72nd Annual Meeting

Thunder Bay, Ontario - May 21-22, 2026

Institute on Lake Superior Geology

Part 1 – Program and Abstracts



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65th Annual Meeting

Institute on Lake Superior Geology

May 21-22, 2026

Thunder Bay, Ontario

HOSTED BY:

Mark Puumala and Peter Hinz

Co-Chairs

Ontario Geological Survey (Retired)

Proceedings - Volume 72

Part 1 – Program and Abstracts

Compiled and edited by Pete Hollings & Mark Smyk

Cover Photos: Top: Amethyst veins in Rossport Formation at the Blue Points Amethyst Mine, north of Highway 11-17 near Big Pearl Lake.Middle: Neoarchean mafic metavolcanic rocks, Highway 102 at the intersection with Mud Lake Road. Bottom: Corestones of the McKenzie Granite at the Archean-Paleoproterozic unconformity, Highway 11-17 near Crystal Beach. All photos courtesy Mark Puumala.

72nd Institute on Lake Superior Geology

Volume 72 consists of:

Part 1: Program and Abstracts

Part 2: Field Trip Guidebook

Trips 1 & 4: "Classic" Geological Sites in the Thunder Bay Area

Trip 2: Geology of the Quetico Supprovince North of Thunder Bay

Trip 3: Gold Deposits of the Shebandowan Greenstone Belt

Trip 5: Structural Geology and Gold Mineralisation of the Mine Centre Area

Trip 6: Amethyst Deposits of Thunder Bay

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

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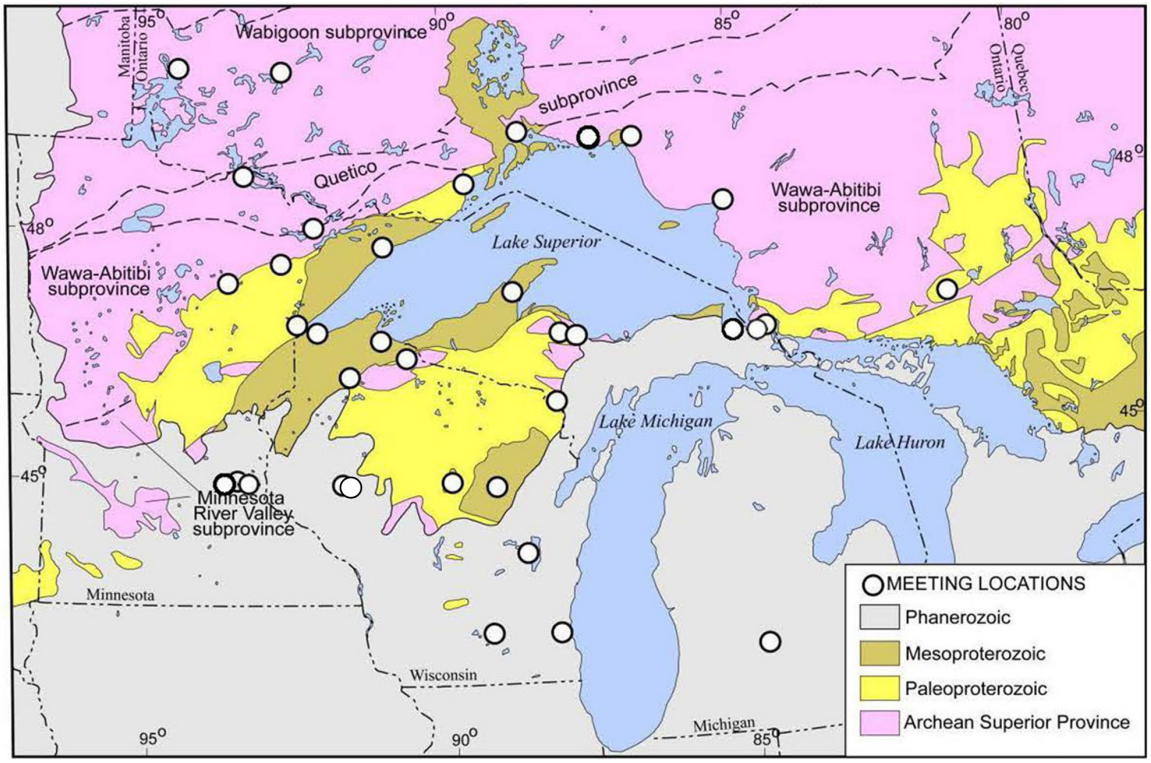
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Institutes on Lake Superior Geology, 1955-2026



#	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
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. 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
70	2024	Houghton, Michigan	T.J. Bornhorst, E. Vye, P. Cobin, & J. Degraff
71	2025	Mountain Iron, Minnesota	A. Radakovich, A. Severson, E. Nowariak, S. Saari, A.C. Hirsch
72	2026	Thunder Bay, Ontario	P. Hinz and M. Puumala



Institute on Lake Superior Geology Goldich Medal

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	Allan MacTavish
2022	Terrence J. Boerboom
2023	Peter Hollings
2024	Suzanne W. Nicholson
2025	Robert Michael Easton
2026	William (Bill) Rose

Sam Goldich and the Goldich Medal

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

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

The initial Goldich Award was presented to Sam by G.B. Morey in 1979 and consisted of a large paper proclamation. For the actual medal, G.B. Morey consulted with the foundry on production details, while Dick Ojakangas and Jorma Kalliokoski worked on the design of the award, suggesting that it be given for "outstanding contributions to the geology of the Lake Superior region." Simultaneously, a committee of J.O. Kalliokosi, 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

Goldich Medal Guidelines

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

Preamble

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

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

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

Award Guidelines

1) The medal shall be awarded annually by the ILSG Board of Directors to a geologist whose name is associated with a substantial interest in, and contribution to, the geology of the Lake Superior region.

2) The Board of Directors shall appoint the Goldich Medal Committee. The initial appointment will be of three members, one to serve for three years, one for two years, and one for one year. The member with the briefest incumbency shall be chair of the Nominating Committee. After the first year, the Board of Directors shall appoint at each spring meeting one new member who will serve for three years. In his/her third year this member shall be the chair. The Committee membership should reflect the main fields of interest and geographic distribution of ILSG membership. The out-going, senior member of the Board of Directors shall act as liaison between the Board and the Committee for a period of one year.

3) By the end of November, the Goldich Medal Committee shall make its recommendation to the Chair of the Board of Directors, who will then inform the Board of the nominee.

4) The Board of Directors normally will accept the nominee of the Committee, inform the medallist, and have one medal engraved appropriately for presentation at the next meeting of the Institute.

5) It is recommended that the Institute set aside annually from whatever sources, such funds as will be required to support the continuing costs of this award.

Nominating Procedures

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

2) Nominations must be in writing and supported by appropriate documentation such as letters of recommendation, lists of publications, curriculum vita's, and evidence of contributions to Lake Superior geology and to the Institute.

3) Nominations are not restricted to Institute attendees, but are open to anyone who has worked on and contributed to the understanding of Lake Superior geology.

Selection Guidelines

1) Nominees are to be evaluated on the basis of their contributions to Lake Superior geology (sensu lato) including:

a) importance of relevant publications;

b) promotion of discovery and utilization of natural resources;

c) contributions to understanding of the natural history and environment of the region;

d) generation of new ideas and concepts; and

e) contributions to the training and education of geoscientists and the public.

2) Nominees are to be evaluated on their contributions to the Institute as demonstrated by attendance at Institute meetings, presentation of talks and posters, and service on Institute boards, committees, and field trips.

3) The relative weights given to each of the foregoing criteria must remain flexible and at the discretion of the Committee members.

4) There are several points to be considered by the Goldich Medal Committee:

a) An attempt should be made to maintain a balance of medal recipients from each of the three estates—industry, academia, and government.

b) It must be noted that industry geoscientists are at a disadvantage in that much of their work 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 Medal Committee

Serving through the meeting year shown in parentheses

Marcia Bjornerud, Academic member - Chair (2023-2026)

Robert Cundari, Government member (2024-2027)

Phil Larson, Industry member (2025-2028)

2026 Goldich Medal Recipient

William (Bill) I. Rose

Michigan Tech University, Houghton, Michigan

Citation for Goldich Medal Recipient

William I. Rose



It is my heartfelt honor to present the late William I. Rose (Bill) with the 2026 Institute on Lake Superior Geology's Goldich Medal. Bill has made tremendous contributions to the field of geoheritage and to increasing public understanding of the value and global importance of Lake Superior geology. This highly significant phase of his career, despite being retired for most of it, came from a genuine desire to encourage people to "get outside and love it", to increase their Earth science literacy, and to deepen their love of Lake Superior. This work is strongly aligned with the criteria and spirit of this distinguished award.

Bill served for 41 years as a professor of geology and volcanology at Michigan Technological University, working alongside scientists from around the world. He mentored countless graduate students, many of whom became close friends and respected colleagues. He took immense pride in their accomplishments and in his role advancing global volcano research. The volcanology program he helped build at Michigan Tech has become one of the world's leading departments, drawing students from around the globe and producing leaders in the field.

In his transition to retirement, Bill's research focus shifted to geoscience education and outreach. This new direction was rooted in his dedication to K-12 educators through projects like the Michigan Teachers Excellence Program (MiTEP) and other teacher professional development in the Keweenaw that focused on Lake Superior geology. Bill held teachers in very high esteem, recognizing them as multipliers and the heart of essential knowledge growth. Working with educators helped launch Bill's commitment to the field of geoheritage, inspiring the multitude of initiatives and learning resources that he developed for both formal and informal learners within the Keweenaw and Lake Superior regions. The thoughtful design of these programs yielded a vast inventory of Keweenaw geosites that could be used to explore the ways Lake Superior geology guides and influences our lives and culture.

Bill shared countless "geostories" with the Keweenaw community - an expression he coined, along with "geopoetry". His enthusiasm and energy never waned, and he never told a story the same way twice. His stories have made the global significance of Lake Superior geology accessible to people and have helped them to see how geology has shaped their own identity, history, and culture - the very essence of *geoheritage*. These stories resonated with people, inspiring a sense of pride rooted in the geology of our place and understanding just how fascinating Lake Superior geology is. His stories have inspired others to share their own geostories in the Keweenaw community, such as the Keweenaw National Historical Park and the Carnegie Museum.

Bill shared every geoheritage outreach resource he created for zero profit in order to help the Keweenaw thrive and to promote greater understanding of Lake Superior geology. Signage, books, geotours, boulder gardens, museum exhibits, concerts in the belly of an abandoned copper mine, geologic contributions to federal grant applications to support local conservation efforts, and the labyrinth Keweenaw Geoheritage website - all of these were given freely to support our community shift from an extractive economic past and to be forward-thinking and supportive of conservation, education, recreation tourism opportunities - all rooted in our rich geology. This generosity is punctuated by the family gift of Silver Island to the Keweenaw Land Trust - an example of Bill's strong advocacy for the protection of Lake Superior geosites and the promise of continued public access and education.

At the very heart of Bill's education and outreach work is *community*. Through this work he fostered relationships at the local, national, and global level. At the local level his efforts have united teachers, artists, scientists, outdoor recreation enthusiasts, conservation organizations, and tourists, all drawn together by a common curiosity of Lake Superior geology.

Nationally, Bill played a vital and formative role in shaping the vision for geoheritage in the United States, contributing to numerous workshops hosted by the U.S. Committee for Geoheritage and Geoparks and the Geological Society of America. At the global level, the Keweenaw has achieved recognition as a leader in the US geoheritage movement through Bill's pursuit of prestigious global designations. He spearheaded the designation of the Jacobsville Sandstone as one of the first Global Heritage Stone Resources in the world and the first in the United States, recognized by the International Union of Geological Sciences (IUGS) and the UNESCO's International Geoscience Program. Bill also promoted the Keweenaw as a strong candidate to become the first UNESCO Global Geopark in the United States. Within both global and national communities, the Keweenaw is largely viewed as a Geopark.

Bill's active membership with the ILSG served as a bridge between the professional geoscience community and the broader public. He was a first or co-author on numerous abstracts and field guides presented at ILSG meetings, including the Geological Field Trip, Eastern Isle Royale, Michigan (2013) and the Self-guided geological field trip to the Keweenaw Peninsula, Michigan (1994). Bill was visionary and big thinking; this is clearly reflected in his research and many contributions to the training and education of both geoscientists and the broader public. Bill's leadership in geoheritage and passion for education and outreach has deepened public understanding, appreciation, and desire to protect Lake Superior geology. I am brimming with gratitude to see Bill's service honored with the prestigious Goldich Medal award.

Submitted by Erika Vye

Great Lakes Research Center, MTU

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)

2025 Robert Bell (1841-1917)

In Memoria

William Ingersoll Rose (1944-2025)



William Ingersoll Rose, aged 81, died at his home in Eagle Harbor, Michigan, on July 17, 2025. Born in Detroit, Bill moved with his family at age five to New Mexico, where his love of rocks and the Earth began. Bill spent his childhood exploring the desert, riding horses, swimming in the neighborhood pool, and working at a local television station. New Mexico planted the seeds of a lifelong fascination with geology. After high school, Bill attended Dartmouth College, where he received Bachelor's and Ph.D. degrees. Professor Dick Stoiber, one of the pioneers of volcano research, recognized potential in the unpolished young man and offered him an opportunity to study volcanoes in Guatemala—a pivotal experience that would shape Bill's life.

Bill and his wife, Nanno, settled in Houghton in 1970 where Bill joined the faculty of Michigan Tech. Bill's work as a volcanologist took him across the globe and occasionally, Nanno and his two sons were able to come along. Following that first trip to Guatemala, Bill developed a deep passion for understanding volcanic eruptions. His adventures throughout Central America, along with his love of its people and landscapes, led him to speak Spanish and immerse himself in local cultures. He devoted himself to forecasting volcanic eruptions to help protect people living near volcanoes.

Bill served for 41 years as a Professor of geology and volcanology at Michigan Tech, working alongside scientists from around the world. He mentored countless graduate students, many of whom became close friends and respected colleagues. He took immense pride in their accomplishments and in his role advancing global volcano research. The volcanology program he helped build at MTU has become one of the world's leading departments, drawing students from around the globe and producing leaders in the field. He was instrumental in establishing signature programs such as the International Masters in Volcanology and Geotechniques and the Peace Corps Master's International program in Mitigation of Geologic Natural Hazards.

In retirement, Bill remained active and engaged. He developed geoheritage materials, led tours of Isle Royale and the Keweenaw Peninsula, and supported teachers, artists, kayakers, hikers, bicyclists, and tourists in learning

about the region's rich geological and cultural history. The Keweenaw has achieved recognition as a leader in the US geoheritage movement through Bill's pursuit of prestigious global designations. He spearheaded the designation of the Jacobsville Sandstone as one of the first Global Heritage Stone Resources in the world and the first in the United States, recognized by the International Union of Geological Sciences and the UNESCO's International Geoscience Programme. Bill also promoted the Keweenaw to become the first UNESCO Global Geopark in the United States. Due to his efforts, within both global and national communities, the Keweenaw is viewed as a Geopark by definition. Many of these geoheritage initiatives were presented at ILSG. His *Field Trip Guidebook for Isle Royale: Keweenawan Rift Geology*, co-authored with Justin Olson, is one of ILSG's Special Publications. For his remarkable work in the Lake Superior region, his teaching, supervisory and outreach efforts, and support of ILSG, Bill was posthumously awarded the Samuel S. Goldich Medal in 2026.

Bill treasured time with his children and grandchildren, especially during family vacations in Eagle Harbor. Always curious, he took the road less-traveled and delighted in whatever he discovered along the way.

Richard Wayne (Dick) Ojakangas (1932 - 2025)



Dr. Richard (Dick) Wayne Ojakangas died peacefully in his sleep on December 16, 2025 at the age of 93. Dick was born November 20, 1932, in Moose Lake, Minnesota, and grew up in Kettle River and Warba. He was very proud of his 100% Finnish heritage. After graduating from Grand Rapids High School, he enrolled as a business major at the University of Minnesota Duluth (UMD), intending to take over the family store in Warba after graduation. However, during his senior year, he took an introductory geology class from Dr. Robert Heller, and switched his major after the first lecture to geology. He joined the Reserve Officer's Training Corps because he felt it was his patriotic duty to serve his country. After graduation, he was assigned to the USAF base in Upper Heyford, England. He married Finnish beauty Beatrice (Peaches) Luoma and they moved to England within one week after their wedding. Due to his geological expertise, Dick was assigned to be a Petroleum Supply Officer, fueling jets with highly toxic JP4 jet fuel. After two years in the Air Force, he continued his studies in geology, earning a master's degree from the University of Missouri, and a PhD from Stanford University. Returning to Duluth, "Dr. OJ" enthusiastically taught geology at UMD for 38 years, where he was beloved by many hundreds of students. Dick was renowned as an entertaining and exceptional geology professor. He began each lecture with a Finn joke, and the punchlines were meticulously written on his calendar. His colleagues in the Geology Department were also his extended family and lifelong friends. He retired in 2002.

Dick wrote or collaborated on more than 60 scientific publications and several books, including the highly acclaimed Minnesota's Geology, and Roadside Geology of Minnesota. He was awarded the prestigious Horace T. Morse Award for Distinguished Teachers from the U of M, and received an honorary PhD from the University of Helsinki, Finland. A long-time member of the ILSG, Dick was awarded the Samuel S. Goldich Medal by the Institute in 1984. He was a fixture at annual meetings, leading field trips and giving presentations, either as himself or as one of his alter egos, like the Old Prospector or Herr Dr. Direktor Professor Wolfgang von Schlummerklutz from the World Panzerenkotklotzen Institute in Europe!

Dick was a passionate traveler and photographer, doing geological research on all seven continents. His work in Antarctica as part of the United States Antarctic Research Program resulted in having Mount Ojakangas being named after him. In India, he found evidence of the first Archaean glaciation ever discovered. In Finland, he and a colleague were the first to determine the direction that glaciers moved through northern Europe. As a world-respected geologist and an engaging, highly understandable speaker, he spread his enthusiasm for science by giving lectures on cruise ships from 1978 to 2017, feeding his obsession with traveling the world.

Curious and inquisitive, Dick entertained many interests and hobbies. He lived an active life - running several

Grandma's Marathon's (all without training) and cross-country skiing (doing the Birkebeiner 54 km race in Wisconsin many times, also without training). Dick was an avid mushroom hunter on all continents. His wife said that he could 'find mushrooms, whether they were there or not!'

Known for his generosity, humor, and warm personality, Dick made sure everyone felt included and always sought out strangers, who promptly became his friends. His trademark greeting "Hiya!" and farewell "Cheers!" are remembered fondly by his family and friends.

Paul Willard Weiblen (1927 – 2025)



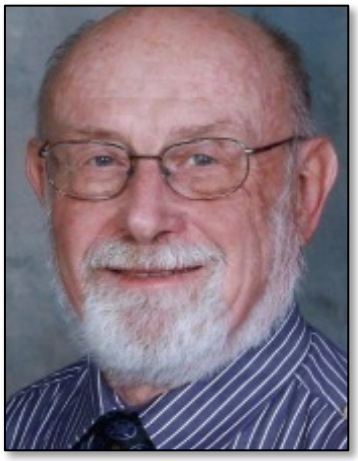
Professor Paul Willard Weiblen, 98 years old, died peacefully in the presence of family on Tuesday, December 23, 2025 in St. Paul, Minnesota. PW, to friends, colleagues and students, was born in Miller, South Dakota in 1927. After graduation from high school in 1945, he entered the U.S. Army. After military service he returned to college and earned a B.A. degree at Wartburg College in Waverly, Iowa (1950), and an M.A. in History at the University of Minnesota (1952). PW came into geology in a roundabout way. Apparently, he was in Istanbul, Turkey working as a travel agent for American Express when he encountered a geologist exploring the world for uranium deposits. Consequently, he returned to the University of Minnesota in 1959 to pursue geology. He focused on the metamorphism of the Paleoproterozoic Thomson Formation of east-central Minnesota for his Master's thesis (1962) and on the geology and petrology of the Bald Eagle intrusion of the Duluth Complex in northeastern Minnesota for his Ph.D. (1965). He stayed at the University in the Geology and Geophysics Department as an Assistant Professor (1965), Associate Professor (1969), Professor (1980), and Professor Emeritus (1997), teaching Minnesota geology and characterizing the minerals of the Duluth Complex with the Minnesota Geological Survey. He was hired specifically to organize and supervise the Department's new Electron Microprobe Laboratory (1965-1980) in the Space Science Centre. He also served as Curator of the petrology collection (1970-1997) and supervisor of the scanning electron microscope facility (1970-1997). Over his 32 years as a faculty member, Paul's analytical expertise and unbridled curiosity led him to pursue, and engage others, in many areas of research. The principal focus of his research was on the petrology and mineral deposits of the Duluth Complex. A highlight was a 1980 American Journal of Science paper, co-authored by Minnesota Geological Survey Chief Geologist G.B. Morey, that summarized the stratigraphy, petrology and structure of the Duluth Complex.

Another significant area of interest in Paul's career was lunar petrology. In the early 1970s, he and Edwin Roedder (USGS) confirmed the phenomenon of silicate liquid immiscibility by examining lunar glasses, and terrestrial basalts. In 1978-79, Paul served as lead curator of NASA's Washington, D.C. lunar sample collection.

The focus of Paul's research in the latter part of his academic career and into his retirement was building and promoting the electric pulse disaggregator (EPD, or "the Zapper"). He was introduced to the EPD and its inventor, Nikolay S. Rudashevsky, during a visit to Russia in 1991. Recognizing the potential of this instrument to create ultraclean mineral separates for a variety of applications, PW built and installed an EPD at U of M in 1992. He actively promoted it to other scientists who have used it to prepare samples for detrital zircon dating, mineral liberation analyses, and microfossil studies.

As a teacher and student advisor, PW was engaging, approachable, and deeply committed to his students. He routinely taught undergraduate and graduate level Igneous Petrology and Optical Mineralogy and offered hands-on classes on electron microprobe analysis. His annual petrology field trips up the Gunflint Trail were legendary. As a graduate advisor, he was open to letting his 11 PhD and 13 MS students develop their own thesis projects, with topics that included igneous petrology; volcanology; structural, metamorphic and field geology; geochemistry, mineralogy, petrography, and economic geology. A particular source of pride was that all but one graduate thesis was based on the geology of Minnesota. PW was awarded the Goldich Medal from the Institute on Lake Superior Geology in 2004 for his lifelong commitment to promoting geologic studies of Minnesota.

Ronald Parker Sage (1938 - 2026)



Ronald Parker Sage, 87, of Kingsford, MI, passed away peacefully on January 28, 2026, after a battle with numerous health conditions. Ron was born on August 4, 1938, in Pontiac, Michigan.

Ron graduated in 1960 with a BSc degree in geological engineering from Michigan Technological University in Houghton. While at MTU, Ron spent most of his free time collecting rocks and minerals in the copper and iron mining districts, earning him the nickname "Rocky". He was a student of Kiril Spiroff, the "Mad Russian". Ron held his Alma Mater in high esteem.

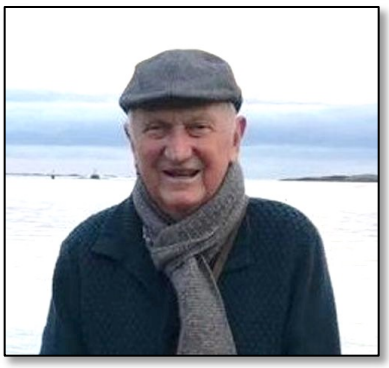
In the early 1960s, Ron worked for three years as an engineer for the Shell Oil Company in west Texas. His duties included well siting, well logging, well workovers, and other production-related activities. In 1966, Ron graduated with a Master's degree in Geology from the Colorado School of Mines. It was here that he was first exposed to alkalic rocks, his study topic and thesis being "Geology and Mineralogy of the Cripple Creek Syenite Stock, Teller County, Colorado". This led to employment with Anaconda American Brass Ltd to investigate Cu-Ni-PGE minerals in the Port Coldwell alkalic complex near Marathon, Ontario. During the summer of 1967, Ron searched for base metals in the Ely greenstone belt in northern Minnesota for Bear Creek Mining. It was in that year that he first met two other greats of Lake Superior geology, Ned Eisenbrey and Gene LaBerge. In 1969, Ron again worked for Anaconda American Brass Ltd., this time north of Lake Superior in the Schreiber greenstone belt, searching for gold and base metals.

In the fall of 1969, Ron joined the Ontario Geological Survey, his professional home for over 30 years. Ron's work for the OGS took him to many parts of the province, but never very far, and never for very long, from Lake Superior. He spent four years on a helicopter reconnaissance in Northern Ontario, then mapped the Slate Islands in Lake Superior, and next worked on a multi-year program to study alkalic rocks north of Port Coldwell along the northern extension of the Trans Superior Tectonic Zone and along the Kapuskasing Structural Zone. In 1978, Ron was assigned to the Michipicoten greenstone belt. Here he spent 10 years mapping Archean supracrustal rocks over approximately 540 square miles, with emphasis on the gold and base metal potential. In 1993, Ron was assigned to a province-wide program of kimberlite documentation to stimulate diamond exploration. Some of this work was again in the Michipicoten area, where diamond-bearing rocks had recently been discovered.

Despite his busy professional schedule, Ron was able to complete his PhD degree in 1986 for a thesis submitted to Carleton University in Ottawa, entitled "Alkalic Rock Complexes and Carbonatites of Northern Ontario, and their Economic Potential."

Ron was a long-time ILSG supporter, giving presentations, leading field trips and Co-Chairing the annual meetings in 1987, 1997 and 2006. In 1997, Ron was recognized for his many contributions when he received the Samuel S. Goldich Medal from the Institute on Lake Superior Geology.

Charles Edward (Charlie) Blackburn (1940 - 2026)



Charlie passed away on Friday March 6, 2026 at the Royal Jubilee Hospital, Victoria, BC.

Although he identified himself as a Welshman, having grown up in a small village near Cardiff, Wales, by an accident of fate during the early days of World War II, Charlie was actually born in Kidderminster, England. He went to Swansea University to complete his Bachelor of Science degree in geology. Charlie loved the summer field mapping excursions in Northern

Norway working towards his goal of becoming a professional geologist. Geology was always his passion and drawing maps, his gift.

Charlie emigrated from Wales to Canada and undertook a Master of Science degree at the University of Western Ontario, London, Ontario where he met his wife of sixty years Christine (nee Spence) – also a recent UK immigrant. It was love at first sight. The couple were married after a two-month courtship. They left for Italy where Charlie studied the metamorphic puzzle of the Seisia-Lanzo zone in the Valle d'Aosta at the University of Padua, Italy. He liked that his office was right opposite the Cappella Della Scrovegni – famous for its Giotto frescoes. His time in Italy left him with an enduring love for the people and culture there.

Charlie returned to Canada in 1969 and in 1970 accepted a position as a mapping geologist with the Ontario Geological Survey (OGS) in Toronto. As a field geologist, Charlie spent summers of his early career in the bush of northern Ontario and didn't see too much of his family. As the children grew, Charlie saw the need to be with his family more and so accepted the position of Resident Geologist in Kenora, Ontario. Many of his over 75 OGS publications resulted from his mapping efforts in the Archean greenstone belts of the western Wabigoon Subprovince and other areas in the Kenora District. He was the lead author of the seminal review of the Wabigoon in the 1991 compendium, *Geology of Ontario*. In the early 90's, he took a sabbatical from his Resident Geologist duties to return to mapping the Separation Lake area. Charlie retired from the OGS at age 60 after 30 years of service and, with his wife Christine, became co-founder of their consulting company, Blackburn Geological Services.

Charlie Chaired the 1985 ILSG annual meeting in Kenora and was on the organizing committee for the 2002 annual meeting, also held in Kenora. He delivered papers and chaired sessions at many ILSG meetings and led field trips to the Separation Rapids rare-element pegmatite field and other locations in the Kenora District, of which he had an encyclopedic knowledge due to his years of mapping and documenting mineral occurrences in the Superior Province.

Report of the Chair of the 71st Annual Meeting

Amy Radakovich, Allison Severson, Eric Nowariak, Aaron Hirsch, Stacy Saari

Mountain Iron, Minnesota

The 71st Institute on Lake Superior Geology (ILSG) was held May 14 to 17, 2025 in Mountain Iron, Minnesota at the Mountain Iron Community Center. The meeting was sponsored by the State of Minnesota's Iron Range Resources and Rehabilitation agency, Bayside Geoscience, the Geological Society of Minnesota, the Mesabi Range Geological Society, George Hudak Geosciences, PLLC, and the University of Minnesota Duluth's (UMD) Swenson College of Science and Engineering Earth and Environmental Sciences department, as well as individual contributors Roger Anderson, Allan MacTavish, Dave Dahl, Tom Erickson, and Barry Frey. The meeting was co-chaired by Amy Radakovich, Allison Severson, Eric Nowariak, and Aaron Hirsch of the Minnesota Geological Survey (MGS), and Stacy Saari of the Minnesota Department of Natural Resources (MNDNR). Patrice Cobin and Julie Stark of Michigan Technological University served as registrars for the meeting. The institute was attended by a total of 137 participants of which 25 were students. Generous donations from the following individuals helped provide a reduced registration and field trip price for students: Kate Clover, Jim and Isabel DeGraff, Tom Erickson, Tom Fitz, Aaron Hirsch, Paula Leier-Engelhardt, Bob Mahin, Vince and Susan Matthews, Jim Miller, Allison Severson, Mark and Lauri Severson, John Verhoeven, and Gerry White.

The 71st meeting consisted of two full days of technical sessions, which ran from Thursday morning, May 15th through Friday afternoon, May 16th. The meeting also held pre-and post-meetingfield trips on May 14th and May 17th. A total of 51 presentations were subdivided into 8 technical sessions; 6 technical sessions for 26 oral presentations (of which 1 was presented by a student), and 2 poster technical sessions with a total of 23 poster presentations (of which 14 were presented by students). The chairs continued the previous meeting's precedent of including two poster sessions to allow both attendees and judges more time to review the posters. The first

presentation of the technical sessions was given by Mark Smyk (OGS - retired; Goldich Medalist in 2005) who gave the citation for Robert Bell, the 2025 Pioneer of Lake Superior Geology. Bell is the 6th person to be recognized for their contributions to Lake Superior Geology prior to the initiation of the ILSG. The technical sessions of the 71st annual meeting of ILSG were published in 2025 as Part 1 of Proceedings Volume 71 (95 pages).

Five Doug Duskin Best Student Paper Awards were given for student oral and poster presentations as judged by the 2024 Student Paper Awards Committee chaired by Aaron Hirsch (MGS). PhD student poster awards were given to Zsusanna Allerton and Madelyn Banks. Undergraduate student poster awards were given to Celia Cortopassi and Lyndsie Vickers. Omar Khali Droubi received the best oral presentation award.

The 71st ILSG also awarded 12 Eisenbrey Student Travel and Participation Awards to help defray the cost of travel to and participation in the ILSG professional meeting for undergraduate and graduate students. The awardees were Drew Casper, Haley Johannesen, Mary Elizabeth Shalifoe, Linsey Hula, Omar Khalil Droubi, Samara Gries, Renee Jeutter, Aidan Kwiatkowski, Celia Cortopassi, Lyndsie Vickers, Zsuzsanna Allerton, and Bekah Thomson.

As usual, field trips were a highlight of the 71st ILSG. Mountain Iron's close proximity to exposures of Archean, Paleoproterozoic, and Mesoproterozoic rocks made it a prime location to run numerous excellent field trips. The meeting offered 8 field trips which included 4 pre-meeting trips on Wednesday May 14, and 4 post-meeting trips on Saturday May 17. Seven field trips focused on the varied Precambrian geology of northeastern Minnesota, and one trip highlighted the unique Quaternary features of the region. Seven of the eight field trips were able to run, with one cancelled due to active wildfires in the field trip area. The remaining 7 field trips were well attended. There were 130 registrants for the field trips, excluding leaders, representing over 100 different individuals (some registrants took multiple trips).

Pre-meeting trip 1 was a "Transect through the Quetico subprovince of northern Minnesota," led by Eric Nowariak (MGS) and Mark Jirsa (MGS-retired). Pre-meeting trip 2 was led by Mark Severson (Natural Resources Research Institute, Teck - retired), Cullen Phillips (New Range Copper Nickel), and Kevin Boerst (Twin Metals Minnesota) and highlighted "Drill Core from three Cu-Ni deposits of the Duluth Complex." Pre-meeting trip 3 asked the question "How do you make iron and/or manganese in Proterozoic iron formation?" and was led by Alex Steiner and Dean Peterson (Big Rock Exploration) and Latisha Brengman (University of Minnesota Duluth [UMD]). Pre-meeting trip 4 was led by George J. Hudak (University of Minnesota; George Hudak Geosciences, P.L.L.C) and Zsuzsanna Allerton and Annia Fayon (University of Minnesota) and highlighted "New geological insights into the genesis of iron ores at Lake Vermillion-Soudan Underground Mine State Park."

Post-meeting trip 5 traveled to numerous "Neoarchean alkalic intrusions in the Wawa and Quetico subprovinces" and was led by Terry Boerboom (MGS-retired) and Amy Radakovich (MGS). Mark (NRRI, Teck - retired), Allison (MGS), and Lauri (earth science teacher - retired) Severson planned to lead post-meeting trip 6 focused on a "Unique Keweenawan inclusion (Colvin Creek) in the Duluth Complex." However, the trip was cancelled due to wildfire conditions, and participants were invited to join other trips or receive a refund. Post-meeting trip 7 led by Dean Peterson (Big Rock Exploration) and George Hudak (University of Minnesota; George Hudak Geosciences, P.L.L.C) visited numerous "Classic outcrops of northeastern Minnesota" Field trip 8 was led by Phil Larson (Vesterheim Geoscience, PLC), Andrew Breckinridge (University of Wisconsin - Superior), and Howard Mooers (UMD) and focused on Glacial Lake Norwood and the Koochiching Lobe." Field trip guides were published in 2025 as Part 2 of the Proceedings Volume 71 (200 pages).

A catered welcome reception was held at the Mountain Iron Community Center on Wednesday evening, May 14, after all of the pre-trips returned. The event was well attended, and offered a chance for meeting attendees to reconnect with colleagues and friends prior to the start of technical sessions. Steve Solkela provided entertainment for a portion of the evening.

The annual ILSG social and banquet were hosted at the Mountain Iron Community Center on Thursday evening, May 15, 2025. Ninety-three people were in attendance at the sold-out banquet. After introductions

and announcements, Mark Puumala announced the location of the 2026 meeting as Thunder Bay, Ontario. The program continued with ILSG awarding the prestigious Goldich Medal to the very deserving Robert Michael (Mike) Easton (Ontario Geological Survey), who unfortunately could not be present at the meeting. Wouter Bleeker (Geological Survey of Canada) provided the citation for Mike, highlighting Mike's long tenure with the OGS, his impressive publication record, and his contributions to ILSG. Another highlight of the banquet was the keynote presentation by Pete Kero, P.E., Senior Environmental Engineer with Barr Engineering Co and visionary behind the award-winning Redhead Mountain Bike Park in Chisholm, Minnesota. His fascinating talk entitled "Mine to Mountain Bike Mecca: The story of the Redhead Mountain Bike Park" detailed the transformation of ten idled open pit iron mines in northeast Minnesota into a world-class recreation destination for mountain biking, hiking, and paddling. Kero fielded many questions from the engaged audience and sold and autographed his book Minescapes: Reclaiming Minnesota's Mined Lands after the keynote presentation, which ended the banquet program.

The Institute's Board of Directors met on Thursday May 15, 2025 to discuss ILSG business and approve the 2026 meeting location. The meeting was attended by Amy Radakovich (Board Chair and Assistant Treasurer), Ted Bornhorst, Carsyn Ames, Peter Hollings (Secretary), and Mark Jirsa (Treasurer). Guests at the meeting were the meeting co-chairs Allison Severson, Eric Nowariak, Aaron Hirsch, and Stacy Saari and also Mark Puumala, the Chair of the proposed 2026 Thunder Bay meeting (approved by the board - see below). Michael Easton was unable to attend.

Institute's Board of Directors meeting notes were taken by ILSG Secretary Hollings, which are as follows:

1. Accepted report of the Chairs for the 70th ILSG, as published in the Proceedings volume, and minutes of last Board meeting, May, 2024 (Hollings).

2. Received and discussed 2024-2025 ILSG Financial Summary (Jirsa/Radakovich). Final approval tabled for Email vote after necessary revisions are made to balances as listed

3. Received, discussed, and accepted 2024-2025 report of the Secretary (Hollings).

4. Approved Alli Severson as on-going ILSG Board member and Pete Hinz and Mark Puumala as co-Chairs.

5. Discussed and approved appointing Amy Radakovich as the Institute Treasurer. This was subsequently approved by the Membership. Mark Jirsa was thanked for his 31 year service to the Institute.

6. Discussed and approved replacing Dean Peterson as the "member from industry" on Goldich Committee (end of term 2025) with Phil Larson.

7. Approved Thunder Bay as the site for the 72nd annual ILSG meeting. The meeting will be Chaired by Pete Hinz and Mark Puumala with tentative dates of May 19 to 23.

8. A number of future meeting locations were discussed including Grand Marais (Jim Miller), Baraboo (Esther Stewart & Carsyn Ames) and Marquette.

9. The revised Eisenbrey guidelines were discussed and approved with edits. Changes expand the list of expenses which are eligible for reimbursement from the Eisenbrey award (ex: registration fees, meals, lodging, and transportation are all now included)

10. There was discussion over the format and page limits for the abstracts. It was agreed that the two page limit would be maintained.

11. The cost of hosting the meeting registration through MTU was discussed. MTU currently charges 12% of the total registration sales as their fee. It was agreed that the hosts of each meeting would evaluate possible hosting options and pick the one that worked best for them. Puumala indicated that next year the hosts would likely go with a Canadian registrar so that registration fees could be charged in Canadian dollars

12. The cost of printing the Proceedings and Field Guide volumes was discussed. It was agreed that future meeting Chairs would explore the possibility of making the full printed volumes a paid option for participants

and providing only the guides for individual trips.

13. The ongoing storage of ILSG poster boards and easels was discussed. MTU has stored them for the last ~10 years but can no longer offer to do that. Boards and easels were stored for the past year at the Minnesota Geological Survey, but there is no room for permanent storage there. It was suggested that the storage and transport of the posters and easels become the responsibility of the meeting hosts, such that after each ILSG meeting, the boards and easels would leave with the host of the following year's meeting. This way storage and transport costs can be built into the next year's meeting costs. Thunder Bay hosts do not need boards next year and did not want to take them across the border given recent border crossing issues. It was suggested that ILSG perhaps have two sets of boards and two sets of easels - one that resides in Canada and one that resides in the USA. Carsyn Ames volunteered to store the boards and easels at the Wisconsin Geological Survey for the next year, delaying the need to make a final decision.

Our large, five-person committee allowed us to divide-and-conquer the innumerable tasks to make The 71st annual ILSG meeting a great success. We were proud to continue the long-standing tradition of bringing people together from many states and provinces to share and learn about the fascinating geology of the Lake Superior region, both in the meeting and 'on the rocks.' The co-chairs would like to thank the many people and organizations who made the meeting possible, including the Mesabi Range Geological Society and UMD students who ran the registration table and helped with merchandise sales, and the numerous individuals who offered to drive rental or personal vehicles on our fieldtrips. The Sawmill supplied all meeting and field trip food, Caribou provided coffee and tea for the field trips, and Peplinjack's Bakery supplied the delicious field trip pastries. Lastly, we would like to thank the numerous generous donors who donated hundreds of rock and mineral specimens, books, and maps that made up the biggest and most profitable book sale and silent auction in ILSG memory. The sale and auction netted a total of approximately $4,500 which will be used to fund student participation at subsequent meetings. We look forward to seeing everyone next year in Thunder Bay!

Respectfully submitted,

Amy Radakovich, Allison Severson, Eric Nowariak, Aaron Hirsch, and Stacy Saari

Co-chairs, 71st Institute on Lake Superior Geology

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 2025, 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:

Kathryn Akin, University of Minnesota- Twin Cities

Alyssa Hellrung, University of Wisconsin

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.

2026 Student Paper Awards Committee

Emily Smyk - Bayside Geoscience

Justin Jonsson - Ontario Geological Survey

Nick Swanson-Hysell - University of Minnesota

Board of Directors

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

Peter Hinz and Mark Puumala, Co-Chairs (2026-2029) - Ontario Geological Survey, Retired

Alli Severson (2025-2028) - Minnesota Geological Survey

Ted Bornhorst (2024-2027) - Michigan Tech, Houghton

Carsyn Ames (2023-2026) - Wisconsin Geological & Natural History Survey, Madison

Amy Radakovich, Treasurer (2025-2028) - Minnesota Geological Survey

Peter Hollings, Secretary (2024-2027) - Lakehead University

Local Committee

Chairs

Peter Hinz and Mark Puumala - Ontario Geological Survey, Retired

Organising Committee

Robert Cundari - Ontario Geological Survey, Thunder Bay, Ontario

Al MacTavish - Thunder Bay, Ontario

Mark Smyk - Lakehead University, Thunder Bay, Ontario

Pete Hollings - Lakehead University, Thunder Bay, Ontario

Jim Miller - Thunder Bay, Ontario

Field Trip Leaders and Guidebook Authors

Field trips have been the mainstay of the ILSG since its inception 72 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.

Trips 1 & 4: Classic" Geological Sites in the Thunder Bay Area - Mark Smyk (Lakehead University) and Mark Puumala (Geological Consultant)

Trip 2: Geology of the Quetico Subprovince and Shebandowan greenstone belt north of Thunder Bay - Riku Metsaranta and Gaetan Launay (Ontario Geological Survey)

Trip 3: Geological assemblages, regional structural framework and tectonic evolution of the Neoarchean Shebandowan greenstone belt - Dorothy Campbell, Justin Jonsson and Vittoria D'Angelo (OGS Resident Geologist Program)

Trip 5: Archean Geology and Metallogeny of the Rainy Lake Wrench Zone - K. Howard Poulsen (Geological Consultant)

Trip 6: Amethyst Deposits of Thunder Bay - Steve Kissin (Lakehead University) and Greg Paju (OGS Resident Geologist Program)

Technical Program

Wednesday May 20 (Parking Lot G14, Lakehead University)

8:00 a.m. ***Field Trip 1:*** "Classic" Geological Sites in the Thunder Bay Area

Leaders: Mark Smyk and Mark Puumala

8:00 a.m. ***Field Trip 2:*** Geology of the Quetico Subprovince and Shebandowan greenstone belt north of Thunder Bay

Leaders: Riku Metsaranta and Gaetan Launay

8:00 a.m. ***Field Trip 3:*** Geological assemblages, regional structural framework and tectonic evolution of the Neoarchean Shebandowan greenstone belt

Leaders: Justin Jonsson and Vittoria D'Angelo

5:00 p.m. ***Return of Trips 1-3***

4:00 p.m. - 8.00 p.m. ***Registration*** *(Faculty Lounge, Lakehead University)*

6:00 p.m. - 9.00 p.m. ***Ice Breaker Social, Poster Setup and Core Shack*** *(Faculty Lounge, Lakehead University)*

Thursday May 21

7:30 a.m. - 4:00 p.m. ***Registration*** *(Faculty Lounge, Lakehead University)*

8:30a.m. - 9:00 a.m. ***Introductory Remarks (****Room UC0050, Lakehead University****)***

Technical Session I

NOTE: Asterisk * denotes a student eligible for a Best Student Paper Award

Session Chairs: Mark Puumala and **Jim Miller**

9:00 a.m. **Stephan, T., Phillips, N., and Hollings, P.**
Timing and conditions of magmatism, metamorphism, and strain partitioning in the western Shebandowan Greenstone Belt (Superior Province)

9:20 a.m. **MacDonald, P., Hastie, E., Malegus, P., Kamo, S., Hamilton, M. and Marsh, J.**
Implications of recent geochronology on the regional geology and timing of gold mineralization in the Red Lake greenstone belt, Ontario

9:40 a.m. **Hollings, P., Vrzovski, J., Cooke, D. and Gorner, E.**
Using epidote and chlorite mineral chemistry to extend the alteration footprint around the Hemlo Au deposit, N. Ontario

10:00 a.m. - 10:30 a.m. ***Coffee Break, Poster Session and Core Shack***

10:30 a.m. **Tiitto*, H., Phillips, N., and Stephan, T.**
Deformation processes in a mid-crustal strike-slip shear zone: Insights from the Archean Quetico Shear Zone, Superior Province, Canada

10:50 a.m. **Sheshnev*, V., Hollings, P., Tolley, J., Angombe, M., Deller, M. and Stern, R.**
Whole Rock and Mineral Chemistry of the Eagle's Nest Intrusion, McFaulds Lake Greenstone Belt, Ontario, Canada: Insights into the Origin and Paragenesis

11:10 a.m. **Carlton*, K., Tikoff, B. and Nachlas, W.**
An introduction to the northwestern Huron Mountains of the Upper Peninsula, Michigan: field relations and preliminary structural interpretations

11:30 p.m. - 1:00 p.m. ***Lunch Break, Poster Session and Core Shack (ILSG Board Meeting by invitation)***

Technical Session II

Session Chairs: Esther Stewart and **Phil Larson**

1:00 p.m. **Salerno, R., Cannon, W. F., Thompson, J., Souders, A., Vervoort J. and Hillenbrand, I.**
Reassessing variations in metamorphism across the Penokean orogen in Northern Michigan: Part 1, new Pressure-Temperature-Time-Deformation constraints

1:20 p.m. **Cannon, W. F., Salerno, R., Drenth, B. and Bedrosian, P.**
Reassessing variations in metamorphism across the Penokean orogen in Northern Michigan: Part 2, Reinterpreting metamorphic nodes

1:40p.m. **Hirsch, A.**
Can we improve the bouguer gravity resolution in the Cuyuna Range? Increasing gravity measurements in a region of high gravity station density.

2:00 p.m. - 2:30 p.m. ***Coffee Break, Poster Session and Core Shack***

2:30 p.m. **Allerton, P. and Hudak, G.**
Characterization of hematite ore from former Ely mines, NE Minnesota

2:50 p.m. **Steiner, R.A., Watson, N., Riley, J., Hammer, M., Thole, J., Feinberg, J., Sandri, H. and Savage, B.**
Oxidation to Ores: Petrological Insights into Supergene Manganese Enrichment at the Emily Deposit, Minnesota

3:10 p.m. **Hagedorn, G.**
Ice flow history, surficial geology, and till composition of Georgia Lake area, northwestern Ontario

Poster Session

3:30 - 5:00 p.m.

6:00 p.m ***Annual Banquet and Award Presentation*** *(Faculty Lounge, Lakehead University)*

Announcement of 73rd Annual Meeting Location

2026 Goldich Award Presentation to Bill Rose

2026 Quiz night

Meeting participants not registered for the banquet are welcome to attend the quiz night

Friday May 22

9:00 a.m. - 12:00 p.m. ***Registration***

Technical Session III

Session Chairs: Shannon Zurevinski and **Therese Pettigrew**

8:30 a.m. **Beyer, S., Cutts, J., Hnatyshin, D., Powell, J., Camacho, A., Cawood, T. and Drever, G.**
Preliminary geochronology of lithium pegmatites and host rocks, Archean Superior Province, northwestern Ontario

8:50 a.m. **Quigley, A., Mahin, R., and Gamet, N.**
Critical Mineral Potential of the Watersmeet Gneiss Dome, MI USA

9:10 a.m. **Bleeker, W. and Wodicka, N.**
Improved Precision and Better Accuracy: SHRIMP-II Detrital Zircon Analysis of Samples Across the Stratigraphy of the Midcontinent Rift

9:30 a.m. **Easton, R.M. and Kamo, S.**
The Badgerow complex, a Midcontinent Rift-related REE-Zr-rich peralkaline intrusion in the Grenville Province near Verner, Ontario

9:50 a.m. - 10:20 a.m. ***Coffee Break, Poster Session and Core Shack***

10:20 a.m. **Nitescu, B., Torres, D., and Gaona, J..**
Models of the regional gravity and magnetic anomalies associated with the Nipigon Embayment

10:40 a.m. **Bain, W. and Hollings, P.**
Coeval silicate melt and PGE-bearing salt melt inclusions in the Thunder and Seagull intrusions, Ontario: An overview of evidence and data processing challenges

11:00 a.m. **Drost, A. and Heggie, G.**
A new look at the Seagull mafic-ultramafic Intrusion and potential hydrogen and helium accumulations

11:20 a.m. **Swanson-Hysell, N., Zhang, Y., Mohr, M. and Schmitz, M.**
Linking the Southwestern Laurentia large igneous province and rapid Duluth Complex emplacement through mantle plume dynamics

11:40 p.m. - 1:00 p.m. ***Lunch Break, Poster Session and Core Shack***

Technical Session IV

Session Chairs: Wouter Bleeker and **Peter Hinz**

1:00 p.m. **Smith, J., Kaski, K., Tschirhart, V. and Enkin, R.**
Integrating petrophysical data with full tensor magnetic gradiometry for improved interpretation and modelling of remanently magnetized intrusions in the Midcontinent Rift

1:20 p.m. **Peterson, D., Steiner, A., Sweet, G. and Boucher, C.**
Physical Magmatic System Interpretation of the Marathon Cu-Pd Deposit, Coldwell Complex, Ontario

1:40 p.m. **Smyk, E., Dolega, S., Churchley, J. and Flank, S.**
Optimizing data collection for better geological interpretations and adding value to your project

2:00 p.m. **Lizzadro-McPherson, D., Vye, E., Degraff, J., and Rose, W.**
Interactive Geospatial Geoheritage: Efforts to Support Place-based Exploration and Digitally Preserve Keweenaw's Geoheritage

2:20 p.m. - 2:50 p.m. ***Coffee Break, Poster Session and Core Shack***

2:50 p.m. **Degraff, J., Hiltunen, L., Lafreniere, D., Lizzadro-McPherson, D., Vye, E., Cowling, B., Bornhorst, T. and Rose, W.**
Digital Preservation and Enhanced Utility of Exploration Core Descriptions from the Keweenaw Copper District, Michigan: Progress toward a Map-based Web Portal

3:10 p.m. **Stone, A., Lizzadro-McPherson, D. amd Vye E.**
Rocks and Roots: The Role of Geoheritage in Biodiversity Stewardship

3:30 p.m. **Smyk, M., Hodge, J. and Robillard, C.**
Pukaskwa Redux: Revisiting and Reconnecting with Superior's Wild North Shore

3:50 p.m **Presentation of Best Student Paper Award and Eisenbrey Awards**

5:00 p.m. ***Field Trip 5:*** Archean Geology and Metallogeny of the Rainy Lake Wrench Zone

Leader: Howard Poulsen

Parking Lot G14, Lakehead University

Poster Presentations

Akin*, K. and Swanson-Hysell, N.
Constraining the 3-D Geometry of the Duluth Complex, MN, Using Magnetic Fabrics and Paleomagnetic Data

Angombe, M., Phillips, N., Hollings, P., Stephan T., Sheshnev, V., Deller, M. and Smith, A.
Decoding Shear Zone Evolution in the McFaulds Lake Greenstone Belt, Ontario: Constraints on Crystal-Plastic Deformation and Timing from in-situ Titanite U–Pb Thermochronology

Bilboe*, M., Zurevinski, S. and Conly, A.
Quartz Trace Element and TEM Analysis of Selected Economic LCT Pegmatites

Buchholz, T., Falster, A. and Simmons, W.
Update to: a complex F-rich alkalic pegmatite in the pyroxene syenites of the Stettin Complex, Wausau Complex, Marathon County, Wisconsin

Chaisson*, A., Smyk, M. and Zurevinski, S.
Petrography and Geochemistry of the Mound Lake Pluton, Northwestern Ontario

Duffy*, P., Brengman, L. and Eyster, A.
Integrated X-Ray Diffraction and Petrography Document Carbonate Mineral Heterogeneity and Hematite Mineralization in the Upper Biwabik Iron Formation, MN

Ellison*, K ., Cisneros, J., Eyster, A. and Brengman1, L.
Comparing mineralogy along a surface to depth transect of the ~2.7 Ga North Limb Soudan Iron Formation, NE Minnesota

Erickson, S., Fayon, A., Allerton, Z. and Hudak, G.
Middle school virtual field trip lessons materials for Archean formations of Lake Vermilion-Soudan Underground Mine State Park

Gilberg*, N., Fralick, P. and Li, Z.
Geochemical Constraints on Mn Cycling in the Paleoproterozoic Gunflint Formation

Gosai*, M., Fralick, P. and Li, Z.
Modified Sequential Iron Extraction Method for Analyzing Rare Earth Elements in Banded Iron Formations

Grauch, V. and Heller, S.
Time-to-depth conversion of seismic-reflection data from eastern Lake Superior and implications for the eastern arm of the Midcontinent Rift

Harding*, M. and Hollings, P.
Geochemistry, Petrogenesis, and Mineralization of the Makwa Deposit, Bird River Sill

Hellrung*, A., Droubi, O., Ruggles, C. and Bonamici, C.
Using Anisotropy of Magnetic Susceptibility and U-Pb Geochronology from the Bush Lake Granite, Florence County, WI to Understand Post-Penokean Continental Growth

Jonsson, J. and Li, Z.
Petrographic Study of Granular Iron Formation in the Gunflint Formation: Evidence for Well-Oxygenated Surface Waters

Marin López*, V., Brengman, L., Eyster, A., Mitchell, J., Pu, X., Mangum, J. and Walker, P.
Quantitative analysis of iron mineral composition and crystal sizes in the contact metamorphosed Biwabik iron formation and the Bald Eagle intrusion, NE, MN, USA

Nowak*, R., Deering, C. and Essig, E.
Origin of the World-Class Eagle, Eagle East, and Tamarack Ni-Cu-PGE Deposits and comparative analysis with other Midcontinent Rift- and Siberian Trap-related intrusions

Nowariak, E. and Severson, A.
Bedrock Geology of the Ericsburg NW, Ericsburg NE, Ray SW, and Ray SE Quadrangles, St. Louis and Koochiching Counties, Minnesota

Paliewicz, C., Post, S. and Thakurta, J.
Petrographic, geochemical, and mineralogical analyses of manganiferous iron formations and associated lithologies at the Cuyuna Range, central Minnesota

Saini-Eidukat, B., Chittick, S. and Nesheim, T.
Current geologic and geophysical research on the Precambrian basement of eastern North Dakota, USA

Stewart, E., McNall, N., Hart, D., Ames, C., Chase, P., Stewart, E. and Graham, G.
Subsurface mapping of the late Ordovician Maquoketa Group in eastern Wisconsin using airborne electromagnetic and well data

Tolley, J. and Hollings, P.
Variations in Olivine Major Element Composition Across the Midcontinent Rift System

NOTE: Asterisk * denotes a student eligible for a Best Student Paper Award

Saturday May 23 (Parking Lot G14, Lakehead University)

8:00 a.m. ***Field Trip 4:*** "Classic" Geological Sites in the Thunder Bay Area

Leaders: Mark Smyk and Mark Puumala

8:00 a.m. ***Field Trip 6:*** Amethyst Deposits of Thunder Bay

Leaders: Steve Kissin and Greg Paju

5.00 p.m. ***Return of Trips 4 & 6***

Sunday May 24 (Parking Lot G14, Lakehead University)

5.00 p.m. ***Return of Trip 5***

Constraining the 3-D Geometry of the Duluth Complex, MN, Using Magnetic Fabrics and Paleomagnetic Data

AKIN, Kathryn[1] and SWANSON-HYSELL, Nicholas[1]

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The Midcontinent Rift developed within the interior of Laurentia during a period of extension and magmatism from 1109 Ma to 1084 Ma (Swanson-Hysell et al., 2019). Emplaced during the development of the Midcontinent Rift, the Duluth Complex is interpreted as the second-largest exposed mafic intrusive complex on Earth. The Duluth Complex is composed of an anorthositic series and a layered series of gabbro and troctolite cumulates (Figure 1; Miller et al., 2002). Many studies have been conducted on the geology, mineralization, structure, timing, and mechanisms of emplacement of the Duluth Complex and nearby Beaver Bay Complex and North Shore Volcanic Group, but there is still some uncertainty surrounding the thickness, and therefore overall volume, of the Duluth Complex.

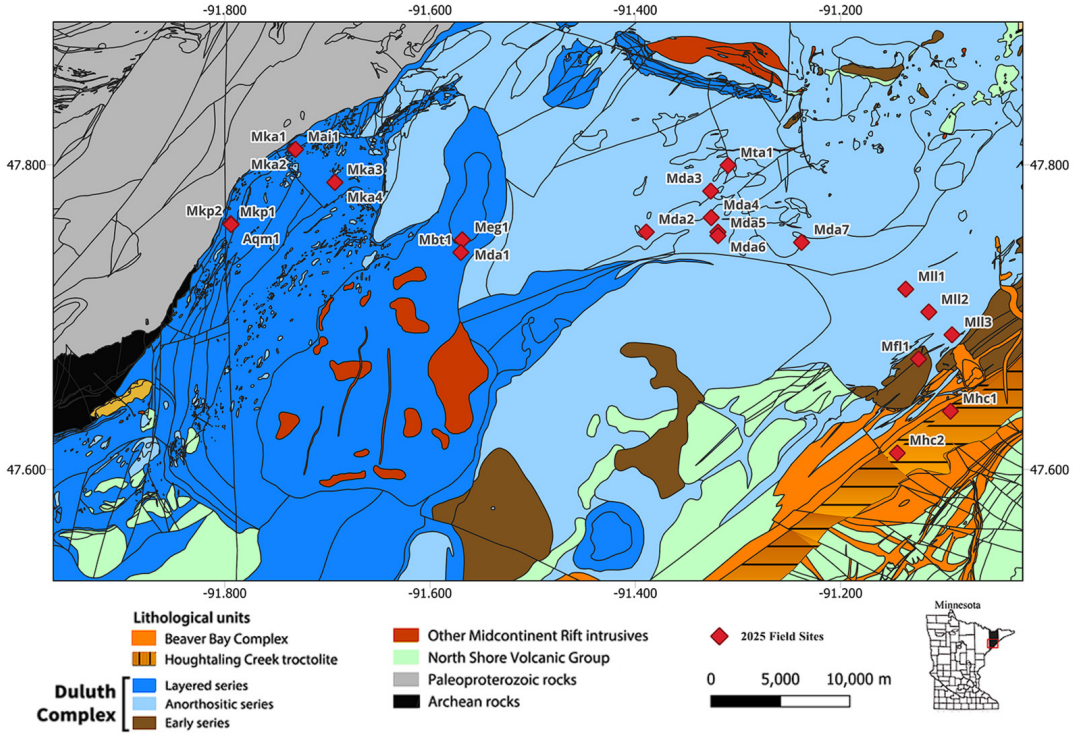


Figure 1: Map of the Duluth Complex field location in northeastern Minnesota. Red diamonds represent sampling locations from the August 2025 field season. Geological map data from Bauer (2022).

The tilt of the Duluth Complex is not well-constrained in the anorthositic series, given the absence of macroscopic igneous foliation, so this research is focused on developing data on the magnetic fabrics of the Duluth Complex along a transect to constrain the igneous foliation and to use these data to develop new estimates of the tilt and thickness of the intrusion. Anisotropy of magnetic susceptibility (AMS) is sensitive to changes in mineral alignment and, therefore, is used to constrain igneous foliation, especially in samples that do not display an obvious macroscopic fabric in the field (Schmidt et al., 2007). Remanent magnetization data collected and compared with the expected directions of contemporaneous volcanics can also provide further insight into tilt.

Together, the new susceptibility and remanence data will provide important petrophysical information for interpreting upcoming USGS aeromagnetic surveys currently being flown in

northeastern Minnesota. New constraints on the intensity of remanent magnetization and its ratio with susceptibility (the Koenigsberger ratio) will be added to the Rock Properties database maintained by the Minnesota Geological Survey (Chandler et al., 2011).

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Miller, J.D., Green, J.C., Severson, M.J., Chandler, V.W., Hauck, S.A., Peterson, D.M., and Wahl, T.E., 2002, RI-58 Geology and mineral potential of the Duluth Complex and related rocks of northeastern Minnesota:, https://hdl.handle.net/11299/58804.

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Characterization of hematite ore from former Ely mines, NE Minnesota

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[2]Earth and Environmental Sciences, University of Minnesota, Duluth, MN 55812, USA

[3]George Hudak Geosciences P.L.L.C., Duluth, MN 55804, USA

The hematite ore deposits located in the Vermilion Range in Ely, northeastern Minnesota, represent some of the highest-grade iron ores ever mined in the United States. These deposits occur within Neoarchean (~2.7 Ga) Algoma-type banded iron formations (BIFs) in the Ely Greenstone belt which is dominantly composed of greenschist facies metamorphosed volcanic, sedimentary and intrusive rocks. The ore bodies, exploited in underground mines such as the Zenith, Pioneer, Sibley and others, consist of steeply dipping, tabular to lens-shaped masses of massive hematite that replace jaspilitic BIF. These bodies are enclosed within greenstone wall rocks and are often localized along brecciated zones within a complex regional fold structure.

Machamer's 1968 study of the Zenith mine details the textural varieties of high-grade hematite ore formed by hypogene hydrothermal replacement of jaspilitic BIF. His petrographic and field descriptions identify five prominent ore textures that reflect stages of replacement, brecciation, cementation, and zoning. The characterization and documentation of these five textures at the Pioneer and Sibley mines are the focus of this research. Hematite ore samples utilized for this study were obtained from the Minnesota DNR Hibbing Core Library. Zenith mine ore samples were not available for re-analysis.

Ore texture types described are consistent with the nomenclature developed by Machamer (1968). Type 1, the most abundant texture, is a dense, uniform material composed almost entirely of crystalline hematite, representing the primary massive replacement ore (Figure 1A). Type 2 texture consists of brecciated fragments of type 1 ore cemented by a later generation of secondary crystalline hematite, which commonly contains minute vugs lined with small hematite crystals and appear in a reticulated pattern resembling a boxwork (Figure 1B). Type 3 texture is similar to type 2 but features a cement composed dominantly of carbonate minerals (primarily ankerite or siderite) rather than hematite (Figure 1C). Type 4 texture is composed largely of carbonate minerals; it may contain fragments of earlier type 1 hematite material as well as earlier-formed carbonates, reflecting deeper or more advanced carbonate replacement (Figure 1D). Type 5 texture consists principally of magnetite with variable amounts of carbonate minerals, hausmannite (manganese oxide, Mn_3O_4) and pyrite; this type is generally non-merchantable due to its lower iron content or higher sulfur. The great bulk of the ore mined at Zenith (and similarly at Sibley mine) consisted of types 1 and 2, with lesser amounts of type 3. Many of the types preserve faint layering parallel to the ore-body walls, produced by alternating textural variations in hematite or by interlayering of massive hematite with more porous hematite or carbonates. Texture types 4 and 5 become more abundant with depth in the Zenith mine (Machamer, 1968).

These five textures record a progressive hypogene upgrade of BIF to hematite ore that is generally similar to what has been observed in recent research at the Soudan mine (Allerton, 2025; Allerton et al., 2025). Upgrade processes include initial silica replacement by massive hematite, followed by repeated brecciation and multi-stage cementation, and downward transition to carbonate assemblages, producing the dense, low-impurity ore that made the Ely deposits economically significant (Machamer, 1968).

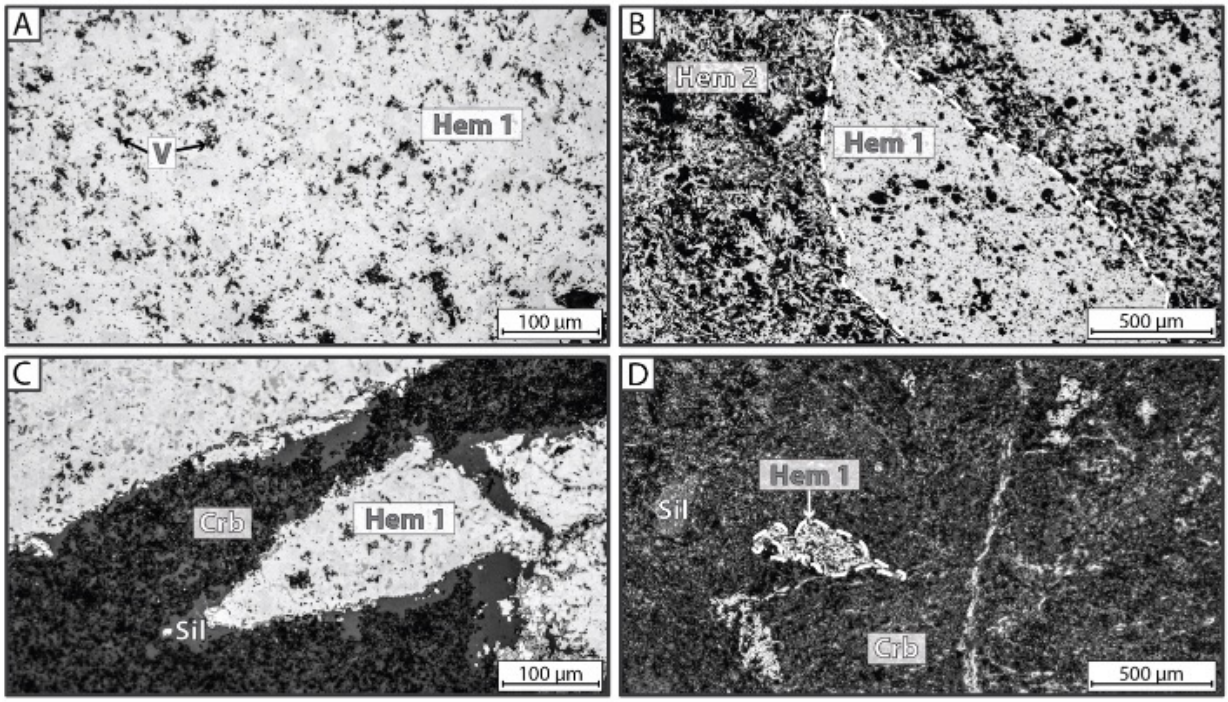


Figure 1: Hematite ore textures from the Sibley and Zenith mines, Ely, MN. A) Type 1 texture showing dense crystalline "matrix" with primary hematite aggregates (white to off white, Hem 1) and vug spaces (black, V). B) Type 2 texture exhibiting brecciated Type 1 material (Hem 1 fragment outlined with white dashed line) cemented by secondary hematite crystals (Hem 2) with reticulated pattern and occasional minute silicates (light gray). C) Type 3 texture displaying brecciated Type 1 material (Hem 1) cemented by mostly carbonates (patchy dark gray, Crb) and some silicates (light gray, Sil). D) Type 4 texture presenting mainly carbonates (patchy light and dark gray, Crb), sporadic silicates (light gray, Sil), and hematite aggregates (Hem 1 fragment outlined with white dashed line) and stingers.

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Decoding Shear Zone Evolution in the McFaulds Lake Greenstone Belt, Ontario: Constraints on Crystal-Plastic Deformation and Timing from in-situ Titanite U–Pb Thermochronology

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Constraining deformation conditions, kinematics and timing of shear zone activity is essential for determining whether mechanical processes concentrate and localize metal deposits. The McFaulds Lake Greenstone Belt in northern Ontario hosts some of Canada's most prospective mineralization, including magmatic sulphide, chromite and volcanogenic massive sulphide (VMS)–type deposits. A robust reconstruction of the belt's deformation history is hindered by an understudied, poorly exposed, arcuate, regionally extensive, dextral shear system including, the Webequie, Triple-J, and McFaulds shear zones.

This study integrates field-based structural observations, microstructural analysis, and in-situ titanite U–Pb geochronology to (1) resolve the kinematic architecture of the major shear zones, (2) constrain the crystal-plastic deformation mechanisms, and (3) determine the temperature and timing of deformation. Newly acquired kinematic results derived from field outcrop-scale S–C fabrics and asymmetrically rotated porphyroclast microstructures indicate that the NW-striking Webequie Shear Zone accommodated dextral-reverse displacement, while the NE-striking McFaulds and Triple-J Shear Zone are characterized by a dextral-normal sense of shear. Deformed quartz in phyllonites and mylonites from all shear zones exhibits fine-grained polygonal aggregates with a few subgrains and a weak crystallographic preferred orientation. These textures indicate that shearing was accommodated predominantly through diffusion-creep–assisted grain-boundary sliding processes.

Five deformed titanite grains from mylonitic tonalite associated with the Triple-J shear zone yielded U–Pb dates of ~2775 Ma and Zr-in-titanite temperatures of 530–640 °C. In contrast, eighteen euhedral to subhedral titanite grains yield dates between ~2768 and ~2812 Ma and Zr-in-titanite temperatures of 650–900 °C. All analyzed titanite grains show no significant difference in temperature or U–Pb dates between rims and cores. We infer that the younger U–Pb dates (~2775 Ma) recorded in deformed titanite constrains the timing of crystal-plastic deformation, whereas the older, higher-temperature dates (~2768–2812 Ma) from intact titanites reflect either metamorphic or crystallization. The overlap in deformation and crystallization ages for both deformed and undeformed titanites suggests that shearing in the McFaulds Lake Greenstone Belt was broadly synchronous with emplacement of the regional tonalite suite. These preliminary results show that both shear deformation and magmatism play a critical role in forming the McFaulds Lake Greenstone Belt and its critical mineral deposits.

Coeval silicate melt and PGE-bearing salt melt inclusions in the Thunder and Seagull intrusions, Ontario: An overview of evidence and data processing challenges.

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The Seagull (~90km north-northeast of Thunder Bay) and Thunder (~12 km north-northwest of Thunder Bay) intrusions are two magmatic sulphide-bearing mafic-to-ultramafic intrusions formed during the early stages of Midcontinent rift (MCR) formation. Investigation of olivine crystals from both intrusions reveals abundant assemblages of polycrystalline silicate inclusions and coeval assemblages of hypersaline inclusions. Both inclusion types occur along primary growth zones in their host crystals and undergo partial homogenization at >700 °C. This indicates that these inclusions contain primary, orthomagmatic fluids trapped at magmatic conditions (i.e., immiscible silicate and salt melt). Scanning electron microscope (SEM) analysis shows that the silicate melt inclusions from both intrusions have similar bulk chemistry and host assemblages of feldspar-apatite-phlogopite-biotite-ilmenite-pyrrhotite with a coexisting volatile phase. Similarly, salt melt inclusions from both intrusions also had similar bulk compositions and comprise mixtures of NaCl-KCl with variable amounts of C- and B-bearing salts.

The time-resolved laser ablation-inductively coupled plasma mass spectrometry (LA-ICPMS)

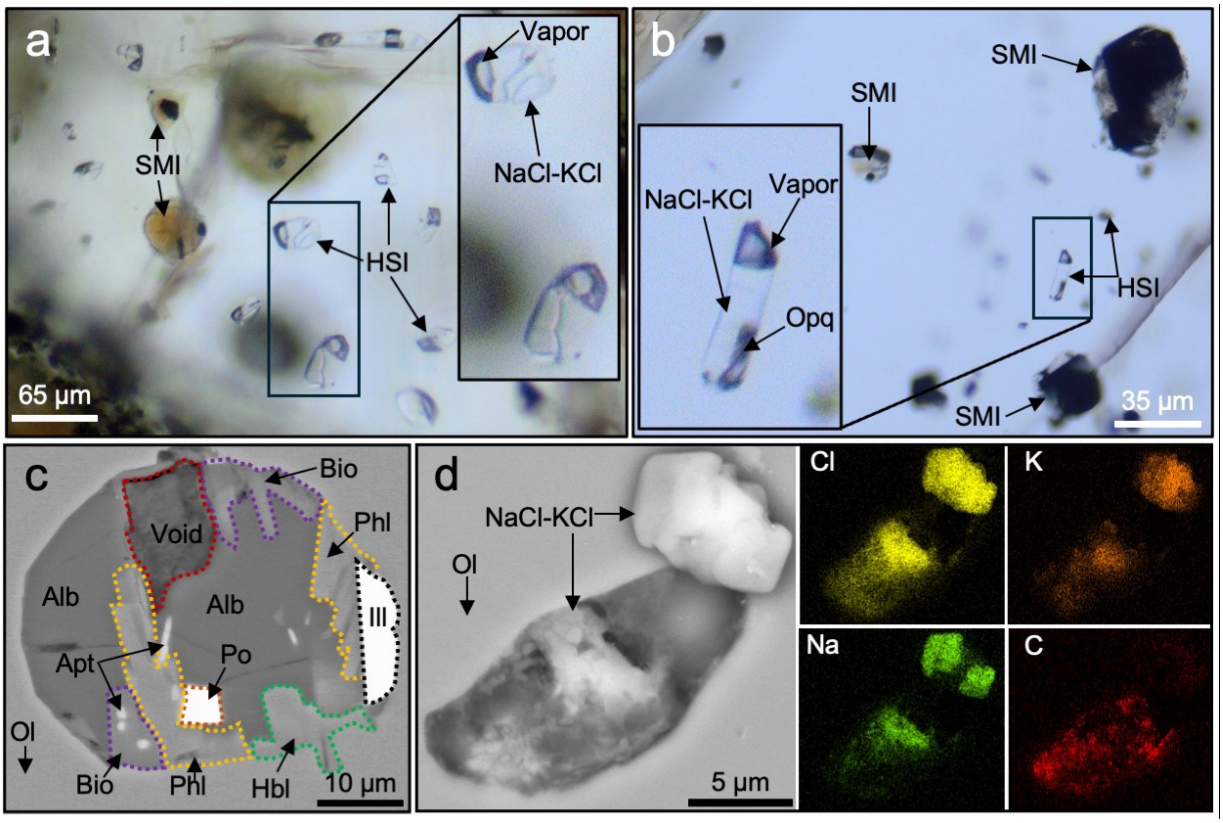


Figure 1: a., b., Photomicrograph of olivine-hosted coeval assemblages of silicate (SMI) and salt melt (HIS) inclusions from the Thunder (a) and Seagull (b) intrusions. c. Annotated backscatter electron (BSE) image of a silicate melt inclusion exposed at the surface of an olivine crystal. Alb=Albite; Bio=Biotite; Phl=Phlogopite; Apt=Apatite; Hbl=Hornblende; Po=Pyrhotite; Ill=Illmenite; Ol=Olivene d. BSE image of a salt melt inclusion exposed at the surface of an olivine crystal and accompanying energy dispersive spectroscopy maps showing the distribution of selected elements for the same area (right).

signals from unhomogenized salt melt inclusions from both intrusions consistently showed unambiguous, overlapping peaks for the following element groups: K-P-La-Ce-Ta-U-Th-Nb-Rb-Sr-Ba-Nd-Li, Co-Ni-Cu-Zn-Ag-Pb-S, and Pd-Pt-Au-Sb-Bi. The overlapping peaks for base metals and S likely reflect the presence of crystalline sulphides. Likewise, the overlap of the PGE+Au and Sb-Bi suggests the presence of PGE-bearing antimonide and bismuthide minerals (i.e. PGM). This indicates that salt melts coexisted with silicate melts during the emplacement of both intrusions and were significantly enriched in base metals and PGEs. This data, along with observations of salt melt inclusions in other mafic-ultramafic intrusions (Mcfall et al., 2021; 2023), suggests that these fluids may be important transport media for Ni-Cu-PGE in orthomagmatic environments.

Salt melt compositions derived from LA-ICPMS data had unusually high PGE concentrations in the 10s to 100s of ppm. These results should be treated critically, as reducing data from salt melt inclusions presents several technical challenges. These include uncertainty in determining a major element internal standard for salt inclusions and matrix mismatch between the inclusions and the external standard. ICPMS systems are also typically limited in their ability to analyze halogens, C, and S, which are typically major element components of salt melt inclusions (e.g. Xu et al, 2024; Bain et al., 2022).

This talk will provide an overview of the geology of the Seagull and Thunder intrusions, present textural and geochemical data from coeval polycrystalline silicate melt and salt melt inclusion in both and discuss the various data reduction schemes being used on this data set. This talk will also discuss a general workflow for salt melt analysis using SEM and LA-ICPMS techniques.

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Xu, X., Bain, W.M., Tornos, T., Hanchar, J.M., Lamadrid, H.M., Lehman, B., Xu, X., Steadman, J.A., Bottrill, R.S., Soleymani, M., Rajabi, A., Li, P., Tan, T., Shihong Xu, S., Locock, A.J., Steele-MacInnis, M., 2024. Magnetite-apatite ores record widespread involvement of molten salts. Geology. 52, 417-422. doi:10.1130/G51887.1 .

Preliminary geochronology of lithium pegmatites and host rocks, Archean Superior Province, northwestern Ontario

BEYER, Steve[1], CUTTS, Jamie[1], HNATYSHIN, Danny[1], POWELL, Jeremy[1], CAMACHO, Alfredo[2], CAWOOD, Tarryn[3], and DREVER, Garth[4]

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With a combined resource estimated at 50 million tonnes Li grading 1.6% Li_2O [1], the PAK and Spark lithium-cesium-tantalum (LCT) pegmatites in northwestern Ontario represent a major potential source of Li, as well as other rare metals such as Nb, Sn, Ta, Rb, and Cs. Together with other Li pegmatite showings in the region (Fig. 1), this suggests high Li prospectivity for the northwestern Superior Province. Better understanding of these significant but understudied pegmatites, together with their peripheral peraluminous granites and other host rocks, will help refine models of rare-metal-enriched pegmatite formation in Archean terranes, and lead to improved discovery success.

Here we present multi-mineral geochronological data for the pegmatites and host rocks to clarify connections between pegmatite emplacement and regional tectonics. The crystallization ages of pegmatites and host rocks were investigated using U and Pb isotopes in zircon and monazite measured by SHRIMP. The oldest rock in the area is gabbro that hosts the Spark pegmatite, in which zircon gives an age of 2861 ±3 Ma. Although this unit is mapped as the 2925 Ma Setting Net assemblage of the Favourable Lake greenstone belt, the age is instead within error of the younger 2858 ±5 Ma Eastern Trout assemblage [2]. Zircon in the Pakeagama Lake granite, a biotite-muscovite-garnet peraluminous granite that hosts the PAK pegmatite, gives an age of 2727 ±4 Ma, the first reported age for this pluton. Zircon from coarse K-feldspar-muscovite-apatite-quartz pegmatite at PAK, and zircon from tonalite that hosts the Pennock Lake pegmatite 20 km northwest of PAK, yield ages of 2727 ±1 and 2728 ±4 Ma, respectively, which are the same age as the Pakeagama Lake granite within error. Similar Th/U ratios, indistinguishable ages, and some textural evidence suggests that PAK pegmatite zircon may be inherited from the Pakeagama Lake granite. An overgrowth on one zircon in Spark gabbro gives an age of 2683 ±6 Ma.

Isotopes of Hf are used to trace the source of the melt from which the zircon crystallized, and were measured *in situ* using LA-MC-ICPMS in the same location as the SHRIMP spots. Zircon from gabbro hosting the Spark pegmatite have the most radiogenic εHf values of 5.30 ±0.33, intersecting the value of depleted mantle at 2.86 Ga. Zircon from the PAK pegmatite and tonalite hosting the Pennock Lake pegmatite are less radiogenic, having εHf values of 2.21 ±0.35 and 1.25 ±0.25, respectively, possibly suggesting mixing with older continental crust.

Lastly, we examine the thermochronology of muscovite in pegmatite zones, and biotite and hornblende in host rocks and contact zones using Ar-Ar isotope systematics. Step heating age spectra for muscovite (n=10) in the PAK, Spark, and Pennock pegmatites, and the Pakeagama Lake granite, are all disturbed and yield integrated ages between 2532 and 2174 Ma. Hornblende (n=1) in gabbro at Spark gives a slightly disturbed age spectrum with a pseudo-plateau age of 2805 ±4 Ma. Biotite (n=3) in metavolcanics at Spark, and at the contact between the Spark pegmatite and metavolcanics, yield pseudo-plateau ages of 2447 and 2446 ±1 Ma, respectively, whereas biotite in the Pakeagama Lake granite yields a pseudo-plateau age of 1955 ±10 Ma, possibly suggesting partial disturbance of Ar systematics during the Trans-Hudson orogeny. *In situ* Ar-Ar ages in transects from grain edge to center in muscovite from the Spark pegmatite range from 2687 ± 16 Ma to 1933 ±42 Ma, the oldest age indistinguishable from the U-Pb zircon overgrowth age of 2683 ±6 Ma in Spark gabbro. It is possible this age (~2685 Ma) represents the emplacement of the Spark pegmatite.

Taken collectively, these data indicate that the host rocks comprise both ~2861 Ma gabbro and ~2727 Ma granite and tonalite. Although pegmatite emplacement has not yet been directly constrained, it may have occurred together with a thermal pulse at ~2685 Ma, as recorded by Ar-Ar dates from muscovite in the Spark pegmatite,

and a zircon overgrowth in the host rock.

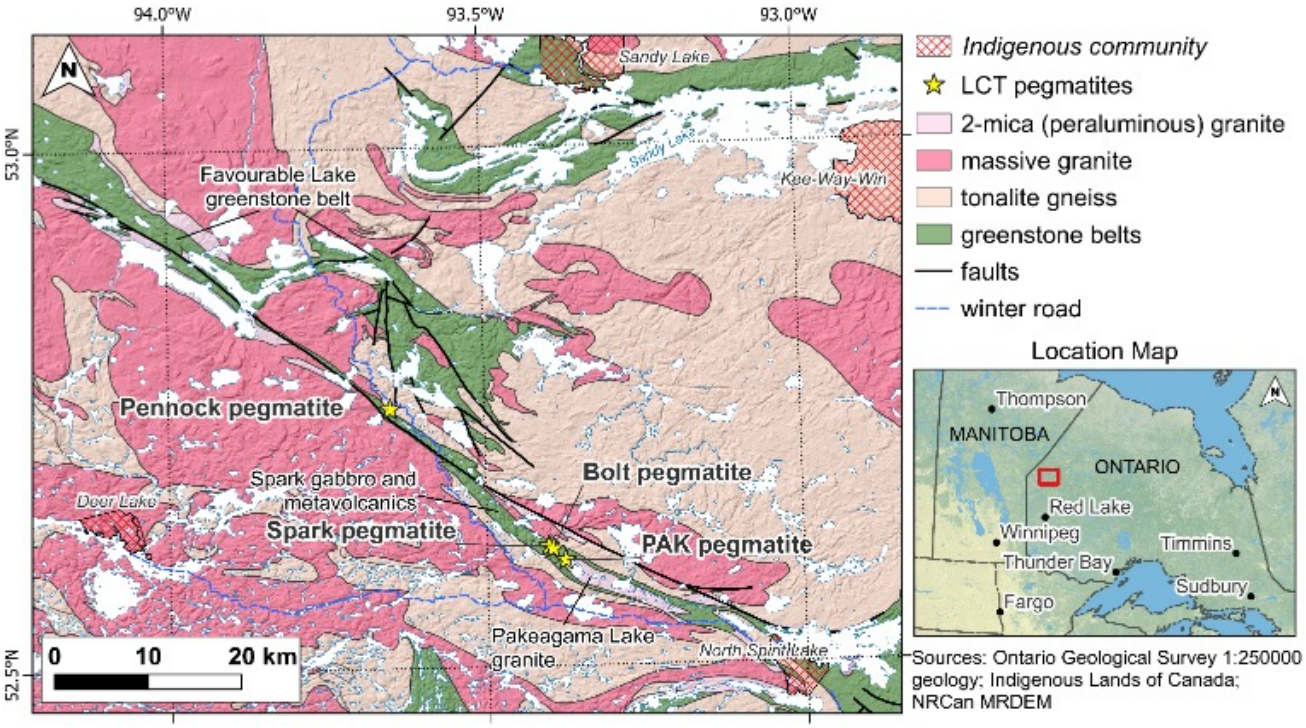


Figure 1. Map showing the location of LCT pegmatites in northwestern Ontario and their host rocks. The area shown in the main map is indicated by the red box in the location map. LCT = lithium-cesium-tantalum; NRCan MRDEM = Natural Resources Canada medium resolution digital elevation model

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Quartz Trace Element and TEM Analysis of Selected Economic LCT Pegmatites

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This study assesses geochemical and textural trends of economic LCT-type pegmatitic quartz using different analytical applications, namely laser ablation- inductively coupled plasma mass spectrometry (LA-ICP MS) trace element geochemistry, microscope-based laser induced breakdown spectroscopy (LIBS) and high-resolution transmission electron microscopy with- energy dispersive X-ray (TEM-EDX) analyses. The study utilized samples from well-documented economic LCT pegmatites (Northwestern Ontario and Manitoba) to assess a variety of modern questions relating to trace element geochemistry. Specifically, this study observes geochemical trends in trace element composition of quartz that display spodumene-quartz intergrowth (SQUI) textures, extrapolates classification of SQUI textures (after Breasley, 2025) to the economic Pakeagama pegmatite (Ontario) and utilizes HR-TEM techniques to image potential Li-bearing nano inclusions hosted within quartz.

Breasley (2021) outlined varieties of SQUI originating from unique crystallization sequences. In this study, SQUI from the Pakeagama pegmatite was compared to the recent proposed classifications to ensure consistency in texture classification can be met in different pegmatite systems. Few studies have targeted quartz trace element trends in Group 1 SQUI-bearing pegmatites. Trace element trends in SQUI should be properly understood to avoid improper conclusions when inferring mineralization trends outlined by Müller et al. (2021). Trends in SQUI-associated quartz trace elements were analyzed and compared with non-SQUI pegmatite quartz trace element trends using LA-ICP-MS and LIBS. It was found that few groups of trace elements, particularly Na and Ge, show weak to moderately depleted values with respect to the ratio of Li/Al specifically in quartz grains associated with SQUI (Figure 1). This is interpreted to be the result of trace elements present in the parent mineral (petalite) preferentially incorporating into spodumene rather than quartz during SQUI formation. Additionally, LIBS analysis suggests that elevated concentrations of Li are incorporated into micas and feldspars in the North Aubry sample, likely related to elevated trace element incorporation seen in quartz.

Nanoinclusions (fluid and mineral) are thought to be a major contributor to trace element incorporation in quartz (Shah et al., 2022). TEM-EDX analysis was conducted to document and image potential nanoinclusions hosted in quartz. The analyzed portion of the North Aubry sample did not host nanoinclusions displaying any detected Li signatures, however, a decrepitated nano-fluid inclusion, with detected sodium and chlorine, was identified (Figure 2). The results suggest that nanoinclusions, while present, may not necessarily contribute significantly to trace element concentrations of Li, Ti, Ge or Be in pegmatitic quartz (possibly due to their presence below detection limits), however, the observed nanoinclusions could suggest the potential Li-brine fluid fluid inclusions and this may be contributing to well-documented quartz trace element concentrations in quartz.

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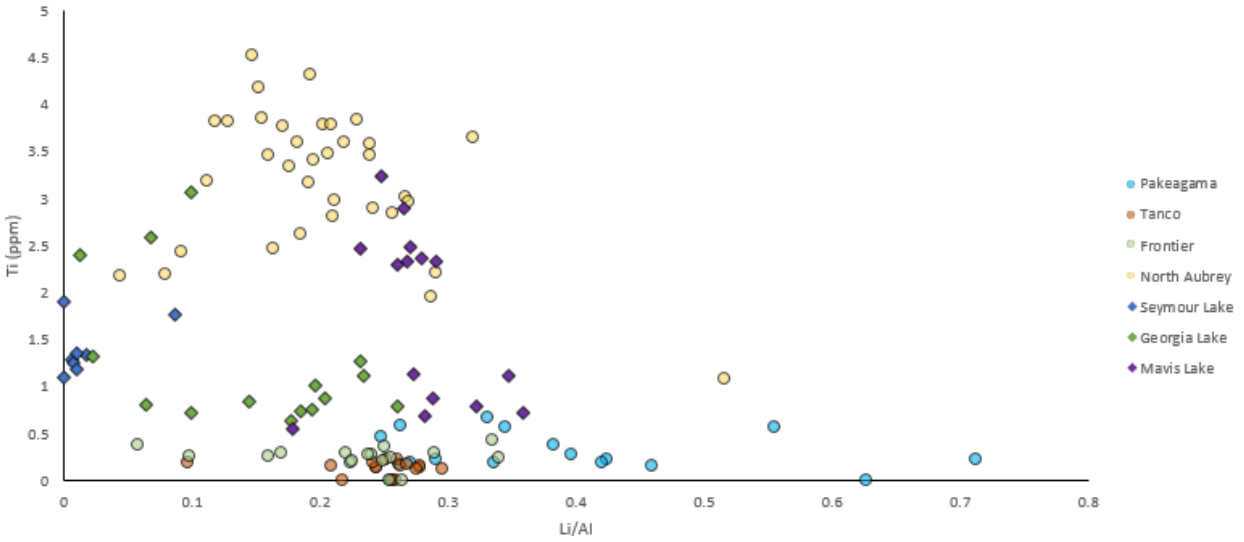


Figure 1: Ge (PPM) Versus Li/Al ratios in analyzed samples. Samples Pakeagama, Tanco and Frontier are SQUI-hosted quartz analyses. Data from three additional non-SQUI samples, Seymour, Georgia and Mavis Lake, were included to better highlight the role SQUI has on quartz trace element incorporation (Seymour, Georgia and Mavis Lake data from Young, 2024).



Figure 2: TEM image of a nanoinclusion in quartz, identified in the North Aubry sample. EDX mapping of the inclusion detected Na and Cl.

Improved Precision and Better Accuracy: SHRIMP-II Detrital Zircon Analysis of Samples Across the Stratigraphy of the Midcontinent Rift

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As part of on-going research on the evolution of North America's Midcontinent Rift (MCR), its stratigraphy, and the detailed setting of its mineral systems, we continue our efforts to improve the age constraints on key geological features of the rift. In addition to many new and improved U-Pb ages on igneous units [*e.g.*, 1,2], we are also undertaking detrital zircon dating of key stratigraphic units across the MCR stratigraphy, from bottom to top (Fig. 1), to resolve remaining questions of depositional ages and sediment provenance. We do so by using the SHRIMP-II ionprobe at the GSC in Ottawa (Fig. 2). With typical spot sizes of ~13x16 µm, fewer corrections during data processing, no down-hole parent-daughter fractionation, and the ability to do multiple, carefully placed spots (away from cracks

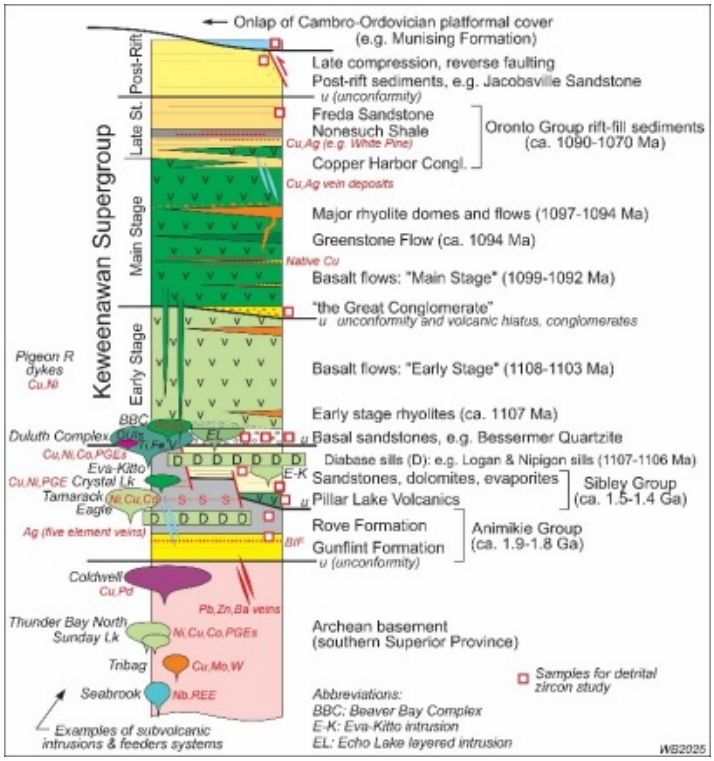


Figure 1: Generalized stratigraphy of the MCR. Many key ages and mineral systems are indicated. Small red squares identify our detrital samples analyzed by SHRIMP.



Figure 2: The SHRIMP-II lab at the Geological Survey of Canada, Ottawa. (SHRIMP: sensitive high-resolution ion microprobe.)

or other complexities) on grains of particular interest, the SHRIMP-II ionprobe yields significantly more precise *and* accurate data than more rapid laser ablation analysis, and a more rigorous check on concordancy [3,4]. A typical sample run will analyze 80–100 grains, with >90% of the results falling within the 95–105% concordancy interval (accuracy) used in final interpretation. With multiple spots (n=3–5) on key grains, the 2σ uncertainty of weighted mean ages can be improved to ±5–15 Ma (precision). All of this does take a fair amount of machine time, with a typical spot analysis taking ~15 mins, and an entire sample run, including calibration on well-characterized zircon reference materials, more than 24 hrs. Analysis is done on polished grain mounts that are imaged in both BSE (backscatter) and CL (cathodoluminescence) mode prior to analysis to guide grain selection and spot location.

Here we briefly discuss some initial results. One such result, on the high-energy "event layer" near the top of the Gunflint Formation, was presented at an earlier ILSG meeting [5]. It confirmed that this layer contains ejecta material from the Sudbury target area in the form of ca. 2460–2450 Ma zircons from the Creighton Granite and Copper Cliff Rhyolite. In the next sample up (Rove Formation greywackes), our results fail to identify any age peaks younger than ca. 1845 Ma, which we consider the maximum depositional age for the Rove Formation [*cf.* 6], i.e. entirely a Penokean foreland basin.

There are hints of some younger grains, perhaps to as young as ca. 1805 Ma, but this requires further work. Interestingly, in addition to some Archean input, there is also one grain at ca. 2311 Ma of the reworked felsic ash material known from the upper Huronian Supergroup [see also ref. 5].

Thin sandstone layers intercalated with the Pillar Lake Volcanics basalt flows, near Armstrong, show youngest grains at ca. 1500 Ma, similar to our Sibley Group sandstone samples, and do not contain any of the abundant younger grains (and peaks) prominent in the basal MCR sandstones discussed below (see Fig. 3). This confirms our interpretation that these thin sandstone beds and the Pillar Lake Volcanics are part of basal Sibley Group rift volcanism and sedimentation at ca. 1500-1480 Ma, not a northern outlier of ca. 1.11 Ga MCR stratigraphy *sensu stricto* [*cf.* 7].

Three samples of the sandstone/quartzites (Bessemer, Nopeming, and Puckwunge formations) immediately below the onset of "Early Stage" basaltic volcanism yield generally similar results with youngest grains in the 1135–1100 Ma age range (weighted means), and strong peaks (modes) at ca. 1125 Ma, 1160–1140 Ma and various older ages (e.g., 1470 Ma, Wolf River Batholith), all the way to 3.3 Ga (Fig. 3). These are just some initial results and a full and complete analysis of all 12 samples will be presented elsewhere.

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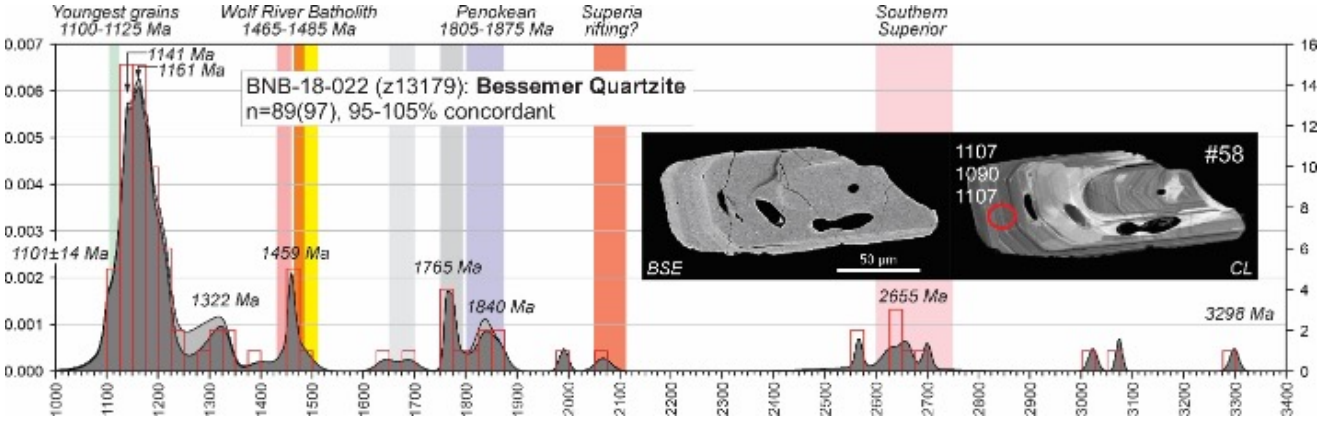


Figure 3: Example of our SHRIMP-II detrital zircon results: probability density plot for the Bessemer Quartzite (BNB-18-022), sampled just below the onset of basalt flows. Inset: images of youngest grains with 3 spots (repeated analyses at the same locality), yielding a weighted mean age of 1101±14 Ma.

Update to: a complex F-rich alkalic 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. This abstract is an update to studies of this dike reported in ILSG 2024 and 2025; interested readers are referred to those abstracts.

As noted by Buchholz et al. (2025) relatively common soft, pale yellow to creamy to brown grains typically contain high Ti-Ce-Fe contents with traces of other elements, and were suspected to consist of an unidentified Ti-Ce4+-Fe phase. Hand-picked grains from several visually identical samples were analyzed using powder XRD to determine crystalline phases present. Results indicate the presence of only three crystalline phases: arfvedsonite, lucasite-(Ce), ($CeTi_2(O,OH)_6$) and cerianite-(Ce), ($(Ce^{4+},Th)O_2$. To balance charges in lucasite-(Ce), Ce is likely present as Ce^{4+} and OH probably absent or negligible. The altered grains may have originally been a LREE-Ti-rich mineral such as chevkinite-(Ce) or aeschynite-(Ce) that were subsequently altered under oxidizing conditions, removing $LREE^{3+}$ and Si (and altering Ce^{3+} to Ce^{4+}), thus allowing the crystallization of lucasite-(Ce) and cerianite-(Ce). Oxidation states appear to have fluctuated during pegmatite crystallization, as Ce3+ rich minerals such as synchysite/parisite, britholite-group minerals, monazite-(Ce) and indeed sparse remnants of chevkinite-(Ce) are present in later crystallizing portions of the dike.

The potential for britholite-group minerals was discussed by Buchholz et al. (2025), and since then two group minerals have been identified: fluorbritholite-(Ce) and britholite-(Ce). Both form small pale pink to whitish rounded masses in pockets and vugs. At a minimum EDS analysis is required to distinguish these two species, as well as distinguish them from visually similar synchysite/parisite series minerals.

Although bismuthinite is known from thin veinlets crosscutting the pegmatite (Buchholz et al., 2025), native Bi has subsequently been found as masses in small interior zone vugs in the pegmatite. Standards-based EDS indicates the Bi contains small amounts of Te; approximately 2-3.5 wt. %. The Te (as Te^{2-}) is probably present as small admixed grains of a Bi-Te mineral such as tellurobismutite, hedleyite or another Bi-Te species.

Possible nacareniobsite-(Y) was found as an inclusion in a small aggregate of fergusonite-(Y). Standards-based EDS data show good agreement with the published composition of the species, but the small size of the grain (approx. 25 μm) and the scarcity of the mineral suggest more examples should be sought to confirm this data. Nacareniobsite-(Y) was first described in 2023 and is so far a one-locality mineral, suggesting this may be the second locality for this species.

Recent thorough cleaning of fresher exposures has revealed that parallel joints or fractures are closely spaced across much of the pit exposure. All are parallel, near-vertical and roughly oriented WNW-ESE. Possible displacement is unknown at this time, but they suggest a degree of oriented stress may have affected portions of the pluton late in its cooling history or at sometime thereafter.

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Reassessing variations in metamorphism across the Penokean orogen in Northern Michigan: Part 2, Reinterpreting metamorphic nodes

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A classic study of regional metamorphism (James, 1955) documented variations in metamorphic grade in Paleoproterozoic sedimentary rocks across the Upper Peninsula of Michigan. James interpreted the spatial variations of index minerals as four discrete nodes of metamorphism with concentric zones, defined in pelitic rocks, ranging from chlorite to sillimanite grade (Figure 1). Those isograds are widely used up to the present day to characterize the Penokean metamorphism of the region. These concentric nodes imply localized sources of heat across the region rather than a more widespread source related to regional orogenic processes.

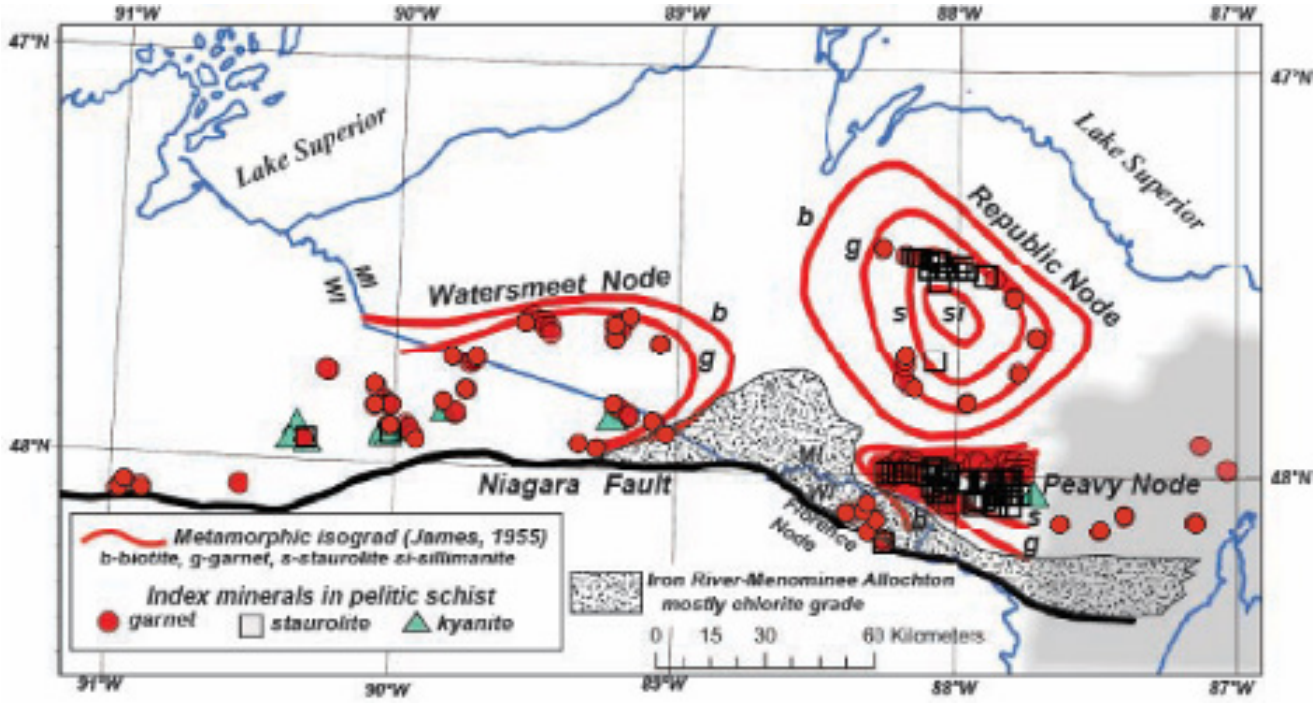


Figure 1. Map showing isograds interpreted by James (1955) and distribution of metamorphic index minerals from James and later studies. Compilation of metamorphic index minerals in northern Wisconsin indicates that the high-grade metamorphism extends well west of the Watersmeet node as mapped by James. Widespread garnet occurrences observed in core drilled through Paleozoic cover rocks also show that metamorphism to at least garnet grade extends far east of the exposed Peavy node. Patterned area is proposed allochthon(s) which include the Iron River-Crystal Falls and Menominee iron ranges. Gray shaded region in SE is area of Paleozoic cover.

We propose an alternative interpretation for the Watersmeet and Peavy metamorphic nodes and their implied discrete heat sources. The index mineral occurrences in Figure 1 show a belt, at least 250 km long, of metamorphism to garnet or higher grade including scattered occurrences of kyanite to about 50 km north of the Niagara fault. That belt is broken by a gap of about 50 km between the Watersmeet and Peavy nodes where rocks are mostly chlorite-grade sedimentary rocks. We suggest that the gap is a result of post-metamorphic northward emplacement of allochthons of low-grade rocks over the more highly metamorphosed rocks, and that the belt of high-grade rocks is continuous beneath the allochthons. The belt of high metamorphic grade rocks, thus, is a result of regional tectonic burial to mid- to lower crustal depths, and related heating during the climactic closing phase of the Penokean orogeny, rather than to largely speculative individual heat sources. More localized

heating by contemporaneous intrusions likely caused some magnification of regional heating such as in the Peavy node (Roy, et al., 2025)

The allochthonous nature of the Paleoproterozoic rocks was first proposed by Sims (1992) and supported by more recent work (i.e. Cannon and Ottke, 1999), and recently acquired aeromagnetic and electromagnetic data. The very close spacing of isograds inferred by James (1955), such as the southeastern edge of the Watersmeet node and southwestern edge of the Peavy node, would require extreme lateral temperature gradients that are difficult to reconcile with progressive heating from a central source. Those abrupt lateral changes in metamorphic temperatures are more consistent with a tectonic contact between the high-grade rocks and overthrust low-grade rocks. If that is correct, it has significant implications for the age of allochthon emplacement and the nature of post-Penokean tectonism in the region. The peak metamorphism of the Watersmeet and Peavy nodes is well constrained to 1837-1825 Ma at depths of 30-35 km (Roy, et al., 2025: Salerno, et al., in press). Emplacement of allochthons with low metamorphic grade directly atop these mid- to lower-crustal rocks implies that the high-grade rocks were largely exhumed before emplacement, and that overthrusting must have been a post-Penokean event. Rapid exhumation of active orogens has been documented in many places globally with rates measured in kilometers/million years, so exhumation observed in Michigan could have been accomplished in 10 million years or less. Thus, the suggested overthrusting could be only slightly younger than the generally accepted ~1830 Ma date for termination of Penokean deformation, nevertheless recording continued post-Penokean regional compressive tectonism in the region.

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An introduction to the northwestern Huron Mountains of the Upper Peninsula, Michigan: field relations and preliminary structural interpretations

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The Huron Mountains of the Upper Peninsula, Michigan, are part of a granite-greenstone terrane and likely represent part of the southern extent of the Superior Craton. Recent field mapping and microstructural analysis indicate the existence of an amphibolite basement intruded by compositionally variable granitoids. The amphibolite basement is a banded schist with a high amphibole content that may represent a strongly metamorphosed mafic protolith. The two plutons of this site each have rapidly varying appearances and expressions of fabrics, banding that varies from non-existent to thick gneissic, and variable compositions from monzogranite to quartz-rich tonalite lithologies. The contacts between the schist and granitoid plutons of this site vary in expression over relatively short distances and, in some cases, can be traced from a planar feature into a 50+ m wide transition zone. The relation between the granitoid and the amphibolites is intrusive, as a range of sizes of amphibolite inclusions can be found within the plutons, usually near the contacts. Mafic and felsic dikes are both abundant. Ongoing work to analyze bulk and trace element geochemistry and U-Pb geochronology will constrain the timeframe of geologic events, the tectonic origin of the groundmass (i.e., which terrane, protolith), and the source of plutonism.

The pervasive regional fabric displays a general northwest strike/northeast dip; however, the foliation expression in outcrop is frequently inconsistent, with tens of degrees of difference in both strike and dip possible within 30 meters or less. In general, traceable exposures of the schist-pluton contacts are parallel or subparallel to foliation. Additional structures found in outcrops include meso- and micro-scale faults and meso-scale or larger shear zone features. In thin section, microstructures indicate solid-state deformation, including myrmekite, cuspate-lobate grain boundaries, and internal grain deformation. These analyses support the model of emplacement of quartz-rich plutons into a meta-mafic basement during regional shearing, in the northwestern Huron Mountains.

Petrography and Geochemistry of the Mound Lake Pluton, Northwestern Ontario

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Mound Lake lies approximately 90 km north-northeast of Thunder Bay and 25 km northwest of Nipigon. The Mound Lake Pluton is a 7 km-wide, ovoid, muscovite-bearing granite that has intruded Quetico metasedimentary rocks. It was first described by Hart (2005) and Hart et al. (2005) and thought to be a prospective fertile granite, capable of hosting or spawning rare metal mineralization (cf. Breaks et al., 2005). This study documents the petrography, mineral chemistry, and whole-rock geochemistry of the Mound Lake granitic rocks.

The study utilized samples from an initial geochemical and geological reconnaissance program (Smyk, 2022). Thirty-one samples were collected from the pluton and another was collected from from a granitic pegmatite dyke in andalusite schist from the shore of Frazer Lake. Analytical methods included transmitted light microscopy, major and trace element whole-rock geochemistry, and quantitative mineral compositional analyses using Scanning Electron Microscopy- Energy Dispersive X-ray Spectroscopy (SEM-EDX) with Back Scattered Electron (BSE) imaging to characterize mineral textures and compositions.

The Mound Lake granitic rocks host irregular pegmatitic patches and miarolitic cavities containing quartz and large, drusy K-feldspar crystals. Massive, medium-grained granitic rocks are crosscut by a variety of aplitic and pegmatitic dykes. Petrographic and mineral compositional analysis identifies the pluton as a two-mica granite, composed of K-feldspar, quartz, muscovite, biotite, and plagioclase, with accessory zircon, apatite, monazite, tourmaline and thorite. Plagioclase, whose compositions range from albite to oligioclase, locally exhibited Na-rich, albite rims. Biotite compositions were found to represent annite/siderophyllite endmembers. Perthitic exsolution and granophyric intergrowths exemplify late-stage crystallization, while sericitization and chlorite alteration are related to post-magmatic hydrothermal activity. The presence of granophyric intergrowths suggests that at least some portions of the magma experienced pronounced undercooling during the final stages of crystallization.

Geochemical data confirm a peraluminous, S-type affinity (Alumina Silica Index of 1.05–1.31) with trace element signatures plotting in the Volcanic Arc Granite (VAG) and syn-collisional fields. Granitic rocks display moderate LREE enrichment and HREE depletion, with variable Eu anomalies reflecting the relative role of plagioclase fractionation and accumulation. The Mound Lake Pluton shows increased Li and Cs (+ Ce, Ta and Be) concentrations along its northern contact (Figure 1). Elevated Ce concentrations correlate with samples with higher monazite content. The consistently peraluminous nature and mineralogy (muscovite + biotite, ± garnet) support the contention that the pluton is a product of metasedimentary melting, likely triggered by thermal relaxation following oblique accretion in the Superior Province (Chappell, 1999). A spodumene-bearing, granitic pegmatite dyke, discovered in 2023 (https://www.geologyontario.mines.gov.on.ca/mineral-inventory/MDI000000003501), approximately 3 km north of the northern contact of the pluton, attests to the fertility of local granitic rocks.

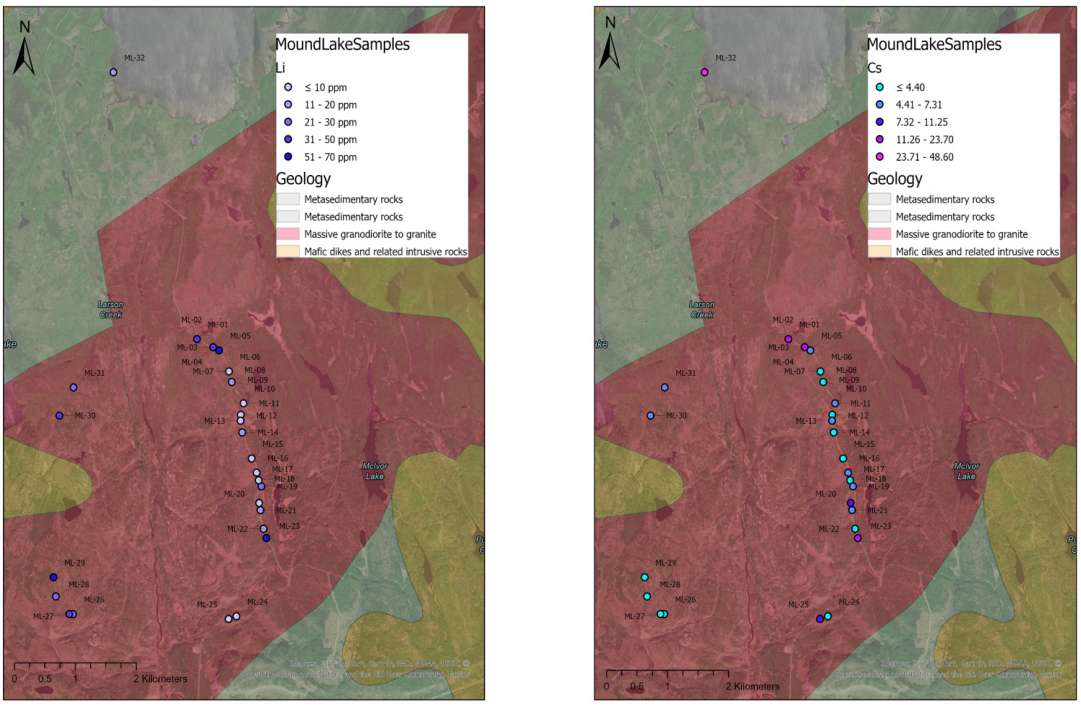


Figure 1. Li (left) and Cs concentrations (right) across the Mound Lake pluton (data from Smyk, 2022).

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Digital Preservation and Enhanced Utility of Exploration Core Descriptions from the Keweenaw Copper District, Michigan: Progress toward a Map-based Web Portal

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The Michigan copper rush starting in 1843 at Copper Harbor (Fig. 1) led to 150 years of mining that produced ~7.5 x 106 MT of copper (1), attracted ~100,000 persons from 40 countries, and profoundly influenced understanding of Lake Superior geology, advances in mining technology, and the region's pattern of life. Companies invested significantly in trenching, coring, and mining operations that generated an enormous body of geologic information. The U.S. Geological Survey (USGS) compiled much of this information in the 1950s as bedrock geology maps with supporting cross sections and reports. Available online in digital form, these map products are derived in large part from a substantial quantity of detailed paper records that are not easily accessed, including core descriptions from exploratory holes drilled from 1899 through the 1970s. Drilling records produced after the 1950s generally have not been used in later investigations also because of difficulty of access. Paper records and microfiche that degrade with time are stored at various locations (2-4), further complicating their use. A few years ago, we began a volunteer project to identify and gather such information into a digital image repository, to extract it into tabular databases, and to explore how to make it available (5) for use by scientists, industry, land-use planners, and the general public (Fig. 2). These early efforts led to a two-year project funded by a Save America's Treasures grant (ST-256897-OMS-24) through the National Park Service, focused on drilling records in the Michigan

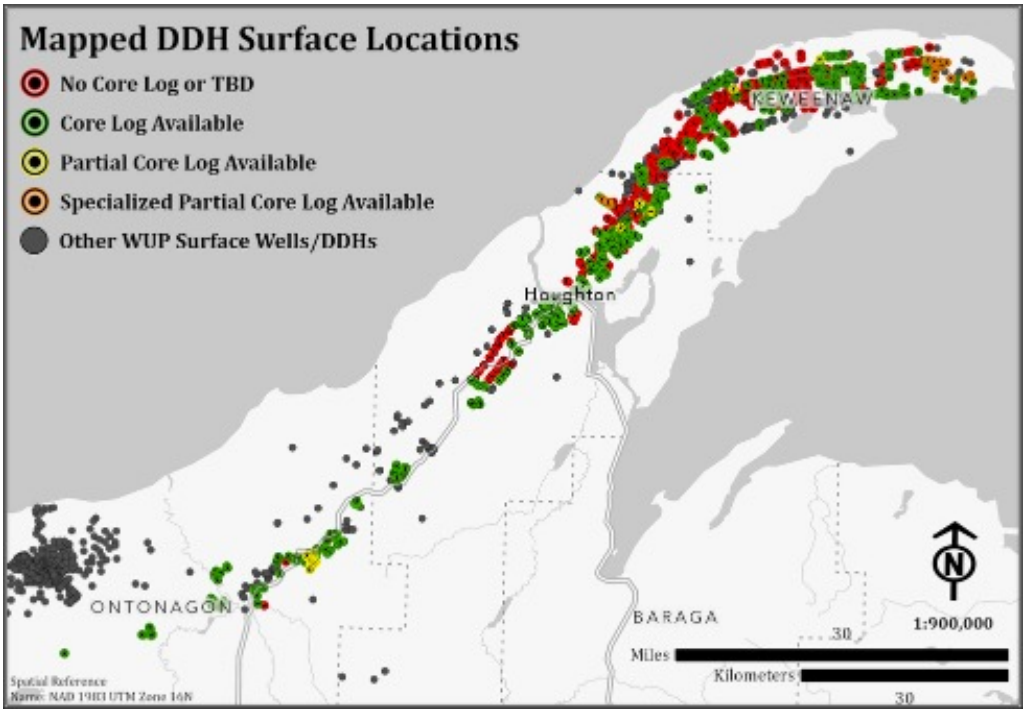


Figure 1: Michigan's native copper mining district with exploratory diamond-drill holes (DDHs) coded by information that is available. TBD – to be determined; WUP – Western Upper Peninsula.

Technological University Archives.

The current project has three phases: 1) scan all paper records of core descriptions, drafted vertical sections, and drilling metadata; 2) convert scanned records to character data and store in files with

tabular formats; 3) create an online, GIS-based, search tool to provide access to the materials. Phase 1 of the project, now complete, has produced scanned core logs for 801 diamond-drill holes from 64 series. After the project was terminated in April 2025 and then reinstated in June, we prioritized Phase 3 to develop the online GIS-based search and delivery tool for scanned files in case funding was lost again. Functional design work is complete and implementation is being tested. Drill hole locations for the GIS-based map were digitized from USGS maps of the Keweenaw Peninsula and supplemented with data from Michigan's EGLE website. A drillhole attribute table contains positional data, hole direction, total depth, and drilling metadata. Phase 2 of the project is ongoing and involves extracting character data from PDF files and creating tabular data for each core description. We are investigating optical character recognition to extract character data combined with AI tools to organize the data into prescribed tabular formats. This has proven successful for high-fidelity records but requires human checking and editing to ensure the accuracy of extracted data. Less well preserved records may require humans to transcribe them and manually enter characters into the tables. Upon making these MTU records available to others in an online format, we hope to extend this work to similar records in the other archives.

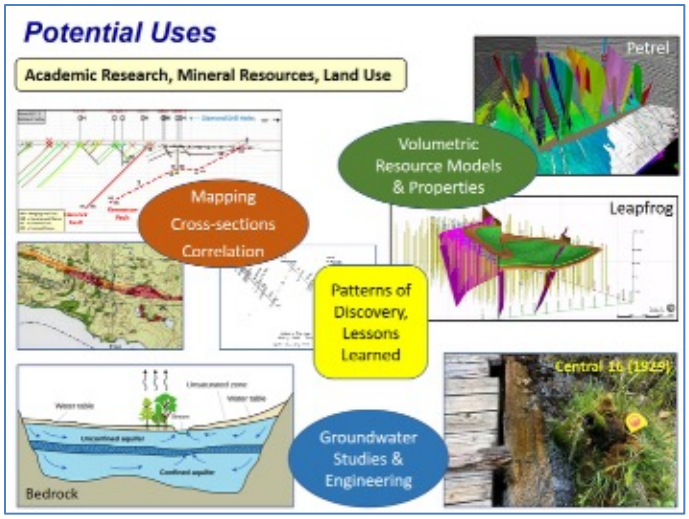


Figure 2: Potential uses of the database upon completion.

Acknowledgements: We thank the U.S. National Park Service for the grant that makes this work possible. Casey Koch and Gwen Martin performed nearly all of the document scanning. This work is possible because of the foresight of many late geologists who gathered and preserved the original paper records.

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A new look at the Seagull mafic-ultramafic Intrusion and potential hydrogen and helium accumulations

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The mafic-ultramafic Seagull intrusion located approximately 80km northeast of Thunder Bay, Ontario and forms part of the Paleoproterozoic 1.1 Ga Midcontinental Rift which extends in an arcuate shape from Iowa through Lake Superior into Michigan (Fig. 1). The intrusion was intruded into the Archean Quetico Metasedimentary Terrain and transects a portion of the Sibley Group Metasedimentary rocks. The Quetico Terrain is dominated by deep water turbidites accumulated in a forearc basin between adjacent volcanic terranes, that underwent inversion during crustal accretion. Partial melting of the Quetico Terrane at depth resulted in the generation and emplacement of S-type melts at shallower levels with both uranium occurrences and LCT pegmatites present (Fig. 2).

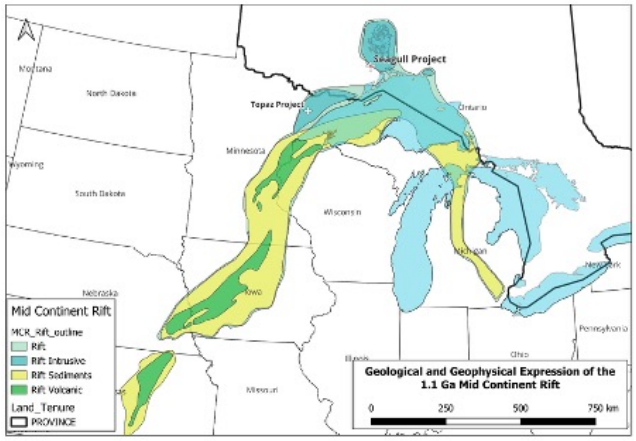


Figure 1. Geological and geophysical interpreted extent of the 1.1 Ga Midcontinent Rift centered on Lake Superior. Distribution of major rock types shown along with location of Seagull Project (Rift Minerals) and Topaz Project (helium: Pulsar Helium)

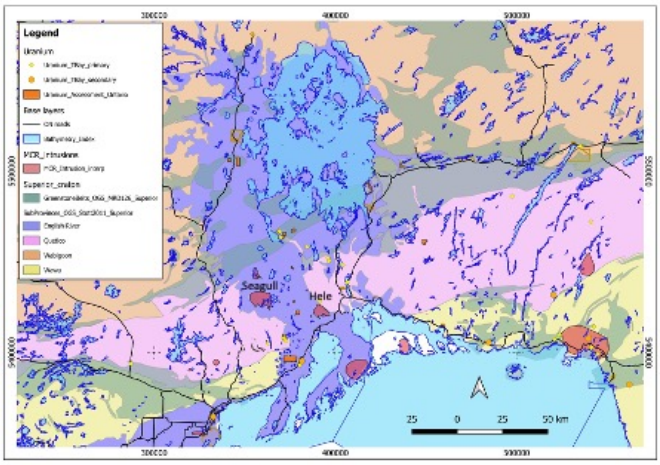


Figure 2. Geology map of the Lake Nipigon area. Archean basement terrains shown in the legend. 1.1Ga Midcontinent Rift rocks shown in purple with early olivine bearing intrusions outlined in red. Uranium occurrences identified are demarked by yellow and orange circles from Ontario OMI database.

Historic exploration between 1998 and 2012 on the Seagull Intrusion included airborne and ground geophysical surveys and approximately 20,000m of diamond drilling. The geology of the Seagull intrusion is characterized by mafic-ultramafic rocks, with in-excess of 700 m of variously serpentinized olivine cumulate rocks, predominantly lherzolites and pyroxenites (Fig. 3). This exploration work identified disseminated to semi-massive sulphide mineralization containing nickel, copper and platinum group elements along parts of the intrusion's basal contact and as reef-type mineralization. Additionally, the exploration operator at the time reported the presence of naturally occurring gases at pressure.

Histoically, the intrusion was targeted for orthomagmatic mineralization, without attention being paid to the presence of gas. With the discovery of an unconventional helium reservoir within the MCR, the prospectivity of the area has pivoted, resulting in new ideas in explored areas. Serpentinization is well known as an alteration process that generates hydrogen. The presence of ubiquitous uranium and LCT pegmatite occurrences in the Archean basement metasedimentary rocks of the Quetico Terrain are a potential source of helium (Fig. 2). Lithostatic pressures, structural plumbing and concentration gradients can potentially result in downward migration of generated gases (Strauch et al, 2023).

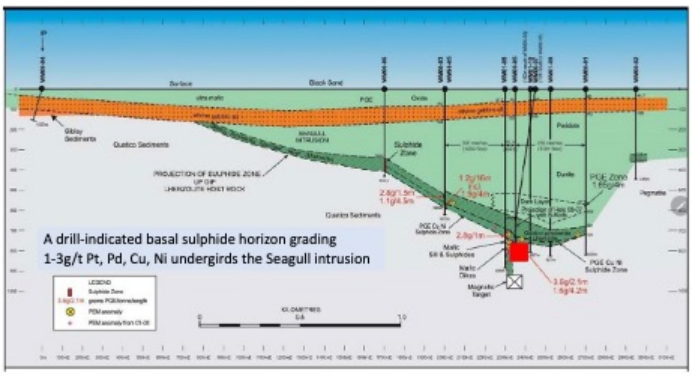


Figure 3. East-West cross-section through the Seagull intrusion as interpreted from diamond drilling. Modified from East West Resources (2002).

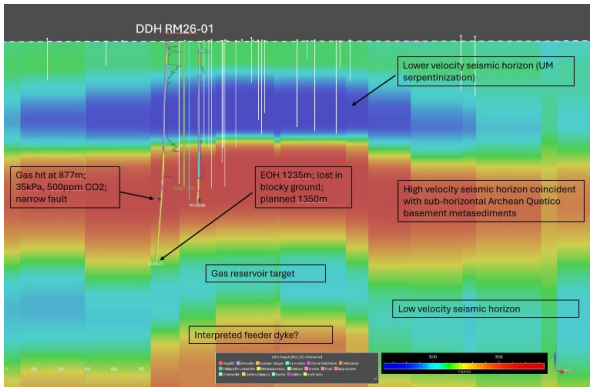


Figure 4. Cross section through inversion model of the Ambient noise tomography (ANT) survey completed by Sisprobe (2024). Historical drill traces shown in white. Cross section at AZ of 027° facing NNW.

In 2024, Rift Minerals completed an ambient noise tomography (ANT) survey with Sisprobe to refine the internal geometry of the Seagull intrusion and to identify subsurface velocity contrasts interpreted to reflect lithological and alteration variations. Integrated interpretation of drilling and geophysical data sets, including ANT velocity modelling, has been used by Rift to refine the interpreted geometry of the Seagull intrusion and underlying basement. The ANT velocity section (Fig. 4) is of high statistical quality and agrees well with stratigraphic variations identified in drilling. An unexplained low velocity interval within or beneath high velocity Quetico basement rocks below the Seagull Intrusion, topping at ~1250m, is being targeted for high pressure gas reservoir potential (Fig. 4).

Rift Minerals and its funding partner Anteros Metals Inc. initiated a drill program in 2026 to test the deep lower velocity feature with drill hole RM26-01. The drill hole intersected disseminated to locally weakly net-textured, orthomagmatic sulphide mineralization in the basal cumulate sequence of the Seagull intrusion grading:*

- 7.25 metres from 587.00 to 594.25 m grading 1.58 g/t Pt+Pd (0.72 part per million Pt and 0.86 ppm Pd), with 294 ppm copper and 2,168 ppm nickel;
- 1.00 m from 606.25 to 607.25 m grading 2.27 g/t Pt+Pd (1.02 ppm Pt and 1.25 ppm Pd), with 1,660 ppm Cu and 2,080 ppm Ni.

* Weighted-average results using a 0.5-gram-per-tonne-platinum-plus-palladium cut-off

During the drilling of hole RM26-01 pressurized gas was encountered at a depth of approximately 877m within a narrow fault zone in the Quetico basement rocks. The 877-metre occurrence is located approximately 100m southwest from drill hole WM01-08, which reportedly encountered pressurized and flammable gas at a similar stratigraphic level when drilled in 2001. The significance, continuity and composition of the gas remain under evaluation.

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Integrated X-Ray Diffraction and Petrography Document Carbonate Mineral Heterogeneity and Hematite Mineralization in the Upper Biwabik Iron Formation, MN

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Core LWD-99-1 preserves the ~1.9 Ga Biwabik Iron Formation located near the Virginia horn, outside the contact metamorphic aureole associated with the intrusion of the Duluth Complex ca. 1.1 Ga. In this study, X-ray diffraction (XRD) and petrographic data are used to: (1) characterize carbonate mineral heterogeneity; and (2) evaluate depositional and post-depositional mineral assemblages. Emphasis was placed on identification of Fe^{2+} bearing carbonates (e.g., ankerite, siderite) and hematite-magnetite relationships. To minimize contamination and weathering effects, outer surfaces were removed during processing, and veins were avoided. Samples were cut, dried, then crushed to a uniform powder using a SPEX ShatterBox. XRD analyses were performed using a PANalytical X'Pert diffractometer, with data collected in θ-2θ geometry over a range of 5-65 degrees, sufficient to capture all minerals of interest. Analysis of diffraction data was done using X'Pert HighScore (Malvern PANanalytical) software.

XRD analysis of 24 samples documents the presence of multiple different carbonate and oxide minerals throughout core LWD-99-1. Carbon was detected in 92% of analyzed samples, with 77% associated with carbonate minerals. All carbonate phases identified petrographically and with scanning electron microscopy (Duncanson et al., 2024) were also detected by XRD, indicating strong agreement between methods. Siderite is the most common carbonate phase, occurring in 41.7% of samples, followed by ankerite at 33.3%, dolomite in 20.8%, kutnohorite in 16.7%, and calcite in 6.3%. Carbonate mineral distribution greatly varies by informal stratigraphic unit. Siderite is prevalent in the Lower Slaty, Lower Cherty, and Upper Slaty, whereas kutnohorite (a calcium manganese carbonate) only occurs in the Upper Cherty. Calcite is restricted to the uppermost part of the Upper Slaty while dolomite and ankerite are most abundant in the Upper Cherty but also appear once in the Lower Cherty and twice in the Upper Slaty. Overall, carbonates are more abundant in the Upper Slaty and Upper Cherty compared to the Lower Slaty and Lower Cherty. Within the Upper Slaty, siderite occurs in 42.9% of samples, ankerite in 28.9%, dolomite in 28.6%, and calcite in 14.3%. In the Upper Cherty, siderite and ankerite each occur in 50% of the samples, dolomite in 20%, and kutnohorite in 40%. These distributions highlight a clear variation of carbonate minerals in the upper portions of the stratigraphy. Additionally, preliminary XRD and petrographic observations of iron oxide minerals suggest an overall increase in hematite occurrence in the Upper Cherty and the Lower Cherty, with petrographic data indicating magnetite is more prevalent in slaty units. Such transitions towards increasing carbonate mineral diversity and increasing hematite up section could link to depositional changes in the system or post-depositional oxidation reactions. Post-depositional mineral reactions and accounting of ferrous: ferric iron ratios are of critical interest as they preserve a record of fluid: rock interaction driven by multiple geologic events. Some redox reactions that involve siderite and magnetite are of broader interest for tracking hydrogen production or stimulation potential (Geymond et al., 2023; 2025). Ongoing work includes detailed accounting and mapping of mineral distributions and mineral reactions across the lateral extent of the iron formation.

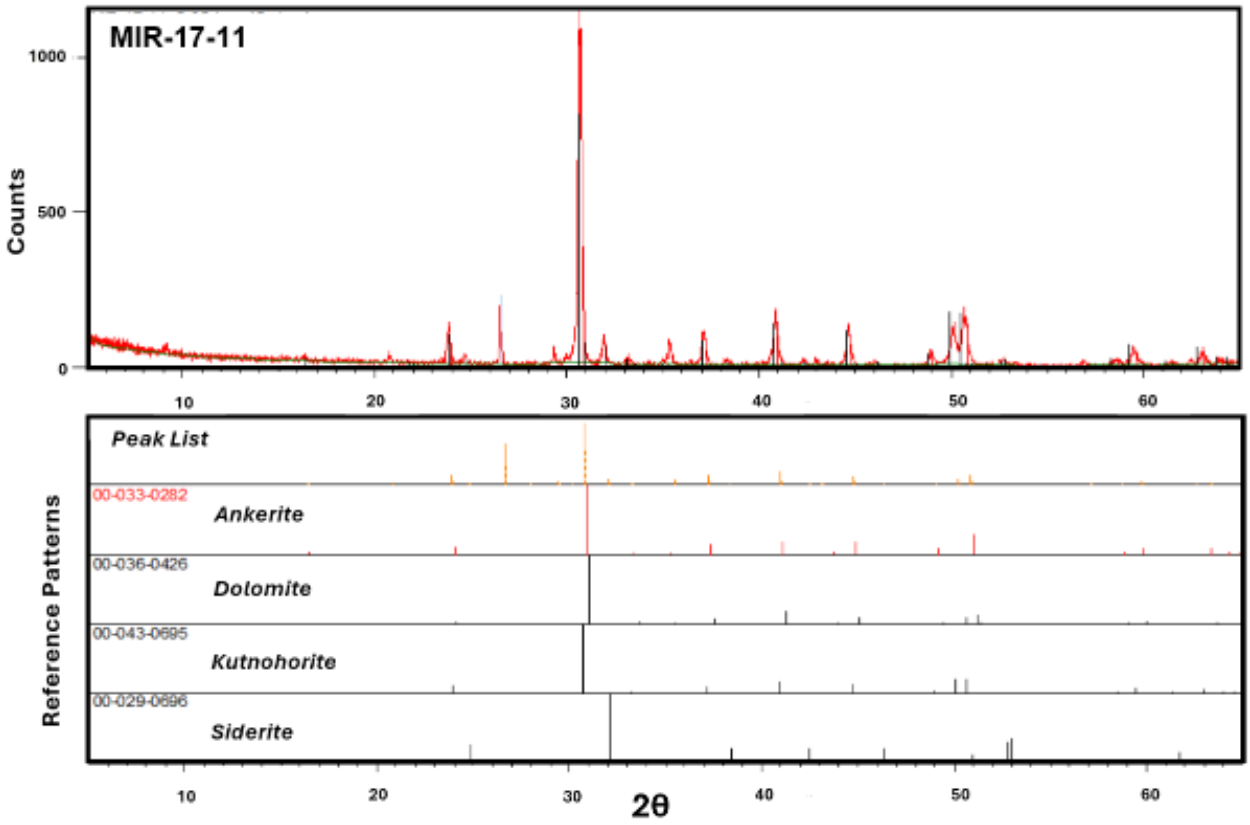


Figure 1: XRD analysis of LWD-99-01 Sample MIR 17-11 taken from the Upper Cherty showing variation in carbonate mineralogy (ankerite (00-033-0282), dolomite (00-036-0426), kutnohorite (00-043-0695), and siderite (00-029-0696)).

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The Badgerow complex, a Midcontinent Rift-related REE-Zr-rich peralkaline intrusion in the Grenville Province near Verner, Ontario

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The Badgerow complex (Lumbers 1975; Easton 2025) is located approximately 8.5 km north of the community of Verner within the northern Nepewassi domain of the Grenville Province (Easton 1992). The main part of the complex is roughly circular, approximately 4.5 by 3.5 km in size (Figure 1), and is only weakly deformed, with a narrow gneissic margin and a massive to slightly foliated interior. It consists predominantly of pink weathering, medium-grained monzogranite with less than 5% mafic minerals (sample 24RME-3047). Near the eastern margin of the complex, fine-grained monzogranite veins crosscut medium-grained gabbro of the complex containing relict pyroxene cores rimmed by amphibole. The monzogranite was sampled for geochemistry and U-Pb geochronology because of the relatively undeformed nature of these rocks, and the fact that the complex is the only near-circular pluton within Nepewassi domain.

Approximately 600 m northeast of the near-circular body, Lumbers (1975) included an approximately 6 km long, up to 1 km wide, lens of gneissic syenite as part of the Badgerow complex. Well-exposed along Highway 575 (Figure 1), the lens is a homogeneous, medium-grained, gneissic amphibole syenite (sample 24RME-3052) hosted by migmatites. Given its mineralogy, and its greater degree of deformation, the lens was assumed to be older than the granitic rocks. It is unclear why Lumbers (1975) included it in the Badgerow complex.

Preliminary geochemical results from the complex were reported in Easton (2025, 2026). Sample 24RME-3052 (Figure 2) is peralkaline and has niobium, yttrium, zirconium and total rare earth

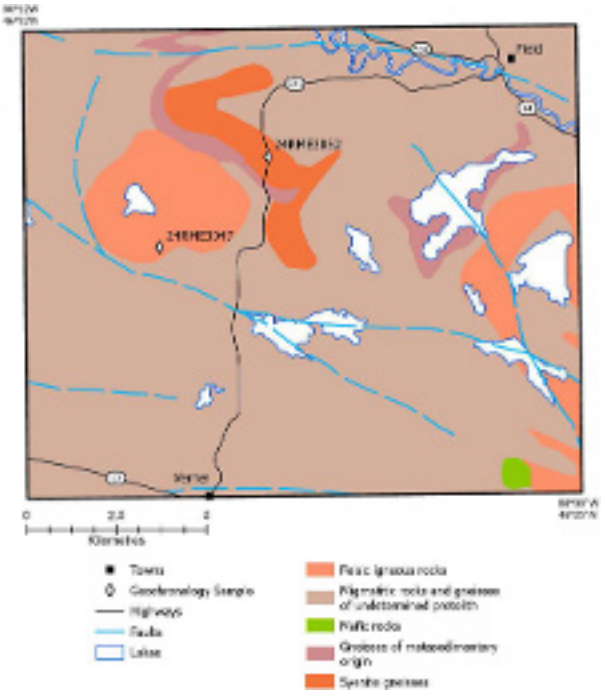


Figure 1. Simplified geological map of the Badgerow complex in the Grenville Province north of Verner (*from* Easton 2025). Sites sampled for geochemistry and for U/Pb geochronology are indicated.

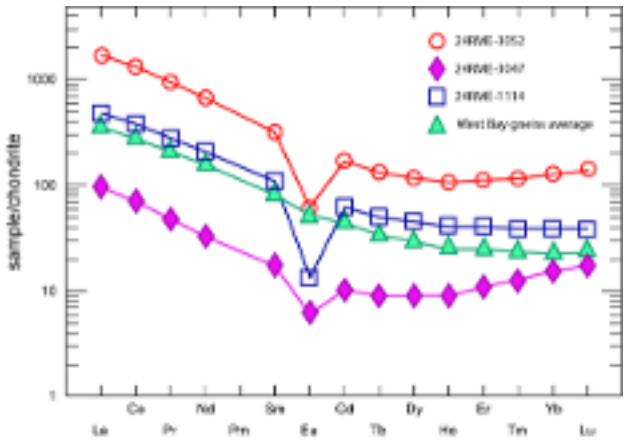


Figure 2. Chondrite-normalized rare earth element plot for granitoid samples mentioned in the text (*from* Easton 2025). Remember the y-axis scale is logarithmic, so the difference between samples 24RME-3047 and 24RME-3052 is larger than it might appear (e.g., La normalized is 97 ppm for sample 24RME-3047 but 1866 ppm for sample 24RME-3052). Sample 24RME-1114 is an undeformed monzogranite exposed near Noelville. Normalizing values of Sun and McDonough (1989) were used.

contents (164, 155, 4800 and 1936 ppm, respectively) that are some of the highest recorded for any igneous rock sample from the Grenville Province of Ontario. There are some similarities between sample 24RME-3052 and the West Bay migmatitic monzonite body to the south of Verner (Easton 2014). Key differences are that the West Bay body samples do not show a europium anomaly (Figure 2) nor are they peralkaline. It is unclear if the gneissic syenite was originally an intrusive or a volcanic rock. If volcanic, it has a comendite composition. In contrast, granite sample 24RME-3047 has a much lower total rare earth content (Figure 2).

Preliminary U–Pb chemically abraded-isotope dilution thermal ionization mass spectrometric results on zircons have been obtained from samples 24RME-3047 and 24RME-3052. Zircons from sample 24RME-3047 are discordant and lie along a reference line anchored between 1097 and 2700 Ma. The most concordant zircon from sample 24RME-3052 gives a $^{207}Pb/^{206}Pb$ age of 1106 Ma (igneous based on Th/U). This age is older than Grenvillian metamorphism in Nepewassi domain (1030-980 Ma, Easton 2026), but similar to the Early Stage of Midcontinent Rift magmatism (1110-1104 Ma, Smith et al. 2026) and the Rb-Sr age of a mantle-xenolith bearing lamprophyric breccia at Elliot Lake (1112.8±4.95 Ma, Legros et al. 2024). Both these potential Midcontinent Rift-related intrusions lie along the northwest-southeast rifting trend of the Early Stage of magmatism, despite their location east of any previously described Midcontinent Rift magmatism. These new results suggest that other Midcontinent Rift-related intrusions may be present in the Sault Ste-Marie to North Bay area.

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Comparing mineralogy along a surface to depth transect of the ~2.7 Ga North Limb Soudan Iron Formation, NE Minnesota.

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The Lake Vermilion-Soudan Underground Mine State Park in Northeast Minnesota is home to the classic 2.7 Ga Algoma-type Banded Iron Formation - a type of authigenic, chemical sedimentary rock known to record past ocean chemistry. Here, we compare multiple generations of mineralization in the Soudan Iron formation to evaluate the relative timing of oxidation reactions. Recent U-Pb and (U-Th)/He hematite geochronology places new age constraints on iron mineralization of microplaty hematite, documenting that this generation of hematite post-dates initial deposition by over 1 billion years (Allerton et al., 2025). Distinguishing between initial mineral formation and later overprinting is critical for reconstructing paleowater-rock interactions within the Soudan system. The goal of this work is to compare drill core and outcrop records from the north limb of the Soudan fold to samples from the mineralized portion of the Soudan mine, with a focus on building a spatial map documenting these oxidation reactions.

To evaluate mineral reactions in the Soudan Iron formation, we combine transmitted and reflected light petrography with X-Ray Diffraction (XRD), focusing on a vertical transect of samples from drill core 26501 from the north limb of the Soudan Iron Formation, comparing these samples to nearby surface outcrop samples, and mine samples from the fold hinge to the west. Preliminary results indicate shallow core samples (28.5 to 95 feet) contain dominant mineral assemblages of quartz, calcite, magnetite, hematite, and minimal iron silicates, while deeper samples (129 to 394 feet) mainly contain quartz, magnetite, carbonate, chalcopyrite, and iron silicate assemblages, lacking visible hematite. To compare optical data to XRD data, we prepared powdered whole rock samples using standard cutting and crushing techniques for XRD scanning at positions ranging from $2\theta = 5°$ to $2\theta = 65°$. Resulting peaks were matched to mineral reference patterns provided by the X'Pert HighScore analysis software and compared to observed mineralogy of thin section samples from drill core 26501. XRD results confirm the presence of quartz, magnetite, and hematite in shallow drill core samples, and an assemblage of quartz, magnetite, and iron silicates in deeper drill core samples.

Combined, petrographic data and XRD data indicate hematite is confined to shallow drill core samples. This observed trend continues in petrographic data from surface outcrop samples near the same location, which also contain abundant hematite. The absence of hematite at depth in drill core samples, combined with the top-down nature of the hematite distribution, could indicate minor amounts of hematite locally formed from surface oxidation distal to the mine site. Next steps include more detailed paragenesis work in combination with larger-scale mapping of the spatial distribution of hematite in drill core along the north limb of the Soudan iron formation towards the historic mine site which sits at the fold hinge. Mapping the extent of multiple generations of oxidation reactions can help document past fluid-rock interactions and allows for identification of preserved ferrous iron-containing assemblages at depth in the iron formation. Such ferrous-iron-containing phases may record depositional information and are of interest for potential natural or stimulated hydrogen generation.

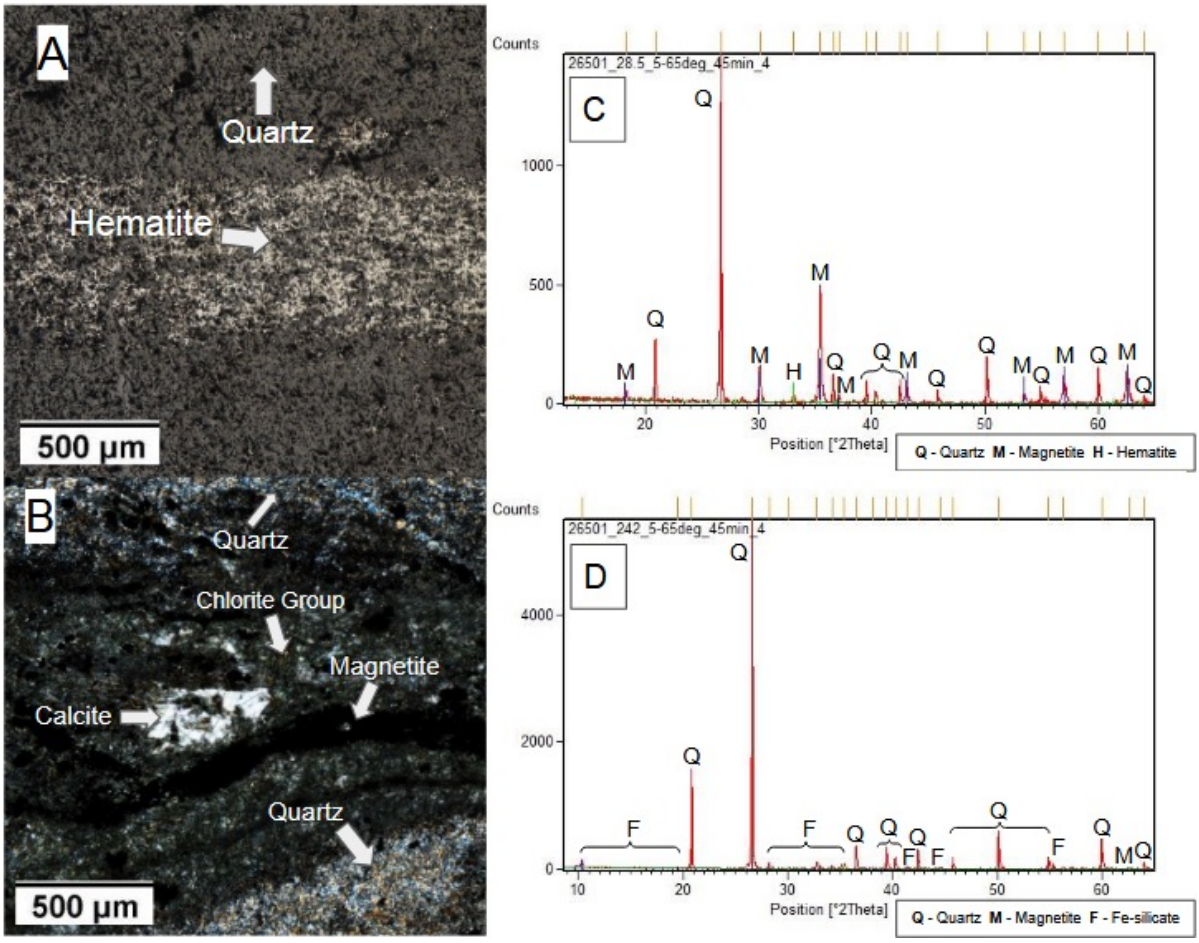


Figure 1.) Petrographic photomicrographs and X-ray Diffraction patterns of the Soudan iron formation from core 26501. (A) Reflected light image of sample 26501-28.5, a shallow (28 feet depth) banded iron formation sample with quartz and hematite. (B) Cross-polarized light image of sample 26501-191, a deeper iron formation sample (191 feet), that contains quartz, calcite, magnetite, and iron-silicate mineral phases. (C) XRD analysis of sample 26501-28.5 (28 feet depth) with peaks that match mineral reference patterns of quartz, magnetite, and hematite. (D) XRD analysis of sample 26501-242 (242 feet depth) with peaks that match mineral reference patterns of quartz, magnetite, and iron silicates.

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Middle school virtual field trip lessons materials for Archean formations of Lake Vermilion-Soudan Underground Mine State Park

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The Lake Vermilion-Soudan Underground Mine State Park located in St. Louis County, Minnesota provides unique opportunities to learn about Archean geology and mineral resources of northern Minnesota. Archean rocks exposed in the park consist of a series of mafic lava flows and intrusive rocks interlayered with classic banded iron formation, iron ore, felsic tuffs, and chlorite-sericite schists (Hudak et al., 2014, Hudak and Peterson, 2014; Peterson et al., 2016) and record deformation associated with the accretionary growth of the Superior craton. A cross-section through the stratigraphy can be observed along a trail through part of the east side of the park. The trail is in the planning stages and is in collaboration with the state park. The purpose of this project is to enhance formal and informal Earth science education in Minnesota. After consultation with local secondary teachers the project expanded to include a virtual field trip with an accompanying lesson as part of the formal education portion of the project.

In 2019 Minnesota revised their science standards (Minnesota Department of Education, 2019). These changes marked a significant change in the pedagogical practices aligned with national trends such as Next Generation Science Standards (NGGS) (NGSS Lead States, 2013). There are a number of shifts in instruction teachers are challenged to make when implementing these standards including using phenomenon based instruction (BSCS Science Learning, 2017; Reiser et al., 2021). Phenomenon based instruction engages students in a series of lessons arranged in a cohort storyline around a real world, observable events.

An additional challenge facing Minnesota educators was moving Earth science in from 8th grade to 6th grade. According to survey data collected from the Minnesota Earth Science Teachers Association many 6th grade teachers did not feel prepared to teach Earth science content. A combination of lack of high quality instructional materials for Minnesota phenomenon and gaps in the required background knowledge are some factors contributing to these findings. This project provided teachers with high quality instructional materials that are aligned with the 2019 Minnesota State Science Standards for 6th grade teachers.

Three, 45-minute lessons were designed to address the stratigraphy standard. The goal for the students is to tell the geological story of the park. The first lessons take students on a virtual walk through the park stopping at six significant outcrops along the way (Figure 1). At each stop students are making observations of the rock outcrops and hand samples while also asking questions. The second lesson, using information about rock formation, processes the map and picture of core samples taken from locations in the park (Figure 2) while applying principles of deformation and stratigraphy. formations and thus the early geologic history of the Earth. The lessons conclude with students writing a story of the Archean formations and thus the early geologic history of the Earth.

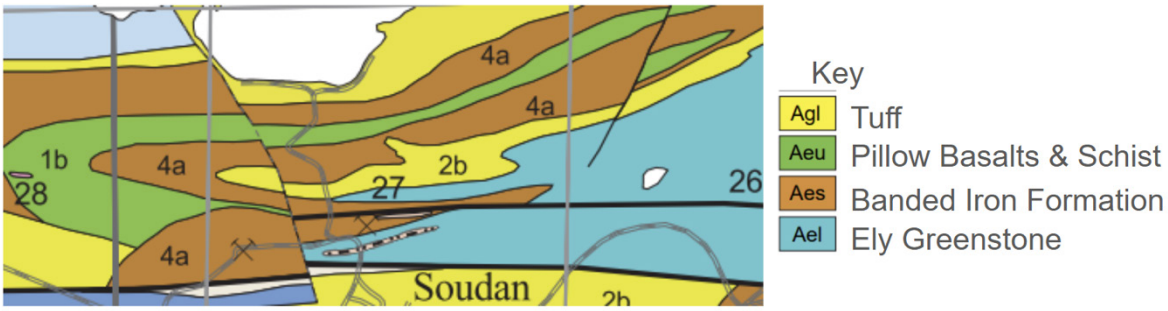


Figure 1: The first two stops orient students to the park and where they learn about the park's iron mining history including an open pit and a trip down to a deep mine. After emerging from the underground mine they make three stops at outcrops: the classic BIF outcrop, the schist in BIF outcrop, and Ely Greenstone pillow basalts. The final stop is to make observations of tuff and the lower section of the Ely greenstone from rocks found on the "ground." (after Peterson et al., 2016)

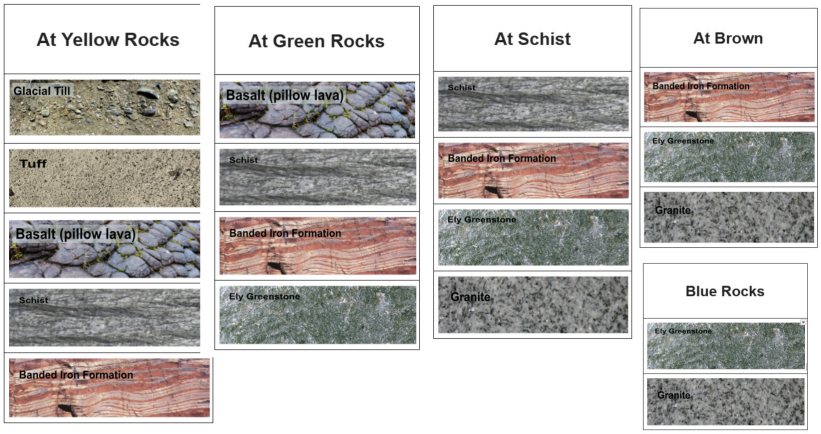


Figure 2: Virtual core samples that students use to correlate and deduce the order the rocks are formed in. Each core sample comes from a point of the map in figure 1. These are not actual core samples rather simplified samples that allow students to correlate the stratigraphy of the area.

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Geochemical Constraints on Mn Cycling in the Paleoproterozoic Gunflint Formation

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Iron formations (IFs) are iron-rich (>15% Fe) and siliceous (>20 wt.% SiO_2) chemical sedimentary rocks that precipitated from seawater. Most IFs were deposited between 2.80 and 1.85 Ga during the Neoarchean and Paleoproterozoic, followed by a near one-billion-year hiatus before reappearing in the Neoproterozoic. The Gunflint Formation in the Animikie Basin, overlain by the siliciclastic Rove Formation, is composed mainly of IFs, chert, carbonates, and minor siliciclastic sediments deposited during the Paleoproterozoic (~1.88 Ga), and represents the final major episode of IF deposition. Therefore, investigating the source materials and redox conditions of the Gunflint Formation is key to understanding this transitional period in the marine environment.

This study conducts a high-resolution stratigraphy and chemostratigraphy study of a 142.9-meter-deep drill hole (MC-1-89), located south of Thunder Bay in the Gunflint Iron Range. Samples were taken in short intervals of ~1-5 meters along the drill core, where 55 samples were analyzed for major, trace and rare earth (REE+Y) element concentrations through ICP-OES and MS.

All samples from drill core MC-1-89 consists of IFs (often magnetite, hematite rich, or jaspilite), chert, carbonates, and siliciclastic rocks (often fine sandstone and argillaceous mudstone). IFs contain a total Fe content ranging from 15-36%. MnO values are enriched in the upper and lower portion of the hole (0.30, 0.57 wt.% respectively), while depths 30-90m show an average of 0.10 wt.%. Samples with >1 wt.% Al_2O_3 and >0.1 wt.% TiO_2 are excluded for REE+Y analysis due to potential detrital contamination. The rest of the samples do not show correlation of REE+Y with $Al_2O_3 + TiO_2$ ($R^2 < 0.1$), suggesting the REE+Y system is authigenic. All samples display positive Eu/Eu* (1.18 – 3.14, average ~1.83), suggesting a strong hydrothermal input. Moreover, most of the samples display a depletion of LREE, enrichment of HREE, along with high Y/Ho ratios (average of 30.4), suggesting marine signatures. All these features are typical of global Paleoproterozoic IFs.

A key distinction between the Gunflint Formation and other Paleoproterozoic IFs is the presence of positive Ce anomalies in many samples, which contrasts with most Archean and Paleoproterozoic IFs. Ce/Ce* values decline with depth (0.35 – 1.92, average =1.32). The elevated Ce might be related to the cycling of Mn oxides in the water column, but further detailed work is still needed to better constrain the mechanism.

Modified Sequential Iron Extraction Method for Analyzing Rare Earth Elements in Banded Iron Formations

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Banded iron formations (BIFs) are chemically precipitated sedimentary rocks characterized by alternating iron-rich and silica-rich layers, formed predominantly in Precambrian marine environments. Rare earth elements (REEs) are among the most used geochemical tools for understanding the origin and deposition of iron formations and other iron oxide–rich sedimentary rocks, because the precipitation of ferric iron oxyhydroxides can adsorb signatures from the water column and thus preserve a seawater REE signature. However, BIFs that formed in shallow-marine settings often contain detrital material, thereby affecting the bulk rock geochemistry. For instance, detrital input may elevate light REEs and suppress yttrium (Y) anomalies, complicating interpretation.

Sequential extraction of different iron phases (e.g., magnetite, iron carbonates, and iron sulphides), developed by Poulton and Canfield (2004), was used to accurately determine the composition of iron-bearing minerals without interference from detrital materials. However, the chemical solutions used in this process introduce additional dissolved ions, thereby increasing total dissolved solids (TDS) and making it difficult to analyze low REE concentrations using ICP-MS. Therefore, this study aims to develop a method to reduce the introduced TDS while still extracting enough REEs for detection by ICP-MS.

Six concentrations (10%, 20%, 40%, 60%, 80%, and 100%) of an ammonium oxalate monohydrate and oxalic acid solution were used for sequential extraction. This solution was used to selectively extract magnetite from two types of samples: (1) magnetically selected magnetite grains, and (2) bulk rock powder from the same sample. The extracted iron solutions were then analyzed for REE anomalies for interpretation. Sample patterns were compared to determine the minimum concentration required to introduce additional elements into the solution without resulting in a high dilution factor. The patterns were also compared with those from Dolega's (2018) bulk-rock acid digestion to assess any improvements in REE patterns. The results and comparison indicate that the REE patterns show the greatest improvement at a solution concentration of 40%. However, one concern is the absence of a positive Y anomaly, which differs from the original bulk rock data (Dolega, 2018). It is likely that reprecipitation causes the interference with Y, but further work is still needed for this investigation.

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Time-to-depth conversion of seismic-reflection data from eastern Lake Superior and implications for the eastern arm of the Midcontinent Rift

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Seismic-reflection data were acquired in the mid 1980s along several lines across eastern Lake Superior by industry and the Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE) (Fig. 1). The lines form part of a larger network of crossing lines over the entire lake, which can be used to develop three-dimensional geologic models of the Mesoproterozoic Midcontinent Rift that lies below. To better interpret these lines, we developed velocity models to convert seismic reflections versus two-way travel time (TWTT) to reflections versus depth. In addition, the velocity models themselves provide insights into the structure of the Midcontinent Rift by recognizing common velocity ranges for certain rock types (Grauch, 2023).

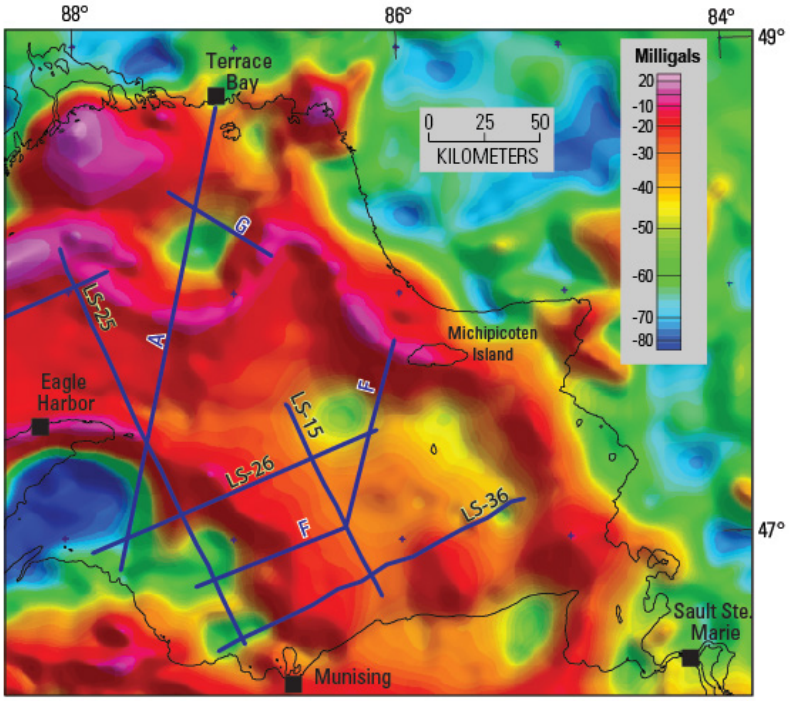


Figure 1. Seismic-reflection lines overlain on Bouguer gravity for eastern Lake Superior. Gravity map from Anderson and Grauch (2018) is displayed in color shaded-relief, with illumination from the northeast. Lake Superior shores are outlined in black.

Digital data are publicly available for lines A, F, and G, collected as part of GLIMPCE. Digital data were derived for the industry lines (LS-15, LS-25, LS-26, and LS-36) by scanning published images from McGinnis and Mudrey (2003) and estimating the location parameters.

Velocity model development was guided by (1) bathymetric data, providing thickness of the low-velocity water column; (2) previous shallow seismic-reflection studies targeting the top of bedrock below glacial till and lake sediments; (3) previous refraction studies, which provide information on depth and compressional velocity at interfaces of large velocity contrast; and (4) correlations across multiple lines, allowing independent constraints on individual lines to influence modeling on crossing lines. In addition, digital data for the GLIMPCE lines were analyzed using common midpoint gathers to check the accuracy of the modeled velocities. Gravity anomalies provided qualitative guidance on broad velocity variations.

The velocity models consist of intervals of constant velocity bounded by prominent horizons recognized in the seismic-reflection TWTT sections before time-to-depth conversion. After

conversion, the resulting reflection sections versus depth show similar overall geometry compared to the TWTT sections, although structural relief is more subdued. Thus, several qualitative aspects of the results are similar to those observed by previous workers (e.g., Cannon et al., 1989; Mariano and Hinze, 1994; Samson and West, 1994). For example, lines that cross the lake from SW to NE are interpreted to show a symmetric basin of fairly uniform basalt thickness except at the edges of the basin, where the basalts rise and thin and are expressed by pronounced gravity highs (Fig. 1). The thickness of the overlying sedimentary section increases toward the middle of the basin to 7–9 km and the underlying volcanic section is locally folded.

In contrast, the velocities derived from the modeling indicate different rock types than anticipated from the previous interpretations at the edges of the basin. The upturned basalt edges have been previously interpreted as basalt layers thrust over the younger Jacobsville Sandstone, with sharply rounded reflection patterns considered as thrust rollovers on lines LS-26 and LS-36 between the crossings with LS-15 and LS-25 (Mariano and Hinze, 1994). Where these authors interpret Jacobsville Sandstone under thrust faults, the models indicate velocities on the order of 6.0 km/s instead of the expected velocity range of 3.0–4.5 km/s for this unit (Grauch, 2023). The higher velocities are consistent with those of igneous or basement rocks instead. An alternate interpretation is that the upturned edges represent the vestiges of magmatic feeder zones and the sharply rounded reflection patterns represent igneous intrusions. The zones may be faulted and folded due to the later compressional regime that affected the region.

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Ice flow history, surficial geology, and till composition of Georgia Lake area, northwestern Ontario

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During the last glaciation, the Lake Superior basin was covered by the Laurentide Ice Sheet. The ice sheet advanced over the landscape, eroding the substrate and depositing a variety of sediments including till (a common sample medium for mineral exploration) and glaciofluvial sand and gravel (a common source of aggregates). During deglaciation, glacial lakes inundated the landscape depositing successions of silt and clay, which can act as a barrier for mineral exploration and infrastructure development. As such, the Ontario Geological Survey completed a three-year field mapping program which measured striations and landforms to decipher different ice flow directions, mapped the surficial geology around the Georgia lake pegmatite, and collected regional scale till samples to identify mineral prospectivity (Figure 1). These data hold broad applications for regional mineral exploration and land use planning / resource management decisions for local communities.

Striation and landform mapping were used to determine the relative age and direction of ice flow over the region. A southwest flow is pervasive across mafic uplands, suggesting this was the paleoflow direction during thickest ice cover (Arrows labeled 1 in Figure 1). As the ice sheet thinned, it became more topographically-controlled resulting in southward ice flow in lowlands, and westward ice flow on mafic uplands (Arrows labeled 2 in Figure 1). Finally, a late-stage re-advance out of the Lake Superior basin created northwestward striations and landforms in the areas around Thunder Bay (Arrows labeled 2 in Figure 1).

Surficial mapping completed in the Georgia Lake area indicate more sediment than previously identified although the sediments are mostly thin (>2 m). Till is common at surface and many new small eskers have been mapped. Glacial lake sediments are present, and at a higher elevation than previously indicated. Postglacial organic accumulations are also abundant over the landscape, specifically over poorly-drained substrates like till and glaciolacustrine silt and clay.

Till samples were also collected as part of the project and analyzed for till matrix geochemistry and indicator minerals. Till compositions indicate two units differentiated based on bedrock provenance. One till contains southwest transported carbonate material while the other contains locally sourced bedrock material. Lithium material transported southwest from the Georgia Lake pegmatite is also clearly identified in both the geochemistry and indicator mineral data. Further work is being completed on the till samples to indicate prospectivity of the region for other deposits.

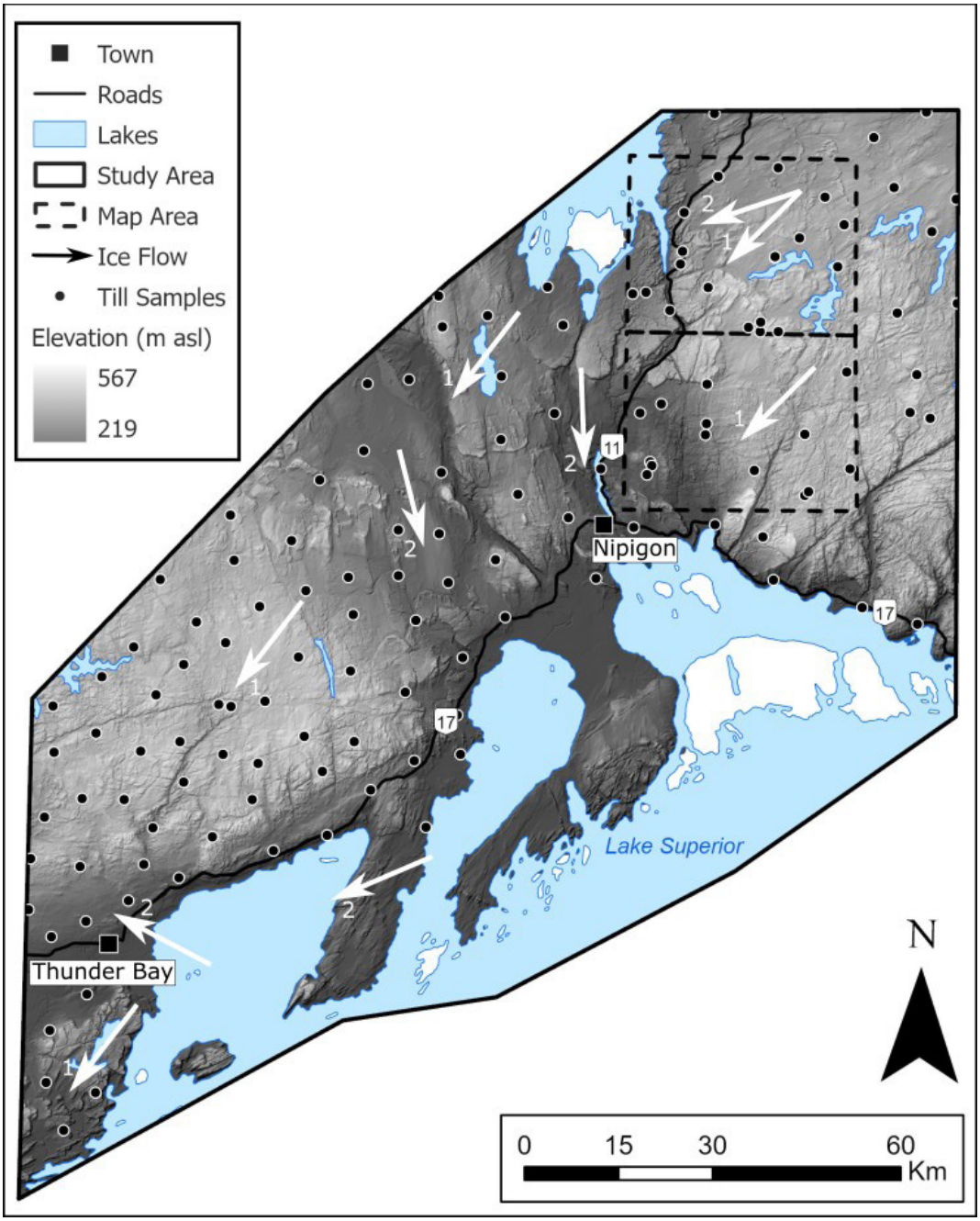


Figure 1: Study area for the project. Highways and towns are labeled. Ice flow directions indicated by white arrows with the corresponding flow event as the number beside (1: older, 2: younger). Surficial geology mapping area is indicated by the dash box. Till sample locations are circles.

Geochemistry, Petrogenesis, and Mineralization of the Makwa Deposit, Bird River Sill

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The Maskwa West-Dumbarton layered mafic-ultramafic intrusion is located approximately 145 km northeast of Winnipeg, Manitoba and is host to the Ni-Cu-PGE Makwa Deposit. The intrusion is related to the 2743 ± 0.5 Ma Bird River Sill (BRS; Scoates and Scoates, 2013) which is approximately 15-25km long and is made up of several separated ~800m thick differentiated mafic-ultramafic intrusive bodies. The Maskwa West-Dumbarton intrusion is emplaced into the mafic metavolcanic MORB-type massive to pillowed basalt Northern Lamprey Falls Formation (Mealin, 2008, Duguet et al., 2009). After the discovery of the Maskwa deposit in 1975, a year later 332,000 tonnes of nickel copper ore was mined in a shallow open pit (Grid Metals Corporation, 2024). In 2004 Mustang Minerals (now Grid Metals Corporation) acquired the property and have since completed extensive drilling and geophysical surveys targeting PGE mineralization.

The approximately 5 km long Maskwa West-Dumbarton intrusion is composed of a ~500m thick upper gabbro-anorthositic section and a ~500m thick lower section of metaperidotite-metapyroxenite (Mustang Minerals Corp., 2014). The intrusion has been metamorphosed to the lower amphibolite facies (Coats and Buchan, 1979) with primary igneous textures Maskwa West-Dumbarton obscured or completely overprinted by alteration. The Makwa deposit is a conventional basal accumulation type magmatic sulphide deposit with the highest grade mineralization hosted within the lowest portion of the ultramafic series (Grid Metals Corporation, 2024). The deposit is comprised of a magmatic assemblage of disseminated to net textured and semi-massive pyrrhotite-pentlandite-chalcopyrite as well as low sulphide platinum group minerals (PGM) mineralization (Grid Metals Corporation, 2024). The open pit resources at Makwa are indicated to be 14.2 million tonnes with 0.48% nickel, 0.11% copper, 0.02% cobalt, 0.37 g/t palladium, and 0.10 g/t platinum (Grid Metals Corporation, 2024). The most recent up to date resource estimate for the high-grade zone indicates 4.8 million tonnes with a grade of 0.89% nickel and a 1.26% nickel equivalent (Grid Metals Corporation, 2024). The purpose of this project is to characterize the stratigraphy of the Maskwa-Dumbarton body and Ni-Cu-PGE mineralization. Assess the effects of alteration on the mineralogy, trace element geochemistry, and ore remobilization.

A fence of five drill holes covering the stratigraphy of the intrusion were selected for this project where 151 core samples were collected. Forty polished thin sections were cut in representative areas for petrographic and scanning electron microscope (SEM) analysis. 141 of those samples were selected for whole rock geochemical analysis. A combination of petrographic and geochemical analysis was used to characterize the Makwa mafic and ultramafic rocks. Primary mineralogy is almost entirely replaced (Fig. 1) therefore preserved relict cumulus textures along with whole rock geochemistry are utilized to determine primary mineralogical composition. The Makwa ultramafic samples dominantly plot as Mg-rich cumulates within the komatiite field (Fig. 2) displaying a trend of Fe-enrichment highlighting strong fractionation. The results of this study will be used to determine the evolution, geotectonic setting, and sulfur source of the sulphides.

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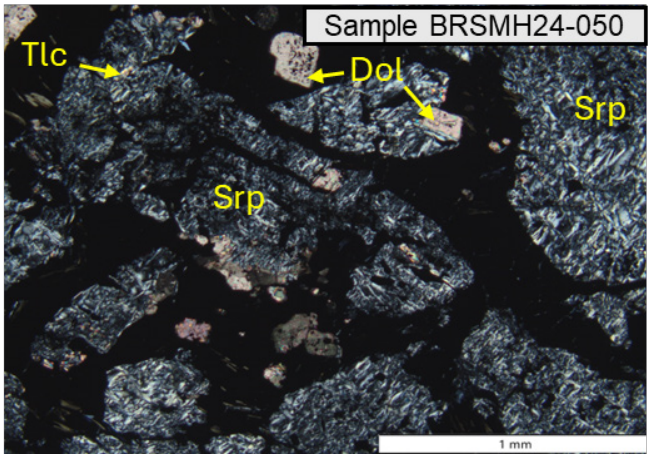


Figure 1. Photomicrograph (XPL) of Makwa peridotite displaying mesh-textured serpentine replacing metamorphic blade shaped olivine in net-textured sulphides.

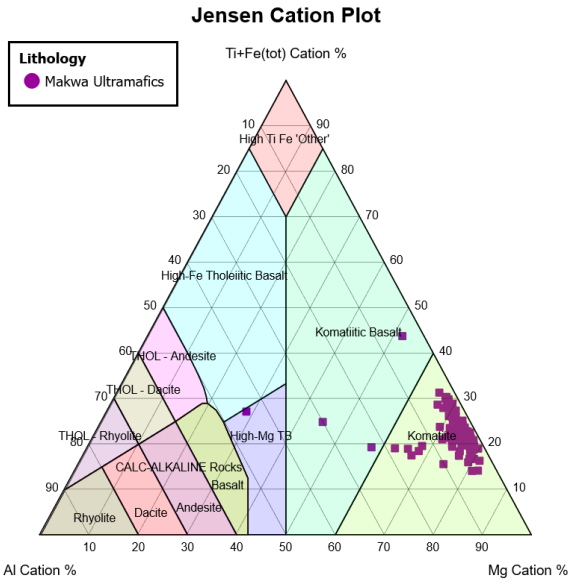


Figure 2. Jensen Cation Plot highlighting Makwa Mg-rich cumulates dominantly within the komatiite field displaying Fe and Al-enrichment trends highlighting strong fractionation.

Using Anisotropy of Magnetic Susceptibility and U-Pb Geochronology from the Bush Lake Granite, Florence County, WI to Understand Post-Penokean Continental Growth

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The Bush Lake granite in Florence County, Wisconsin, is well suited to constrain the timing of granitic magmatism relative to Proterozoic deformation events as the youngest intrusion in the Dunbar Gneiss Dome. The Dunbar Gneiss Dome is south of the Niagara fault zone, which marks the suture of the Pembine-Wausau terrane to the Superior craton during the 1.85 Ga Penokean orogeny (Schulz and Cannon, 2007). This suture may have been reactivated during later orogenic events, such as the ca. 1.75 Ga Yavapai orogeny, the ca. 1.65 Ga Mazatzal orogeny, and/or the ca. 1.45 Ga Baraboo orogeny. Emplacement and deformation of the Bush Lake granite determined through U-Pb geochronology, microstructural analysis, and anisotropy of magnetic susceptibility (AMS) fabric data provides insight into the tectonic history of the region.

The Bush Lake granite is a weakly peraluminous biotite granite that contains quartz, plagioclase, megacrystic alkali feldspar, and accessory allanite, zircon, titanite, and apatite. Microstructures in the Bush Lake granite indicate variable solid-state deformation, including interlobate grain boundaries and undulose extinction in quartz, as well as grain size reduction of quartz and feldspar. Magnetic mineralogy, which informs the AMS fabric, is dominated by paramagnetic biotite with trace magnetic oxides. AMS fabrics generally record NW-SE striking foliations and moderately plunging to subvertical lineations (Figure 1), which are consistent with predominantly NE-SW shortening at a high angle to the Niagara fault zone and associated vertical thickening of the crust. Based on solid-state deformation microstructures, this magnetic fabric formed after emplacement and crystallization of the unit and records a younger period of deformation than previously thought. Cathodoluminescence (CL) imaging shows that most Bush Lake zircons preserve oscillatory zoning of likely magmatic origin, though many zircon crystals also have irregular, disturbed zoning and low-CL regions consistent with alteration. The Bush Lake granite was previously interpreted to have intruded at ~1835 Ma as a late-stage intrusion of the Paleoproterozoic Penokean orogeny, coeval with other nearby granites (Sims et al., 1985). Based on U-Pb SIMS analyses of zircon, the Bush Lake granite is interpreted to have emplaced at 1749 ± 1 Ma, making it coeval with the 1754 ± 11 Ma Amberg granite, ~28 km southwest (Holm et al., 2005), rather than the more proximal ~1835 Ma granites in the Dunbar Gneiss Dome. Solid-state deformation recorded by the Bush Lake granite may signify a broader regional deformation event in northern Wisconsin after 1750 Ma, possibly related to re-activation of the Niagara Fault Zone during the Yavapai orogeny or later events.

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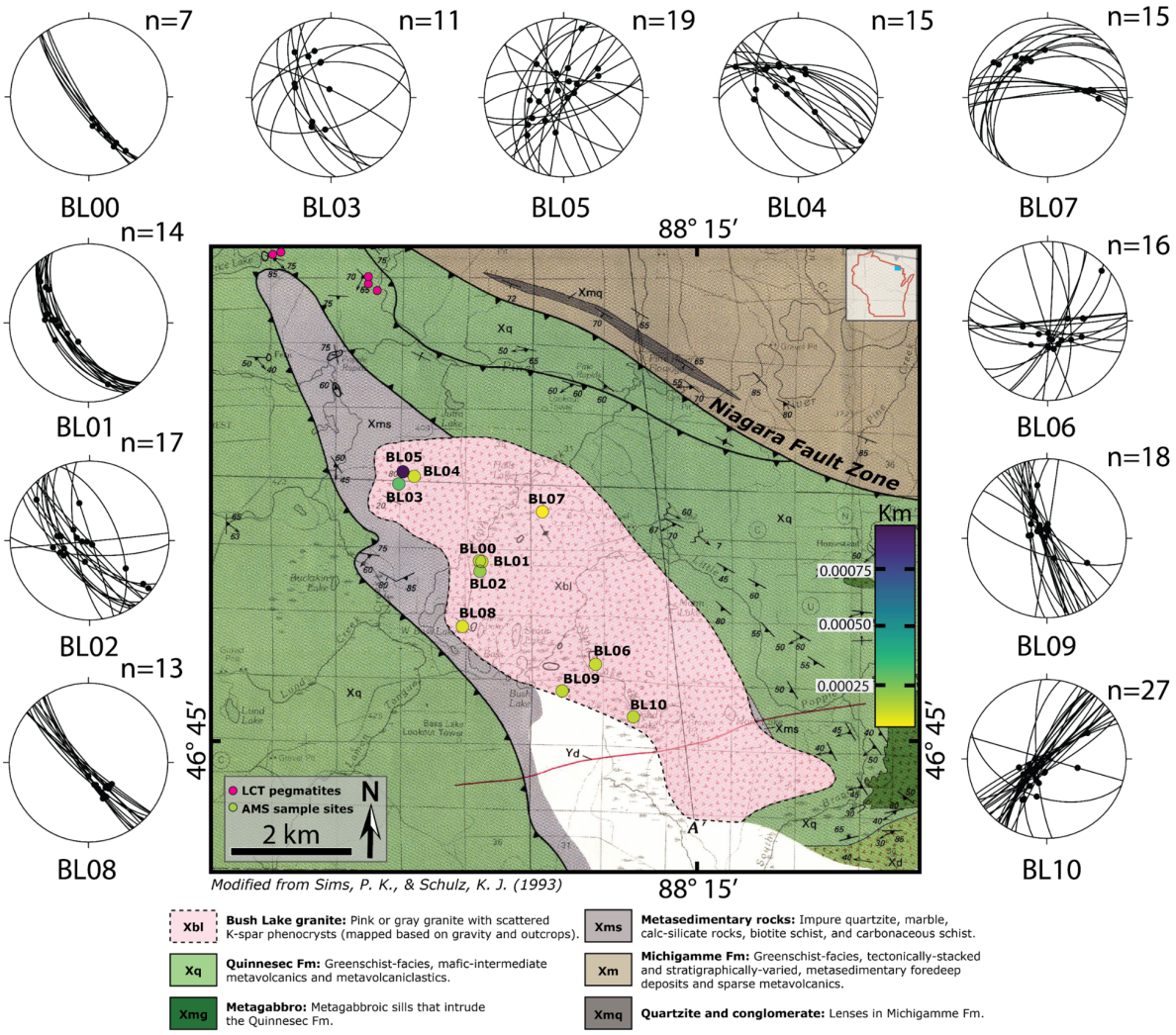


Figure 1: Simplified geologic map of the Bush Lake pluton (pink) in Florence, Wisconsin, with sample locations plotted and colored by average magnetic susceptibility [SI]. Lower hemisphere equal area net projections bordering the map show the AMS foliation plane and lineation at each site for each specimen. At each site, ≥ 2 rock samples are collected from different parts of the outcrop to test for slumping. Sample BL07 is an example of a failed test with two distinct sample groupings and does not provide reproducible data.

Can we improve the bouguer gravity resolution in the Cuyuna Range? Increasing gravity measurements in a region of high gravity station density.

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In East-central Minnesota, the Cuyuna-Penokean orogen is made up of deformed Precambrian rocks of the Penokean-Fold-Thrust belt and adjacent terranes. This complexly folded and thermally overprinted region hosts the 2nd largest known manganese occurrences in the US (Cannon et al., 2017) and has been mined intermittently since the early 1900s. Despite decades of mining, mapping the geology is difficult with most of the bedrock overlain by thick glacial sediments from multiple glacial advances. Mapping of this critical resource and the surrounding region has relied on very limited outcrops, historical mining records, drill core, and geophysical datasets. The Minnesota Geological Survey (MGS) houses state-wide aeromagnetic, gravity, and rock property geophysical datasets that are a key tool in mapping the bedrock geology. The MGS gravity database consists of over 60,000 variably spaced measurements (Chandler et al., 2010). In the Cuyuna-Penokean area, specifically the areas around the Emily District, North Range, and parts of the South Range, the average gravity measurement spacing is ~1.6km with select areas at 0.8-1km. Station spacing of this density is generally considered very good coverage for regional geologic modeling. Due to the complex geology of the area, the MGS set out to determine if increased gravity data will further improve the geophysical resolution and subsequent geologic mapping.

Over three field seasons, as part of an Earth Mapping Resources Initiative (Earth MRI) funded project, 210 new gravity points were measured, processed, and added to the gravity database. Gravity stations were tied to an existing base station, and three new field base stations were created in the area to reduce gravity loops. Measurements were prioritized along five transects perpendicular to structure: 2 North-South and 3 Northwest-Southeast profiles. Due to the varying age and accuracy of the gravity database and base stations, tie-point measurements were made at existing gravity station locations for comparison and if any corrections were needed.

Multiple comparisons were made between the original and updated datasets with raw 2D Bouguer gravity profiles and gridded Bouguer gravity and second vertical derivatives analyzed (Blakely, 1996). An increase in gravity measurement density resulted in variable differences along profiles resulted in less smoothing and small shifts in slope in some regions but little to no difference in others. Both Bouguer and 2nd vertical derivative gravity grids showed significantly less variability due to inherent smoothing from the minimum curvature gridding process. Two-dimensional modeling was also performed to assess the impact of increased gravity measurement density to geologic mapping.

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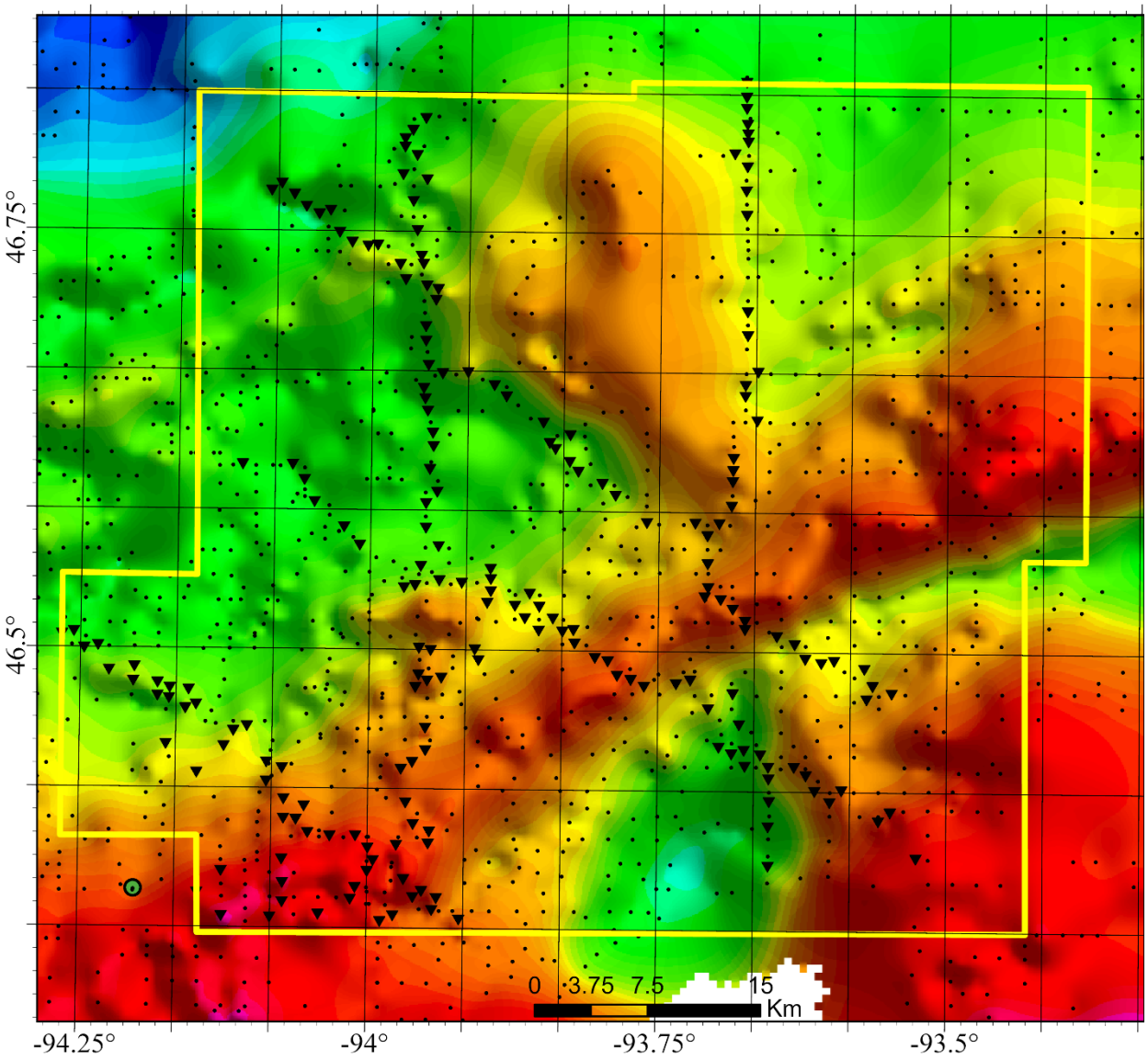


Figure 1: Bouguer gravity map of the Emily District, North Range, and South Range. Black dots are the existing gravity stations. Triangles are the new gravity stations. Circle in bottom left corner is the base station used for this study. Gravity values range from -14.9 - -67.8 mGals.

Using epidote and chlorite mineral chemistry to extend the alteration footprint around the Hemlo Au deposit, N. Ontario

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The Hemlo deposit is a world class Archean Au deposit situated in Northern Ontario, Canada with historic production of >21 Moz of Au over 35 years of continuous operation. The deposit has a strike length of ~3 km with a well-documented alteration footprint surrounding mineralization. LA-ICP-MS analyses of epidote, chlorite and pyrite from within and surrounding the deposit (Fig. 1) have identified major and trace element variations in mineral chemistry that allow for the discrimination of deposit-proximal and deposit-distal signatures.

Epidote compositions vary with distance from Hemlo, with the highest concentrations of As and Sb in epidote proximal to the mineralized zones. Anomalous trace element compositions in epidote can be detected up to 1.5 km further than the mapped alteration footprint. Chlorite also displayed variation in trace elements with deposit-proximal chlorite displaying exponentially higher Ti/Sr and V/Co values than deposit-distal and intrusion-related chlorite. The Ti/Sr ratio for chlorite expanded the geochemical footprint of the Hemlo deposit by up to 1 km. Pyrite displayed anomalous enrichments in a number of elements, with Au, Te and As proving to be the most effective pathfinder elements in pyrite as they were detected at anomalous concentrations up to 2.5 km from the deposit.

Several post-mineralization intrusions that surround the deposit were evaluated using epidote and chlorite chemistry to assess whether they generated any false positive geochemical anomalies. The distal post-mineralization intrusions have epidote with consistently low As and Sb concentrations and elevated Fe/Al values relative to deposit-related epidote and can be easily distinguished. Intrusion-

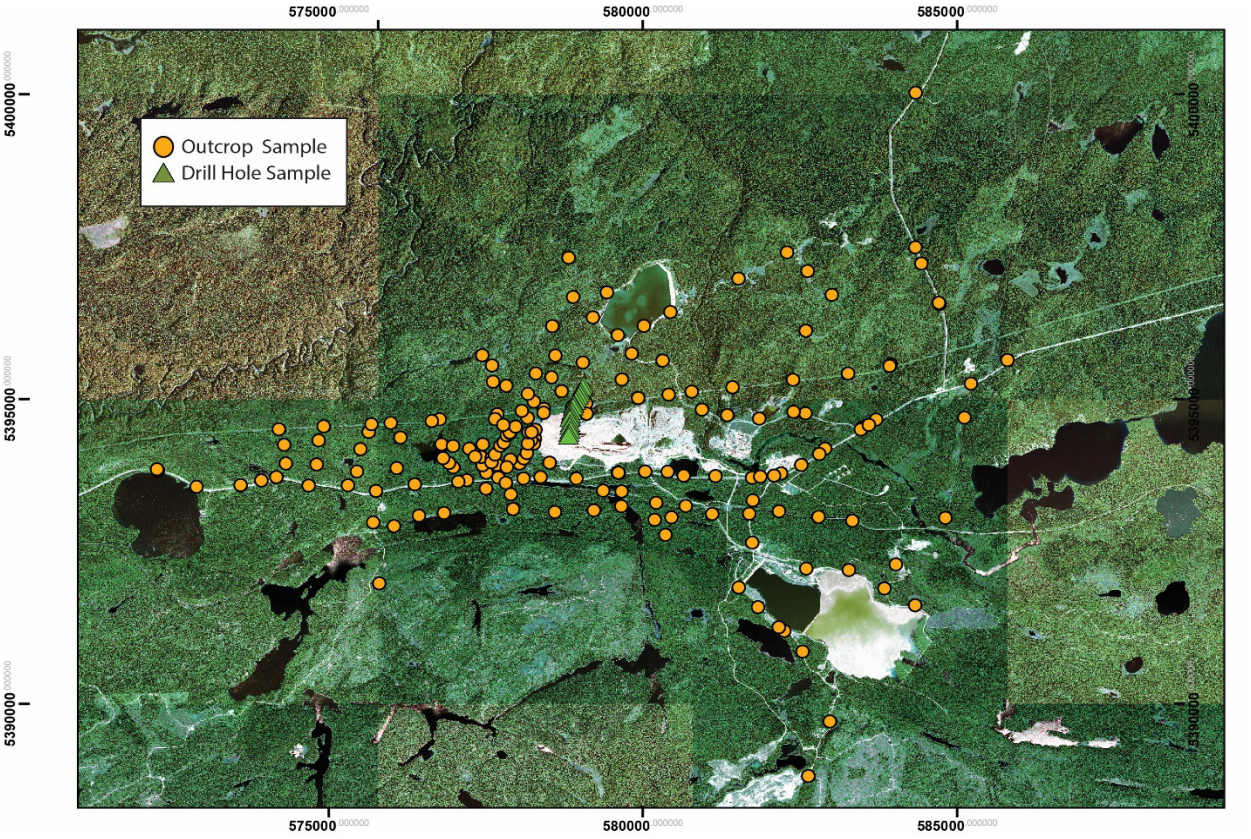


Figure 1. Location of samples collected for this study

related chlorite displayed low Ti/Sr and V/Co values relative to the deposit chlorite and was also found to be more enriched in Fe relative to deposit-proximal chlorite. These results indicate that the post-mineralization intrusions did not produce false positive mineral chemistry anomalies.

Variations in chlorite Fe-Mg content can be tracked spectrally using the position of the diagnostic 2250 nm absorption feature. Chlorite displays a range of wavelengths from 2240 – 2256 nm throughout the Hemlo district. Chlorite with lower wavelengths (< 2248 nm) display lower average Fe/Mg (<1) values whereas chlorite with longer wavelengths (> 2252 nm) display higher Fe/Mg (>1) values. Spectral variations 1550 nm absorption feature of epidote can be used to track compositional variations between the Fe-(epidote) and Al-(clinozoisite) epidote group endmembers. Epidote throughout the Hemlo area displayed a range of wavelengths from 1540 – 1564 nm. These variations in spectral features of epidote could be correlated to epidote major element variations with wavelengths > 1550 nm having on average lower Fe/Al values (< 0.8), whereas wavelengths < 1448 nm displayed average Fe/Al values of ~1.

The systematic variations in syn-mineralisation epidote and chlorite compositions around Hemlo suggests that methods developed for investigating geochemical footprints defined by green rock alteration around porphyry systems may also be applicable to Archean orogenic gold deposits.

Petrographic Study of Granular Iron Formation in the Gunflint Formation: Evidence for Well-Oxygenated Surface Waters

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Granular iron formation (GIF) exhibits distinct features compared to banded iron formation (BIF), being characterized by granule-rich textures and commonly interpreted as detrital, with some grains derived from sedimentary reworking of iron-rich clays, mudstones, arenites, and even stromatolites. Other granules consist of concentric hematite cortices that likely precipitated from Fe(II)-rich waters upon interaction with oxygenated shallow seawater. Previous studies have demonstrated that GIF provides valuable insights into shallow marine environments, as physical energy from waves, tides, and storms is largely restricted to depths above the storm wave base. The 1.88 Ga Gunflint Formation comprises both BIF and GIF, along with chert, carbonates, and minor siliciclastic materials, deposited on a storm-dominated continental shelf. In this study, we examine the petrography of GIF from the lower Gunflint Formation to identify evidence for redox variations in a shallow marine environment.

Thin sections of the GIF commonly exhibit oolitic textures, with subordinate peloids and oncoids. Ooids and oncoids are typically composed of hematite, whereas peloids commonly consist of a chert core with hematite rims. Most granules display well-developed concentric hematite cortices, suggesting that iron oxides were directly precipitated from an Fe(II)-rich water column. The grains are not uniformly in contact with one another; instead, many appear to be suspended within the matrix, indicating co-deposition of granules with silica gel. Approximately 30% of the matrix consists of carbonate material, which is randomly distributed within the chert matrix. Hematite grains in the GIF exhibit platy to needle-like morphologies, with grain sizes generally less than 15 μm. Most grains fall within the 1–5 μm range, suggesting an authigenic origin. Some ooids contain manganese carbonates within their inner rims, similar to those observed in the matrix, indicating Mn enrichment in bottom sediments.

Our findings suggest that during the early depositional stage of the Gunflint Formation, bottom sediments of the surface water were enriched in Mn, indicating that surface waters were sufficiently oxidizing to promote the precipitation of Mn oxides. However, subsequent early burial of organic matter may have facilitated Mn reduction. Importantly, redox conditions in the shallow marine environment appear to have been oxidizing enough to preserve Fe oxides, but not sufficiently oxidizing to retain Mn oxides. The occurrence of bacterial reduction suggests an increase in organic carbon burial during this time, potentially associated with enhanced primary productivity; however, further investigation is required.

Interactive Geospatial Geoheritage: Efforts to Support Place-based Exploration and Digitally Preserve Keweenaw's Geoheritage

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The Keweenaw Peninsula, renowned for many superlatives – world's largest native copper deposit, first major industrial mining complex in the United States – continues to inspire scientists, historians, and the general public. Ongoing geoheritage efforts enable these groups to explore the deep connections between the underlying geology, landforms, mining industry, and the people working and living on this land for over a millennia. Geoheritage uses a structured approach to identify, manage, and protect geosites and areas with geologic features of significant scientific, educational, cultural, or aesthetic value. Grassroots efforts, spearheaded by Bill Rose, have raised awareness and elevated the prestige of Keweenaw Geoheritage on the global stage despite lacking any formal designation. Bill's efforts with others to create the first U.S. Geoheritage Park is still in the development stage, while other efforts led by Michigan Technological University (MTU) personnel are helping to bring Bill's dream to fruition through two geospatial projects: 1) the Keweenaw Geoheritage Geodatabase and companion webGIS-viewer; and 2) Preservation, Indexing, and Enhanced Utility of Historic Copper Mining Drill Hole Records.

The Keweenaw Geoheritage geodatabase and webGIS-viewer serve as a living atlas designed to facilitate ways of understanding relationships people hold with the Keweenaw's geology. The publicly accessible interactive map explores how geology influences education, conservation, and sustainable economic development initiatives in the region (Fig. 1). Each geosite provides a) a brief description of how the site contributes to Keweenaw's Geoheritage, b) a 360-view, and c) a description of the scientific, educational, cultural, economic, and aesthetic significance of the site (Lizzadro-McPherson & Vye, 2024). This effort supports the co-stewardship of cultural heritage, restoration of legacy mining sites, conservation issues, and the development of economic opportunities based on the region's globally significant geology.

The diamond drill hole (DDH) project aims to digitally preserve at-risk paper core logs, map DDH locations and details, and produce a robust database with a webGIS-based finding aid. The DDH core records document the more recent history of exploratory drilling by the copper mining industry (1899-1970) and contain information still relevant to geological research and exploration for critical minerals. The inventory of records is a tabular database of transcriptions of down-hole data from each scanned core log. An interactive webmap-based finding aid with PDF records and tables of interval descriptions on an open access data portal is in development. These innovative, interactive, geospatial resources aim to enhance scientific inquiry and broaden public engagement and exploration of Keweenaw's iconic geologic landscape.

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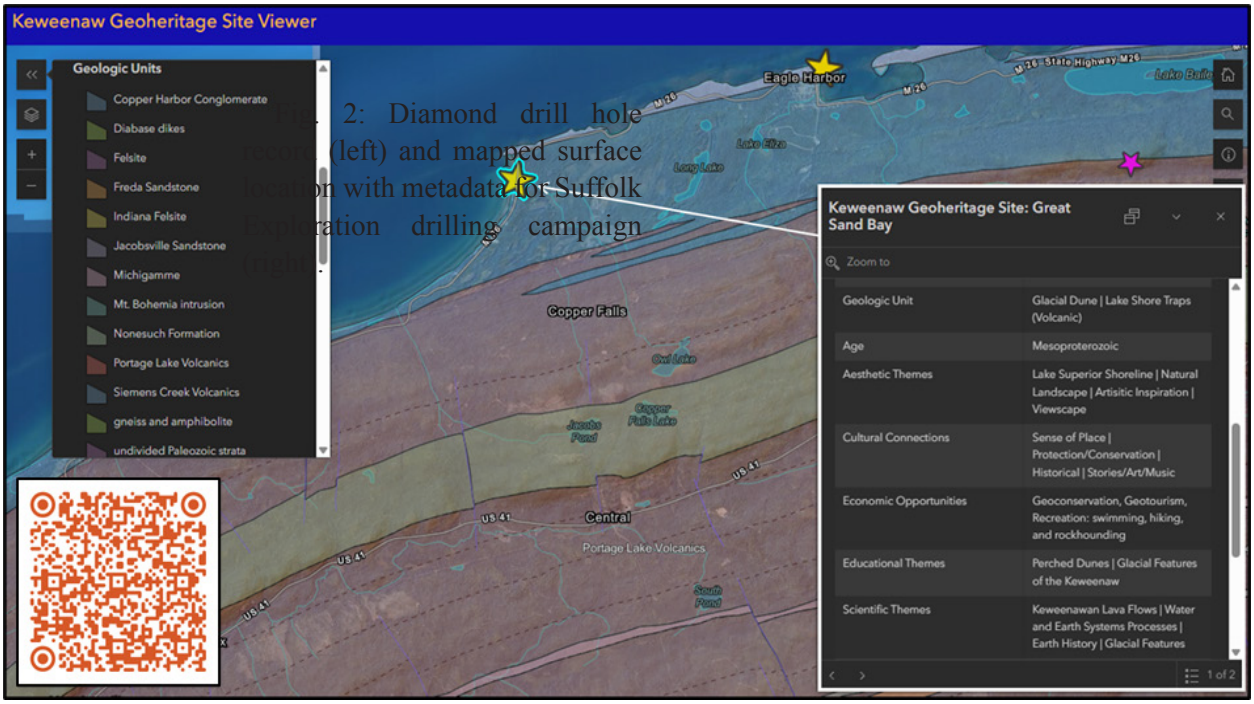


Fig. 1: Keweenaw Geoheritage Viewer with pop-up displaying the core geoheritage values of the geosite at Great Sand Bay, Keweenaw County, MI.

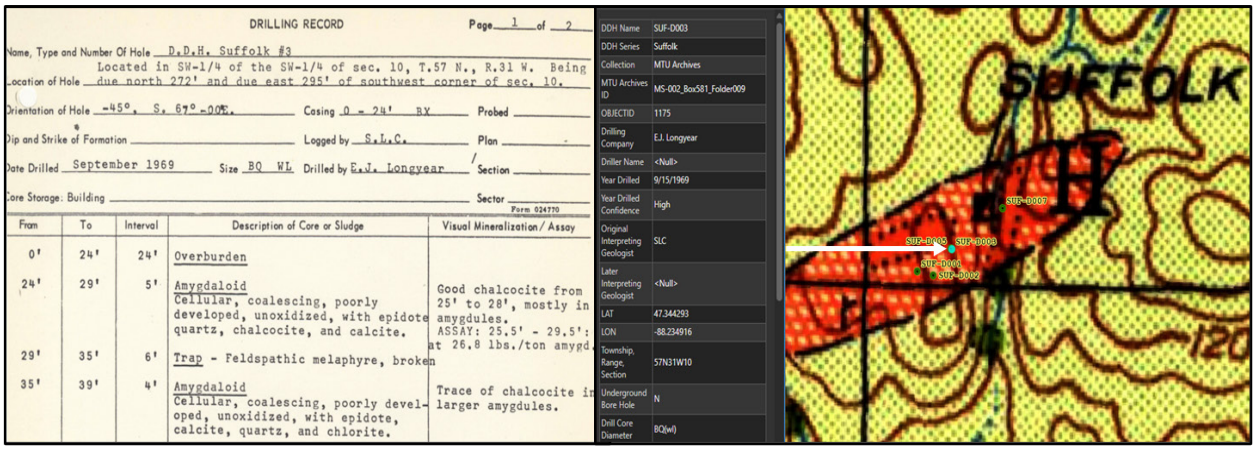


Fig. 2: Diamond drill hole record (left) and mapped surface location with metadata for Suffolk Exploration drilling campaign (right).

Implications of recent geochronology on the regional geology and timing of gold mineralization in the Red Lake greenstone belt, Ontario

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As part of the Ontario Geological Survey's Red Lake bedrock mapping compilation project, geochronology samples were collected from the Red Lake gold camp to improve the ages of volcanic assemblages, sedimentary units and intrusive suites. Eighteen samples were analyzed using ID-TIMS and LA-ICP-MS uranium/lead methods on zircon grains. The new ages suggest significant revisions to the geographic presence and/or stratigraphy of the Balmer, Ball, Trout Bay and Confederation assemblages; as well as expanding the regional presence of the Huston conglomerates and identifying the presence of English River terrane sedimentation in the Uchi Subprovince. Newly dated intrusions from throughout the belt refine the timing of synvolcanic, syntectonic, and post-tectonic magmatism, along with improving the known timing of early gold mineralization and later remobilization. Geochronology from the LP Fault highlights a sequence of felsic and porphyritic intrusive magmatism that is coeval with known gold mineralizing events in the main camp.

Quantitative analysis of iron mineral composition and crystal sizes in the contact metamorphosed Biwabik iron formation and the Bald Eagle intrusion, NE, MN, USA.

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Integrated experimental, theoretical, and field data demonstrate the potential viability of hydrogen production via subsurface fluid-rock interaction in systems with significant ferrous iron content (Mayhew et al., 2018; Ellison et al., 2021; Geymond et al., 2022; 2023; 2025; Templeton et al., 2024). As olivine is a key mineral of interest for hydrogen generation either through natural water-rock interaction, or engineered production, we focus on quantifying mineral compositions, crystal size distributions, and modal mineralogy in lithologic units from northeast Minnesota to enable future quantification of hydrogen production feasibility.

Units of focus are the troctolitic portion of the Bald Eagle Intrusion (BEI; drill core LOD-6, n=16 samples), and the olivine-rich contact metamorphosed Biwabik iron formation (drill cores 8041 and 8016, n=12 and 13 samples respectively). Olivine and serpentine crystal size distributions (CSD) were quantified using image-based analysis. Combining 2D CSD measurements from BEI depths 970, 1091, and 1212.5 feet (n = 407 crystals from 3 samples; Figure 1A) yielded 8.0% partially serpentinized olivine, and 35.2% fully serpentinized olivine, with the remaining 56.8% of the sample composed of plagioclase, oxides, and minor phases external to olivine crystals. Olivine compositions (Fo_{76}) are similar across BEI samples from multiple depths. In addition to olivine, BEI samples contain pyroxenes, labradorite, and titanium-bearing magnetite and ilmenite, with serpentine-group minerals present along key fracture sets. Reaction boundaries between olivine and serpentine were observed using transmission electron microscopy (TEM; Figure 1B, C). Serpentines are either amorphous or nano-crystalline with variations in crystallinity dependent on orientation in the fracture. Banding was observed in both Focused Ion Beam sections within serpentines proximal to olivine edges (Figure 1C). In metamorphosed Biwabik iron formation samples, olivine compositions are iron-rich (Fo_{12}). In addition to olivine, meta-iron-formation samples contain quartz, oxides, sulfides, pyroxenes, amphiboles, chlorite, mica, calcite, with minor amounts of garnet, plagioclase, serpentine, and accessory phases. CSD analysis of metamorphosed iron formation sample 8016-271 (n = 190 crystals from 1 sample) yielded 55.3% olivine. Next steps include comparison of 2D CSD analyses with 3D X-ray computed tomography data.

Overall, the presence of abundant olivine indicates the area could be of interest for future hydrogen generation. To quantify hydrogen generation potential, heterogeneity between serpentinized and un-serpentinized zones should be quantified to extend data from the mineral to the intrusion and formation scale, in addition to connecting hydrologic, geomechanical, and geochemical parameters to mineral data. Next steps include workflow modifications to improve scalability, and application of the workflow to the contact metamorphism Biwabik iron formation.

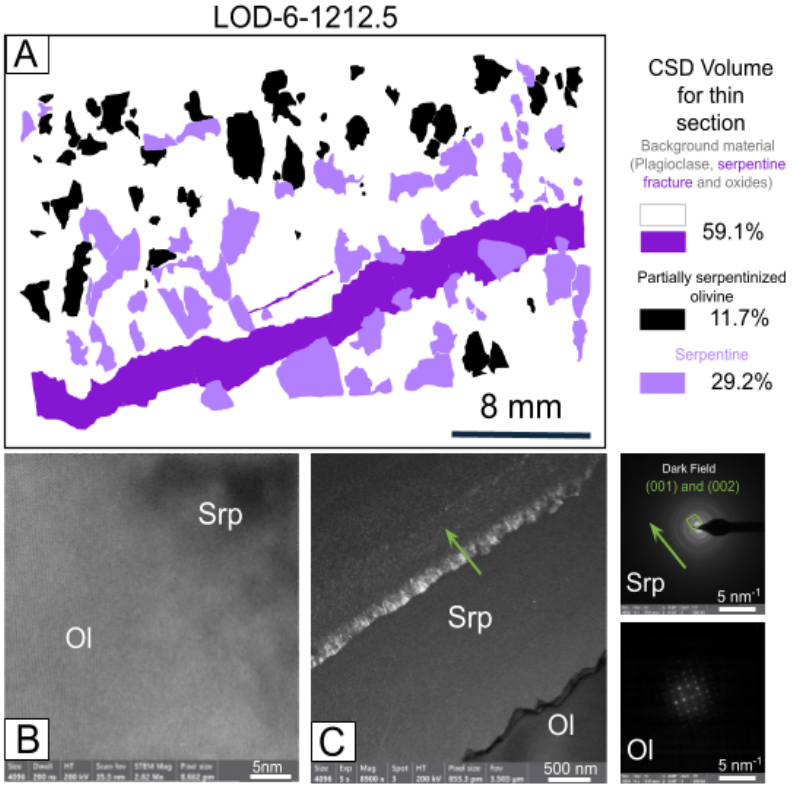


Figure 1. Image-based CSD analysis and Transmission electron microscopy images for sample LOD-6-1212.5. A) Traces of olivine and serpentine crystals in thin section with mineral proportions calculated using CSD analysis after Higgins, 2000. B) STEM image of reaction boundary between olivine and serpentine. C) TEM image of serpentine and olivine boundary. Top right diffraction pattern of serpentine with a green oval around planes (001) and (002) where the brightest area shows direction of growth of serpentine. Green arrows show crystal orientation. Bottom right diffraction pattern of olivine.

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Models of the regional gravity and magnetic anomalies associated with the Nipigon Embayment

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The Nipigon Embayment, a region dominated by Proterozoic rocks around Lake Nipigon, extends northward for approx. 150 km into the Superior craton from the Nipigon/Thunder Bay region on the northern shore of Lake Superior. The Embayment is characterized by the presence of intruded mafic-ultramafic rocks and diabase sills dating from the early magmatic stage of Keweenawan rifting in Lake Superior (Heaman et al., 2007).

The relationship between the Nipigon Embayment and the MCR has long been a topic of scientific investigation. Various researchers proposed that the Nipigon Embayment represents a viable candidate for a possible third branch of the MCR system (e.g., Hinze and Chandler, 2020), based on various lines of evidence, such as the existence of mafic-ultramafic igneous rocks in the upper crust with geochemical and geochronological similarities to the MCR rocks (e.g., Heaman et al. 2007; Hollings et al., 2007), and the anomalous upper mantle beneath the region reflected in weak seismic anisotropy (Ola et al., 2016), low velocity (Frederiksen et al., 2007; 2013; Foster et al., 2020), and electrical resistivity (Ferguson et al., 2005). However, some investigators suggest that the Nipigon Embayment is related to pre-existing structures, arguing against this region representing a third branch of the MCR due to its lack of Keweenawan extensional features (e.g., Hart and MacDonald, 2007).

In this contribution, the gravity and magnetic regional anomalies associated with parts of the Nipigon Embayment are evaluated, both qualitatively, using various filters, and quantitatively, using 2.5D forward modelling. The positive mass anomalies that account for the regional gravity highs in the area covered by the Nipigon sills are equivocal and could be related either to Nipigon magmatic rocks or to covered older rocks bodies, such as Archean mafic-ultramafic intrusions and greenstone belts. If it is assumed that some of these anomalies are related to the Nipigon magmatic rocks, then the gravity models suggest the existence of structures that may have acted as feeders for the emplacement of the Nipigon Embayment mafic-ultramafic intrusive bodies and diabase sills. The

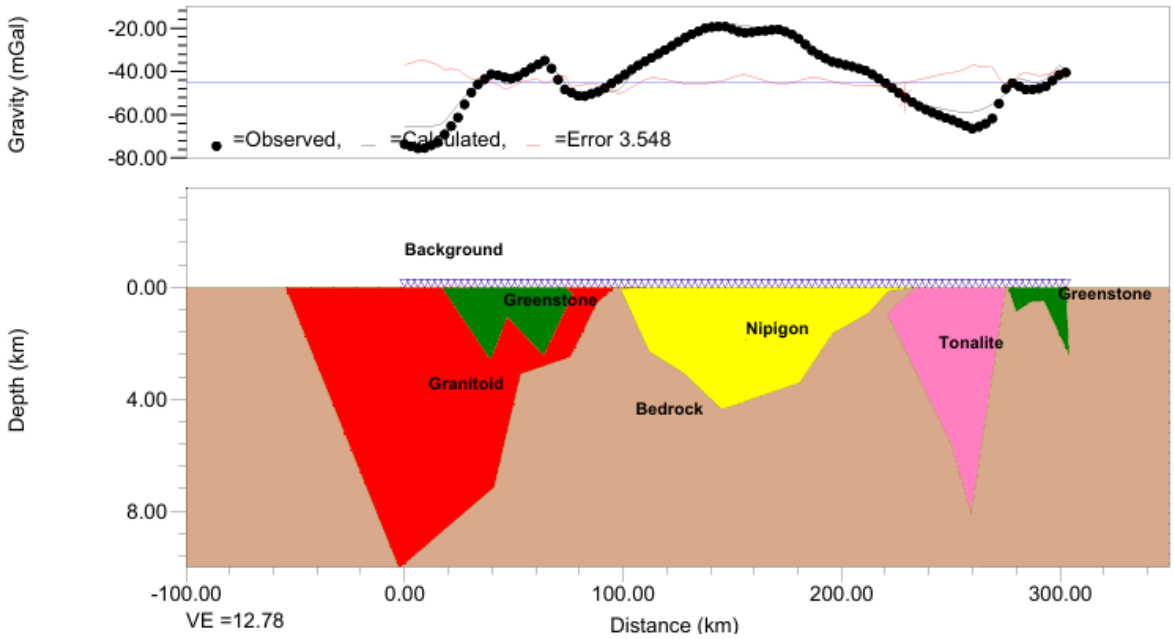


Figure 1: 2.5D forward model of the Bouguer gravity anomaly along an W-E profile in the northern part of the Nipigon Embayment, assuming that the cause of the anomaly is related to Nipigon magmatic rocks. Density values: Nipigon magmatic rocks 2.89 g/cc; greenstone belt mafic rocks 2.9 g/cc; granitoid and tonalite 2.64 g/cc; background 2.67 g/cc.

magnetic models of the regional magnetic anomalies indicate the presence of a significant subsurface volume of highly magnetic rocks within the Nipigon Embayment crust. These results are compatible with the interpretation of this region as a segment of the crust affected by magmatism in the initiation stage of the MCR, possibly as an incipient, undeveloped part of the rift controlled by pre-existing structures.

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Origin of the World-Class Eagle, Eagle East, and Tamarack Ni-Cu-PGE Deposits and comparative analysis with other Midcontinent Rift- and Siberian Trap-related intrusions

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The 1.1 Ga Mesoproterozoic Midcontinent rift hosts the Eagle, Eagle East, and Tamarack Ni-Cu-PGE deposits and Embayment Prospect. These deposits are hosted by ultramafic igneous rocks and have some of the highest Ni-Cu grades on Earth. We use new bulk-rock data and published datasets (bulk-rock, mineral chemistry, and isotopic analyses) to examine major, minor, and trace element trends of both Midcontinent rift-related alkaline and tholeiitic intrusions (Nowak et al., 2025). In addition, we compare the geochemical data to local kimberlite-hosted lower-crustal xenoliths and local igneous (Archean) and sedimentary (Paleoproterozoic) country rocks. We found the peridotite magma compositions dominantly consist of primitive mantle compositions with varying abundances of subduction-related components, alkaline-transitional melts, and local country rock contaminates (e.g., Baraga and Animikie Basin sediments). The subduction-related components are interpreted to be derived from previous Archean and Paleoproterozoic subduction events and likely hosted within the sub-continental lithospheric mantle. Importantly, these subduction-related components are also interpreted to have acted as oxidizing agents within the melt, stabilizing sulfate (+2 FMQ (fayalite–magnetite–quartz) to FMQ) while inhibiting sulfide crystallization as the magma ascended through ~50 km of the Superior craton. This study largely corroborates the previous findings with respect to the contribution of local country rock contamination to the Eagle–Tamarack peridotite host rocks, which is estimated to be minimal (<5%). However, the incorporation of <5% reductive pelitic siltstone contamination results in strong shifts in the oxygen fugacity of the peridotite melt, from +2 FMQ to slightly below FMQ, as determined from spinel $Fe^{3+}/\sum Fe$ ratios (Figure 1). This shift in oxygen fugacity resulted in the transition from total sulfate (+2 FMQ) to sulfate + sulfide (<+2 FMQ to FMQ) to total sulfide (<FMQ). This shift in oxygen fugacity is a key contributor to the formation of Ni-Cu-PGE-rich massive sulfides within the Eagle peridotite. This study presents an expanded geochemical interpretation for the exploration of Midcontinent rift-related Ni-Cu-PGE deposits to include peridotites with subduction-like signatures and contaminated via <5% reductive sedimentary country rocks. Based on these findings, we also comparatively analyze geochemical samples from

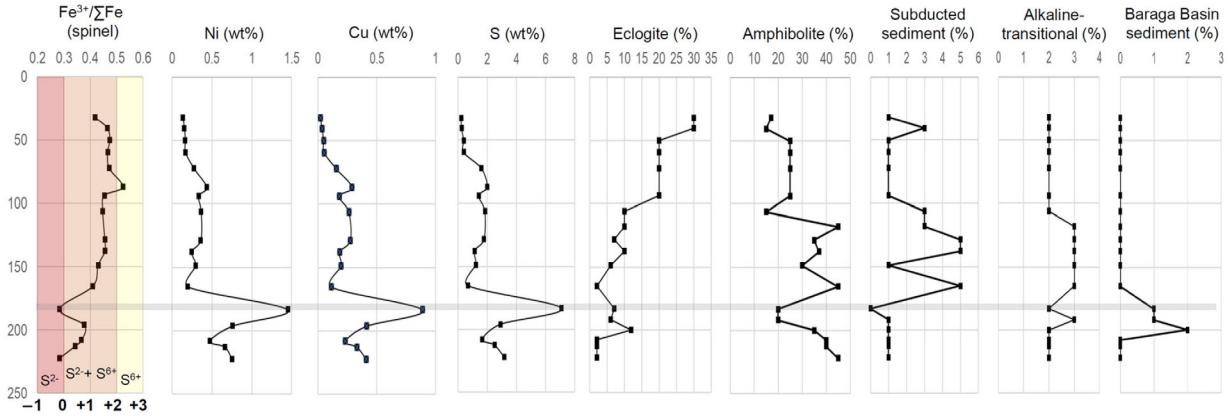


Figure 1: Downhole profiles of drillhole 03EA034 of $Fe^{3+}/\sum Fe$ ratios of spinel (Ding et al., 2010); with oxygen fugacity estimates (relative to FMQ) this study), Ni, Cu, and S (all in wt%; this study), and the relative proportion (%) of compositions (eclogite, amphibolite, subducted sediment, alkaline-transitional, and Baraga Basin sediments) used to reconstruct the multi-element compositions of Eagle peridotite. Analytical error (accuracy; 1σ) is estimated to be smaller than the symbol size.

Midcontinent rift-related prospective intrusions and Siberian-Trap-related intrusions in order to better determine economic vs. subeconomic host rock signatures.

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BEDROCK GEOLOGY OF THE ERICSBURG NW, ERICSBURG NE, RAY SW, AND RAY SE QUADRANGLES, ST. LOUIS AND KOOCHICHING COUNTIES, MINNESOTA

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New geologic mapping presented here portrays the Precambrian bedrock geology and tectonic history of the axial zone of the Quetico subprovince across four 7.5' quadrangles in portions of east-central Koochiching County and far western St. Louis County, Minnesota. The map records the Neoarchean deposition, deformation, metamorphism, and migmatization of turbiditic sediments, along with the intrusion of the granitic rocks of the Vermilion Granitic Complex during the accretion of the Wawa subprovince to the southern margin of the Superior Province, and continuing through the intrusion of the Paleoproterozoic Fort Frances dike swarm.

The metasedimentary rocks of the Quetico subprovince, now predominantly biotite schist, granofels, and migmatite, have been subject to at least four successive contractional and transpressional deformation styles documented in the map area. The map pattern and dominant structural grain of bedrock is controlled by structures associated with D_2 and D_3 deformation. D_2 deformation produced map-scale, tight to isoclinal F_2 folds with well-developed ENE-WSW-striking subvertical S_2 axial-planar foliation. D_3 deformation coincides with the development of ENE- and NW-trending ductile shear zones with dextral motion. F_3 folds are coaxial to F_2 folds and manifest as isoclinal refolds and reorientations of D_2 structures. D_4 deformation post-dates the dominant D_2 and D_3 deformational events and is represented by steeply plunging broad, open folds and NNW-trending fault and fracture zones.

New geochemical analyses illustrate rocks of the Vermilion Granitic Complex are generally calk-alkaline, weakly peraluminous to metaluminous, magnesian granitoids with minor amphibole-rich dioritic to gabbroic rocks. Based on geological and geochemical features, the Vermilion Granitic Complex can be subdivided into groups with distinct lithologies, geochemistry, and magma sources. Tonalites, trondhjemites, and granodiorites (TTG) of the Early Magmatic Suite are distinctly more sodic than the younger Lac La Croix Suite granitoids. Compared to the Early Magmatic Suite, Lac La Croix Suite granitoids are relatively more alkalic, more aluminous, and have steeper REE profiles.

Quetico metasedimentary rocks and the Vermilion Granitic Complex have been subject to at least two metamorphic events recording the burial, uplift, and intrusive history of the subprovince. M_1 metamorphism is likely contemporaneous with D_2 and early D_3 deformation, based on the presence of syn- and post-kinematic, inclusion-rich porphyroblasts. Peak metamorphic conditions reached amphibolite facies during M_1 and have been constrained to 525-575°C with pressures exceeding 6 kbars based on phase equilibrium modeling outside the thermal influence of the Lac La Croix Suite. Proximal to the Lac La Croix granite, M_1 metamorphic features have been overprinted by a high-temperature, low-pressure event, M_2, presumably due to the intrusion of voluminous granitoids of the Lac La Croix Suite during the waning stages of D_3 deformation. M_2 metamorphism manifests as inclusion-poor garnet, sillimanite-, cordierite-, and andalusite-bearing assemblages in metasediments and granitic orthogneisses.

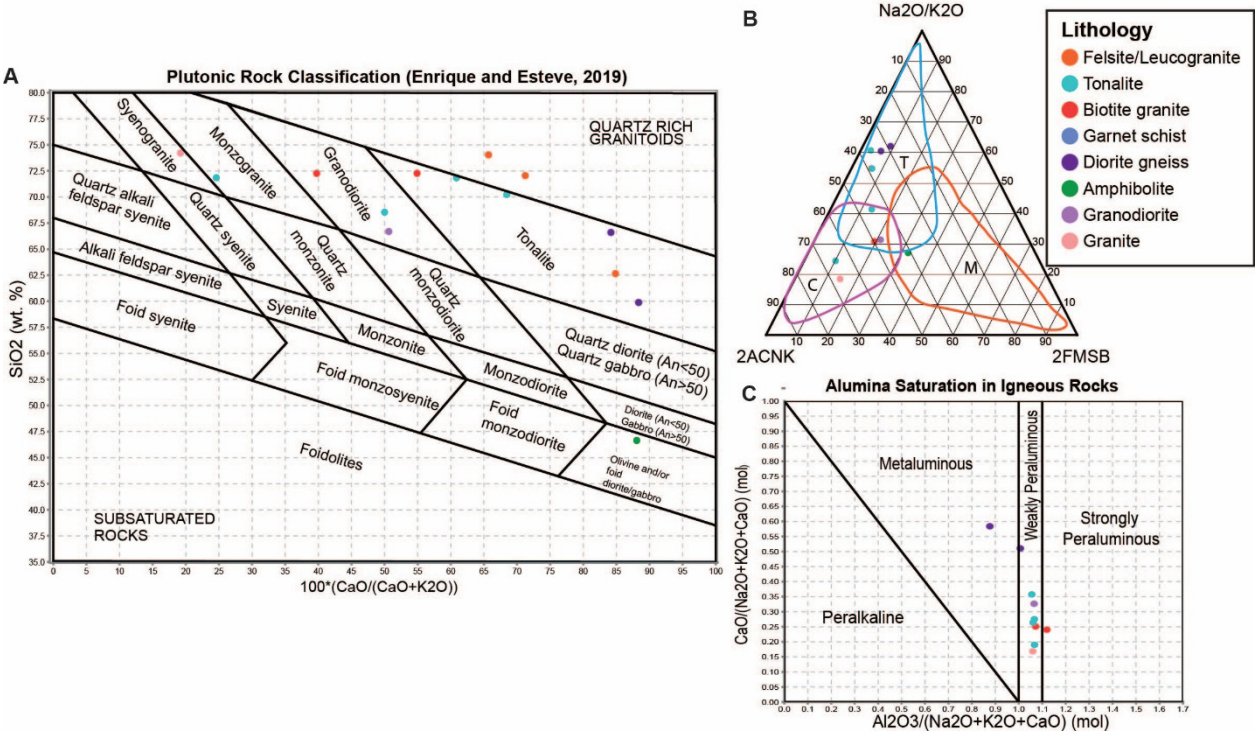


Figure 1. A. Plutonic rock classification of igneous rocks in this study, after Enrique and Esteve, 2019. B. 2ACNK (2* molar Al_2O_5/(CaO+Na_2O+K_2O), Na_2O/K_2O, 2 FMSB (2*(FeO_{tot}+MgO)$_{wt.\%}$*(Sr+Ba)wt.%) source identification diagram, of Laurent and others (2014). Fields for TTG (T), continental or C-type (C), and metasomatized mantle or M-type (M) granitoids from Moyen (2019) have been added. C. Alumina Saturation plot after Barton and Young (2002) for all intrusive units within the map area.

Petrographic, geochemical, and mineralogical analyses of manganiferous iron formations and associated lithologies at the Cuyuna Range, central Minnesota

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The Paleoproterozoic Cuyuna Range of central Minnesota hosts one of two significant manganese deposits in the United States and contains anomalously high manganese concentrations (up to ~50 Wt. % Mn) when compared to other Banded Iron Formations in the Lake Superior region (Cannon et al., 2017). The area was highly deformed and metamorphosed during the Penokean Orogeny and encompasses the Emily District at edge of the Animikie Basin to the north, and the North and South ranges which occur within the older fold and thrust belt to the south (Boerboom and Chandler, 2004; Southwick et al., 1988; Morey, 1990). Although the area has a rich history of iron mining and ongoing manganese exploration, many questions remain regarding the occurrence, nature, and mechanisms of manganese mineralization.

This work includes new petrographic, lithogeochemical, and mineralogical data collected and analyzed from 201 drill core samples from 37 drill holes across the Emily District, North Range, and South Range (Figure 1). The regional pilot study is part of a larger USGS Earth Mapping Resources Initiative to map and better-constrain the mineral potential of the region. We emphasize the lithologic variability of mineralized iron formations throughout the range, but especially within the Emily District, which from past studies is known to be most-enriched in Mn-content.

Cuyuna iron formations generally range from cherty to slaty (thick bedded to thin bedded / granular to non-granular) with manganiferous units extending from enriched (5-10% Mn), manganiferous (>10 % Mn) and highly manganiferous (>35 % Mn). Although textural and mineralogical differences of mineralized units vary widely with increasing grade, the variability and significance of non-enriched lithologies throughout the Cuyuna Range also offer insights regarding possible sources or mechanisms of mineralization, especially when taken within the context of recently integrated historic drill logs and prior works (e.g., McSwiggen et al., 1995).

Textural and mineralogical variation among mineralized units exhibit many signs of hydrothermal modification during manganese enrichment. Many grains have been replaced with manganese oxides and hydroxides in both cherty and slaty iron formations and the occurrence of vugs associated with other hydrothermal accessory minerals such as carbonates, epidote, micas, and clays, along with abundant sieved and altered grains indicate that many pulses of variable hydrothermal activity likely resulted in disequilibrium of most preserved mineral assemblages.

Non-mineralized units such as graywackes are typically highly altered to sericite and kaolinite and pyritic graphitic argillites have been observed to exhibit non isochemical characteristics illustrating high mobility of Fe and Mn. The occurrence of silicified and oxidized zones as they relate to variations of grade are also characterized along with variability of downhole changes of Mn, Fe, SiO_2, Al_2O_3, and LOI plotted as split logs which also show changes of Co, Cu, and Zn to further assess the possibility of other critical minerals associated with manganese.

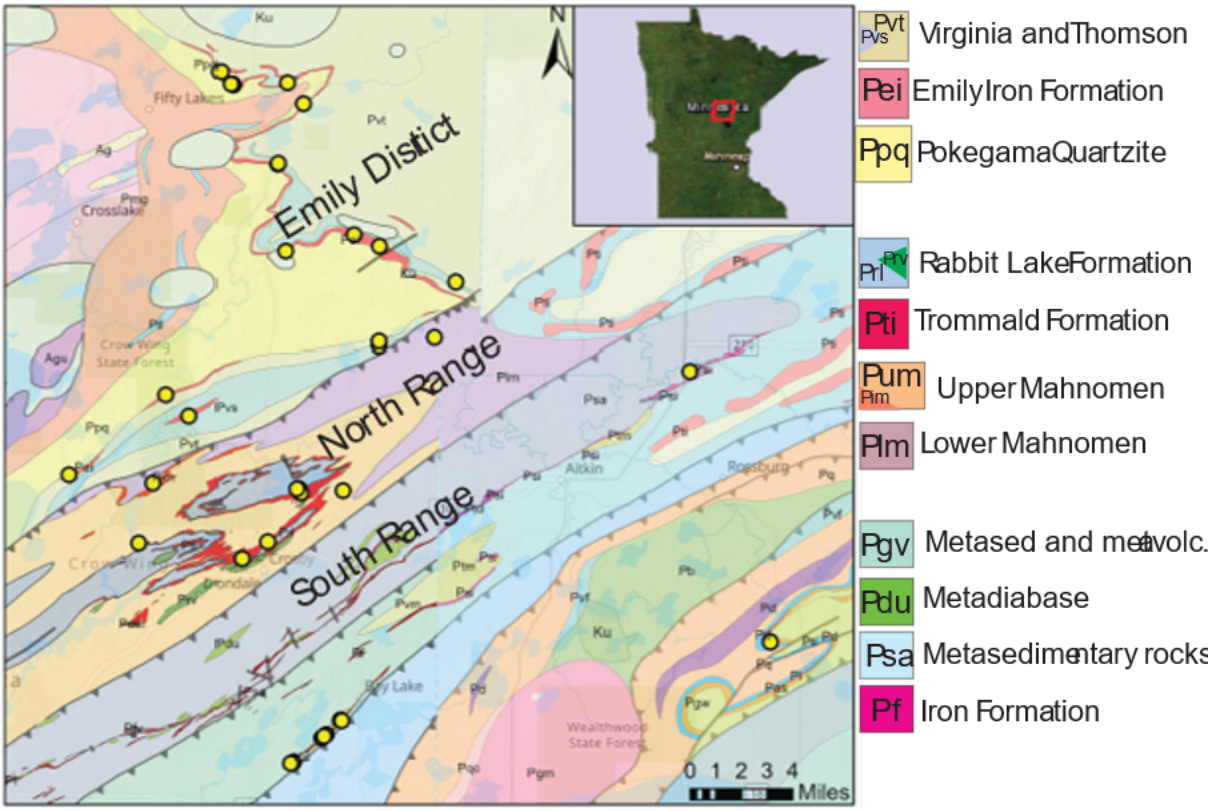


Figure 1: Geologic map after Boerboom and Chandler (2004; 2022) showing drill hole locations sampled in Crow Wing and Aitkin Counties, central Minnesota.

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Physical Magmatic System Interpretation of the Marathon Cu-Pd Deposit, Coldwell Complex, Ontario

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The goal of geologic mapping and/or drill core logging in mafic magmatic ore deposits is to not just know what the lithology is at a specific outcrop and/or drill hole interval, but to know with some confidence where you are in the mineralized intrusion, i.e., within the overall magmatic system. Generation Mining (GenM) contracted Big Rock Exploration (BRE) to reevaluate the Coldwell Complex hosted Marathon Cu-Pd deposit using a magmatic system approach.

Mineralized mafic intrusions are typically composed of three principal minerals, plagioclase-olivine-pyroxene along with various proportions of apatite, Fe-Ti oxides, and Fe-Cu-Ni sulfides. Variations in mineralogic estimates of the three principal minerals by many geologists over decades of time can be the difference between calling a rock an anorthosite, a gabbro, a troctolite, or a peridotite. In deposit areas with decades upon decades of exploration history, these basic lithologic calls by many different geologists can directly influence how a mafic magmatic ore deposit is interpreted and/or modeled. Problems in interpretation can come to the forefront when drill hole intervals are logged strictly by lithology and subsequently digitally assigned a LithCode.

Another method of logging and interpreting mineralized mafic intrusions is to approach it from the physical process side, i.e., as a magmatic system. Utilizing a magmatic system approach begins with an understanding of the initial conditions of the system. Initial conditions include the intrusive geometry and

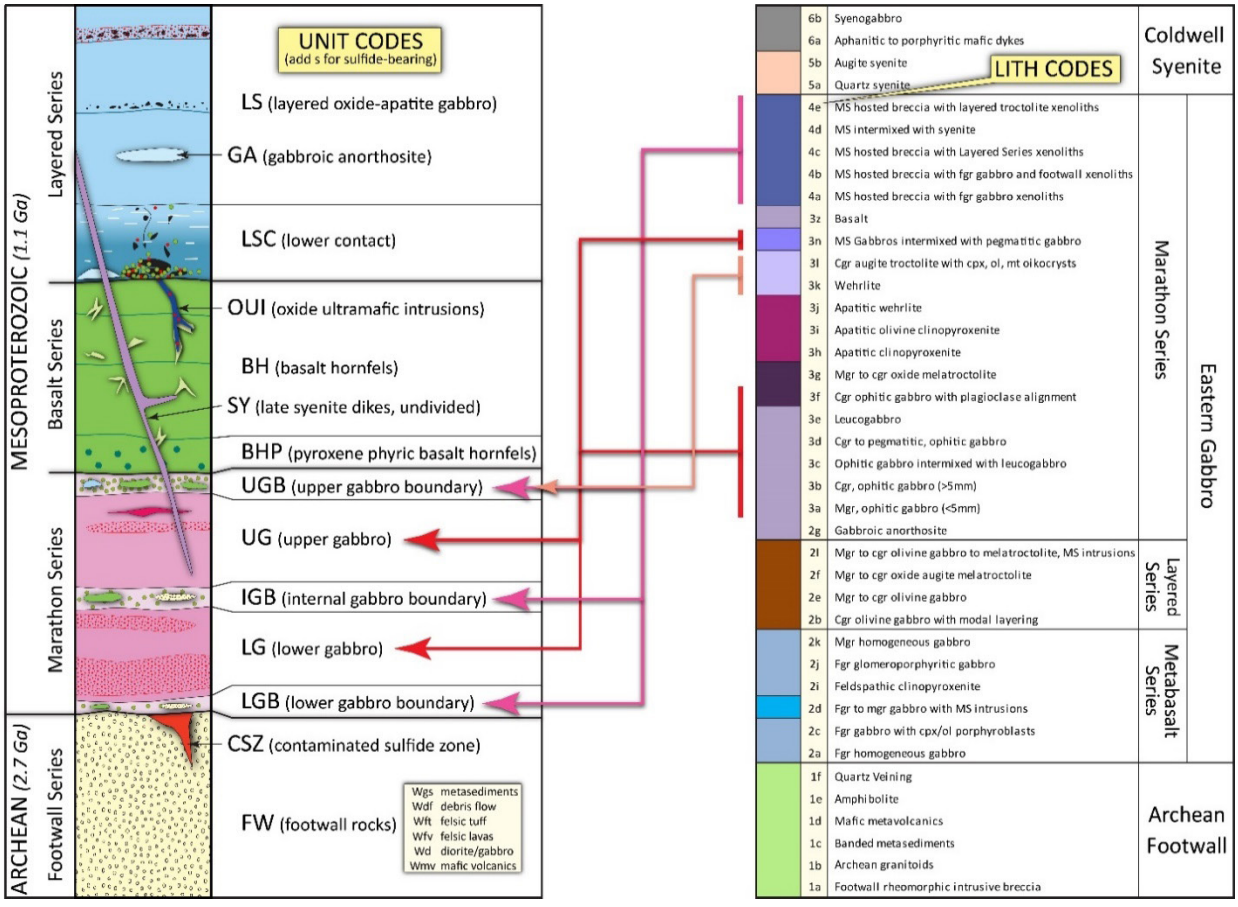


Figure 1. Schematic model of the magmatic architecture of the Marathon Cu-Pd deposit.

flow paths, the lithology of the footwall, hangingwall and sidewall rocks, and the magmas composition, crystallinity, plagioclase-olivine phenocryst content, trace element signature and sulfide content. In general terms, mafic intrusions have slower moving marginal boundaries, which are commonly xenolith-rich, surrounding a faster flowing and xenolith-poor 'clean' central core. Magmatic shearing is induced by the differential velocity, from margin to core, in which magmas intrude can lead to pronounced local mineralogical variability in the outcome. For example, phenocryst sorting leads to modal layering, and kinetic sieving processes raises large particles, which can be phenocrysts, autoliths and/or xenoliths, upwards in the intrusion. The rocks formed in these mafic magmatic systems, though largely governed by the initial conditions, locally can vary by associated chemical, thermal, and momentum boundaries.

BRE coupled these magmatic first principals with GenM assisted field work and drillhole relogging to reevaluate the Marathon Cu-Pd deposit magmatic system. A schematic model of the interpreted magmatic system at the Marathon Cu-Pd deposit is presented in Figure 1, and stratigraphic profiles depicting the historic lithology-based coding (Lith Codes) and recently proposed magmatic systems approach coding (Unit Codes) is given in Figure 2. This talk will highlight many of BRE's research findings on the Marathon Cu-Pd deposit magmatic system.

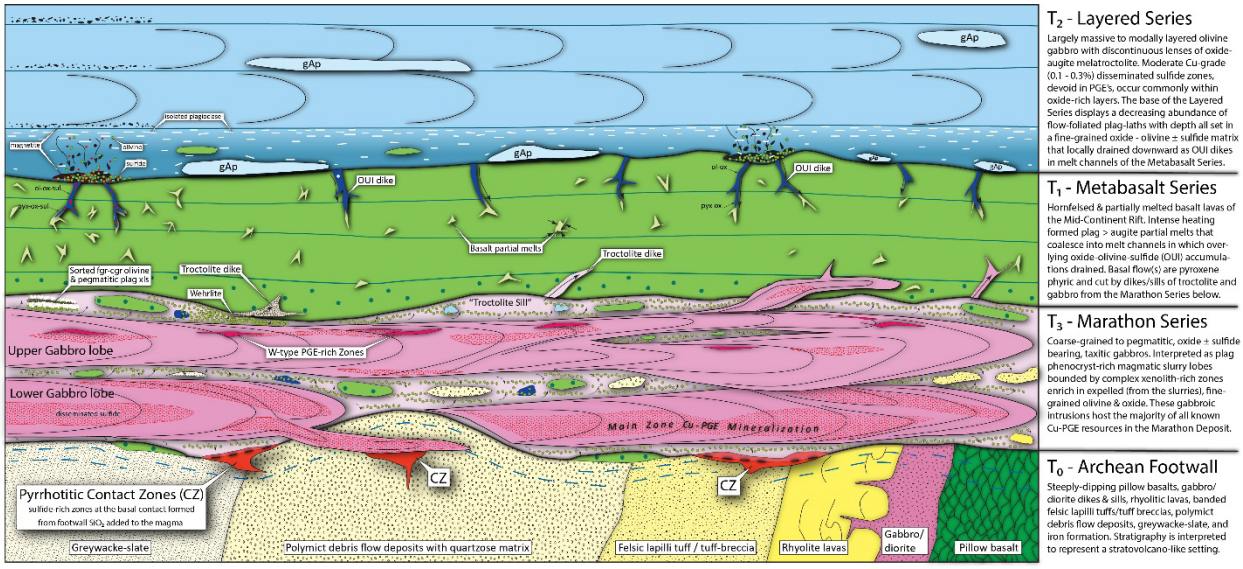


Figure 2. The proposed magmatic system approach Unit Codes (left) versus the historic GenM Lith Codes (right) assigned to the rocks of the Marathon Cu-Pd deposit. Rectangular arrows point to how logged lithologies can be assembled into discrete magmatic system units of the Marathon Series.

Critical Mineral Potential of the Watersmeet Gneiss Dome, MI USA

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Precambrian gneisses and schists on the northern margin of the Watersmeet Dome in Michigan's Upper Peninsula are unusually enriched in rare earth elements, fluorite and incompatible elements including U, Th, Hf, and Zr (Barovich et al., 1991; Sims, 1990). Rocks are mainly Archean gneisses and amphibolites although elevated REEs, fluorite and incompatible elements are associated with a gneiss and schist unit of possible Paleoproterozoic age (Barovich et al., 1991). The area is within Earth Mapping Resources Initiative (EMRI) critical mineral focus areas for both IOCG/IOA and Magmatic REE deposits (Dicken and others, 2022). The Michigan Geological Survey (MGS) conducted detailed geologic mapping and sampling, as well as collected geophysical and geochronological data. An RS-230 BGO gamma-ray spectrometer was used to take over 600 total gamma (K/U/Th) measurements from outcrops. Additionally, an unmanned aerial vehicle (UAV), high resolution magnetic survey was flown. A previously undescribed magnetic, fine-grained schist comprised 85% of the highest total REE samples (high of 1659 ppm TREE). The schists are associated with magnetite and fluorite and coincide with a kilometer-wide central magnetic anomaly, as well as a three kilometer, roughly east-west trending, sinuous anomaly. In plots, granitoids, gneisses, and schists show three distinct populations. Group 1 clusters in the VAG-syn/COLG field, has no europium anomaly and average 72 ppm TREE. Group 2 is transitional between VAG-syn/COLG and WPG, has a marked europium depletion, and contains an average of 136 ppm TREE. Group 3 is enriched in REE with an average 711 ppm TREE, plots in the WPG/A-Type granite field and has moderate europium depletion. All three groups are peraluminous. Group 3 rocks include enriched REE magnetic schists, magnetic granitoids, and gneisses all of which are located in proximity to each other as well as to magnetic highs. Highly fractionated, non-peralkaline felsic granites can have geochemical characteristics which overlap those for typical A-type granites

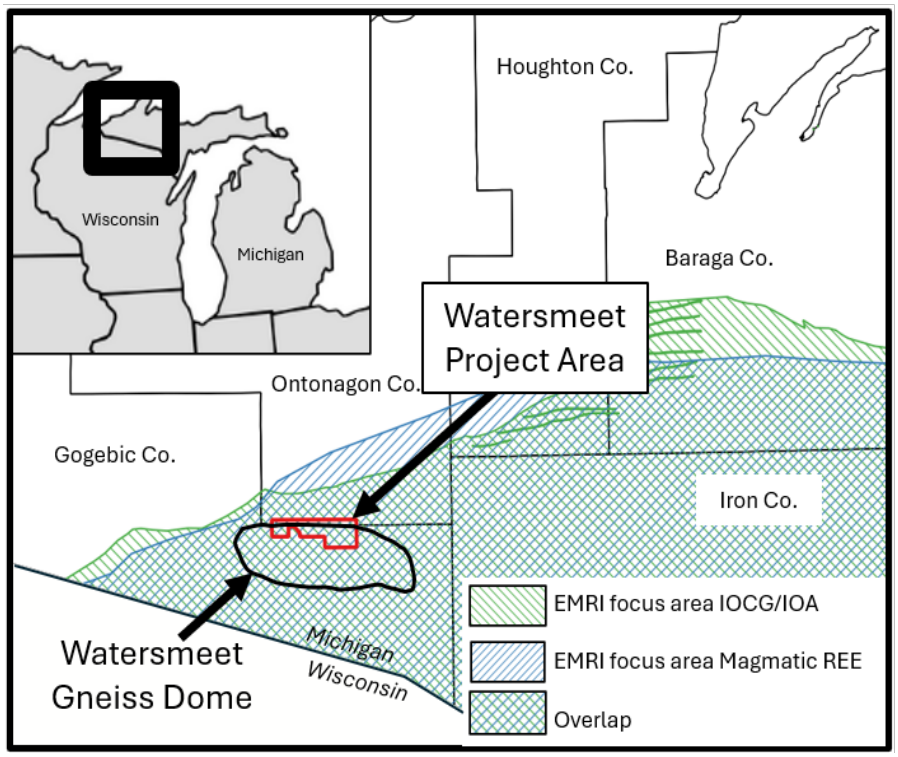


Figure 1: Map showing the location of the Watersmeet project area.

(Whalen and others, 1987). Some fractionation is indicated in Group 1 and Group 2 rocks by a semi-continuous trend of decreasing Zr, Nb, Ce, and Y. Group 3, however, displays no such evidence of fractionation, which is typical of A-Type granites. Numerous REE, F, Th, and/or U-bearing silicate, oxide and carbonate minerals including fluorite, thorite, pyrochlore, allanite, columbite, parasite, and yttrialite were identified using SEM within alteration halos along fractures and occasionally within veins. Zircons with strong pleochroic halos are common, particularly within biotite grains but also observed with amphiboles. The presence of fluorite and REE bearing-fluorocarbonates indicate that REE enrichment was facilitated, at least in part, by fluorine-rich hydrothermal fluids. Preliminary, unpublished U-Pb zircon geochronology indicate that all units are Archean and the previous proposed Paleoproterozoic ages may represent a thermal resetting event.

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Current geologic and geophysical research on the Precambrian basement of eastern North Dakota, USA

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In the entirety of the state of North Dakota, no crystalline basement is exposed due to Phanerozoic sedimentary cover. Regional geophysical mapping, combined with lithological data and radiometric dates, have correlated the Wabigoon and Wawa subprovinces of the Superior Craton into eastern North Dakota (Figure 1). However, understanding of the geologic and the geophysical characteristics of the basement in this region is, with some exceptions, relatively poor compared to many other areas (Figure 2).

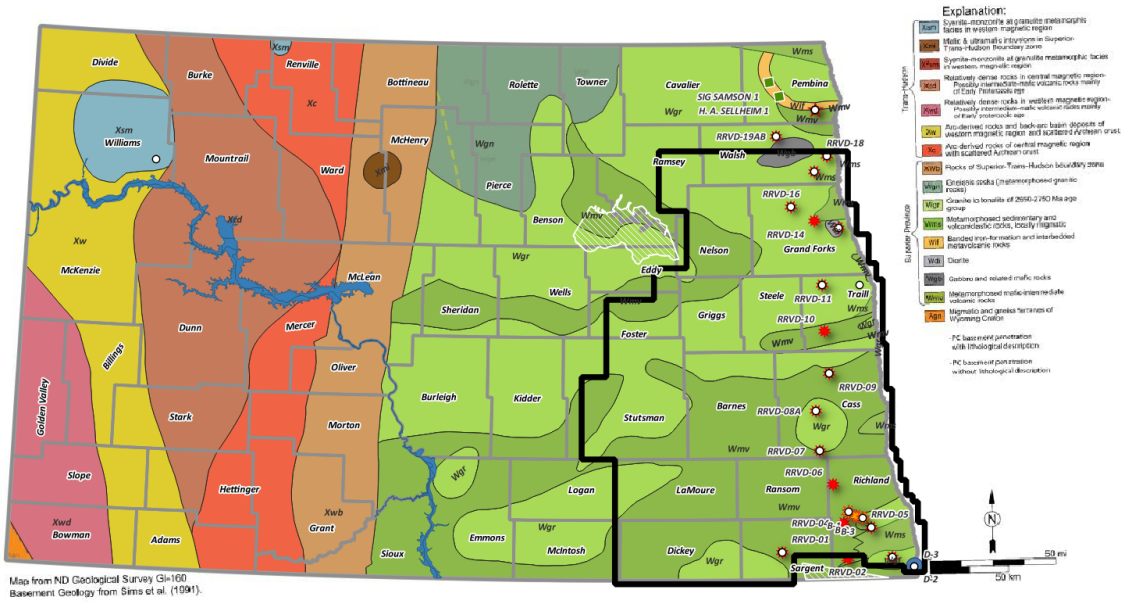


Figure 1: Map of North Dakota Precambrian geology, RRVD drill core locations, and proposed survey area (black outline). Open symbols: geochronology samples. Base map from Sims et al. (1991).

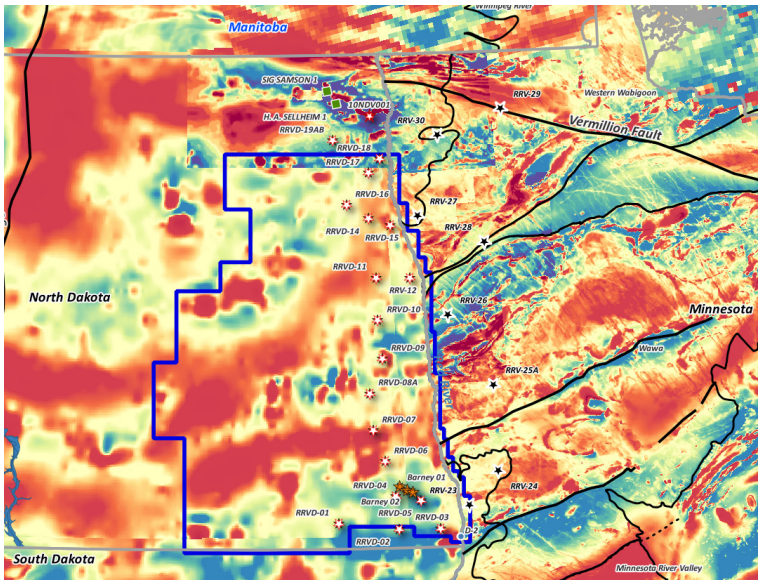


Figure 2: Regional aeromagnetic map, and proposed survey area (blue outline), showing the difference in resolution between ND and MN. (The NE corner of ND does already have higher quality aeromagnetic data.)

The North Dakota Geological Survey (NDGS), working with the Earth Mapping Resources Initiative (Earth MRI) of the U.S Geological Survey (USGS) (www.usgs.gov/special-topics/earth-mri), and North Dakota State University are undertaking a renewed initiative to obtain high quality geochronologic, geochemical, geophysical, and radiometric data over eastern North Dakota. Depth to basement is on the order of a few hundred meters in eastern ND, but increases to thousands of meters westward underneath the Williston Basin. For that reason, the focus of the initiative is on the eastern region where depth to basement is less than 1000 m.

As part of Earth MRI, the USGS is planning to carry out a high-resolution airborne magnetic and radiometric survey in eastern North Dakota, to be flown in 2026-27. The survey will be designed to meet complementary needs related to geologic mapping and mineral resource research. The survey design is being coordinated with the NDGS to provide complete coverage of a region that crosses the boundaries of multiple subprovinces and greenstone belts within the Archean Superior Province. The mineral systems of interest in the survey area include Mafic magmatic, Porphyry Sn, and Metamorphic. Potential critical mineral commodities include Cr, PGE, Au, Co, graphite, REE, Li, Ta, and Sn. There is additional potential for Mn, Ni, Cu, Fe, Mg, and Cs.

Samples of drill core from the 1977 Red River scientific drilling project (Moore, 1978; Kelley, 1980; Beaudry et al., 2024, Pereira et al., 2024), and from other cores, will undergo geochemical, geochronological, petrological, and geophysical investigation. Portable XRF analysis for trace elements is underway, as is a gravimetric survey of eastern ND by the NDGS.

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Reassessing variations in metamorphism across the Penokean orogen in Northern Michigan: Part 1, new Pressure-Temperature-Time-Deformation constraints

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The Penokean orogeny (1890-1830 Ma) represents the earliest collisional event in a long subduction sequence active throughout the Paleoproterozoic to Mesoproterozoic along Laurentia's southern margin. Traditionally, spatial variations in metamorphic grade in the Penokean orogenic belt were described as three "nodes" (Fig. 1) and ascribed to the main accretionary phase which ended at 1830 Ma. However, the swath of younger $^{40}Ar/^{39}Ar$ cooling ages at ~1750 Ma across the terrane suggests later collisional episodes also played an important role in modifying the Penokean orogenic belt (Schneider et al., 1996). This observation, coupled with newly mapped younger structures by recent geophysical surveys, raises questions about which features are truly Penokean in origin, and which reflect later overprinting by younger tectonic events (Drenth et al., 2021). Elucidating the causes and timing of post-Penokean modification of crust in central Laurentia is key for accurately reconstructing the outward growth of proto-North America throughout the Proterozoic.

We have used multiple geochronometers and isotope systems to unravel the metamorphic evolution of the Penokean orogenic belt. New geochronology and thermodynamic modeling of metasedimentary rocks reveal variations in the timing of metamorphism and subsequent cooling histories between metamorphic nodes (Fig. 1). Directly adjacent to the Niagara fault zone, rocks in the Peavy node have garnet Lu-Hf ages of 1837±7 Ma, reflecting the age of granulite facies metamorphism in the lower crust. Overlapping garnet Sm-Nd (1830±65 Ma) and apatite U-Pb (1822±28 Ma) ages indicate rapid exhumation of these lower crustal rocks near the end of the Penokean orogeny. In contrast, rocks in the Watersmeet and Republic nodes, located farther inboard from the paleomargin, reflect later lower-grade amphibolite facies regional metamorphism after the end of the Penokean orogeny, from 1825±5 to 1782±15 Ma. Unlike the Peavy node, these samples have offset Lu-Hf and Sm-Nd ages reflecting the different closure temperatures of the two isotope systems in garnet. Dispersed Lu-Hf and Sm-Nd ages indicate prolonged residence of these rocks at mid-crustal depths and correspond with protracted cooling paths of 1-3°C/Mya, until final exhumation began at ~1750 Ma.

Our results illustrate that the metamorphic nodes in the Penokean orogenic belt do not reflect the same conditions or cooling histories, and do not all represent the same tectonic event. Instead, our data reveal a sequence where early granulite facies metamorphism and rapid exhumation are linked with the end stages of the Penokean orogeny and are restricted to the belt of high-grade rocks north of the Niagara fault. Regional amphibolite facies metamorphism persisted after, requiring continued crustal thickening following both the accretionary phase of the Penokean orogeny and exhumation of deep crustal rocks. The implications of this are two-fold. 1) The metamorphic nodes in the Penokean orogenic belt are not cogenetic but rather reflect different tectonic events and different times. 2) Post-Penokean regional metamorphism followed by widespread uplift and cooling after ~1750 Ma represent significant modification of the Penokean orogenic belt throughout Geon-17. More broadly, younger overprinting on this terrane reveals that outboard tectonic activity following the Penokean orogeny played a major role in the modification of Paleoproterozoic and Archean crust in central Laurentia.

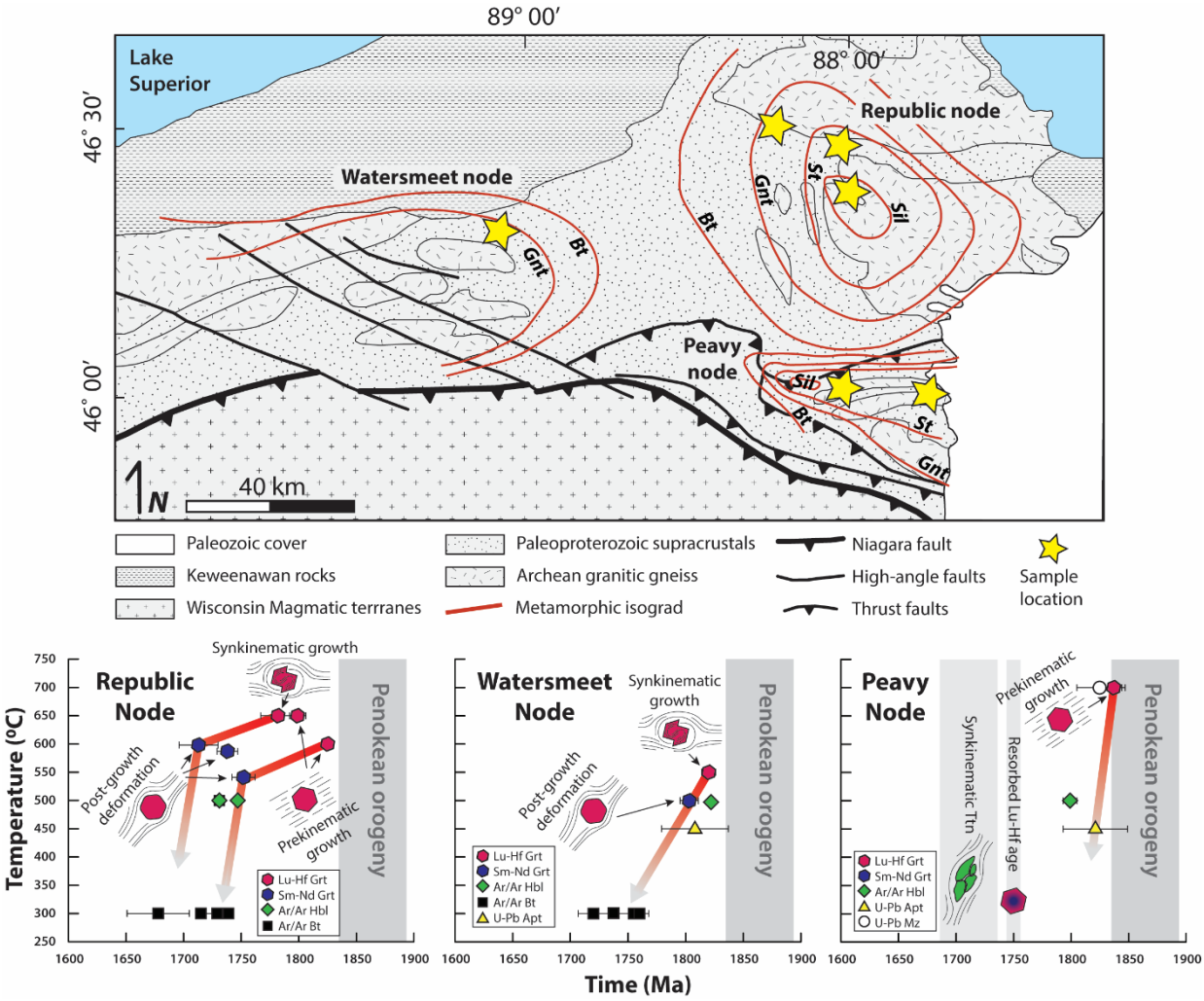


Figure 1: Top, generalized geologic map showing metamorphic nodes in the Penokean orogen in northern Michigan and sample locations in our study (map after Tinkham and Marshak, 2004). Bottom, temperature-time diagrams showing cooling histories of garnet-bearing rocks in three metamorphic nodes. Microstructures indicate deformation during uplift at ~1750 Ma proceeded after peak metamorphism. $^{40}Ar/^{39}Ar$ data are from previous studies and references are compiled in Salerno et al. (2026).

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Whole Rock and Mineral Chemistry of the Eagle's Nest Intrusion, McFaulds Lake Greenstone Belt, Ontario, Canada: Insights into the Origin and Paragenesis

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Orthomagmatic Ni-Cu-(PGE) deposits originate in the mantle, where source composition and degree of partial melting are the first-order controls on composition and metal fertility of the derived magmas (Naldrett, 2011). During ascent, these magmas undergo differentiation, producing more evolved compositions that reflect both the characteristics of the mantle source and subsequent magmatic processes (Barnes, 2023; Smith et al., 2024). The Eagle's Nest intrusion is a mafic-ultramafic, blade-shaped dike, which is host to the only known economically significant Ni-Cu-(PGE) mineralization within Meso- to Neoarchean McFaulds Lake Greenstone Belt. The Eagle's Nest is part of the mafic to ultramafic magmatism of the Koper Lake subsuite, of the larger Ring of Fire Intrusive Suite (ca. 2736–2732 Ma; Houlé et al., 2020; Metsaranta and Houlé, 2020). Two different parental magma compositions have been proposed for the Eagle's Nest intrusion, including a low- and a high-Mg komatiitic magma, both of which are inconsistent with the observed mineralogy of the intrusion (Mungall et al., 2010; Zuccarelli, 2020). To better understand the origin and nature of the Eagle's Nest intrusion, this study integrated petrography, whole-rock geochemistry, mineral chemistry, as well as radiogenic and stable isotope systematics.

The Eagle's Nest intrusion can be subdivided into the marginal and inner zones. The marginal zone comprises mafic intrusive rock in contact with the wall rock tonalite, exhibiting the most evolved mineralogical and geochemical characteristics. The marginal zone gradationally transitions into the inner zone, which consists of ortho- to mesocumulate ultramafic rocks with more primitive compositions, reflecting the accumulation of olivine and chromite in cotectic proportions, along with variable amounts of intercumulus silicate phases and interstitial sulfides. Using the whole rock geochemistry of olivine-chromite cotectic cumulate rocks, combined with olivine and chromite mineral chemistry, a new parental magma composition was determined for the Eagle's Nest intrusion. The new estimate suggests a komatiitic basalt magma that contained ~11 wt% FeO_t and ~15 wt% MgO. The new parental magma estimate is more evolved than previously proposed compositions, however, it is consistent with the composition of identified chilled margins, associated mafic dikes, and olivine from the Eagle's Nest intrusion. Using the newly obtained estimate, the petrographically determined crystallization sequence was recreated at low pressures, suggesting the Eagle's Nest formed in shallow crustal levels. Whole-rock geochemistry and Sm-Nd isotopes indicate that the Eagle's Nest magma was derived from a depleted mantle source above the garnet stability field. During transport, this magma underwent crustal contamination by the host tonalite and older supracrustal rocks. Assimilation of sulfur-bearing supracrustal material likely triggered sulfide saturation, supported by the mass-independent fractionation values of the measured $\Delta^{33}S$. The intrusion's distinct petrological and metallogenic features likely reflect both the emplacement dynamics and the parental magma composition, resulting in its unique metal endowments within the greenstone belt.

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Integrating petrophysical data with full tensor magnetic gradiometry for improved interpretation and modelling of remanently magnetized intrusions in the Midcontinent Rift

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Magnetic surveys are widely used in mineral exploration to detect and delineate subsurface structures and ore-bearing systems. As near-surface, high-grade deposits become increasingly rare, exploration is shifting toward deeper targets and more complex geological settings. Full tensor magnetic gradiometry (FTMG), particularly when deployed with highly sensitive SQUID-based quantum sensors, provides high-resolution measurements of all components of the magnetic field gradient tensor, offering enhanced imaging of subtle geological structures and ore bodies that conventional total magnetic intensity (TMI) surveys may not resolve (Rudd et al., 2022). FTMG reduces the influence of regional magnetic fields, diurnal variations, and cultural noise, supporting more robust 3D inversion and geological interpretation. Despite these advantages, adoption of FTMG has been limited by logistical complexity, depth constraints, and a lack of publicly available datasets particularly in geologically complex or remanently magnetized areas. To address this, the Geological Survey of Canada is acquiring and openly disseminating precompetitive SQUID-based FTMG datasets (e.g. Fig. 1), providing real-world data for benchmarking inversion workflows and testing emerging quantum sensors.

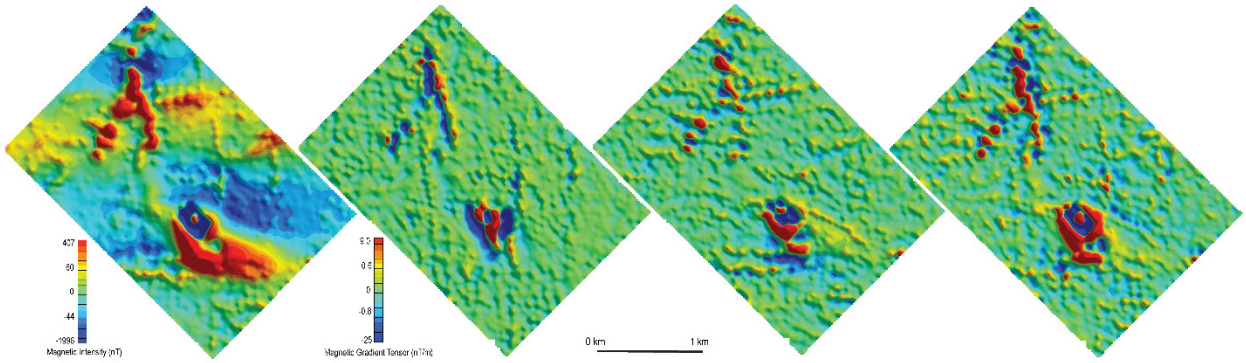


Figure 1: Maps of the total magnetic intensity (TMI) (a), and three components of the magnetic gradient tensor: Bxx (b), Byy (c) and Bzz (d) over the Escape Intrusion within the Thunder Bay North Intrusive Complex of the Midcontinent Rift.

The Midcontinent Rift (MCR) provides a geologically complex environment to evaluate FTMG in remanently magnetized settings. Mafic-ultramafic conduit-type intrusions in this region, including the Escape and Current intrusions of the Thunder Bay North Intrusive Complex (TBNIC), exhibit strong remanent magnetization, generating distinct and heterogeneous magnetic anomalies (Kaski et al., 2024; Fig. 1). These characteristics make the MCR an ideal setting to assess how FTMG resolves both induced and remanent magnetic components. In this study, we integrate SQUID-based FTMG inversions with petrophysical, petrographic, and geochemical data, including magnetic susceptibility, natural remanent magnetization, and mineralogical composition, to examine how lithologic variability, serpentinization, and magnetic mineral development influence the intensity and orientation of remanent magnetization, providing a more geologically realistic framework for interpretation and modeling.

Preliminary results show that integrating FTMG with rock property data improves resolution of key geological contacts and remanent magnetic sources, enabling more robust 3D modeling of conduit-hosted Ni-Cu-PGE systems. This study highlights the value of combining high-resolution geophysical and petrophysical datasets for interpreting complex magnetic anomalies.

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Optimizing data collection for better geological interpretations and adding value to your project

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"Data are disembodied information. Data are not the same as knowledge." ~ W. Olsen (2012)

A well-designed field or drill program is developed from the beginning to produce substantiated, appropriate and robust datasets. However, data are commonly considered interchangeable with interpretations and are often misreported to fit a geologist's bias within the context of a project. Common instances of data distortion include: (1) identifying and classifying rocks as pre-named units with assumed occurrences; (2) designating altered rocks as separate lithologies; (3) recording qualitative descriptions rather than quantitative variables; (4) not standardizing all aspects of data collection; and (5) generating incomplete geochemical datasets in the pursuit of select geochemical data. It is a human instinct to apply human interpretations to systematic rocks and processes, but collecting purely observational, quantified geologic data can provide significantly more flexible information during later interpretation. Some findings may emerge from a dataset without being expected or predicted in advance (Olsen, 2012). More 'expected' findings might follow the usual predictable patterns, but unpredictable trends may be obfuscated by unintentionally engineered data biases.

The most impactful approach to optimize data collection procedures is standardizing all data input for recording rock identification and descriptions, photos, and QA/QC practices. Collecting alteration, mineralization, and structural data as separate data to the lithology, rather than integrated into lithology names (e.g., carbonatized basalt), allows for separation of different datasets for multiple applications and discourages segregating single rock units due to varying characteristics. Many issues are resolved by generating mandatory fields that can only be populated by standardized terms using drop-down menus. Another approach is quantifying and binning as many descriptors as possible. A simple change is including mineral abundance ranges in mineral description fields. For example, describing weak epidote alteration as '*Weak (2-5%)*' provides a quantitative visual cue to the core logger/mapper, ensuring consistent descriptions and binning similar mineral percentages together. Another consideration is developing sampling programs that submit all samples for consistent analytical packages. Cost-saving measures are often implemented by selectively submitting samples for different packages or only submitting samples that are anticipated to return good assay data. These practices can identify high-grade samples, but can also miss secondary, unpredictable mineralization. Without a range of geochemical data, it is impossible to assess truly elevated values from background values.

Purely objective geologic data can provide new interpretations depending on the approach/aims of the geologist. Consistent and comprehensive data collection may produce unexpected results and provide a valuable final product – a strong asset that increases the value of a project, property, or deposit.

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Pukaskwa Redux: Revisiting and Reconnecting with Superior's Wild North Shore

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In August, 2025, the Senior Author served as Geologist-in-Residence (GIR) at Pukaskwa National Park, on Lake Superior near Marathon. The GIR program at Pukaskwa is a partnership between the Canadian Federation of Earth Sciences and Parks Canada, with volunteer expenses funded by the APGO Education Foundation. It is a two-week, volunteer position that started at Pukaskwa in 2022. The role of the GIR is to highlight Pukaskwa's remarkable geological features and to educate park visitors and Parks Canada interpretive staff about the local geology. Guided hikes, "walk and talk" sessions, drop-in opportunities and presentations were employed to convey knowledge and messaging.

As a result of the 2025 GIR program, ideas are being considered to develop a self-guided geology field trip for the readily accessible "front country" trails at Pukaskwa that expose a variety of Neoarchean supracrustal rocks of the Schreiber-Hemlo greenstone belt. Its "back country", featuring the Coastal Hiking Trail, is underlain mainly by Neoarchean granitoids of the Pukaskwa Batholith. Archean rocks are intruded by Paleoproterozoic and Mesoproterozoic diabase dykes, the latter of which are associated with Midcontinent Rift magmatism. There are numerous features attributed to Quaternary glaciation, including prominent roches moutonnées (Figure 1), potholes and glacial polish/striae. Modern shoreline and aeolian processes continue to redistribute sediment and create unique and critical habitats for rare and endangered plant species.

The GIR program serves to remind us of the importance and value of participating in outreach activities, sharing information and underscoring the critical role that geology plays in ecological processes. The program is expanding to Fundy National Park in 2026 with the hope that further National Parks will be added in the future to provide more opportunities for geoscience outreach and education to a broader audience.



Figure 1: Geologist-in-Residence, Mark Smyk, pointing out a prominent roche moutonnée at Horseshoe Beach during a guided hike of the Southern Headland Trail, Pukaskwa National Park, August, 2025

Oxidation to Ores: Petrological Insights into Supergene Manganese Enrichment at the Emily Deposit, Minnesota

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Electric Metals (USA) Limited's Emily Deposit in Minnesota's historic Cuyuna Iron Range contains zones reaching +50 wt. % manganese, making it the highest-grade manganese resource in North America and one of the highest-grade manganese deposits in the world. Manganese-oxide ores of the Emily Deposit are proposed to have formed through supergene enrichment due to deep, potentially protracted weathering of folded iron formation strata during the deposit's 1.9-billion-year history. Weathering of manganese-bearing carbonate facies oxidizes the original rhodochrosite, drawing the manganese into solution. The manganese enriched groundwaters then migrate down-dip, along stratigraphic boundaries before redepositing manganese as oxides in the porous grainstones of the iron formation. The recent exploration drilling campaign by Electric Metals USA Limited and Big Rock Exploration provided a wealth of geologic, geochemical, and microscopic data that may be used to evaluate the hypothesized ore genesis mechanism on a deposit scale and constrain the metallurgical behavior of the ores. Here we present an analysis of a large exploration geochemical dataset using deposit-wide mass-balance calculations to determine the element mobility within the iron formation. The geochemical results are then contextualized within geology by combining optical and X-ray microscopy to identify mineral phases and phase transitions, as well as intergrowths of secondary minerals. Mass balance calculations show depletions in manganese from the weathered carbonate facies of the Emily Iron Formation and parallel enrichment of manganese into the grainstones. Integration of preliminary optical and X-ray microscopy shows a breakdown of early-formed minerals in the source carbonates and replacement by Fe-oxides and oxyhydroxides along bedding and fractures. Secondary manganese minerals appear to surround primary grains in the grainstones and may be replacing early formed ferruginous cements. These observations support the hypothesized ore-genesis model and provide the necessary information for subsequent metallurgical evaluation of the Emily Deposit including the manganese-iron-silicate mineral associations that may impact ore upgrading, grinding, and hydrometallurgical outcomes.

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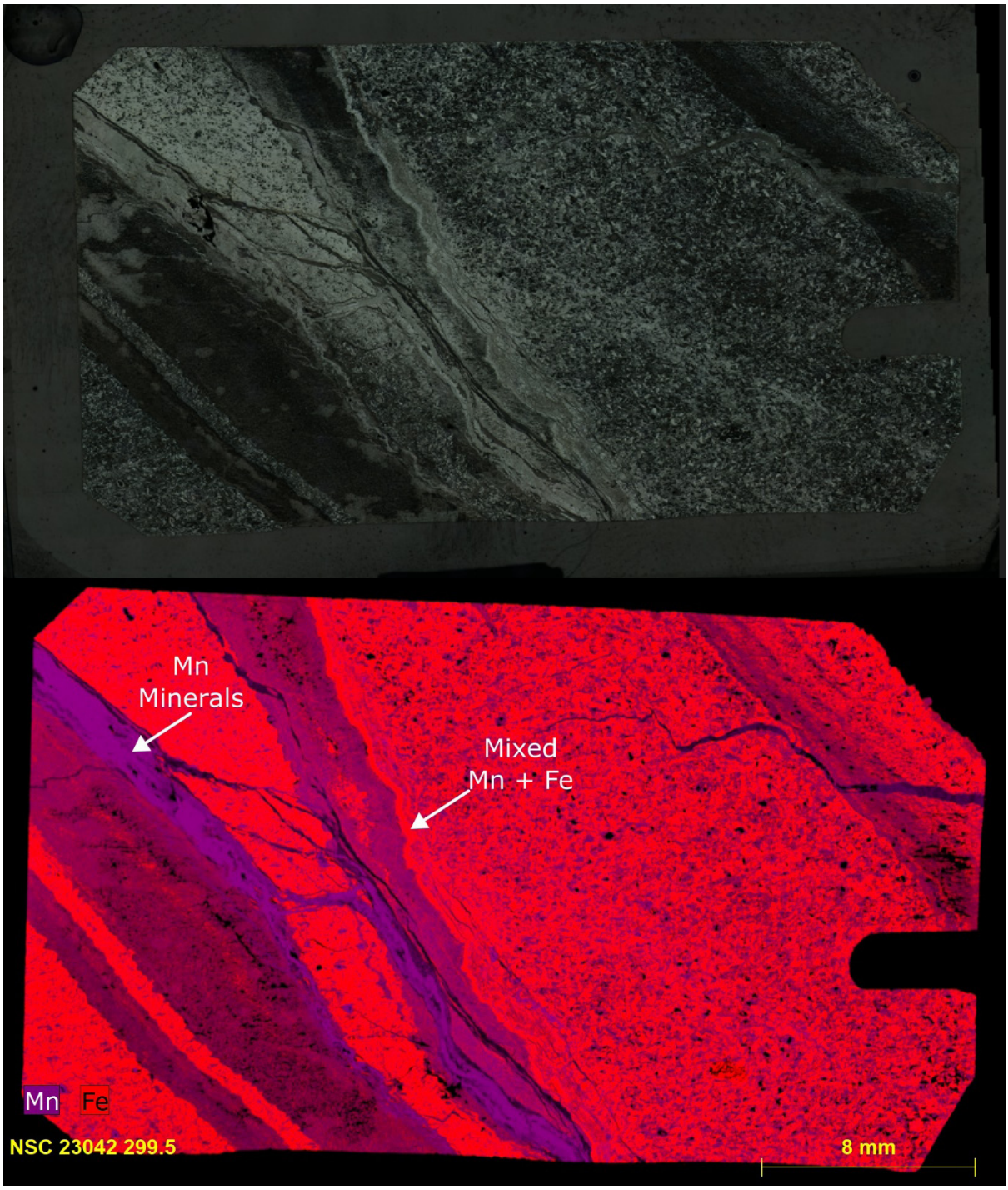


Figure 1 – Full section reflected light (above) and X-ray map showing texture of iron and manganese minerals. Areas with mixed iron and manganese minerals and pure, coarse grained manganese species are highlighted.

Timing and conditions of magmatism, metamorphism, and strain partitioning in the western Shebandowan Greenstone Belt (Superior Province)

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The Shebandowan Greenstone Belt is an Archean granite–greenstone terrane within the Wawa subprovince of the Superior Province, comprising calc-alkaline to tholeiitic, felsic to ultramafic supracrustal metavolcanic rocks, synvolcanic to late intrusive suites, and felsic hypabyssal dikes and sills. Despite its economic and tectonic significance, the timing and conditions of magmatism, metamorphism, and deformation remain incompletely constrained. Here, we integrate structural geology, high-precision geochronology, metamorphic petrology, and microstructural analyses to establish a coherent tectonometamorphic framework for the western belt.

Strain varies from weakly deformed domains (e.g., felsic intrusions and pillow basalts) to high-strain mylonitic zones, mainly affecting diorites and metavolcanic rocks. The orientation of the main ductile foliation orientation is relatively consistent across the study area, while stretching lineations range from shallow to steep. These variations correlate with spatial changes in vorticity, reflecting strain partitioning between high-strain shear zones and coarse-grained, feldspar-rich, and thus, mechanically strong intrusive bodies (Stephan et al. 2025). Peak metamorphic conditions of ~600–700 °C are constrained by pseudosection modeling and conventional thermometry, consistent with Zr-in-titanite temperatures (570–700 °C). Retrograde conditions of ~400–500 °C are preserved in post-kinematic assemblages. Quartz microstructures, crystallographic preferred orientations, and grain-size piezometry indicate deformation at ~400–600 °C and differential stresses of ~20–60 MPa, suggesting deformation near the brittle–ductile transition. CA-ID-TIMS U-Pb zircon geochronology identifies two magmatic phases based on concordant ages: an intrusive phase at 2718 Ma (e.g. felsic intrusion of Moss Lake Stock and Obadinaw Stock) and a younger phase at 2707 Ma (e.g. Greenwater Stock). An upper intercept age constrains volcanism at 2712 Ma in the metavolcanic sequences. In situ U–Pb titanite dates of 2711±76 Ma (2σ) and 2672±100 Ma record metamorphic events spanning greenschist- to amphibolite-facies conditions. A Re-Os molybdenite age of 2708±12 Ma overlaps with both magmatism and metamorphism, linking mineralization to tectonometamorphic processes.

These results indicate synkinematic magmatism and amphibolite-facies deformation under predominantly horizontal tectonics. Strain was strongly partitioned due to competency contrasts between coarse-grained intrusive rocks and fine-grained metavolcanic units. This integrated dataset provides new constraints on the coupling between magmatism, deformation, metamorphism, and mineralization in Archean granite–greenstone belts.

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Subsurface mapping of the late Ordovician Maquoketa Group in eastern Wisconsin using airborne electromagnetic and well data

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The late Ordovician Maquoketa Group is a fine-grained unit and regional aquitard separating the upper, fractured Silurian dolostone aquifer from the deep, Cambrian-Ordovician sandstone-dolomite aquifer in eastern Wisconsin. Here, the Maquoketa Group lithostratigraphy includes, from top to bottom, the Brainard Formation (marls and shale), Ft Atkinson Formation (carbonate wackstone-through grainstone and marls), and Scales Formation (black shales and marls). The shale-rich composition of the Maquoketa Group is readily distinguished from the overlying Silurian dolostone by airborne electromagnetic (AEM) data (Minsley et al., 2022). We undertook subsurface mapping and characterization of the Maquoketa Group to address regional issues of groundwater quantity and quality. For Wisconsin users, the resulting 3D surfaces can be used as inputs to groundwater models and aid land-use decisions by providing information on the depths, thickness, and rock properties of this aquitard.

We used AEM data tied to borehole logs and core to generate raster surfaces and understand facies changes and structures across study area (Figure 1). Despite cultural interference mainly from roads, the AEM data nicely imaged the top of the Maquoketa Group aquitard. The Maquoketa Group basal surface and its internal formations were imaged by the AEM data but with greater uncertainty, and the base of the unit dipped below the penetration depth of the AEM data to the east. .The Maquoketa Group extends from about 850 feet (259 m) above sea level near its western subcrop extent to 100 feet (31 m) above sea level at the eastern edge of the map area, with thicknesses between about 220 – 450 ft (67 – 137 m). The north-south strike of depth-structure elevation contours is abruptly offset in three locations, labeled on Figure 1. One of these (location 2) corresponds to the Precambrian Spirit Lake Tectonic zone (Holm et al., 2007) and fault offset of Silurian bedrock (Luczaj, 2011). Several new and existing drill core tie to the AEM data in the western study area, and lithologic variation in the cores corresponds to vertical changes in the resistivity profile of the Maquoketa Group. Internal variability in the resistivity of the Maquoketa, as imaged by the AEM data, apparently decreases to the east. Future air rotary drilling will test whether this signal is due to decreased data resolution as these units dip eastward, or whether it reflects an increase in shaley facies to the east.

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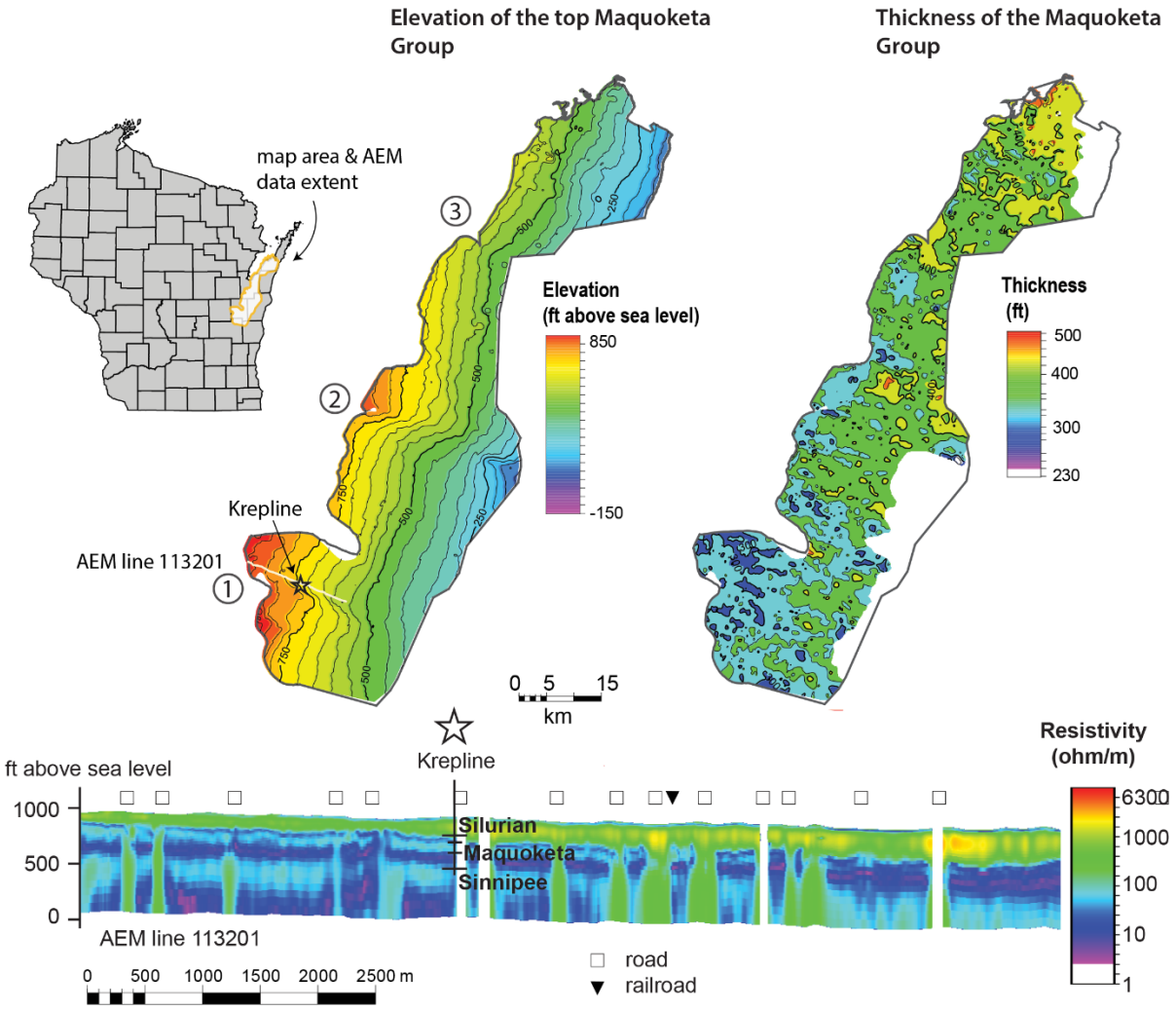


Figure 1: Maps showing the elevation and thickness of the Maquoketa Group (top) and an example AEM line (below). The inset map of Wisconsin (left) shows counties outlined in black and the eastern Wisconsin study area outlined in orange. Circled numbers to the left of the top Maquoketa elevation map locate offsets in depth-structure contours. The star locates the Krepline core on the map and AEM line, and formation contacts from core are tied to AEM line. Roads and railroads, symbolized above the line, cause cultural interference with the AEM signal.

Rocks and Roots: The Role of Geoheritage in Biodiversity Stewardship

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Conservation of natural surficial landforms with regional, scientific, or cultural significance has long been an intrinsic component used by scientists and educators who follow the principles of geoheritage. On the Keweenaw Peninsula, intact outcrops of Copper Harbor Conglomerate, Portage Lake Volcanics, and Jacobsville Sandstone each provide accessible learning opportunities to both students and citizens and create spaces for deeper emotional connections to the landscape. Culturally and geologically important sites are currently used in both educational tools and to increase community-wide engagement in geologic studies (Cowling et al. 2023; Lizzadro-McPherson and Vye 2023).

The principles of natural heritage, hereto referred also as 'bioheritage', strongly overlap with that of geoheritage. As geoheritage promotes connection to landscape via geological features, bioheritage facilitates connection through valuable natural features – ecosystems, flora and fauna – and encourages the conservation of landscapes that promote biodiversity. Sites that are identified by bioheritage ecologists, botanists, zoologists, and geographers as being of regional, scientific, or cultural significance often coincide with areas of high geodiversity. Categorization of these natural features show geographies dependent on both surface geology and glacial landforms; for example, the statewide distribution of volcanic bedrock lakeshore (Fig. 1), an imperiled natural community in Michigan, is wholly limited to surface-level exposures of Keweenawan rocks (Cohen et al. 2013) and supports a series of rare plants and animals found nowhere else in the state (Albert et al. 1997; MNFI 2026). Conservation of one outcrop for geological reasoning can therefore work beneficially for bioheritage, and vice versa.

In the summer of 2025, we conducted interdisciplinary research highlighting the natural connections between underlying geological formations, community ecology, and rare plant



Figure 1: Portage Lake Volcanics featured prominently along a high-quality volcanic bedrock lakeshore natural community recognized under both geoheritage and natural heritage.

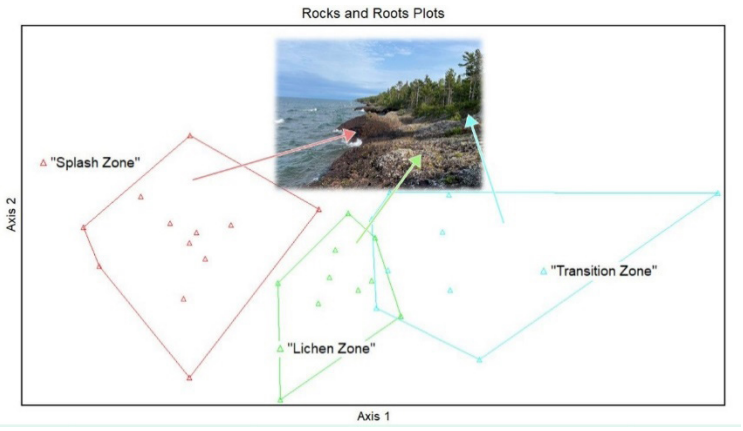


Figure 2: Pilot data examining ecological structure of bedrock lakeshore systems. Different zones of bedrock exposure promote plant communities of unique species composition.

distributions on volcanic bedrock lakeshores of the Keweenaw Peninsula. The project involved collaboration between botanists, geologists, geographers, and conservationists. Pilot data yielded significant plant community differences between bedrock types and microhabitats, and the summer was documented in an educational StoryMap (Stone et al. 2025) (Fig. 2). Meandering transects outlining subtle distinctions in ecosystem processes based on geological formation identified multiple new rare plant populations, including the discovery of red anemone (*Anemone multifida*) on the Keweenaw Peninsula (Fig. 3). The project has since led to multiple additional collaborations in the Western Upper Peninsula focused on geo- and bio-education.

Partnerships between bioheritage and geoheritage scientists can be valuable sources of interdisciplinary research and collaboration. Despite originating in disparate academic fields, the two disciplines can work in tandem to increase scientific understanding of our geological features while producing valuable teaching tools. Future research and educational opportunities are plentiful as the two worlds of geoheritage and bioheritage establish common ground.



Figure 3: Red anemone (Anemone multifida), a rare plant identified during field research on the Keweenaw Peninsula.

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Linking the Southwestern Laurentia large igneous province and rapid Duluth Complex emplacement through mantle plume dynamics

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Midcontinent Rift volcanism was protracted, spanning from ca. 1109 to 1084 Ma with major magmatic pulses separated by ~10 Myr and >30° of latitudinal plate motion (Figure 1). The long duration of magmatism and large spatial displacement of the continent are difficult to reconcile with a single stationary mantle plume beneath the rift. A corresponding question is what caused the renewal of voluminous magmatism ca. 1096 Ma that produced the massive Duluth Complex layered mafic intrusions and comagmatic lavas of the North Shore Volcanic Group after a period of relative magmatic dormancy (Miller and Vervoort, 1996), and after Laurentia had drifted >3000 km since the rift's initiation (Swanson-Hysell et al., 2019, 2021).

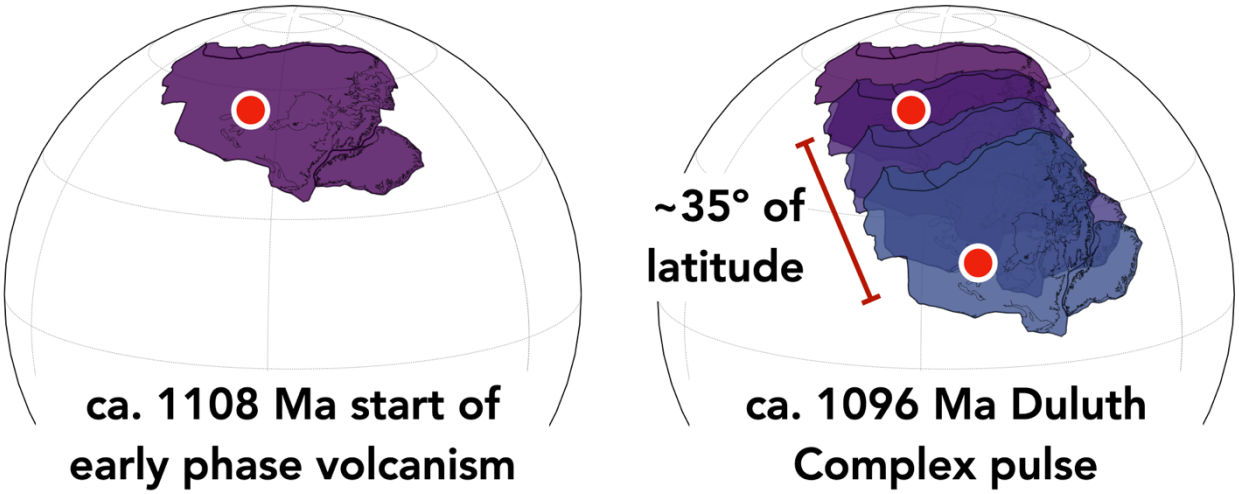


Figure 1: The plate motion of Laurentia reconstructed from Midcontinent Rift paleomagnetic data revealing large-scale latitudinal change between the start of early phase volcanism and the major pulse of magmatism that emplaced the Duluth Complex ca. 1096 Ma. The red dot indicates the location of the Lake Superior region in each reconstruction.

High-precision $^{206}Pb/^{238}U$ zircon dates developed through CA-ID-TIMS geochronology have resolved temporally distinct pulses of magmatism across Laurentia's interior. In southwestern Laurentia, the Southwestern Laurentia large igneous province (SWLLIP) encompasses >750,000 km^2 of ca. 1.1 Ga mafic sills, dikes, and lava flows. New dates from SWLLIP mafic rocks reveal a rapid, voluminous magmatic pulse at ca. 1098 Ma, with thick sills emplaced across Death Valley, the Grand Canyon, and central Arizona within ≤0.25 Myr (Mohr et al., 2024). Approximately 2 Myr later, the bulk of the Duluth Complex anorthositic and layered series was emplaced ca. 1096 Ma in <1 Myr (500 ± 260 kyr; Swanson-Hysell et al., 2021). Both pulses were rapid and voluminous, characteristic of plume-related large igneous provinces.

The close temporal and spatial relationship between the ca. 1098 Ma SWLLIP pulse and the ca. 1096 Ma Duluth Complex pulse supports a geodynamic link through lateral plume spreading. Rates of lateral plume spread predicted by mantle plume lubrication theory (Sleep, 1997) are consistent with a model in which a plume derived from the deep mantle impinged beneath southwestern Laurentia, then spread to the thinned Midcontinent Rift lithosphere over ~2 Myr, elevating mantle temperatures and generating melt. Buoyant plume material would have been directed to the rift through "upside-down drainage" at the base of the Laurentian lithosphere (Sleep, 1997; Swanson-Hysell et al., 2021),

wherein material flows along the topography of the lithosphere–asthenosphere boundary from thick to thin lithosphere. This hypothesis reconciles the close temporal relationships between voluminous magmatism across Laurentia and provides an explanation for the anomalous renewal of high magmatic flux within the protracted magmatic history of the Midcontinent Rift.

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Deformation processes in a mid-crustal strike-slip shear zone: Insights from the Archean Quetico Shear Zone, Superior Province, Canada

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The brittle-ductile transition, where most earthquakes nucleate, occurs at ~10-15 km depth in the crust (Sibson, 1983). The structures produced at the brittle-ductile transition in active shear zones are challenging to study as they occur at depth. To further understand shear zone structures at depth, this study focuses on an analogue structure for active strike-slip systems, the Quetico Shear Zone, due to its estimated erosional depths of 10-15 kms, which exposes the Archean brittle-ductile transition zone (Percival et al., 2012). The Quetico Shear Zone is a right-lateral, strike-slip shear zone located within the Wabigoon and Quetico subprovinces and has a strike length of at least 400 km (Kennedy, 1984). This project focuses on the eastern extent of the shear zone, north of Thunder Bay, and aims to constrain the kinematics, structures, conditions, and timing of deformation processes within the shear zone and adjacent to paleo-earthquake surfaces. The extent of deformation from the shear zone was analyzed through macro- and microstructures using field mapping and microscopy. The conditions of deformation were constrained using paleopiezometry through electron backscattered diffraction of recrystallized quartz (Cross et al., 2017) and Ti-in-quartz geothermometry through secondary ion mass spectrometry measurements of recrystallized quartz (Wark and Watson, 2006). To constrain the timing of deformation, laser-ablation split-stream inductively coupled plasma mass spectrometry of apatite, monazite, titanite, and zircon was performed to produce U-Pb dates (Kylander-Clark, 2017).

We found that Quetico Shear Zone deformation is characterized by increased mylonitization and brittle deformation with increasing proximity to the shear zone trace (within 500 m) where paleo-earthquake surfaces (i.e., pseudotachylite veins) were found (Fig. 1). Mylonitization produces recrystallized quartz ribbons and a strong foliation unique to the Quetico Shear Zone (stronger than regional Quetico Subprovince transpressional structures), particularly in granitic units (Fig. 1C-E). Non-granitic rock units within the core of the shear zone display pervasive brittle deformation with numerous faults (Fig. 1A). Granitic rock types display more variable orientations due to the isolated quartz ribbons deforming around larger feldspar grains. The recrystallized quartz grain sizes do not correlate with increased mylonitization and proximity to the shear zone. Recrystallized quartz grain sizes remained constant within error, with calculated stress values ranging from 69 to 116 MPa, with a median of 80 MPa. The temperatures of quartz recrystallization range from 457 to 589°C, with a median of 487°C, with no clear evolution with increasing proximity to the Quetico Shear Zone trace. Apatite and titanite provided the best ages for deformation, mainly producing interpreted ages younger than the Quetico subprovince metamorphism. The interpreted Quetico Shear Zone deformation ages are approximately from 2620 to 2600 Ma. The exhumed Quetico Shear Zone appears to be deformed at a constant stress shortly after the Kenoran orogeny.

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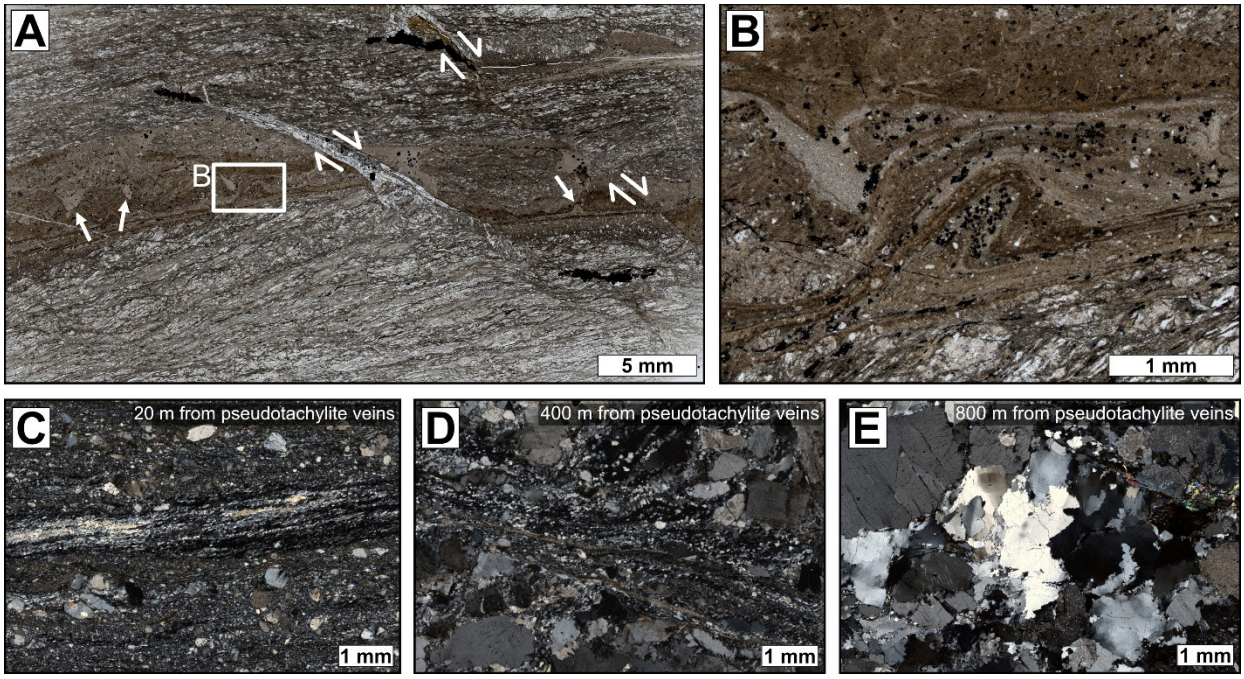


Figure 1: Quetico Shear Zone structures proximal to pseudotachylite veins: A: Plane-polarized light photomicrograph displaying pseudotachylite veins (medium brown layers cutting the white to light brown mylonitic fabric) from the core of the shear zone. Co-seismic injection veins are highlighted with white arrows. Right-lateral, late brittle faults are indicated by kinematic arrows. B: Magnified view of a pseudotachylite that has been viscously deformed. Cross-polarized light photomicrographs showing quartz microstructures of quartz-rich metamorphic rocks from increasing distance from the pseudotachylites: C: Extremely fine-grained quartz ribbons with minor feldspar porphyroclasts within a mylonite. D: Very fine-grained quartz within a quartz ribbon adjacent to fine-grained quartz in a protomylonitic granite. E: Fine- to medium-grained recrystallized quartz within a weakly deformed granite. Note that the recrystallized grain size is consistent in C-E.

Variations in Olivine Major Element Composition Across the Midcontinent Rift System

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Olivine [$(Mg,Fe)_2SiO_4$] is an early crystallising phase in mafic–ultramafic Ni–Cu–(PGE) deposits and a sensitive recorder of mantle melting history. Its forsterite content reflects the parental melt composition, while the Ni concentration and trace element ratios can be used to constrain petrogenetic processes and the physicochemical conditions of melting. However, the plutonic nature of these deposits means primary compositions can be overprinted by sub-solidus re-equilibration and late-stage fluid interaction, complicating the recovery of primary magmatic signals. Deconvoluting these signatures is critical to understanding melt generation, fractionation, and ultimately the mineralisation processes that govern the formation of these deposits.

The Midcontinent Rift System (MRS) one of the most extensively mineralised large igneous provinces and renowned for its magmatic Ni–Cu–(PGE) deposits. Despite this, olivine compositional data is sparse. We present new and collated major element olivine data from multiple Ni–Cu–(PGE) deposits across the MRS to evaluate regional-scale trends in forsterite and Ni contents. We examine deposit-scale variability and explore broader implications for the underlying magmatic architecture of the rift system.

This study builds on previously collected electron probe microanalyses (EPMA) of olivine from mineralised magmatic Ni–Cu–(PGE) deposits of the MRS within Canada e.g., Sunday Lake (Durán, 2025), Steepledge (Harding, 2024), Escape Lake, Current and Hele, and contributes new olivine compositional data from several unmineralized intrusions, namely Inspiration Sill, St. Ignace Island and Nipigon Sills. These data are further supplemented by olivine compositions from USA-based mineralised Ni–Cu deposits e.g., Tamarack (Goldner, 2011; Taranovic, 2015) and the Duluth Complex (Peterson, 2025). Together, this data constitutes the first regional-scale compilation of olivine chemistry across the MRS.

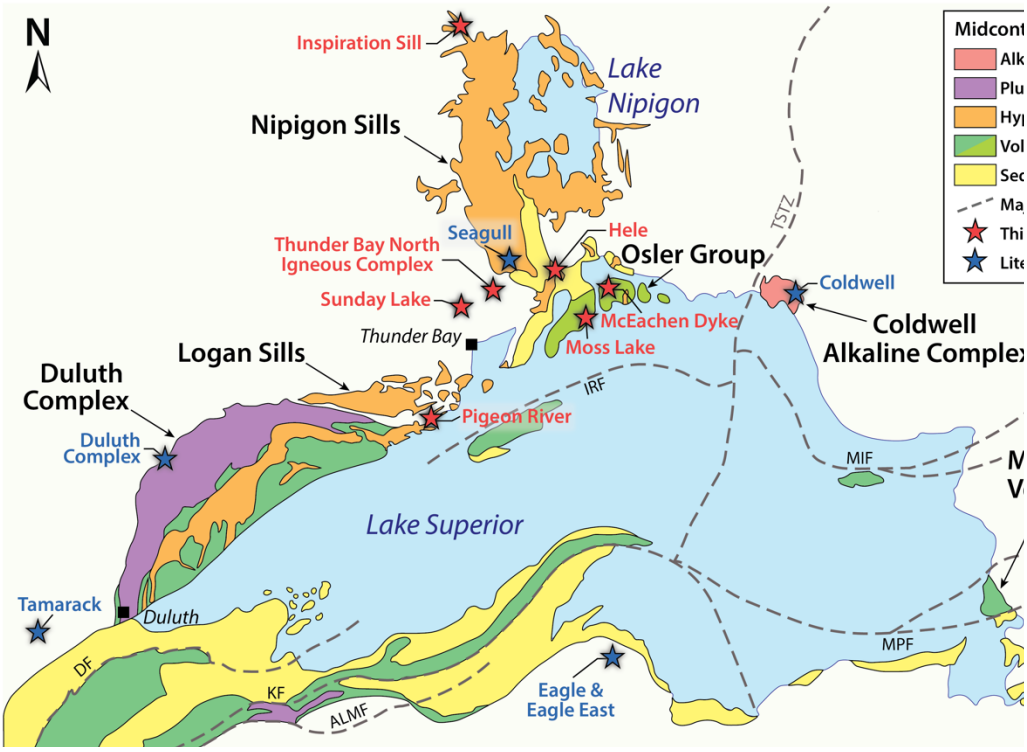


Figure 1: Simplified geological map of the Midcontinent Rift System highlighting the distribution of major rock types. Locations of the mafic–ultramafic intrusions sampled in this study are denoted by stars (red = data collected in this study; blue = literature data). Modified after: Good et al. (2015).

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