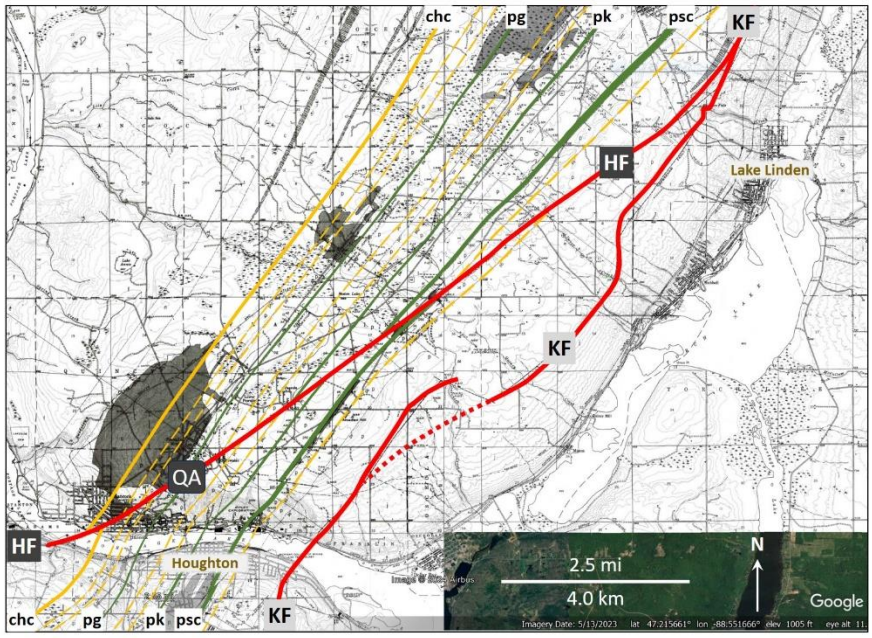


***Figure 1**: Hancock (HF) and Keweenaw (KF) faults shown on USGS bedrock geology maps (**1, 2**). Major layers: pb-Bohemia conglomerate, psc-Scales Creek flow, pk-Kearsarge flow, pg-Greenstone flow, chc-Copper Harbor conglomerate (base).*

Like other faults of the KFS, the Hancock fault has a major component of reverse slip that occurred during compression related to the Grenville Orogeny (**3**). Recent mapping and fault-slip measurements on the population of faults associated with the KFS reveal that the fault system has a right-lateral component of strike slip. This raises the question of whether the left-lateral offset of units across the Hancock fault in map view can be reconciled with net reverse and right-lateral slip along the KFS. The work reported here builds on previously reported work on the Hancock fault in the Quincy Mine workings to address this and other questions about its geometry, slip kinematics, and deformation (**4**).

An adit in east Hancock provides access to the 7th level of the historic Quincy Mine, whose workings run along and across the Hancock fault at four locations (Figs. 1 and 2). The current phase of the project focused on acquiring data from the fault southwest of the adit, which data

were combined with data previously collected from the adit toward the northeast. Fault-slip measurements were made on all accessible fault surfaces and consisted of fault attitude, slickenline rake, and slip sense where possible. The Hancock fault's strike and dip were measured at well-exposed locations, and the thickness of its gouge and breccia were measured where possible. Orientations were measured using the FieldMove Clino app as well as a Brunton compass. Stereonet and FaultKin freeware were used to plot and analyze the orientation data.

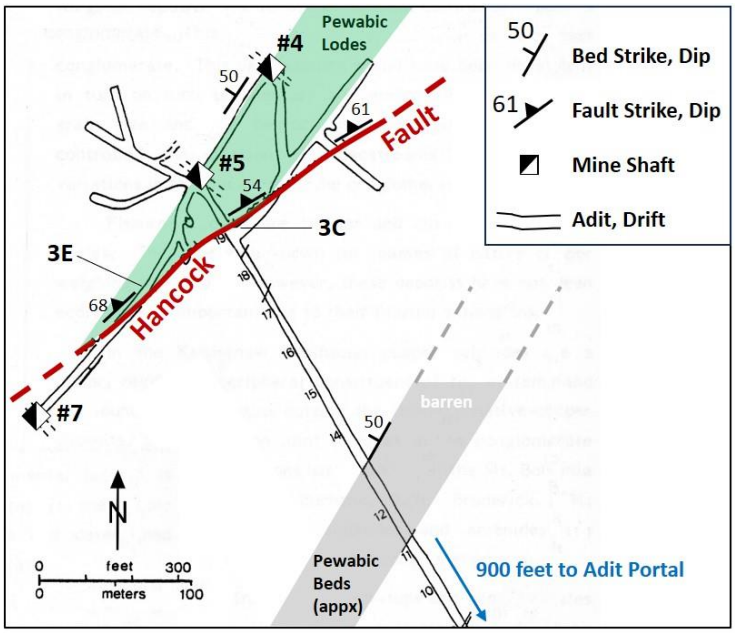


***Figure 2**: Geology along the Hancock fault in the Quincy adit and connected mine workings.*

The project is ongoing but some results have emerged. The Hancock fault cuts upward across stratigraphy in the direction of thrusting at angles between 4° and 18°, similar to cut-off angles for the Keweenaw fault (**5**). The low cut-off angles of both faults, which have significant reverse slip, are consistent with the properties of a detached thrust system. Both faults also have components of strike slip as indicated by the population of nearby faults, but right-lateral slip is slightly dominant over left-lateral slip. This implies that the significant left-lateral offset of PLV layers seen in map view is the result of mostly reverse slip on the Hancock fault as it cuts slightly clockwise to strike of the layers.

Acknowledgements
Funding for this work was provided by the ILSG Student Research Fund and is gratefully acknowledged.

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Lithostratigraphy and Geochronology of the Lower Northeast Sequence of the North Shore Volcanic Group, Cook County, MN, USA

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The Lower northeast sequence (LNE) of the North Shore Volcanic Group (NSVG) in northeastern Minnesota represents some of the earliest known sedimentary and volcanic rocks of the Midcontinent Rift System (MRS) including the Puckwunge Formation (PF), Grand Portage Lavas (GPL), Esther Lake Lavas (ELL), and the Hovland Lavas (HL) (Miller and others, 2002). New 1:24,000 field mapping in northern Cook County, paired with U/Pb TIMS zircon geochronology have established an updated lithostratigraphic sequence of the LNE and understanding of its relationships with surrounding intrusive rocks, providing new insights on magmatic evolution and spreading rates during the Plateau Stage of MRS magmatism.

The LNE is a shallow to moderately south dipping bimodal volcanic sequence that youngs southward and is segregated from the overlying Upper northeast sequence by the cross-cutting Brule-Hovland Gabbro, a complex of texturally and mineralogically varied gabbroic and diabasic intrusions (Fig. 1). To the north, the LNE is bounded predominantly by cross-cutting Early Stage Duluth Complex granophyric intrusions and locally by underlying Paleoproterozoic metasedimentary sequences.

The arenitic sandstones and conglomerates of the PF, which forms the base of the LNE, lie unconformably on top of Paleoproterozoic bedrock and forms the base of the LNE on to which the NSVG rocks were erupted. GPL volcanics were erupted disconformably atop the PF, and consist of geochemically primitive basalts, as compared to overlying LNE volcanics (Mattis, 1972). Basal units of the GPL are defined by pillowed and fragmental olivine basalts, transitioning to thick flows of massive to sparsely amygdaloidal basalts with rubbly tops.

The boundary between the GPL and the overlying ELL is marked by a distinct change from olivine tholeiite basalts to thick, pilotaxitic flows of amygdaloidal, oxide-rich ferro-andesites and andesitic basalts which exhibit steeper REE

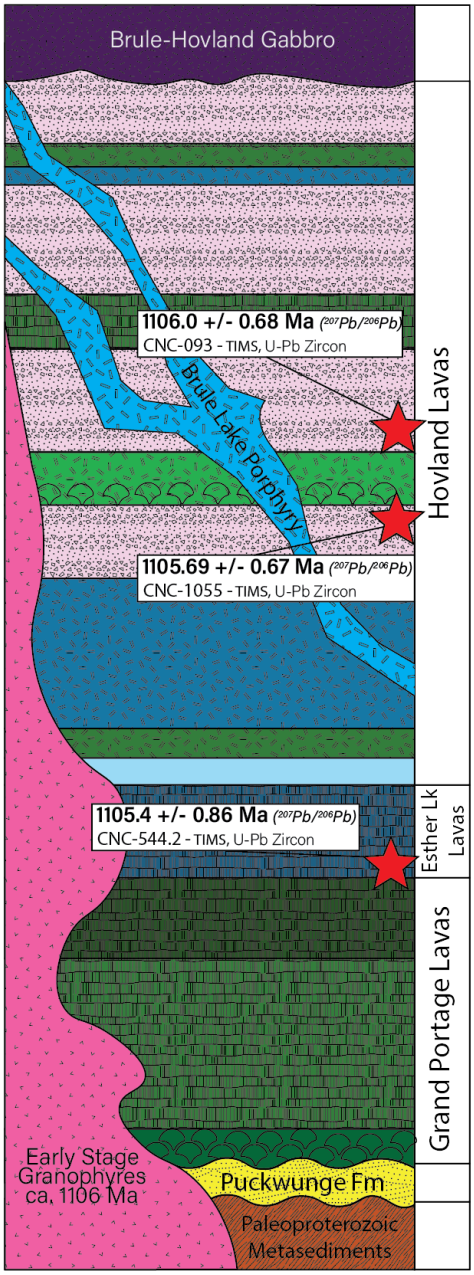


Figure 1. Schematic Stratigraphic Section of the LNE showing locations of geochronologic samples. See text for details.

profiles than GPL basalts. U/Pb zircon geochronologic analysis of a thin rhyolite flow interlayered with the massive andesitic basalts near the base of the ELL returned an age of ca. 1105.4 Ma (Fig. 1).

Bimodal volcanics of the HL sequence above the ELL are typified by feldspar-phyric to glomeroporphyritic flows of basalt, basaltic andesite, trachyandesite, and rhyolites. Plagioclase phenocrysts within the mafic and intermediate lithologies are fractured, locally resorbed, contain inclusions of olivine and clinopyroxene, and have compositions estimated to be more calcic than the groundmass feldspars. Mafic and intermediate lithologies are locally pillowed, though most flows do not show evidence of subaqueous eruption. Rhyolites constitute a large volume of the upper half of the HL sequence. These rhyolites exhibit abundant autobreccia textures, flow foliation, pumice fragments, and phenocrysts of feldspar and quartz. Microscopically, HL rhyolites are texturally diverse, containing microlites, perlitic structures, fiamme, and spherules interpreted to be a product of volatile-rich lavas and pyroclastic flows. U/Pb zircon analyses of upper HL rhyolites returned ages of ca. 1105.69 Ma and 1106.0 Ma (Fig. 1). Basalt flows intercalated with the rhyolite units are thick, structured flows with basal breccias, columnar jointed massive flow centers, and amygdaloidal flow tops.

Subvolcanic, plagioclase ultraphyric diabase dikes and sills of Burnell's (1976) Brule Lake Porphyry (BLP) are abundant throughout the HL. The BLP contains 20-70% plagioclase phenocrysts hosted within a compositionally varied matrix, and although they have not been dated, a synvolcanic interpretation has been applied to these intrusions based on their local amygdaloidal nature and textural similarities to the HL.

New ages from rhyolites in the basal portion of the ELL and upper portion of the HL at ca. 1106 Ma suggest these lavas are volcanic expressions of the coeval Early Stage Duluth Complex Cucumber Lake and Misquah Hills granophyres exposed to the north of the LNE (Vervoort and others, 2007). The Early Stage granophyres are interpreted to be a product of assimilation of continental crust (Vervoort and others, 2007). Such a change in magma composition is reflected in the lithologic and geochemical character of the ELL and HL as compared to the underlying GPL. The overlap in ages presented here suggests rapid eruption rates at ca. 1106 Ma, which indicate the entire ELL and HL sequence erupted within ~1 Ma. Phenocryst-rich volcanic and hypabyssal rocks throughout the HL and BLP may have been derived from anorthositic cumulates that formed in the roof of a mid-crustal staging chamber during a period of slow rift spreading, and subsequently remobilized during magma recharge and venting events at 1106 Ma.

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Major element geochemistry and first zircon U-Pb age dates of Precambrian basement rocks in eastern North Dakota

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We are re-examining cores of the 1977 Red River Valley Drilling Project (Moore, 1978). Other previous work includes study of the paleoweathered horizon on the Precambrian bedrock (Kelley, 1980), Klasner and King (1986), Sims et al. (1991) and various ILSG abstracts. We sampled the Precambrian portions of three of these cores (RRVD #5, #8, #11) from eastern North Dakota, and a core cut by Kennecott Exploration Company in 2010 (10NDV001; Nesheim, 2013) (Fig. 1; Table 1). Samples were analyzed at Washington State University (WSU) for U-Pb zircon age dates. Kelley (1980) reported major element analyses and new analyses were carried out at WSU and North Dakota State University using XRF (Table 2).

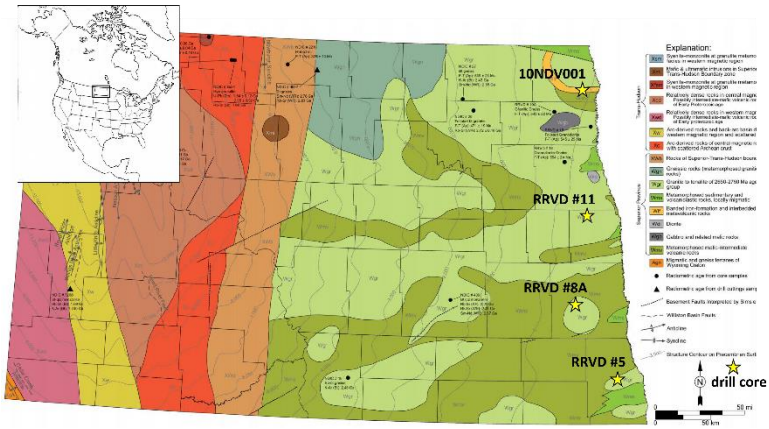


Figure 1. Precambrian geology map of North Dakota after Nesheim (2012) and Sims et al. (1991), with location map and core locations (stars) for this study

Table 1. Summary of samples, lithology, and zircon age dates

Core / depth	Lat / Long	lithology	Zircon age (MSWD)
RRVD 5	46.225514	Fine to medium grained	2715.0 +/- 18.1 Ma (3.4)
379 ft (115.5 m)	-96.932504	quartz monzonite	
RRVD 8A	46.897502	Fine to medium grained	2782.7±9.3 Ma (0.72)
600 ft (182.9 m)	-97.370662	chlorite gneiss	
RRVD 11	47.614926	Medium grained biotite	2 populations: younger
693 ft (211.2 m)	-97.291738	granitoid	2671±23.2 Ma (3.0)
10NDV001	48.61706	Medium grained	2694.5±13.6 Ma (1.19)
837 ft (255.1 m)	-97.316902	magnetite-rich granitic gneiss	

Table 2. Whole rock major element analyses

wt.%	1	2	3	4
SiO_2	74.00	68.91	64.30	65.80
TiO_2	0.16	0.18	0.13	0.42
Al_2O_3	13.7	10.43	17.40	15.20
Fe_2O_3	1.36		2.04	4.67
FeO		1.65		
MnO	0.01	0.31	0.02	0.10
MgO	0.04	0.44	0.71	0.00
CaO	1.49	4.60	0.91	1.65
Na_2O	4.60	0.87	8.16	6.00
K_2O	4.22	6.82	5.96	5.90
P_2O_5	0.09	0.03	0.06	0.05
SO_3		0.04		
LOI		5.44		
sum	99.67	99.72	99.68	99.79

1: RRVD 5-383.5"; 2: RRVD 8A-602';
3: RRVD 11-695'; 4: 10NDV001-836'

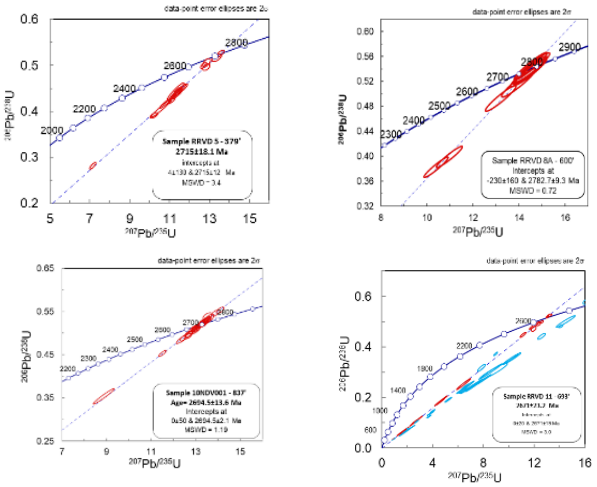


Figure 2. U-Pb concordia diagrams for zircons from the Precambrian core samples with weighted mean $^{207}Pb/^{206}Pb$ ages. Error ellipses represent 2SE uncertainties. Open ellipses with thick grey lines depict outlier U-Pb zircon analyses removed from final age determinations.

The analyzed rocks contain 64-74 wt.% SiO_2, with RRVD 11-695' showing high total alkalis (Na_2O+K_2O = 14.12 wt. %). All show Neoarchean zircon ages (2.7 –2.8 Ga) with the granitoids showing slightly younger ages than the gneisses (Table 1; Fig. 2). Sample RRVD 11-693 appears to be a 2 component rock with two zircon populations. These chemical results and measured ages are consistent with those measured in other areas of the Superior Craton (cf. Li et al., 2020).

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The geology and ore deposit model of the high-grade Emily Manganese Deposit, Cuyuna Range, Minnesota: Results from the 2023 drilling program

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The Emily deposit is the highest-grade manganese resource in the USA. The deposit is located along the western margin of the Paleoproterozoic Animikie Basin (Southwick and Morey, 1991) and is hosted by the Emily Iron Formation, a shallow water Superior type iron formation. Recent work by Big Rock Exploration on a drilling program for Electric Metals has identified coherent zones of high-grade mineralization (30 to ≥40 wt.% Mn) over a 1.25-kilometer strike length. An ore deposit model has been developed that incorporates the deposition of primary thin-bedded manganese-iron carbonates (Fig. 1) and later conversion into massive manganese oxide through early folding (Fig. 2) and prolonged periods of weathering, oxidation, and erosion.

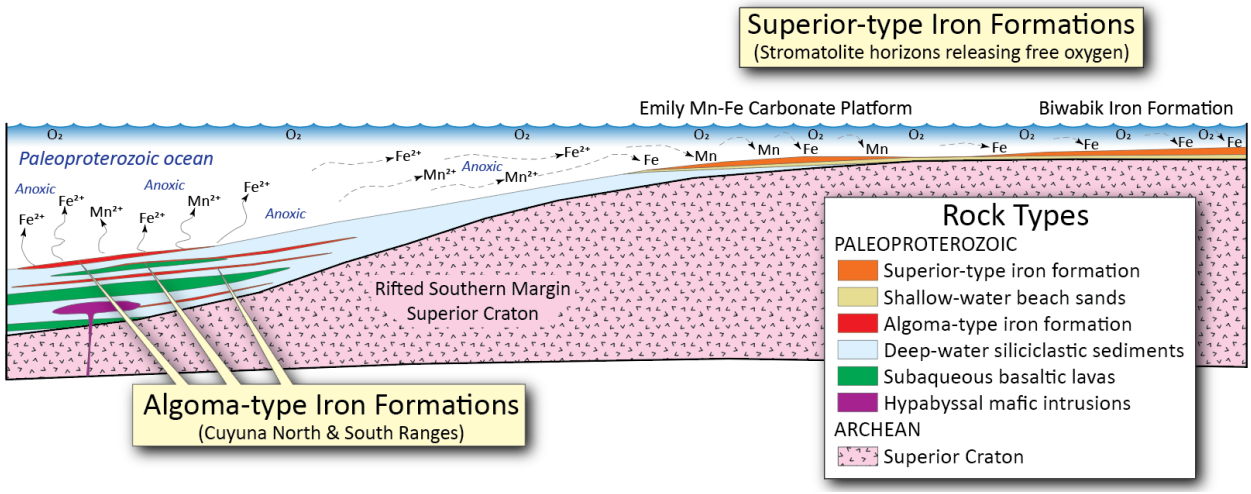


Figure 1. Model of the primary depositional setting of the Paleoproterozoic Superior-type iron formations of the western Animikie basin.

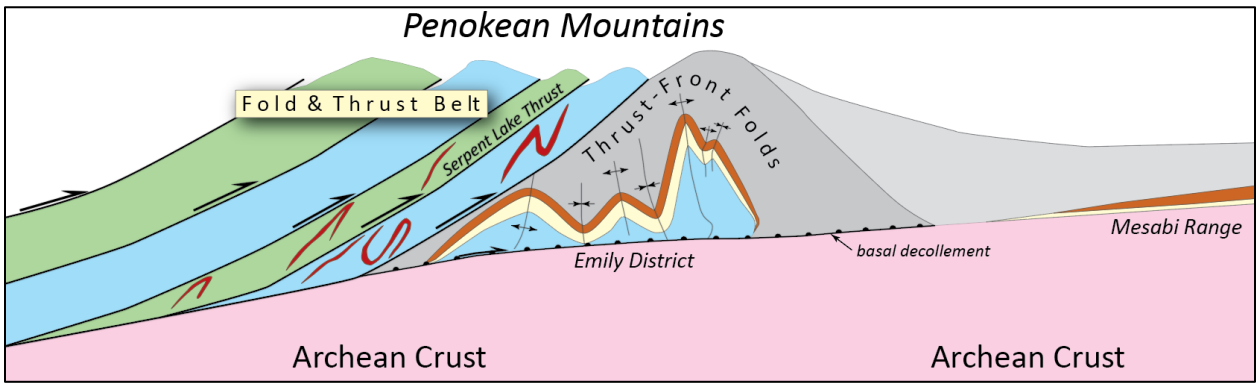


Figure 2. Schematic model for the formation of the Emily District thrust-front folds as related to the Penokean fold & thrust belt of the Cuyuna North and South iron ranges.

Historic exploration and drilling in the 1940's and 1950's by Pickands Mather and US Steel identified iron and manganese-bearing mineralization within the Emily Iron Formation (Strond, 1959). US Steel developed but did not implement a preliminary mine plan for mining of the Emily Deposit. Following approximately 50 years of inactivity, Cooperative Mineral Resources (subsidiary of Crow Wing Power) pursued a pilot mining operation using pressurized water that ultimately proved unsuccessful. As a follow up investigation into the outcomes of the pilot mining, a small-scale drill program was completed in 2010-2012. An Emily deposit drilling program was designed and executed by Big Rock Exploration, LLC, in 2022-2023. A total of 29 drill holes were completed to extend mineralization and refine the previous resource estimates. A total of 13,107 feet of drilling was completed for this program. Data collected for this project includes lithological, structural, geotechnical, and geochemical data from drill cores as well as geophysical data from selected drill holes.

Through interpretation of legacy, recent and new drilling data, Big Rock Exploration has redefined the stratigraphy of the Emily Iron Formation and developed an ore deposit model for the high-grade manganese oxides of the Emily deposit (Fig. 3). This ore deposit model and associated geological model have been used to support an updated and expanded mineral resource estimate for the Emily Deposit, to be completed by Forte Dynamics.

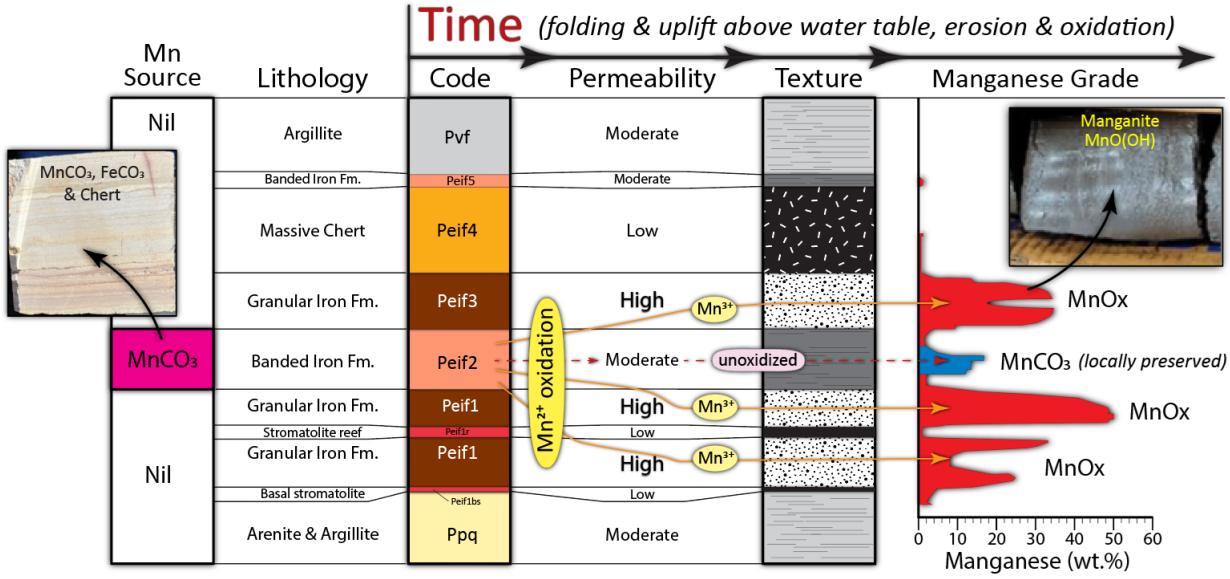


Figure 3. Integrated stratigraphy, permeability, texture, and Mn-grade diagram for the Emily deposit.

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Deformation conditions, micromechanics, and fault zone development in mafic protoliths at the Lac des Iles mine, northwestern Ontario

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Faults and their associated damage zones are important geologic structures that serve as permeable pathways through the upper crust; however, the effect of host lithology on fault core development and damage zone structure remains poorly constrained. The development of fault cores and damage zones is typically controlled by the strength and composition of the protolith, conditions of deformation, and fluid chemistry (Caine et al., 1996). Fault zones are characterized by a variably developed fault core composed of unconsolidated gouge or silicified breccias, outward into a highly fractured damage zone and then a relatively unaltered protolith. Trapped mineralization may be offset or remobilized by later faulting. Faults may act as conduits or barriers for fluid flow depending on the proportion of fault core to damage zone (*i.e.,* the fault zone architecture; Caine et al., 1996; Faulkner et al., 2010). Permeability is typically enhanced in damage zones due to the high density of fractures and is diminished in fault cores due to the presence of clay-rich fault gouges.

This study examines deformation conditions and fluid-rock interaction of fault zones within the Lac des Iles Complex. The Lac des Iles Complex is a series of mafic-ultramafic intrusive bodies occurring within the Marmion terrane of the Superior Province (Figure 1). The complex has been dated at 2689 ± 1.0 Ma and was emplaced into a ~3.01 to ~2.68 Ga granite-greenstone terrane (Djon et al., 2018). Extensive Ni-Cu-PGE mineralization has been offset by two late reverse faults in the high-grade zones (>4 g/t Pd) called the Camp Lake fault and the Offset fault. A depletion in Pd is observed within the damage zone of each fault, approximately 145 – 180 meters from the actual fault. This depletion is likely due to late fluid flow within the damage zones.

Fault cores in tonalite mainly are composed of breccias with calcite to quartz-rich matrix, while fault cores in gabbro are composed of chlorite-rich gouges (Figure 2). Fracture densities in felsic protoliths have a higher fracture density than mafic protoliths suggesting that fluid flow would be more effective in felsic protoliths which may have contributed to depleted mineralization. This implies that host rock lithology strongly affects fault zone structure, including alteration assemblages, fracture densities, and permeabilities. We hypothesize that the development of a frictionally weak, chlorite-rich fault core impeded the development of a more fracture-dense damage zone in the gabbros. Electron microprobe analyses on chlorite grains reveal three generations of chlorite growth have occurred: pre-faulting at ~350°C, syn-faulting at ~150 – 200°C, and post-faulting at ~150°C (Figure 3). Elemental gains and losses from unaltered protolith to fault core were examined to understand the interactions between alteration and fault zones. Within fault cores and damage zones, there is an observable gain in Mg and Fe in mafic protoliths, due to the precipitation of new chlorite within the fault zone. In mafic protoliths, fluid-rock interactions play an important role in the development of fault core and damage zone structures.

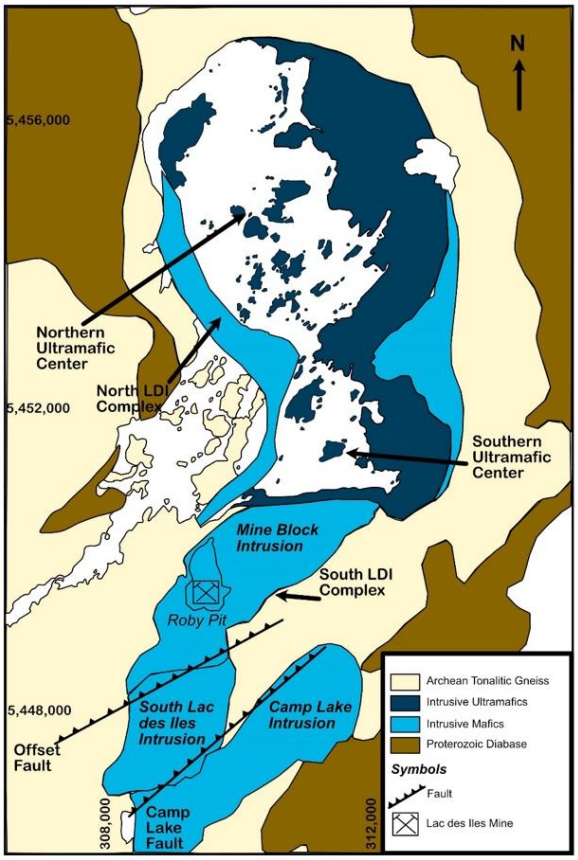


Figure 1 Local geology of the Lac des Iles Intrusion with faults of study. Modified from Djon et al., (2018).

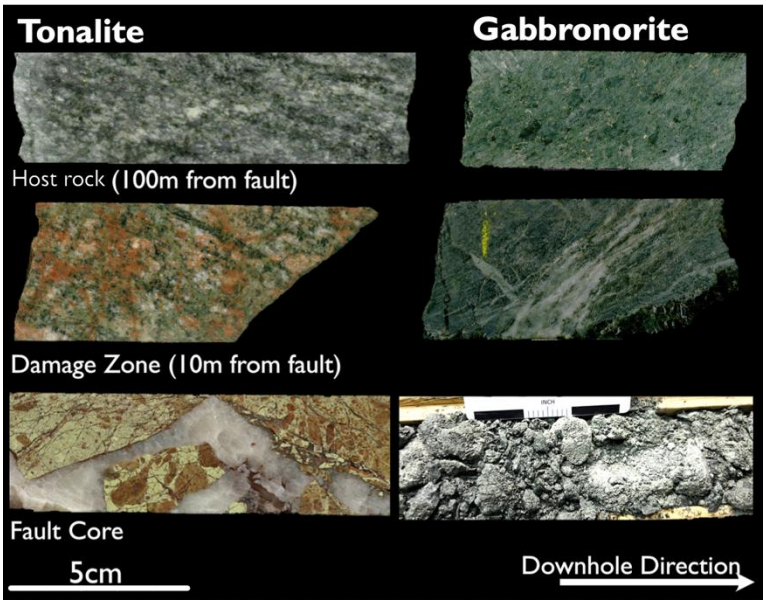


Figure 2 Variations in drill core with proximity to faulting.

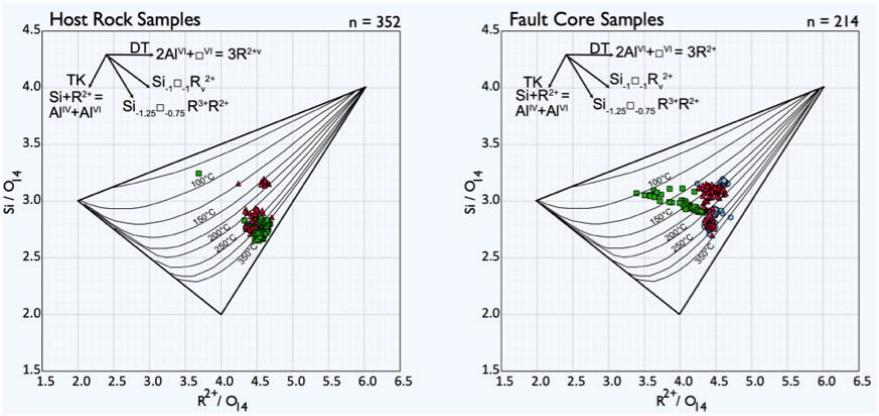


Figure 3 Results of chlorite thermometry from electron microprobe analyses.

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Identification of Fertile Parent Granitoid Units in the Superior Province of Ontario

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Peraluminous granites are widely distributed throughout the Superior Province of Ontario, most notably within and adjacent to the metasedimentary rocks of the English River and Quetico subprovinces from which they were derived by partial melting. There has been a significant amount of work that proposes a direct genetic relationship between peraluminous, S-type granitoids (i.e., fertile parent granites) and rare-element pegmatites of the lithium-cesium-tantalum (LCT) group across the world (see for instance Černý, 1989, 1991; Wise, Müller and Simmons, 2022, and references therein).

A fertile granite is the parental granite to rare-element pegmatite intrusions. Many granitic melts have the capability to generate fertile granite plutons that will, in turn, produce even more fractionated melts enriched in incompatible elements. In the case of the LCT group pegmatites, the residual melt may percolate into the surrounding host rock and crystallize rare-element pegmatites (Breaks, Selway and Tindle, 2003). Identifying fertile parent granites is an important step in the exploration for rare-element pegmatites as it greatly reduces the search area on a regional scale (Breaks and Tindle, 1997). A significant amount of work was performed by the Ontario Geological Survey (OGS) in the late 1990s and early 2000s to improve our understanding of rare-element pegmatites and their parent granitoid units in the Superior Province, with a focus on northwestern Ontario (e.g., Breaks, Selway and Tindle, 2003).

In 2022, ten areas of the Superior Province in Ontario were identified for study as part of the fertile granite project (Figure 1). Locations for sampling were selected to complement the existing granitoid geochemical databases acquired by the OGS, as well as to provide coverage in areas previously not investigated for the presence of fertile granitoid rocks and associated LCT group pegmatites. The 2022 field season was intended as a preliminary investigation of the selected areas. A total of 100 samples were collected (Figure 1) and analyzed for major, trace element and rare earth element geochemistry at the Geoscience Laboratories (Sudbury) to identify potential fertile parent granite bodies. Due to several staffing changes during the spring and summer of 2023, focus on the project was delayed and did not resume until the winter of 2023-24.

Further work in support of the fertile granite project will include preliminary evaluation of the geochemical data set generated during the summer of 2022, compilation of geochemical data from previous studies and planning for additional sampling during the 2024 field season. The primary deliverable of the project will be an MRD compiling previously released whole-rock geochemical data related to fertile granites. This compilation will be supplemented with the new whole-rock geochemical data acquired during this study. Additionally, several articles will be generated and released during the course of the project in both the Resident Geologist Program Recommendations for Exploration (released annually in January) and the Report of Activities (published annually in the spring).

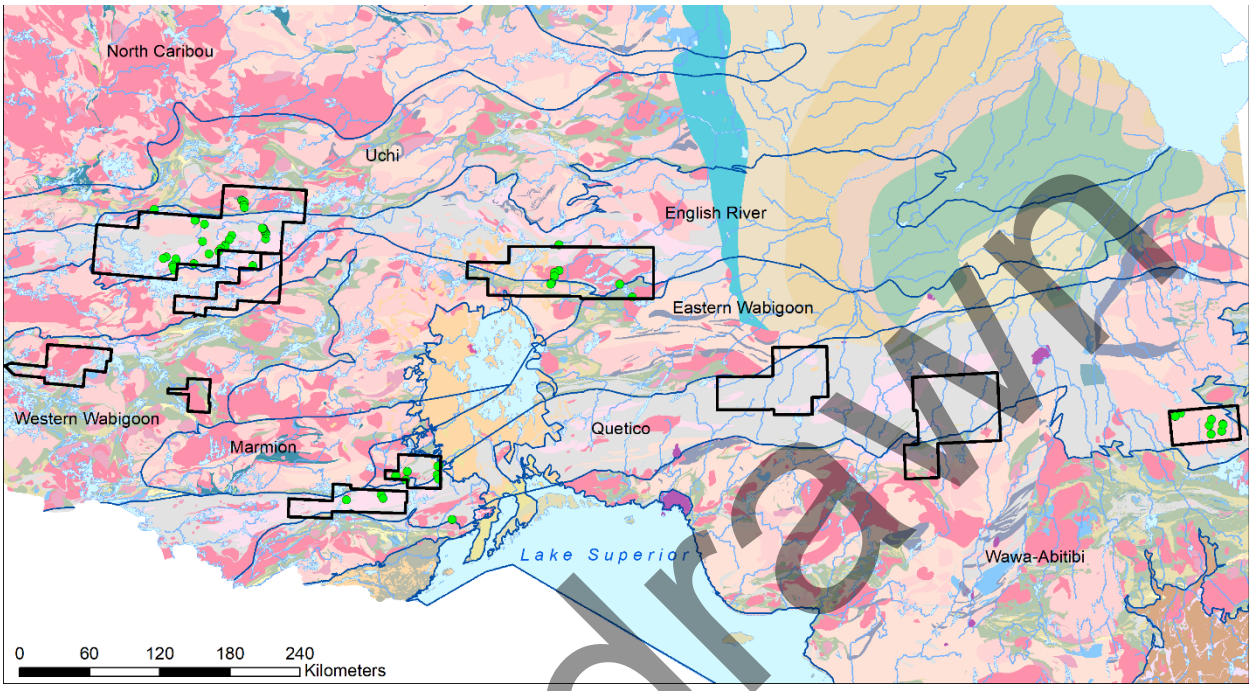


Figure 1. Locations of fertile granite project target areas (outlined in black) and sample locations (green dots) collected in 2022. Regional geology from Ontario Geological Survey (2011, see publication for a detailed geological legend). Subprovince boundaries are based on Stott (2011) and are outlined in blue (*from* Cundari, 2022).

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Lidar Topography: Bright opportunity for Reading Keweenaw Landscapes

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A GeoAtlas for Keweenaw, Houghton, and Baraga counties will soon be publicly accessible as an exciting new tool for understanding landscapes through lidar surveys and convenient geospatial display tools. In this presentation, we discuss hypotheses that emerged from a "first look" at this remarkable data which reveals greater detail than standard topographic maps. The purpose of this discussion is to stimulate robust investigation to build new geological awareness of geomorphology. The work may be a useful element for geoeducation because of the improved resolution.

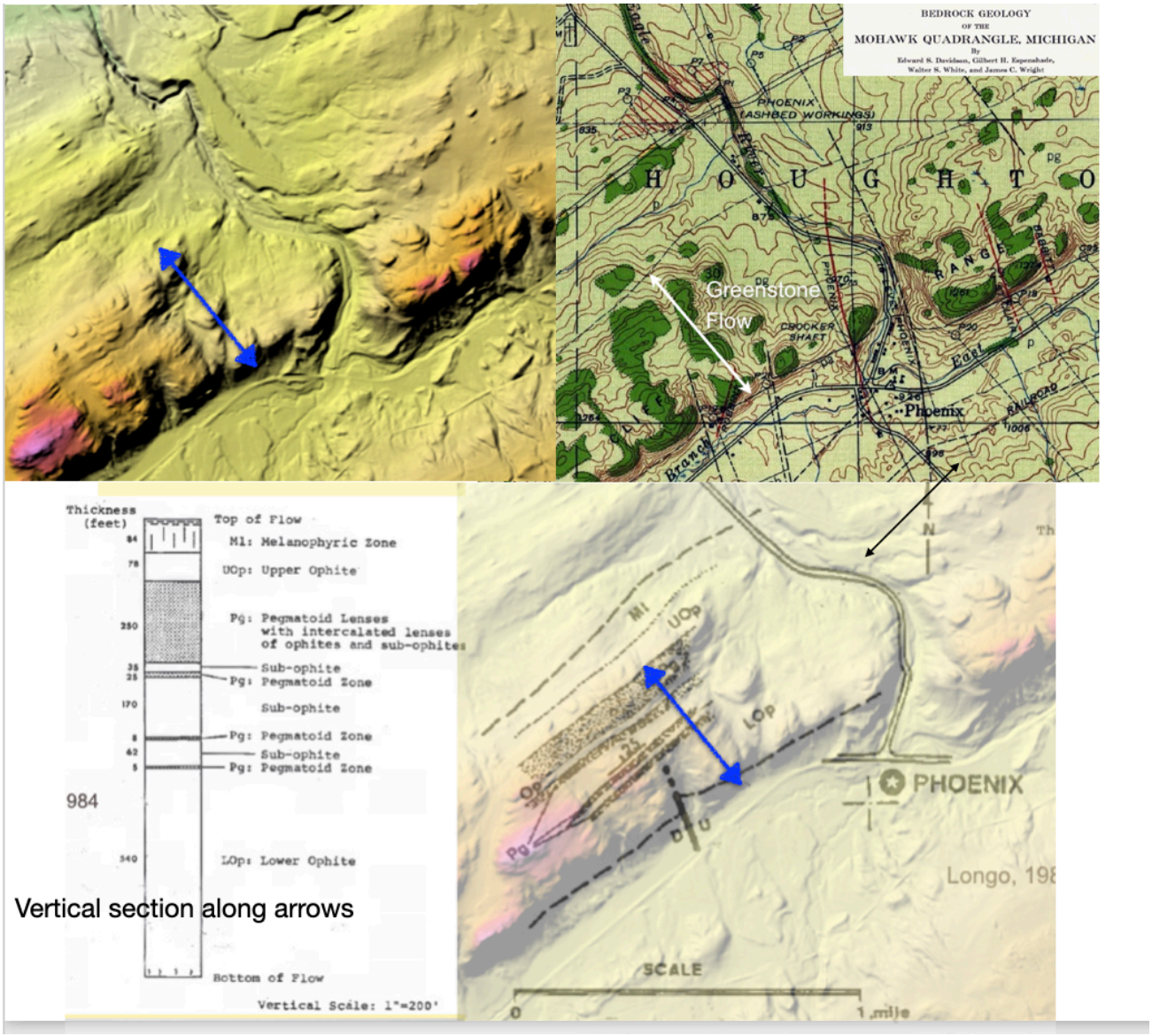


Figure 1: Lidar topography may reveal in situ differentiation within thick lavas of the Portage Lake Volcanics. Here, lidar data from the Keweenaw GeoAtlas is used with field mapping data from Cornwall (1951) and Longo (1984). These thick lavas reveal cooling of about 1000 years where the interior texture of the basalt is pegmatoidal, contrasting with ophitic textures near the bottom and top of the flow where solidification was faster. Arrows show the same crossections on lidar and geologic maps.

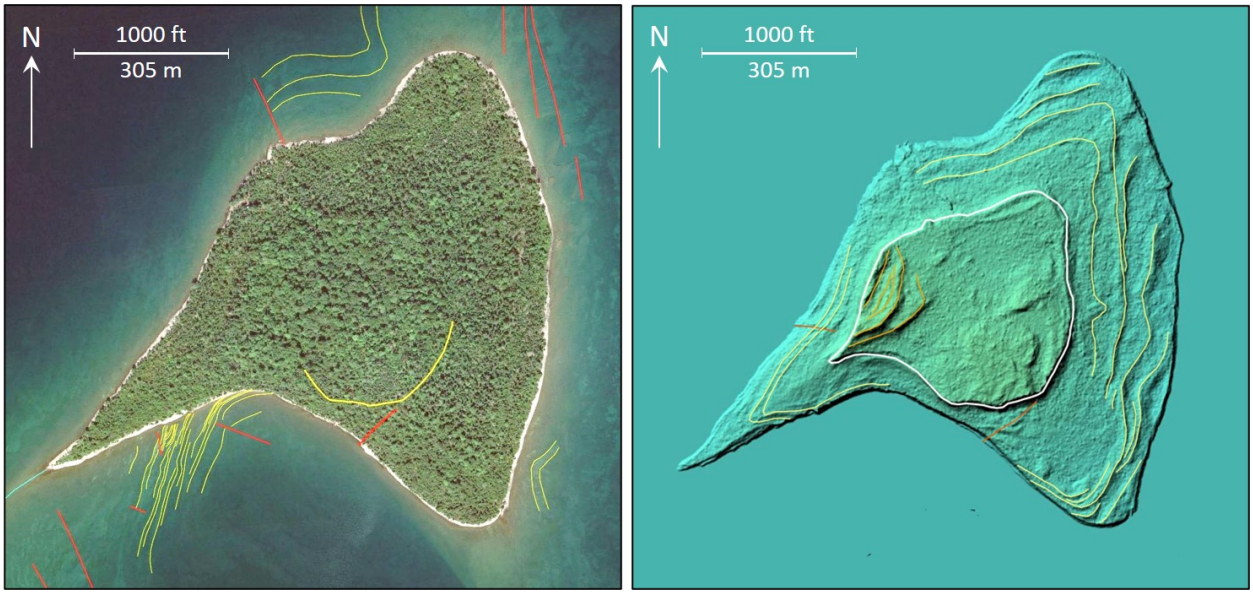


Figure 2: Geology at Traverse Island in Keweenaw Bay. Left -aerial image from Google Earth with offshore tracing of Jacobsville Sandstone strata (yellow) and fractures (red). Onshore features are from Denning (1949). Right – onshore tracing of sandstone strata from 2-m resolution Lidar data. White outline is a caprock of "quartzite" with a possible channel form at its western edge.

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Michigan Coastal Path: A Social Commitment to Geoeducation

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The geology of the Midcontinent Rift is beautifully exposed for researchers, teachers, students, and geotourists in the Keweenaw Peninsula and Isle Royale (http://carnegiekeweenaw.org/social-post/keweenaw-shorelines-bill-rose). Michigan holds title to the surrounding bottomlands of the Great Lakes under the Public Trust Doctrine in addition to a public trust interest in the shorelands up to the ordinary high water mark (OHWM). Michigan confronts the challenge of discerning the boundaries between public trust interests and private property rights at the shore (Norton *et al, 2013)*. In 1968, the Michigan Legislature adopted an elevation-based approach for discerning the ordinary high water mark (OHWM). In 2005, the Michigan Supreme Court reaffirmed that Michigan's public trust interest extends up to the OHWM, but it left unresolved questions of exactly how the two methods of marking ordinary high water relate to one another, and precisely how far up the shore the state has authority to regulate private shoreline development extends. (Norton *et al*, 2011). Here we describe the definitions of high water lines for geologic discussion. ***How may both landowner and hiker amicably agree on the high water mark when we meet along the shore?***



Figure 1: Shoreline exposures reveal the rock details clearly - veins of calcite (near the Copper Harbor Light) and native copper (Washington Island).



Figure 2: Shoreline of Copper Harbor Conglomerate on Manitou Island. The zonation and succession of shorelines may be seen and used to define the high water mark.

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Jacobsville Geoheritage is Globally Celebrated and Locally Loved

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The Jacobsville Sandstone is a well-known red bed sandstone of Neoproterozoic age from Upper Michigan, USA (Cannon and Nicholson, 2001) and is part of the Keweenaw Supergroup related to the Midcontinent Rift System. The rift formed ~1100 Ma and is a ~3000 km long feature in North America, centered on the Lake Superior area. The Jacobsville is the youngest of the area's Precambrian rocks and was deposited during the Rigolet Phase of the Grenvillian Orogeny (1010-980 Ma) (Hodgin et al 2022). Cliff exposures show crossbedding and channels interpreted as fluvial deposits.

Jacobsville Sandstone was a fashionable building stone in much of Eastern North America. From 1885 to 1920, it was used in hundreds of prominent buildings including the famous Astoria Hotel in New York City (Eckert, 2000). It was mined from several quarry sites near Jacobsville, Michigan. The location is part of a significant geoheritage location where native copper has also been mined, valued, and utilized for thousands of years. The development of copper mining drove extensive immigration of Europeans to Upper Michigan. The Jacobsville quarries offered an alternative to underground employment in the booming mining industry of the Keweenaw.

Since quarrying has ceased, Jacobsville quarries have been overgrown and are often overlooked. Highlighting the significance of these places and increasing access offers an opportunity to teach locals and visitors about Earth's history and natural/cultural resources. It connects people to a significant element of Keweenaw geoheritage often eclipsed by the history of copper mining. In recent years we have been building awareness of the geohistory and geoheritage of Jacobsville quarrying. This awareness is building educational outreach focused on this remarkable rock formation which features in many local towns.

The International Union of Geological Sciences (IUGS) and UNESCO's International Geoscience Programme (IGP) have announced that the Jacobsville Sandstone - a rock formation named for Jacobsville, Michigan - is now one of only 15 Global Heritage Stone Resources (GHSR) in the world and the first in the United States (Rose et al, 2017). Global Heritage Stone Resources (GHSR) are scientific designations created and managed by the Heritage Stone Subcommission – HSS (IUGS/IAEG) to enhance the geological knowledge, use, and conservation of natural stones of historical importance worldwide.

Highlights of recent Jacobsville geoheritage efforts include boat tours that explore the rock exposures in spectacular cliff views and Michigan historic signage in Houghton and other towns.

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Fig 1: Red Jacket firehouse in Calumet (built in 1898–99) – National Register of Historic Places. Use through Creative Commons by Andrew Jameson.



Fig 2: One of many cliff exposures of the Neoproterozoic Jacobsville Sandstone, here about 1 km N of the town of Jacobsville, 19 km SE of Houghton, in Michigan's Keweenaw Peninsula. Cliff exposures are found in dozens of locations within Keweenaw Bay. Photo by Steve Brimm.



Fig 3: Jacobsville Quarry near Portage Entry, in operation, about 1895 (MTU Neg 03965, Michigan Technological University Archives and Copper Country Historical Collections, Houghton, Michigan Michigan Technological University Archives).

United Nations Educational, Scientific and Cultural Organization

International Geoscience Programme

Compiled historical drillhole and geochemical data from the Cuyuna Range, Minnesota, provides powerful new insights for geological and mineral potential investigations.

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The Minnesota Department of Natural Resources (DNR) staff of Lands and Minerals (LAM) compiled a large tabular dataset of drill hole locations, geological logs, and geochemical data from the Cuyuna Iron Range of central Minnesota as part of the federally funded Earth Mapping Resources Initiative (Earth MRI). These data will help to determine where potential resources of iron and manganese, as well as other critical minerals, may exist in the underlying bedrock.

Iron in the Cuyuna Range was discovered in 1903 by Cuyler Adams and was actively mined until 1984. Prior to the end of WW1, there were 37 active mines on the Cuyuna Range. The lack of outcrop hindered the geological understanding and definition of the resources, and over 12,000 exploration holes were drilled over this period (Morey et al., 1977). Some of the historical explorers and mining operators in this area included: Orelands Mining Company, Evergreen Mining, Pittsburg-Pacific, Pickands-Mather, Oliver Iron Mining (division of US Steel), Inland Steel, Rogers-Brown Company, and Zontelli Brothers (Sutherland, 2016). Since the end of active mining in this district, the DNR LAM office in Hibbing has accumulated thousands of mining and mineral exploration documents from various companies.

Current estimates suggest that the Cuyuna Range is among the top three largest manganese occurrences in the United States, justifying continued interest in its resource potential (Strong, 1959; Beltrame et al., 1981; Kilgore and Thomas, 1982; Cannon et al., 2017). From the 1940s to 1960s, the US Bureau of Mines (USBM) assembled, coded, and entered location and geochemical data for about 40% of the 12,833 drill holes available from the USBM Minnesota Mineral Development Atlas. USBM used criteria such as depth of overburden, past mining activity, availability of manganese data, and the availability of the sample material to determine which data to prioritize. All data were entered from public land survey (PLS) sections if there were fewer than 80 drillholes. For PLS sections exceeding 80 drillholes, then only 5 drillholes were entered for each quarter-quarter. This compilation resulted in data for 5,045 drillholes across the entire Cuyuna Range (Morey et al., 1977).

Further, in the early 1990s, the Minnesota Geological Survey (MGS) created several databases to compile the assays and geologic logs from the USBMs dataset. Their database contains around 12,000 holes which have limited assay data and generalized geologic logs. Many of these drillhole sites were also entered in the Minnesota Well Index. As part of the Earth MRI project the MGS transferred thousands of maps and drill logs to the DNR.

Compiling and managing 10,000s of documents and drill hole locations is a complicated and enormous undertaking, however, the use of geospatial software (i.e., ArcGIS), artificial intelligence and machine learning, and MicroMine 3D modelling software has accelerated the process. Without these technological resources, it would be difficult and time consuming to track

duplication among the various exploration documents as well as the rebranding of drillhole names by successive explorers. The DNR merged the USBM and MGS databases and used the MicroMine software to help identify and resolve missing intervals, overlapping intervals, missing or incorrect azimuth and inclination, drillholes without analytical data, missing total depth, values beyond the end of the drillhole, and coincident drillhole collars. It would be nearly impossible to uncover these errors by hand.

DNR staff curated and compiled a collection of US Steel data from the 1950s that was not included in its entirety in either the MGS or USBM compilations. These and other historic exploration data added drill logs and assays for hundreds of holes to the DNR's drillhole compilation, mainly from the Emily area. Intervals that were assayed from these holes were often missing geological information, likely because the alteration and mineralization made interpretation difficult for the earliest explorers. Any missing collar elevations were obtained from 2012 1-m Lidar, knowing that inaccuracies may exist from previously mined areas or existing stockpiles post-exploration. DNR staff consolidated lithology types by limiting modifiers related to alteration or mineralization and extracted all assay data to create a working 3D model of the Emily district. Not only will future users have access to this model, but they will also be able to easily search by key words, sort based on geochemical results, and view the geographical location of the data.

The data compilation is the first of a three-phase project which will be followed by ground and airborne geophysics and later supported by petrographical, lithochemical and geochronological analyses. Subsequent geologic mapping, mineral potential evaluation, and a geological interpretation for the rest of the Cuyuna district will complete this project. The project will culminate in an Earth MRI data release and report in 2026.

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Understanding the evolution of the upper Midwest Archean gneiss dome corridor using apatite, titanite, and monazite LA-ICP-MS U-Pb geochronology and microstructural analyses

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The origin of the Archean gneiss dome corridor stretching across Minnesota, Wisconsin, and northern Michigan is an important question for understanding the Paleoproterozoic tectonic evolution of the upper Midwest. The formation of these gneiss domes was originally attributed to orogenic collapse during the Penokean orogeny (1.86-1.83 Ga) (Schneider et al., 2004). More but more recent work, however, indicates their exhumation may be more closely linked to a suite of younger structures and metamorphism which are broadly concurrent with the Yavapai event between 1.78-1.75 Ga (e.g., Tinkham and Marshak, 2004; Schulz and Cannon, 2007). In this study, we leverage new LA-ICP-MS U-Pb geochronology and microstructural observations using EBSD (electron backscatter diffraction) to shed light on the timing of metamorphism and deformation related to the exhumation of these domes to understand the broader tectonic framework in which they formed.

We investigate a suite of metamorphosed and deformed rocks collected from both inside and adjacent to these gneiss domes in northern Michigan (Figure 1). We show that these rocks have metamorphic U-Pb ages ranging from Neoarchean to Mesoproterozoic, reflecting the prolonged tectonic history of the southern margin of Laurentia (Figure 2). In the Paleoarchean Watersmeet gneiss, titanite grains have U-Pb intercept ages of 2550±46 (2σ, n=36) Ma, concurrent with the Sacred Heart orogeny. The U-Pb concordia ages of apatite in the Watersmeet gneiss at 1869±32 (2σ, n=27) Ma, and monazite U-Pb ages in the Hardwood gneiss at 1826±21 (2σ, n=36) Ma, reflect metamorphism of these rocks during the Penokean orogeny. Several samples have apatite U-Pb concorida ages that indicate heating continued for tens of millions of years after the end of the Penokean orogeny at about 1830 Ma: at 1815±32 Ma (2σ, n=17) in the Republic trough, at 1803±29 Ma (2σ, n=49) in the Hardwood gneiss, and at 1796±29 (2σ, n=51)Ma in the Michigamme Formation directly adjacent to the Watersmeet dome.

Our dataset documents the influence of post-Penokean orogenic events on the rocks of the gneiss dome corridor in northern Michigan. In the Neoarchean Carney Lake gneiss, migmatitic rocks have titanite U-Pb ages of 1752±71 Ma (2σ, n=53), indicating reactivation during the Yavapai orogeny. In the Solberg schist, in the Felch trough, titanite grains have recrystallized into aggregates of subgrains, likely formed during deformation. These titanite grains have U-Pb ages of 1713±32 Ma (2σ, n=82), which we interpret to reflect the timing of deformation-induced recrystallization. The U-Pb ages of apatite in the Solberg schist are markedly younger at 1588±28 Ma (2σ, n=46) and align with the timing of the Mazatzal orogeny. Together, these new U-Pb data add to a growing body of evidence that the present architecture of the gneiss dome corridor in the upper Midwest is at least in part due to post-Penokean orogenic events.

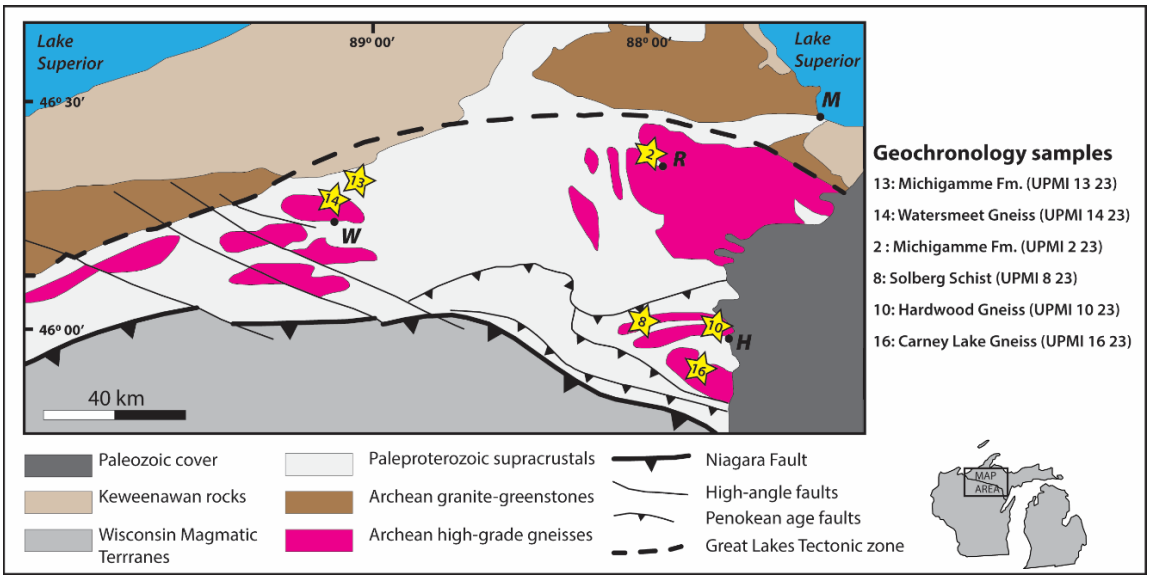


Figure 1. Generalized geologic map of the study area (modified from Tinkham and Marshack, 2004) showing the locations of sample sites with yellow stars. Black dots show the position of towns W: Watersmeet, R: Republic, H: Hardwood, and M: Marquette.

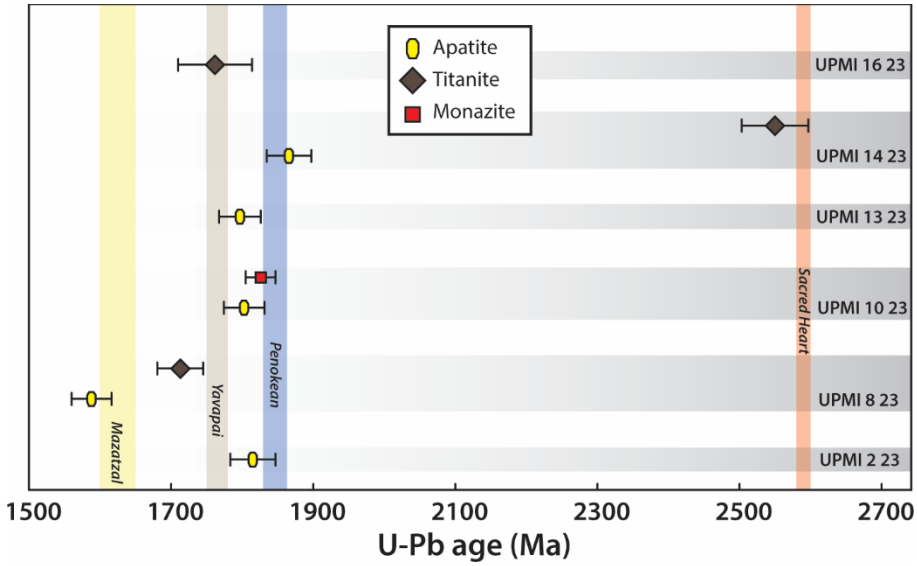


Figure 2. The LA-ICP-MS U-Pb ages of apatite, titanite, and monazite for the samples in this study. The vertical bars represent the timing of major orogenic events along the southern margin of the Superior craton and Laurentia.

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Analysis of deformation-related structures in the Eau Claire Volcanic Complex, Wisconsin

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This study is focused on the Penokean-aged (1.8-1.9 Ga) deformation fabrics and microstructures in the Big Falls region of the Eau Claire Volcanic Complex (ECVC), Northwestern Wisconsin. Varying intensities of deformation and metamorphism within the Penokean Orogeny are extensive and well documented, particularly in the External Domain in the northern parts of the orogen. However, the southernmost regions are more poorly studied because outcrops are present as rare erosional outliers in river channels. Structural interpretation, and by association terrane boundaries, have largely been inferred from geophysical data. This project focused on describing the structural and metamorphic fabric development at two field areas: one studying the origin of the gneissic banding within the amphibolitic banded gneiss (Figure 1A), while the other being a study on the genesis of the migmatitic fabrics (Figure 1B). The goal of this research is to petrographically and geochemically interpret the deformation mechanisms of the ECVC and improve its tectonic context to the rest of the Penokean orogeny.

There are two main volcanic terranes within the Penokean Orogeny and are sutured together by the Eau Pleine Shear Zone. The Pembine-Wausau terrane is characterized as a juvenile arc-system formed through subduction and was accreted onto the southern edge of the Superior Craton. This was followed by the accretion of the Marshfield Terrane; an Archean microcontinent overprinted by Paleoproterozoic magmatism. Historical interpretations of the ECVC suggested these rocks were deposited on the Marshfield Terrane, but recent geochemical and petrochronological studies show a mantle-derived, oceanic affinity (Lodge et al, 2023; Weber et al., 2023). Therefore, revisiting and reinterpreting the tectonic context of the ECVC to the Marshfield Terrane is warranted.

The previous interpretation of the bedrock at Big Falls County Park suggests gneissic banding was inherited from igneous layering from a layered mafic intrusion (Cummings, 1984). This study describes field and petrographic observations that indicate intense ductile fabric development during shearing such as asymmetric inclusions, pressure shadows, and feldspar grain-boundary migration within the gneiss (Figure 1A, 1C). Comparison of these textures with other sheared amphibolites and amphibolitic gneisses support the interpretation that banding is, at least in part, caused by intense shearing (e.g. Bozkurt et al., 1997). Geochemical analysis of the Big Falls Region shows a hydrated, mantle-derived signature closely related to an E-MORB oceanic-arc system, indicating that these magmas are not derived from an Archean, continental fragment (Weber et al. 2023). Structural analysis of these rocks shows extensive fabric shearing and deformation, supporting the theory that these rocks are structurally emplaced.

Petrographic and outcrop analysis of the tonalite intrusion and “lensoidal amphibolite” in the Little Falls region indicates the gneissic fabrics and banding are migmatites. Two possible theories for the genesis of the migmatites are suggested: anataxis of the amphibolite and granulite facies metamorphism (Ashworth 2011) or melt injection from the tonalite intrusion during the Penokean deformation. Previous interpretations of the Little Falls region indicated three episodes of metamorphism (Cummings 1984). Evidence of a weak foliation and recrystallization in the tonalite intrusion (Figure 1D) containing xenoliths of banded amphibolite gneiss suggests at least two metamorphic events. However, its relationship to the thermal event that formed the migmatites is uncertain.

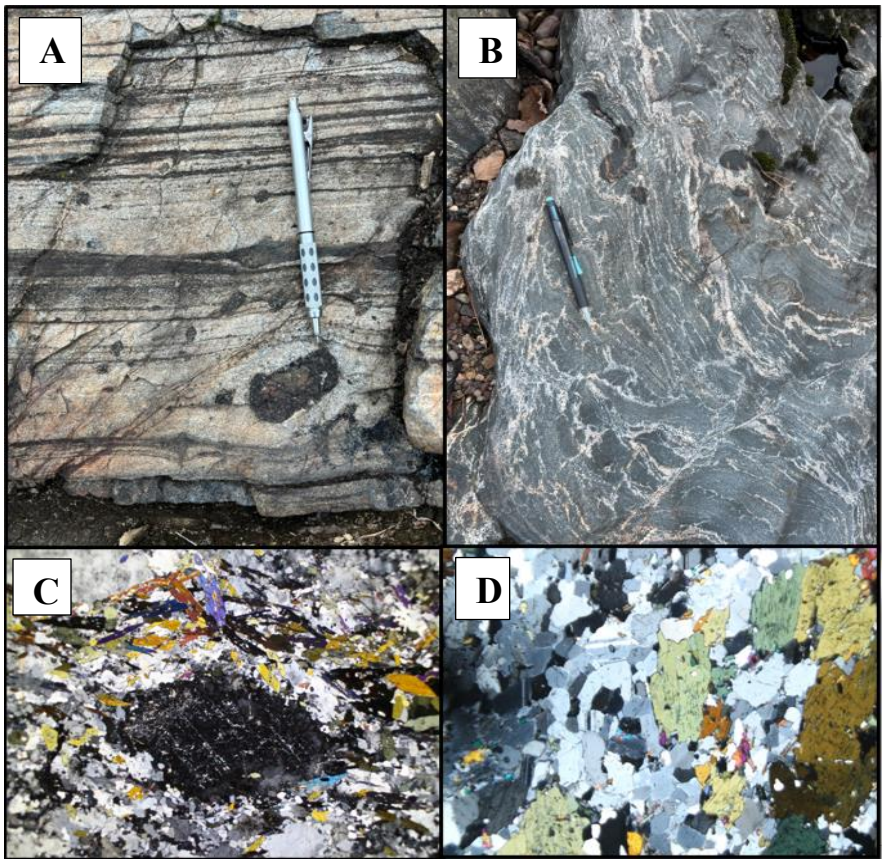


Figure 1: **A**: Outcrop photo of amphibolitic bands and sheared garnet-hornblende porphyroblasts in banded gneiss, Big Falls County Park, Wisconsin. **B**: Outcrop photo of migmatite at Little Falls County Park, Wisconsin. The neosome consists of quartz, plagioclase, and feldspars while the paleosome consists of hornblende, biotite, and chlorite in the picture. **C**: Photomicrograph (XPL, 10x) of strained feldspar crystal with grain boundary migration, and an amphibole band being deflected via shearing above the feldspar grain. **D**: Photomicrograph (XPL, 10x) of the tonalite intrusion at Little Falls which contains quartz, plagioclase, biotite, hornblende, and chlorite.

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Geochemistry and Petrology of the Eagle's Nest Intrusion, McFaulds Lake Greenstone Belt, Northern Ontario

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The Eagle's Nest intrusion hosts economically significant orthomagmatic Ni-Cu-(PGE) mineralization located in the McFaulds Lake greenstone belt within the northern regions of the Archean Superior province, approximately 500km northeast of Thunder Bay, Ontario. The Eagle's Nest intrusion is part of the 2734 Ma ultramafic-dominated Koper Lake subsuite of the larger Ring of Fire intrusive suite (Metsaranta et al., 2015; Houlé et al., 2020). The mineralized ore body of the Eagle's Nest intrusion is zoned, with massive sulfide mineralization at its northwestern extent that gradationally becomes semi-massive, net-textured and disseminated to the southeast (Zucceralli et al., 2022). Mineralization consists of 11.1 million tonnes of proven and probable mineral reserves containing 1.68% Ni, 0.87% Cu, 0.89g/t Pt, 3.09g/t Pd and 0.18g/t Au (Burgess et al., 2012). The intrusion was emplaced along a sub-horizontal conduit, forming a blade-shaped dike (Barnes and Mungall, 2018). Mineralization is consistent with gravitational sulfide segregation at the basal, northwestern contact of the intrusion. Subsequent deformation rotated the intrusion into its present day, subvertical orientation, with a width of ~500m, thickness of ~150m and vertical extent >1600m.

Parental magma composition of the Eagle's Nest intrusion has been determined on a number of occasions but with contrasting outcomes. A low MgO komatiitic magma composition with ~22% MgO and ~12% total FeO was proposed by Mungall et al. (2010). In contrast, Zuccarelli et al. (2022) reported olivine compositions of $Fo_{82\text{-}86}$ consistent with picritic parental magmas containing moderate MgO (10-20%) and high total FeO (>12%). The contrasting results means that parental magma composition of the Eagle's Nest intrusion needs to be further constrained. The objectives of this study are to petrographically and geochemically characterize the (1) unmineralized portions of the Eagle's Nest intrusion and (2) associated offshoot dikes in the vicinity, and (3) constrain the parental magma characteristics by using geochemical, petrographic, mineral chemistry, and radiogenic isotope techniques.

A total of 136 samples were collected for this study. Forty-four samples came from offshoot dikes consisting of fine- to medium-grained mafic to ultramafic units. Eighty-seven samples were collected from within the intrusion comprising peridotite (Fig. 1), gabbro, and chilled margin samples. Lastly, five samples were collected from the host wall-rock of the intrusion which consists of tonalite. One-hundred and twenty-one samples were analyzed for major and trace elements using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS), respectively. An initial batch of 30 thin sections was prepared consisting of 15 offshoot dikes, eight contacts, and seven peridotite samples. Twenty samples from the intrusion were selected for Sm-Nd isotopes.

To constrain the parental magma composition, three approaches will be considered: (1) examination of preserved chilled margins along the length of the chonolith, (2) examination of chilled margins preserved in the magmatic breccia matrix within the stratigraphic hanging-wall

of the intrusion, and (3) mineral chemistry of fresh olivine preserved within the peridotite horizons of the intrusion. The parental magma composition obtained from these three methods will be further compared to ensure consistency between the methods. The intrusion's magmatic history will be constrained using the obtained Sm-Nd isotope data, which will provide further insights into the mantle source and contamination history of the melts that formed the Eagle's Nest intrusion.

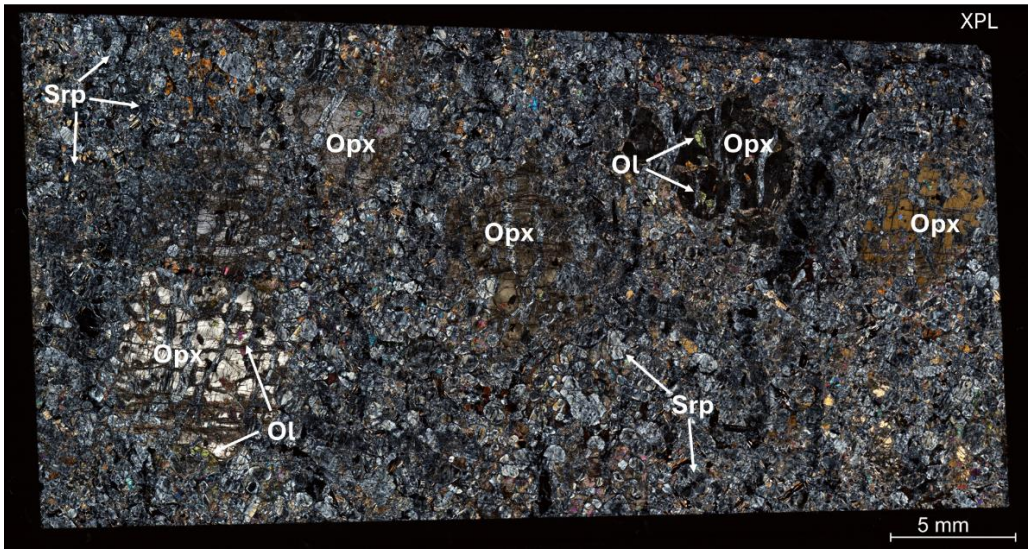


Figure 1. Photomicrograph in crossed-polarized light (XPL) of a peridotite sample containing serpentinized cumulus olivine and poikilitic orthopyroxene with fresh olivine within the oikocryst.

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New LA-ICP-MS U-Pb geochronology of-Archean rocks, central Upper Peninsula, Michigan, USA: a step toward refining the final assembly of the Superior craton

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The central Upper Peninsula, Michigan consists of two contrasting Archean terranes of the Superior Province: the granite-greenstone terrane of the Wawa-Abitibi Subprovince in the north (Northern Complex) and the gneisses of the Minnesota River Valley Subprovince (MRVS) in the south (Southern Complex). The two terranes are separated by the Great Lakes Tectonic Zone (GLTZ). The suturing of the MRVS to the southern margin of the Superior Province and development of the GLTZ, long interpreted to have occurred at about 2.69 Ga, has more recently been suggested to be related to the ca. 2.58 - 2.6 Ga Sacred Heart Orogeny (Schmitz et al. 2018; Cannon et al. 2024, *this volume*), a proposal that we are still evaluating. In this study we present new LA-ICP-MS U-Pb geochronology for Archean crystalline rocks from both the Northern Complex and Southern Complex, across the GLTZ. This age characterization is essential to define/refine the regional geochronologic framework of 'basement' rocks in the central Upper Peninsula. This is essential to understand subsequent geologic processes.

Heavy mineral separates were produced using Electro Pulse Dissagregation (EPD) followed by heavy liquid separation at Zirchron (AZ, USA). Individual zircon grains were hand-picked and mounted in 25 mm epoxy resin mounts and polished to a 1 μm finish. All samples were imaged via cathodoluminescence in the Denver Microbeam Lab (USGS) using the JEOL 5800 LV SEM. LA-ICP-MS analyses were made using a Nu AttoM sector field ICP-MS coupled to a NWR 193 ArF excimer laser system in the Mineral Isotope Laser Laboratory (MILL) at Texas Tech University. Typical laser ablation conditions during all analytical runs were a fluence of 3 J/cm^2, 8 Hz, and 240 laser pulses using a 15 μm laser spot. Data was reduced using Iolite v.4 (Paton et al. 2011) and final age calculations were made using IsoplotR (Vermeesch, 2018). We are presently working on zircon LA-MC-ICP-MS Hf isotope analyses to characterize the source components of Archean crystalline rocks from the Northern Complex and Southern Complex.

Zircon grains from nine rocks in the Southern Complex and six rocks in the Northern Complex were targeted for LA-ICP-MS U-Pb analysis. Examples of samples analyzed from Southern Complex granitic gneisses are shown in Figure 1. For all samples, the age spectrum of concordant grains is complicated with multiple inherited populations within a single sample. This observation is like that presented by Ayuso et al. (2018) for the ca. 2700 Ma Carney Lake gneiss and ca. 2750 Ma Hardwood gneiss, south of our current study area. Examples of crystalline samples analyzed from the Northern Complex are shown in Figure 2. A single age population for zircon grains analyzed with little to no evidence of Early or Middle Archean inheritance is common for Northern Complex basement samples. These data support the fundamental difference between the primitive volcanic/plutonic terrane of the Northern Complex and an older Archean continental crustal component in the Southern Complex.

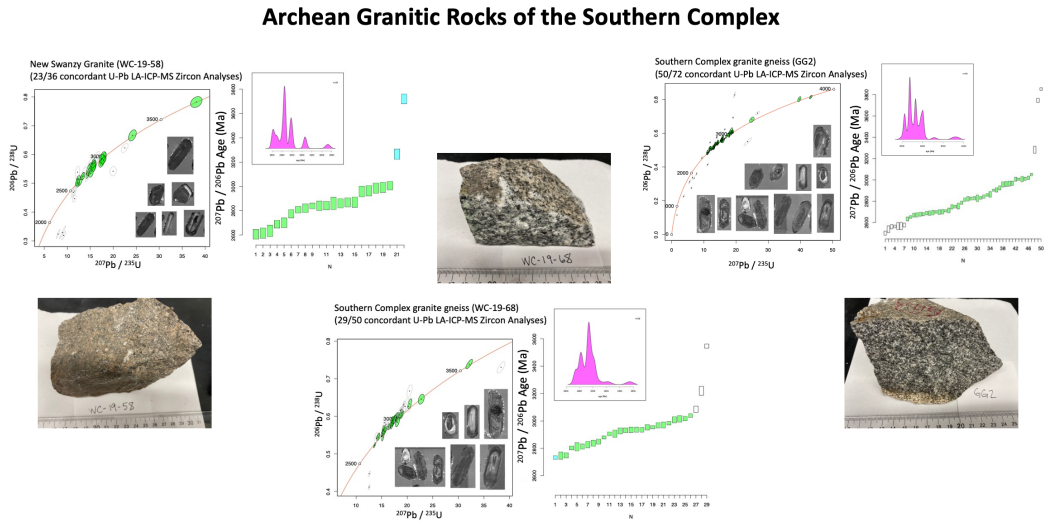


Figure 1. Examples of a subset of Archean granitic rocks sampled from the Southern Complex, MI

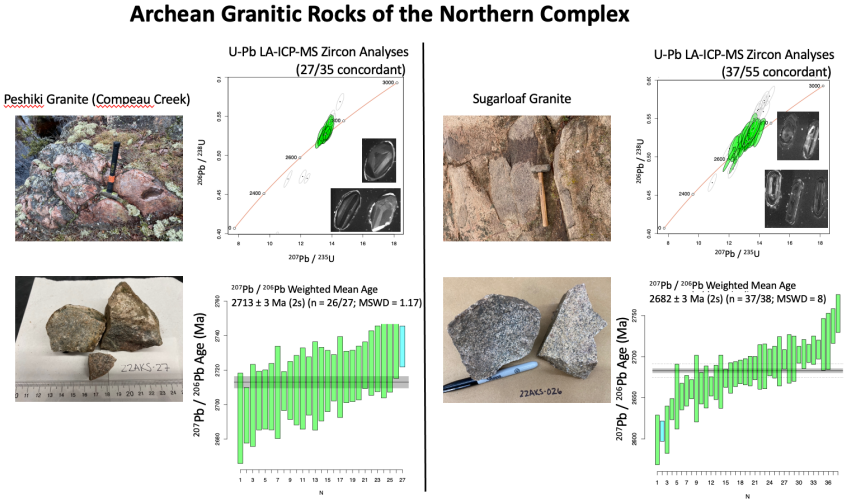


Figure 2. Examples of a subset of Archean granitic rocks sampled from the Northern Complex, MI

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Geochemical fingerprints from the late Mesoproterozoic epeiric seaway of the Nonesuch Formation, Wisconsin and Michigan, USA

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The Oronto Group (Copper Harbor Conglomerate, Nonesuch Formation, and Freda Formation) of the southern Lake Superior Region preserves an exceptional record of late Mesoproterozoic environments and associated microfossils (e.g., Cumming et al., 2013; Fedorchuk et al., 2016; Strother and Wellman, 2021). A lacustrine rift basin is often cited as the most plausible depositional setting for the ca. 1080 Ma Nonesuch Formation because of its association with alluvial deposits of the underlying Copper Harbor Conglomerate and overlying Freda Formation and because of its location within interior Laurentia (Elmore et al., 1989; Slotznick et al., 2023). Our recent sedimentologic and stratigraphic evidence demonstrates deposition of the lower Oronto Group within a tide- and wave-influenced estuary (Stewart et al., 2023, see also Hieshima and Pratt, 1991; Jones et al., 2020). New geochemical results from Nonesuch Formation carbonates (Figure 1), including strontium (Sr), carbon (C), and oxygen (O) isotope compositions, rare earth element - yttrium (REY) patterns, and trace element ratios complement and add new dimension to this environmental interpretation.

Strontium isotope compositions refine the Precambrian marine $^{87}Sr/^{86}Sr$ curve (Chen et al., 2021), with the Nonesuch recording relatively radiogenic compositions at ca. 1080 Ma between previously reported values of 0.706600 at ca. 1109 Ma and 0.705965 at ca. 1058 Ma. Most shale-normalized REY patterns from Nonesuch Formation carbonates are characterized by positive lanthanum anomalies and elevated yttrium: holmium (Y/Ho) ratios. Many of the same samples are also enriched in heavy REE, while others record light REE enrichment. These patterns indicate Nonesuch Formation carbonates precipitated from brackish water, consistent with REY patterns observed in modern estuaries (Lawrence and Kamber, 2006). One sample has a flat shale-normalized REY distribution and likely precipitated within part of the estuary dominated by fluvial input.

The combined geochemical evidence suggests Nonesuch Formation carbonates were minimally altered by diagenesis, and diagenetic alteration was dependent on sedimentary facies. While C and O isotopes are uncorrelated, initial Sr isotope compositions correlate positively with O isotopes, and C isotopes group by sedimentary facies. Minor diagenetic alteration thus resulted in less radiogenic Sr isotope compositions and did not impact C isotope compositions, which instead reflect facies-dependent incorporation of remineralized, isotopically light organic carbon during deposition or early diagenesis. Although ΣREY correlates with initial Sr isotope composition, there is no covariation between initial Sr isotope composition and lanthanide anomalies or Y/Ho ratios. This implies that carbonates likely precipitated in shallow pore waters where ΣREY was modified by contribution from surrounding detrital material, and REY profiles were determined by original pore water chemistry in connection with the overlying water body.

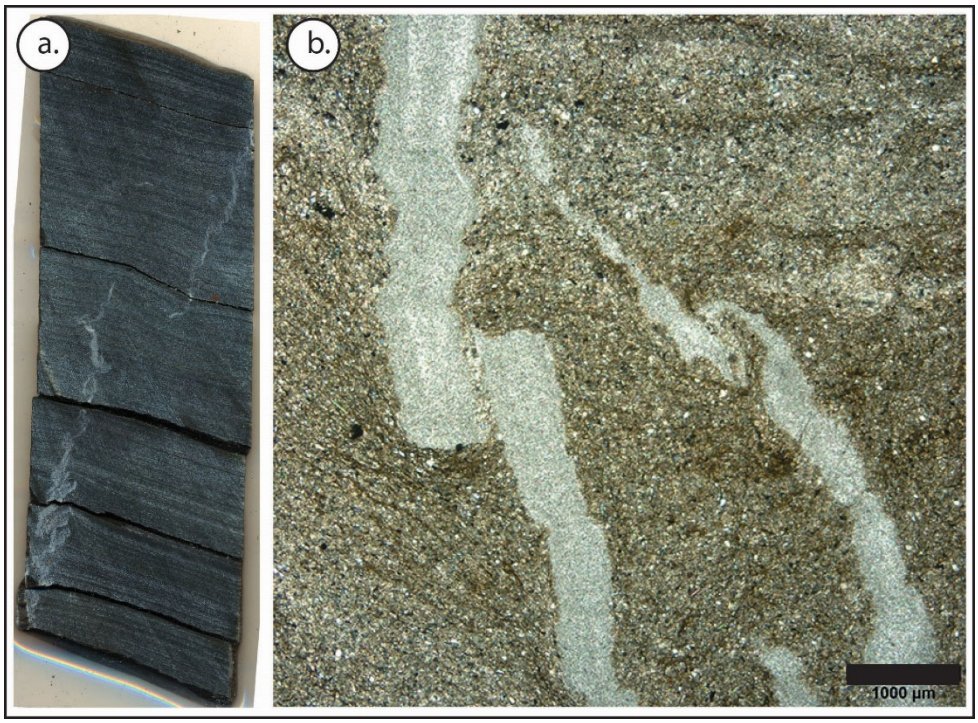


Figure 1. Example of carbonate sampled for geochemistry from the Nonesuch Formation. (a) core scan showing fine-grained siliciclastic sediment (dark gray) and carbonate (light cray). Note molar tooth crack cross-cutting laminae. Core is 1 inch (2.54 cm) wide. (b) photomicrograph showing carbonate spar (light color) infilling molar tooth crack. Plain polars, scale bar is 1000 µm. Modified from Stewart et al. (2023).

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Characteristics of graphitization across a metamorphic gradient in the Michigamme Formation of the Marquette Trough and Baraga Basin, MI

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Graphitization of carbonaceous material (CM) occurs by the progressive aromatization of carbon, expulsion of heteroatoms, and three-dimensional stacking of graphene layers — a process that alters the structure, isotopic, and trace element chemistry of the residual CM. Graphitization is generally considered thermally driven and has been extensively studied in the context of predictable changes in crystallinity as measured by Raman spectroscopy or X-ray diffraction, ultimately yielding the development of several graphite geothermometers (Henry et al., 2019). More broadly, crystalline graphite is an industrial mineral used in lithium-ion batteries and critical for the energy transition away from fossil fuels. The efficacy of graphite in the anode of batteries is directly related to its physicochemical properties which are a function of its geologic origin. The variably metamorphosed and deformed black shales and slates of the Michigamme Formation provide a natural laboratory to revisit our understanding of the graphitization process and the associated changes in structure and chemistry of CM in the context of technological applications.

The Michigamme Formation is a Paleoproterozoic metasedimentary and metavolcanic sequence that is widespread in the Upper Peninsula of Michigan. The lower part of the formation is finer-grained black shale and siltstone, typically with a prominent slaty cleavage. In the Marquette Trough and Baraga Basin, the focus areas of our study, this fine-grained sequence has been mapped and formally designated the Lower Slate Member of the Michigamme Formation. Highly carbonaceous units are ubiquitous near the middle of this member and vary from ~70 meters on average along the Marquette Trough to 150 meters or more in the Baraga Basin. Along the Marquette Trough, the outcrop trace of the Lower Slate transects a regional metamorphic gradient from chlorite to staurolite grade whereas the metamorphic grade in the Baraga Basin is uniformly low, within the chlorite zone. In the Marquette Trough, the graphitic beds sampled for this study are along the north limb of this complex syncline, mostly dip steeply southward, and have a well-developed slaty cleavage that is axial planar to the larger structure of the trough. Deformational features diminish to the north and the northernmost of our samples, in the Baraga Basin, are from nearly flat lying beds with no penetrative structural features. An important and widely accepted distinction of the Michigamme Formation is that the development of the penetrative regional cleavage predates the final metamorphic event. Thus, graphitization of the CM occurred under both stressed (tectonic) and static conditions.

A suite of thirteen core samples from the Upper Peninsula Geological Repository and three outcrop samples, all from carbonaceous sections of the Michigamme Formation, were selected for detailed evaluation (Figure 1). In all samples, CM occurs as disseminated and elongated fine-grained (<20 μm) particles that tend to be concentrated in bands parallel to the metamorphic fabric defined by phyllosilicates and quartz. Analysis of total carbon on decarbonated samples yielded values ranging from 1 to 24 wt.% C, with an average value of 7

wt.%. Carbon isotopic analysis from decarbonated samples yielded a general trend towards heavier $\delta^{13}C$ values with increasing metamorphic grade, ranging from -32.05‰ (Sample 4) to -21.85‰ (Sample 13). Raman spectroscopic analysis of CM yielded a similar trend with metamorphic grade across the sample suite. The R2 ratio, which is one parameter used to evaluate metamorphic grade, decreases from 0.64 in Sample 15 to 0.35 in Sample 8. These R2 values correspond to a temperature range from ~325°C to ~500°C using the empirical geothermometer from Aoya et al. (2010). Notably, Samples 11 and 13 from the garnet zone are significant outliers in both the Raman and C isotope datasets. Combining these results with additional data from scanning electron microscope imaging, X-ray diffraction mineralogical analysis, and laser ablation ICP-MS analysis of CM concentrates will yield a more detailed look at the evolution of CM with metamorphism and deformation. These results will help refine our understanding of the geologic processes that lead to economic graphite deposits and fine-tune graphite deposit models with an application focus.

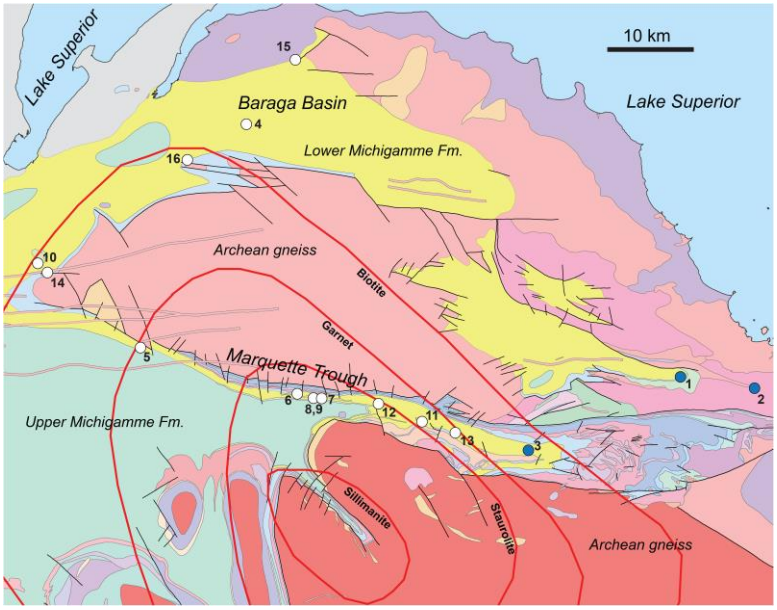


Figure 1. Geologic map and metamorphic isograds (red lines) of the field area in the Upper Peninsula region of Michigan. Map is generalized from Cannon and Ottke (1999). Core samples are noted with white dots, and blue dots for outcrop samples.

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Sulfur-isotope ratios in Paleoproterozoic Michigamme Formation at the Lake Superior Region: Implications on basin evolution and ambient seawater composition in the Greater Animikie Basin

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A considerable variation in δ^{34}S-ratios of sulfide minerals has been found in a sulfide-mineral-rich succession of slate, metasiltstone, and metagreywacke in the Paleoproterozoic Michigamme Formation located within the Baraga Basin at the eastern edges of the Greater Animikie Basin in the Lake Superior Region (Ojakangas, Morey, and Southwick, 2001). Sulfide minerals such as pyrite, chalcopyrite and pyrrhotite display δ^{34}S-values ranging between 2 and 40‰ (V-CDT) and appear to systematically vary with respect to the stratigraphic intervals (Figure 1). This variability is gradational and devoid of any anomalous spike. It is predominantly a function of stratigraphic location and it shows no relationship with the type of sulfide mineral or the textural mode of occurrence. This observation rejects the possibility that the δ^{34}S values were influenced by selective infiltration of externally derived sulfur-rich fluids along the stratigraphic layers of the Michigamme Formation. It also overrules the possibility that the observed δ^{34}S values were caused by low-grade metamorphism and recrystallization of the sedimentary rocks of the Michigamme Formation.

The values are consistent with primary δ^{34}S ratios in sulfide minerals which were precipitated from intergranular fluids within a sequence of clastic sediments in a basin shortly after deposition. Consequently, the measured δ^{34}S ratios in the stratigraphic horizons represent S-isotopic signatures inherited from the S-reservoir in the ambient basin, as well as changes introduced by basin-evolution and diagenesis of the siliciclastic sediments in a marine foreland depositional environment along the eastern portion of the Greater Animikie Basin.

While the observed general trend of gradual increase in δ^{34}S-values in the lower and upper members of the sequence can be explained by a systematic chronological trend in the global seawater composition (Paiste et al., 2020), a significant rise and fall in δ^{34}S-values in the Lower Slate and Upper Greywacke Members can be attributed to a limited-term separation of the Baraga Basin from an open-ocean circulation to an isolated basin environment in response to structural adjustments caused by the formation of a fold and thrust belt along the southern shore line of the foreland basin during the waning stages of the Penokean Orogeny (Schulz and Cannon, 2007). In this period of isolation, the sulfur-isotope composition was primarily controlled by intrabasinal bacterial fractionation leading to a significant rise in the δ^{34}S values up to 40‰ in the observed sediments. Upon subsequent erosional removal of the thrust sequence, and associated structural readjustments, the connection of the Baraga Basin to an open ocean was restored and the δ^{34}S-values in the new sedimentary rocks mimic values that are consistent with deposition in a larger open ocean setting.

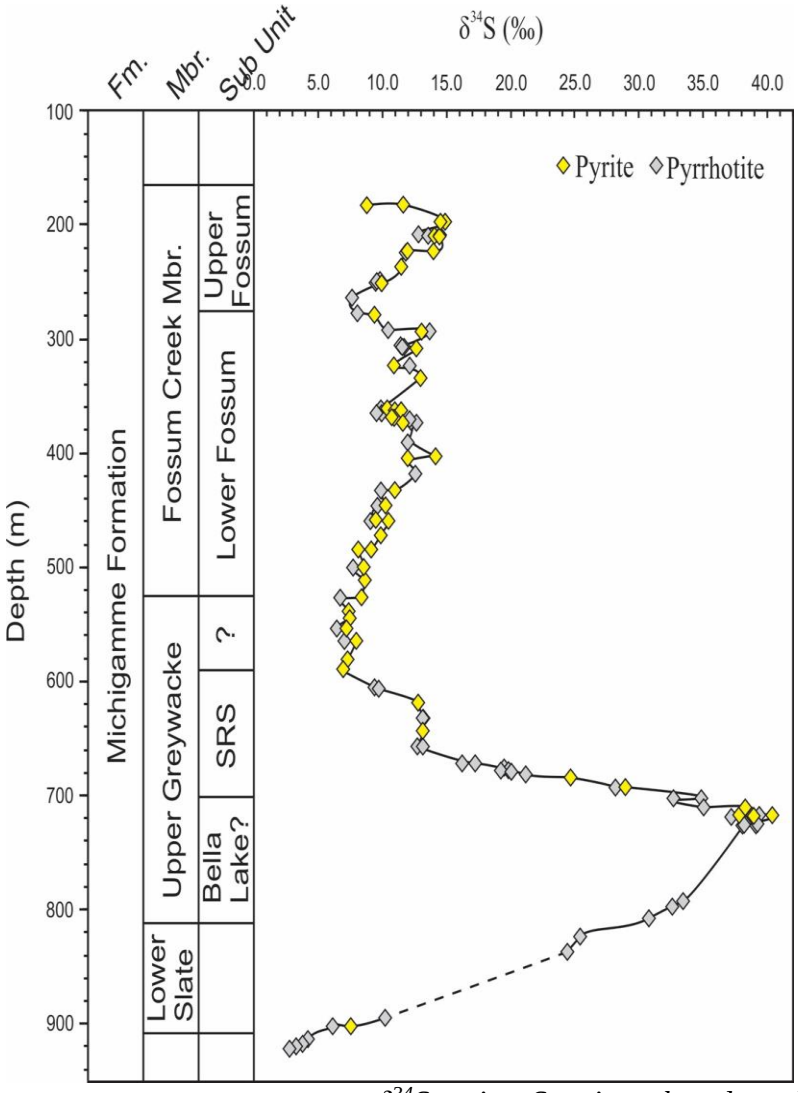


Figure 1: Observed variation in $\delta^{34}S$-ratios. Stratigraphy adapted from Rossell and Coombes (2005)

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An evaluation of structural and mineralogical controls on gold mineralization on the GoldRich property in the Abbie Lake area, Wawa, Ontario

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The GoldRich property in the Abbie Lake area is an active gold prospect in the Michipicoten greenstone belt, within the Wawa subprovince of the Archean Superior province of the Canadian shield. The property is located 30 km northeast of Wesdome's Eagle River mine and 10 km northeast of Wesdome's Mishi property in northern Ontario. The Main Shear trench on the GoldRich property is an area of regional metamorphism dominated by ductile deformation hosting orogenic gold. The Main Shear trench hosts mylonites of felsic and intermediate composition with varying strain intensities; all lithologies strike east-west. The mylonite of intermediate composition is characterized by having en-echelon quartz veins perpendicular to the foliation. Gold occurrences have been found in zones of high strain, in both felsic and intermediate mylonite lithologies. This HBSc thesis project relies on detailed trench mapping, microstructural and petrographic analyses, and geochemical methods to discover how gold is hosted on this property. Understanding the controls on gold mineralization will guide future exploration.

Gold mineralization in the Main Shear trench is related to deformation. Based on geochemical and petrographic analysis there is no correlation observed between alteration mineralogy and gold mineralization. Microstructural analysis revealed pervasive subgrain-rotation quartz recrystallization in both mylonitic lithologies indicating that the Main Shear trench has undergone deformation at the upper greenschist to lower amphibolite facies regional metamorphic conditions. Gold is associated with deformation, microstructurally related to recrystallized quartz grain boundaries, boudinaged veins, and shear bands.

Based on these results, it is recommended that further exploration on this property should be focused on locating zones of similar structure and strain intensity, including areas of boudinage, regardless of lithology, to continue building the gold prospect.

Petrology and Geochemistry of Felsic Magmatism in the Paleoproterzoic Eau Claire Volcanic Complex, Northcentral Wisconsin

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The 1.8-1.9 Ga Eau Claire Volcanic Complex (ECVC) (Figure 1) is the type locality for Penokean-age magmatism formed on an Archean crustal block (~2.6-3.0 Ga) called the Marshfield Terrane during the Penokean Orogen (Sims et al., 1989; Schulz & Cannon, 2007) and has influenced historic tectonic models and terrane-boundary maps. The other volcanic terrane within the Penokean Orogen, the Pembine-Wausau terrane (PWT), is interpreted to have formed with minimal influence of older crust and hosts about 150 million tonnes of volcanogenic massive sulfide (VMS) ores. The 'continental' setting of the Marshfield Terrane assumes a different metallogenetic system than the 'oceanic' setting of PWT and may be less prospective for the same VMS mineralization. However, recent U/Pb isotopic and other geochemical data (Lodge et al., 2023; Weber et al, 2023) indicates parts of the ECVC were mantle-derived and not contaminated by older Archean crust and challenges this 'continental' model.

The ECVC is challenging to study because of a lack of mineral exploration (and drilling) coupled with rare outcrop exposure due to glacial/fluvial sediment and Paleozoic rock cover. This project studies remote, inaccessible outcrops along the Eau Claire River to refine the tectonic model and terrane boundaries of the southern Penokean Orogen. Samples obtained from mapping were petrographically characterized and analyzed for major and trace element geochemistry. Thirteen samples were analyzed for major and trace elements via WD-XRF and compiled with other geochemical datasets from the region. Trace element geochemical data are used to determine magmatic and tectonic settings of these rocks and improve regional tectonic models for the ECVC.

Felsic magmatism in the region consists of fine-grained quartz-muscovite schists (Figure 1A) and banded quartzofeldspathic gneisses interpreted to be felsic volcanism and medium-grained massive granodiorite (Figure 1B). Fine-grained quartz-muscovite schist are characterized by approximately 5% quartz porphyroclasts that are 1-3mm in size. The matrix is very fine-grained quartz, feldspar, and muscovite that can have variable amounts of chlorite. Banded quartzofeldspathic gneisses have fine grained biotite and amphibole in quartz and feldspar-rich matrix that may define volcaniclastic textures at the outcrop-scale. Medium-grained, massive granodiorite is 15% biotite/hornblende and is characterized by weak to minimal foliation. These granodiorites are interpreted to be intruding felsic volcanic rocks, amphibolites, and metasedimentary units (Figure 1C). At one outcrop, the contact region is exposed revealing the formation of a megabreccia matrix, incorporating gneiss fragments that can reach up to 1 meter in size. These gneissic metasedimentary rocks are fine-grained with alternating bands of light and dark layers, ranging from straight to intensely folded.

Samples from the ECVC on Zr/Ti vs. Nb/Y classification diagrams reveal a bimodal magmatic suite which is commonly associated with extensional tectonic settings. Felsic volcanic and intrusive rocks on Nb vs. Y discrimination plots suggest that felsic magmatism was likely formed in syn-collisional or volcanic arc settings. Rhyolite fertility discrimination diagrams (Zr/Y vs. Y) show that both felsic volcanic and intrusive suites from the ECVC are FII-type rhyolites, typical of upper-crustal melting in rift zones. Therefore, the ECVC region may be prospective for VMS mineralization and the tectonic setting should be further evaluated.

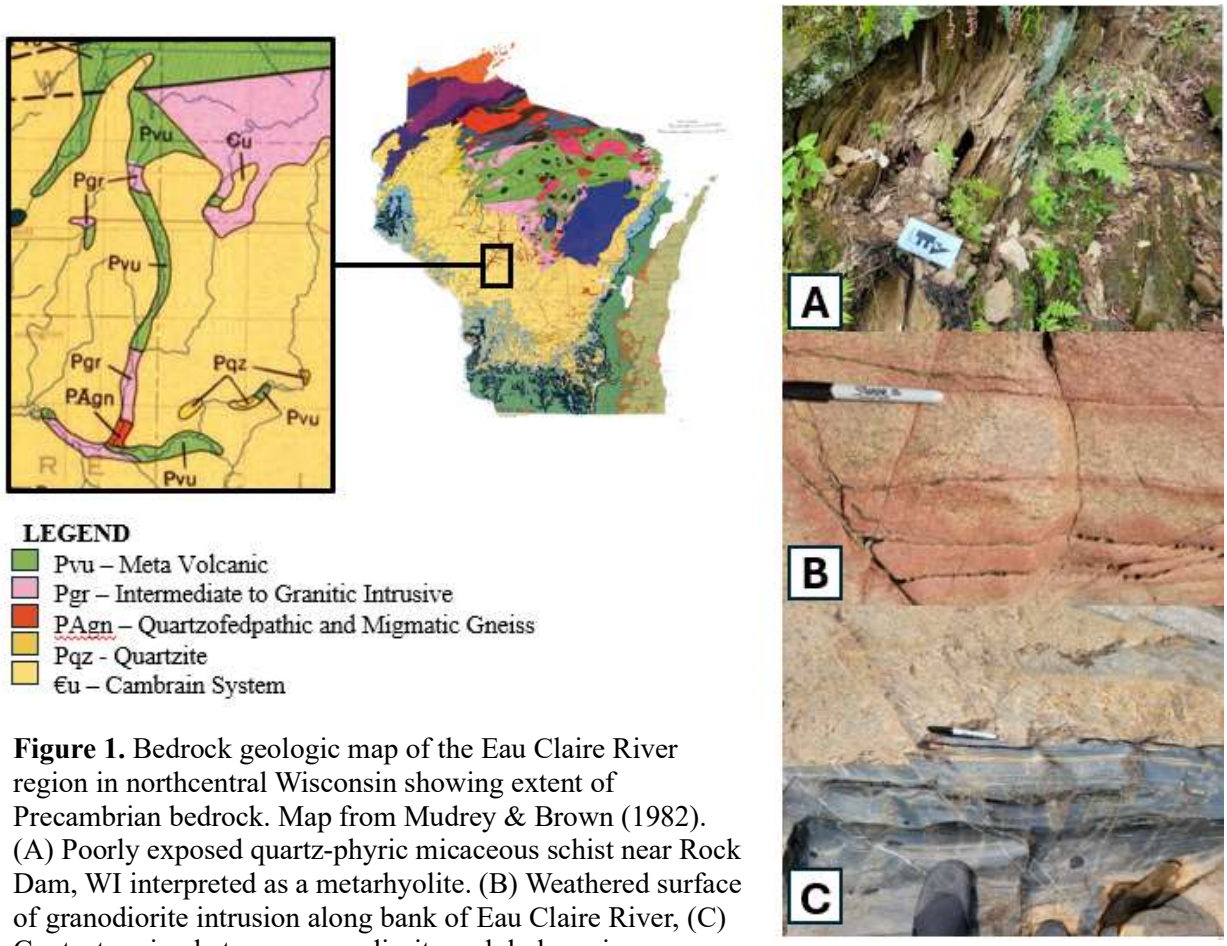


Figure 1. Bedrock geologic map of the Eau Claire River region in northcentral Wisconsin showing extent of Precambrian bedrock. Map from Mudrey & Brown (1982). (A) Poorly exposed quartz-phyric micaceous schist near Rock Dam, WI interpreted as a metarhyolite. (B) Weathered surface of granodiorite intrusion along bank of Eau Claire River, (C) Contact region between granodiorite and dark gneiss or metasedimentary rocks.

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The Keweenaw Geoheritage Summer Internship Experience

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Earth science education benefits from holistic interpretation of geologic features, processes, and landscapes through multiple ways of knowing (Deloria & Wildcat, 2001; Morton & Gawboy, 2003; Ricci & Riggs, 2019; Semken, 2005). Geoheritage is an evolving field that emphasizes the importance of the varied personal values people have for geologic features and explores the wide-ranging relationships we have with landscapes; as such it is an excellent place-based education tool to explore connections to our underpinning geology (Semken et al, 2017; Tormey, 2019). In this project setting, the Keweenaw region of Michigan's Upper Peninsula on Lake Superior, we demonstrate a regional, place-based approach to help deepen participant understanding of the billion-year-old geologic processes at the heart of the Midcontinent Rift system. These processes created both the Lake Superior basin and the largest known native copper deposit on Earth in a region further defined as the ancestral and contemporary homelands and waters of the Keweenaw Bay Indian Community (KBIC) on Lake Superior.

The *Keweenaw Geoheritage Summer Internship Experience* was created in partnership with the Keweenaw Bay Indian Community's Natural Resources Department (KBIC NRD) and Tribal Historic Preservation Office (THPO), and Michigan Tech's Great Lakes Research Center (GLRC) and Geospatial Research Facility (GRF). The experience was created to support intergenerational and multicultural learning about the Keweenaw landscape, its stories, and geology. Tribal and non-tribal high school student interns, community partners, and knowledge holders spent time together reading the landscape and sharing reflections on our varied relationships with land and water.

Week 1 entailed a 5-day field experience visiting valued sites of the Keweenaw Bay Indian Community that also teach us how geology impacts land, life, and culture in our place asking "*what gifts does geology offer us? what are the relationships with land and water in this place?*". During the field experience, youth interns collected and documented local knowledge by engaging in multi-sensory and multimedia documentation strategies to record their experiences (photos, audio recordings, drawing, 360 virtual reality images, etc.). Sacred Anishinaabe knowledge was not sought or shared in these experiences.

Data collected during the field experience was then used as the foundation for a 5-day geospatial workshop following the field experience. The goal of the workshop was for youth interns to design, create, and publish ARC GIS StoryMaps depicting their personal reflections of the diverse relationships with local landscape and understanding of its formation. ARC GIS StoryMaps is a story-authoring, web-based application that enables sharing of maps in the context of narrative text and other multimedia content. Workshop participants worked with the data they collected during the field experience in combination with supporting data layers and

maps specifically created for the experience. Interns were mentored by the geospatial research team who helped students develop digital storytelling skills, inspired brainstorming sessions for topics to explore in the maps, and facilitated peer-review of StoryMap content prior to publication. Upon completion, students presented their work at a community open house; all StoryMaps created have been peer-reviewed by all project partners and are now published.

The StoryMaps reflect a deepened understanding of relationships between geology, mining, and current environmental justice issues within our community. In the context of the Keweenaw, the European copper mining boom is most prominently interpreted in our place; students also reflected on the long history of mining, ways of mining, changing narratives, and missing human stories seen and experienced when visiting our landscape. Of note, respect, gratitude, and deepened relationships with land and water featured in all StoryMaps. Students shared reflections on reciprocity and their responsibility to help steward their place.



Figure 1: Left - students deepen their understanding of mining impacts to Buffalo Reef and our local communities; Right: students brainstorm story arcs for the foundation of their StoryMap

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R.W. Boyle's History of Geochemistry and Cosmochemistry

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Robert W. Boyle (1920-2003) was a well-respected geochemist with a long career at the Geological Survey of Canada. He is perhaps best remembered for geological and geochemical studies of gold, silver and other commodities, and for his association with mining camps, such as Yellowknife, N.W.T. and Keno Hill, Yukon. Retiring in 1985, Boyle devoted much of his final two decades to trips to far-flung libraries, gathering information exotic and/or obscure, and penning a major 3-volume review of the evolution of human knowledge of the nature and use of metals and other materials, and of diverse fields within geochemistry, cosmochemistry and biogeochemistry. The result, with copious help in compilation, was almost 2,000 pages of discussion (90% of it typed, fortunately!), backed by a formidable bibliography of almost 3,000 references. It was essentially complete at the time of his death, but altogether lacking in illustration. In time, his G.S.C. colleague Bob Garrett made some editorial notes, and then, in 2011, Charles Butt assessed the manuscript and made a detailed scientific and editorial review, heavy in marginalia. However, the work evidently arrived too late for the glory days of Survey and Society printing budgets, and it sat upon the shelf. In 2015, Ryan Noble, of the Association of Applied Geochemists, broadcast the existence of the manuscript, which attracted Wilson, who undertook to advance the work of the earlier editors, with encouragement from Boyle's daughter, biochemist Heather Robinson.

Volume 1 of the trilogy is set for publication in 2024 (Boyle, 2024). It covers the vast span of human time from the inception of mining and agriculture to the fall of Rome in the West (476 A.D.), and so ventures onto ground traditionally left to aspects of the Classics, Ancient History and Archaeology. Despite the western time frame, it is a worldwide review, covering, besides Europe and the Middle East, India and China and the Americas, every part of the globe where Boyle found relevant knowledge to impart. The intended volumes 2 and 3 explore, respectively, history through the critical 19th century, and then the 20th century (and so to the present). Volume 1 traverses the long development of early thought on the nature of matter. In addition to the various, often conflicting strains of philosophy, there is an equal treatment of the harnessing of materials (Stone, Bronze and Iron ages), and the early stages of the broad swathe of Earth sciences, mining and metallurgy. Early practical ideas on "Earth, air, fire and water" are discussed, e.g., geochemistry and mineralogy, cosmochemistry (meteorites), and early ideas on the hydrosphere and atmosphere.

How was the raw manuscript processed? In brief, Wilson: a) ported Boyle's references into a database, the easier to split up the long bibliography by chapter, rendering each section and volume a stand-alone story; b) utilised his MINLIB bibliography to update Boyle's references, which for Volume 1 had ended in 1987; c) split up the seminal chapter 3, which provides reviews for some 29 metals and commodity groups (e.g., Au, Ag, Cu; Fe; Sn, Pb; industrial minerals, gemstones and organics); d) added a third layer of editing and consistency checks; and e)

ultimately added 132 individual or composite illustrations in 93 numbered figures, including two original versions of the periodic table. Some of the additions (mostly to post-1987 research) are inserted in the text, others are collected in endnotes to each section. Some of the additions may be skating on thin ice (in which case, it is Wilson who falls through), a problem that one suspects would not have unduly worried the author of the original text.

Boyle himself travelled widely across Canada, and the world. In terms of the Lake Superior region, Volume 1 has multiple references to the native copper and native silver of the Mesoproterozoic Midcontinent Rift (Fig. 1; see, e.g., Bornhorst and Barron, 2013; Wilson, 2023). One of two additional text boxes is devoted to native copper, while the other concerns the wider literature on the chemical elements, including some of the most accessible, popular titles. An explicit reference is made to native elements, of which Boyle was fond (e.g., Zn, Pb), including the obvious starting point of Au, Ag and Cu, and listing some 30 elements (many of them very rare in their unalloyed forms).



Figure 1. Samples from famous occurrences of native metals in the Lake Superior region. Left: A spectacular, 4,264-kilogram mass of **native copper**, the exterior coloured by secondary Cu salts (Calumet, Keweenaw peninsula, Michigan). Right: **native silver** revealed in sawn and polished faces of calcite-veined fractured diabase from the Silver Islet mine in northwestern Ontario, a rich but short-lived venture on the east side of the Sibley peninsula, east of Thunder Bay, in Lake Superior.

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Cooling of an Archean metamorphic terrane: garnet diffusion study of the Quetico Subprovince, Canada

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Archean metamorphic terranes are traditionally suggested to have cooled significantly slower than their Phanerozoic counterparts. Many have argued that the contrast in metamorphic timescale reflects changes in Earth's tectonic regime. However, diffusion chronometry-based cooling rate data on Precambrian rocks are very limited. We present a case study of metamorphic timescales on the Neoarchean Quetico metasedimentary belt of the Superior Province, which has been hypothesized to represent a fore-arc accretionary prism. We combine conventional thermobarometry and phase-equilibrium modeling to constrain the peak temperature and pressure and estimate metamorphic cooling rates from major element diffusion in garnet. We then compare cooling rates across the Quetico Subprovince and with those from Phanerozoic metamorphic terranes of similar conditions. The results will contribute to the diffusion chronometry data available on Precambrian orogens for assessing any fundamental change in global tectonics.