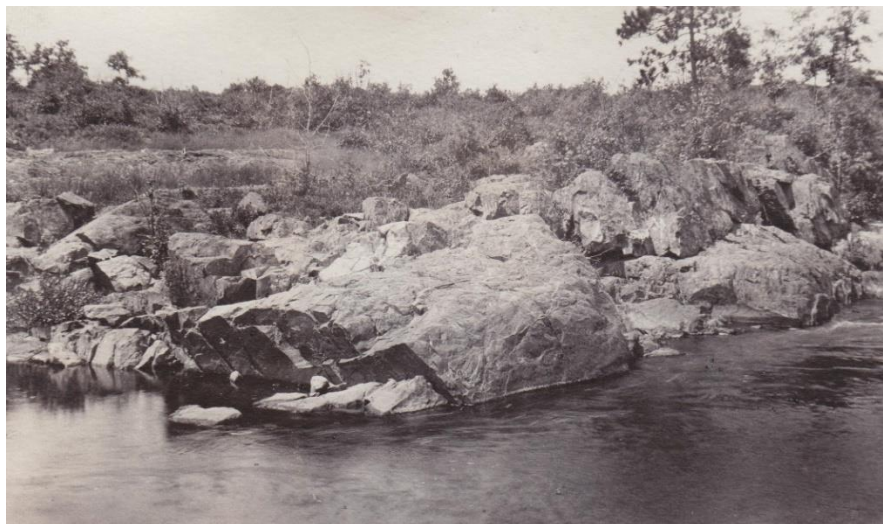


69th ANNUAL MEETING

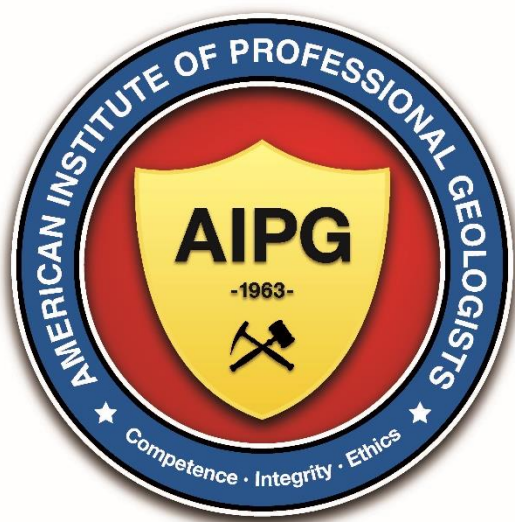
Eau Claire, Wisconsin — April 24-25, 2023

INSTITUTE ON LAKE SUPERIOR GEOLOGY

Part 1 — Program and Abstracts



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69th ANNUAL MEETING

INSTITUTE ON LAKE SUPERIOR GEOLOGY

**April 24-25th
Eau Claire, Wisconsin**

HOSTED BY

Rob Lodge, Esther Stewart, Carsyn Ames Co-Chairs

**University of Wisconsin- Eau Claire and Wisconsin Geological
and Natural History Survey**

**Proceedings - Volume 69
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Compiled and edited by Carsyn Ames

Cover Photos. Left— Photograph showing a group of men, women and children traveling through a forest north of Chippewa Falls, Wisconsin in a horse-drawn carriage, Chippewa Co., 1916. Center— Cross-bedding in basal Cambrian sandstone Eau Claire Co., 1919. Right — Outcrops of rhyolite schist along the north fork of the Eau Claire River, Eau Claire Co. 1919.

69th INSTITUTE ON LAKE SUPERIOR GEOLOGY

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PART 1: PROGRAM AND ABSTRACTS

PART 2: FIELD TRIP GUIDEBOOK

Trip 1: PRECAMBRIAN GEOLOGY OF THE CHIPPEWA RIVER VALLEY

Trip 2: WISCONSIN'S PALEOZOIC STRATIGRAPHY AND TOUR OF CRYSTAL
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Trip 3: PRECAMBRIAN GEOLOGY OF THE EAU CLAIRE RIVER VALLEY

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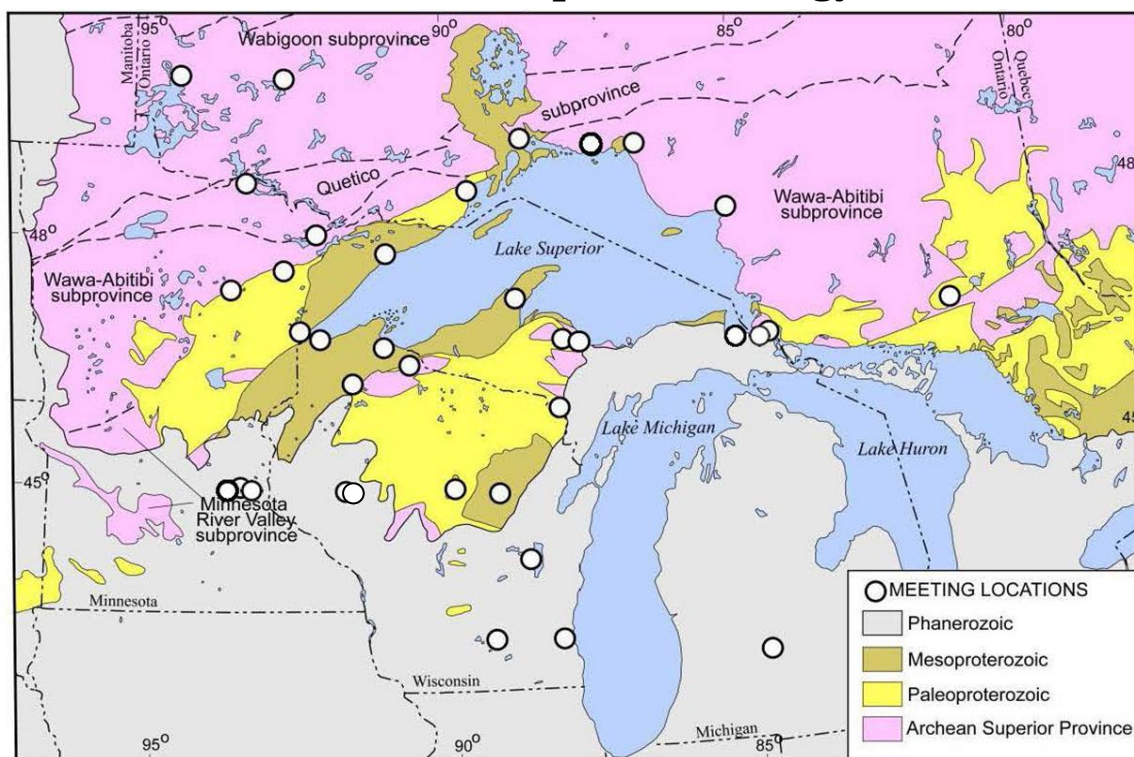
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Part 1: Program and Abstracts

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Institutes on Lake Superior Geology, 1955-2023



#	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

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

Sam Goldich and the Goldich Medal

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

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

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



INSTITUTE ON LAKE SUPERIOR GEOLOGY GOLDICH MEDAL

Goldich Medal Guidelines

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

Preamble

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

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

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

Award Guidelines

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

Nominating Procedures

- 1) The deadline for nominations is November 1. Nominations shall be taken at any time by the Goldich Medal Committee. Committee members may themselves nominate candidates; however, Board members may not solicit for or support individual nominees.
- 2) Nominations must be in writing and supported by appropriate documentation such as letters of recommendation, lists of publications, curriculum vita's, and evidence of contributions to Lake Superior geology and to the Institute.
- 3) Nominations are not restricted to Institute attendees, but are open to anyone who has worked on and contributed to the understanding of Lake Superior geology.

Selection Guidelines

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

Goldich Medalists

1979	Samuel S. Goldich	1998	Zell Peterman	2016	Mark A. Jirsa
1980	<i>not awarded</i>	1999	Tsu-Ming Han	2017	Philip Fralick
1981	Carl E. Dutton, Jr	2000	John C. Green	2018	Val W. Chandler
1982	Ralph W. Marsden	2001	John S. Klasner	2019	Mark Severson
1983	Burton Boyum	2002	Ernest K. Lehmann	2020	<i>not awarded</i>
1984	Richard W. Ojakangas	2003	Klaus J. Schulz	2021	Alan MacTavish
1985	Paul K. Sims	2004	Paul Weiblen	2022	Terrence J. Boerboom
1986	G.B. Morey	2005	Mark Smyk	2023	Peter Hollings
1987	Henry H. Halls	2006	Michael G. Mudrey		
1988	Walter S. White	2007	Joseph Mancuso		
1989	Jorma Kalliokoski	2008	Theodore J. Bornhorst		
1990	Kenneth C. Card	2009	L. Gordon Medaris, Jr		
1991	William Hinze	2010	William D. Addison & Gregory R. Brumpton		
1992	William F. Cannon	2011	Dean M. Rossell		
1993	Donald W. Davis	2012	James D. Miller		
1994	Cedric Iverson	2013	Tom Waggoner		
1995	Gene La Berge	2014	Laurel Woodruff		
1996	David L. Southwick	2015	Rodney J. Ikola		
1997	Ronald P. Sage				

2023 GOLDICH MEDAL RECIPIENT

Peter Hollings

Goldich Medal Committee

Serving through the meeting year shown in parentheses.

Steve Kissin (2018-2023*) Lakehead University (Committee Chair)

Dorothy Campbell (2019-2024*) Ontario Geological Survey

Dean Peterson (2022-2025) Big Rock Exploration

**Terms of the committee members were extended 2 years because of the cancelation of the 2020 meeting and the logistical difficulties of voting during the 2021 virtual meeting.*

Citation for the Goldich Medal Recipient to Peter Hollings



ILSG Members, it is our privilege to present the citation for this year's recipient of the prestigious Goldich Medal to Dr. Peter Hollings.

Pete received his Bachelor of Science with Honours in Geology from the Royal Holloway and Bedford New College, University of London in 1992. He continued as a postgraduate research assistant at Royal Holloway and Bedford New College until 1994 when he enrolled as a Ph.D. student at the University of Saskatchewan. He earned his Ph.D. in 1998 and his doctoral dissertation was titled "Geochemistry of the Uchi subprovince." He had a one-year postdoctoral fellowship at Saskatchewan, followed by a two-year NSERC postdoctoral fellowship at the University of Tasmania.

Pete joined the faculty at Lakehead University in 2001 as an Assistant Professor and in 2009 was promoted to full Professor, a title he continues to hold. Since 2013 Pete has been Director of the Centre of Excellence for Sustainable Mining and Exploration (CESME) at Lakehead University. He has served as Chair of the Department of Geology and as interim Dean of the Faculty of Science and Environmental Studies at Lakehead.

Pete has been recognized for his research through several awards. In 2004 he and his co-authors were awarded the Julian Boldy Award by the Mineral Deposits Division of the Geological Association of Canada for an outstanding paper. In 2008 he was awarded the William Harvey Gross Medal by the Mineral Deposits Division of the Geological Association of Canada for significant contributions to the field of economic geology by a geoscientist under the age of 40. He was part of the team recognized by an award in 2012 and in 2014 by AMIRA International. In 2015 he was named the NSERC Distinguished Researcher for Lakehead University and in 2016 he was named the Lakehead University Research Chair in the NSERC/CHIR category. He received the Howard Street Robinson Medal from the Geological Association of Canada in 2017. In 2021, a paper on which he was co-author was awarded the 2020 Cameron-Hall Copper Medal for the most outstanding scientific publication in the journal *Geochemistry: Exploration, Environment, Analysis (GEEA)*. Pete was awarded the NOHFC Industrial Research Chair in Mineral Exploration for a term from 2020 to 2025.

Pete has an impressive professional record of publications and presentations. As of 2022, he has been first author or co-author of 145 refereed journal articles, 13 book chapters, 234 reports, 136 papers in refereed conference proceedings, and 87 abstracts in conference

proceedings.

While this is an impressive list of accomplishments, it is Pete's ongoing contributions to our understanding of Lake Superior geology and to the Institute on Lake Superior Geology that make him a worthy recipient of the Goldich Medal.

Pete has extensively conducted research on the geology of the Lake Superior region and the broader Superior Province. He has focused on both the Midcontinent Rift System (MRS) and Archean greenstone belts and their mineral resources. More than 30 of his published papers in refereed journals are on Lake Superior geology as well as about half of both his 30 first-authored conference proceedings and 29 first-authored refereed abstracts. He has contributed to more than 60 technical reports on Lake Superior geology. Of his 27 invited presentations, half have dealt with Lake Superior geology.

Pete has a significant number of publications and presentations relevant to the discovery and utilization of natural resources in the Lake Superior region. Some of his numerous economic geology publications and presentations on topics outside of the Lake Superior region are also applicable to our regional geology. An area of emphasis in Peter's research is the application of geochemistry and petrology to explore for ore deposits, including Ni-Cu-PGE deposits (e.g., Lac des Iles Mine and the Thunder Bay North igneous complex). His other areas of interest include igneous geochemistry of the MRS, Archean greenstone belts and granites, the tectonic setting of komatiites, and Archean gold deposits.

As the Director of CESME, he provides leadership in promoting the discovery of and environmentally responsible exploration for natural resources. Pete has also made contributions to understanding of the natural history and environment of the Lake Superior region as demonstrated by numerous publications focused on the timing and evolution of local rocks and mineral deposits.

Pete's research is firmly rooted in field work and uses geochemical and other data to test existing ideas and concepts and to develop new ones. He has successfully used local and regional geochemical data to provide evidence and/or implications for broader geological questions, such as atmospheric oxygen in the Precambrian, continental growth and lithospheric recycling, the Superior Province cratonic keel, and the earliest phases of Midcontinent Rift development. In addition to data-driven new ideas and concepts, Pete's research efforts have resulted in development of new analytical approaches that can be applied to the Lake Superior region and beyond.

As a Professor at Lakehead University, Pete is actively involved the education of geoscientists through classroom teaching and thesis supervision. He is committed to training and mentoring as evidenced by the large role students play in his research. He has supervised and co-supervised 37 honours undergraduate research projects and 32 Masters graduate student theses. Most of this student-focused research has involved Lake Superior geology. His former students now have senior positions with government and industry, and some have gone on to complete PhDs. Moreover, he supports and encourages students to attend and present their research at ILSG.

ILSG plays a significant role in Pete's professional activities. He has authored/co-authored (many with his students) 75 ILSG abstracts (nearly 4 per year), six ILSG field trip guidebooks, and ILSG Special Publication #1, *Field trip guidebook for the Slate Islands, Ontario*. At his very first ILSG meeting in 2002, Pete co-authored an abstract and served on the Student Paper Awards Committee.

Pete has Chaired or Co-Chaired four in-person annual meetings (Nipigon, 2005; International Falls, 2010; Thunder Bay, 2012; Terrace Bay, 2019) and the virtual meeting in 2021. He has served as the Secretary of the ILSG from 2003 to the present. As Secretary, he is responsible for email communications with the members of ILSG. As a member of the Board, he attends and chairs the annual Board meeting. In ILSG Board meetings he always considers and defends the best interests of Institute. Pete is the ILSG webmaster and played a key role in the current design of the ILSG website which he updates and maintains. Through his efforts, Lakehead University is the digital archive to all of the past ILSG proceedings and field trip guidebooks and provides open access of this content worldwide. A testament to the quality and accessibility of these documents was ILSG's receiving the 2016 Outstanding Geologic Field Trip Guidebook Series Award by the Geoscience Information Society (GSIS), which Pete accepted on behalf of the Institute. The stature of ILSG in the regional, national, and international geological communities has been elevated because of the increased presence of ILSG on the worldwide web, in large part because of Pete's efforts.

Over the years, we have all witnessed Pete in action. He is collegial, easy to approach and gets along well with others, whether they be students, colleagues, or industry geoscientists. He is both a good listener and a good speaker. And he is open-minded. He has high personal standards and expects them to be reflected in the work of his students and research colleagues. Pete is truly enthusiastic about the geology of the Lake Superior region and about ILSG.

Pete has made and continues to make substantial contributions to the field of geology and to the Institute on Lake Superior Geology. Pete has more than met the qualifications that are engraved on the Goldich Medal itself: "For outstanding contributions to the geology of the Lake Superior region."

We congratulate the 2023 Goldich Medalist, Peter Hollings.

Citation by:

Theodore J. Bornhorst, Goldich Medalist 2008

Mark C. Smyk, Goldich Medalist 2005

Honoring the Pioneers of Lake Superior Geology

(Adopted by the Board of Directors, 2016)

Preamble

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

Award Guidelines

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

The Board will review this award every five years.

Pioneers of Lake Superior Geology

2017 Douglass Houghton (1809-1845)

2018-20 *not presented*

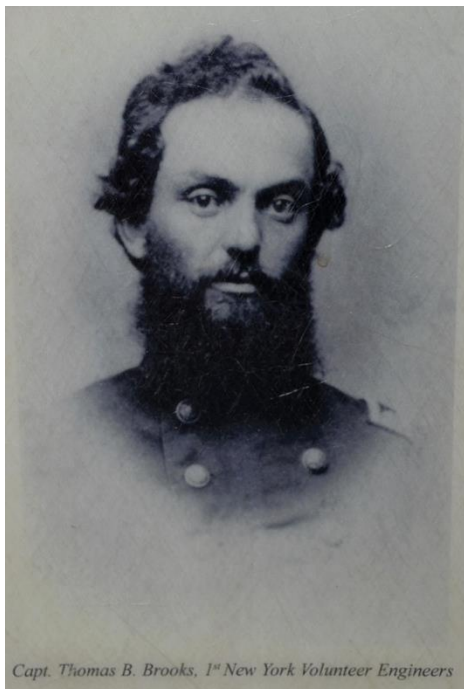
2021 Newton Horace Winchell (1839-1914)

2022 Thomas Leslie Tanton (1890-1971)

2023 Thomas Benton Brooks (1836-1900)

2023 Nomination for Thomas Benton Brooks Pioneer of Lake Superior Geology

“During many years Major (T.B.) Brooks was the chief authority in the region on matters pertaining to geology, the ores and the mines of the iron region of Lake Superior.”¹



Capt. Thomas B. Brooks, 1st New York Volunteer Engineers

Shortly after the U.S. Civil War Major Thomas Benton Brooks moved to the Marquette Iron Range. There over the course of less than a decade, he became the premier geologist, prospector, mining and civil engineer, and mining company executive of the region. During these formative years of the iron ore industry, when the Lake Superior region was providing about one-quarter of the iron ore used in the U.S., he was employed by the Iron Cliffs Company, the predecessor of the Cleveland-Cliffs Company, the Michigan and Wisconsin Geological Surveys, and served as a consultant to iron ore exploration and mining companies of the region. His contributions had a significant role in mapping the Precambrian geology and iron ranges of Michigan and Wisconsin and a lasting impact on the iron ore industry of the region. As stated by Prof. C.R. Van Hise, Brooks' successor as the premier geologist of the Lake Superior region²: “Notwithstanding the immense advantage which it has been to have Brooks' work as a

foundation, it has taken many years of labor fairly to complete the structural story to which Brooks contributed important chapters. Only those who have labored in the Lake Superior region and who understand its peculiar difficulties can give Brooks credit for the remarkable work he did. His geological work is my ideal of what should be done in a new region of complex geology.”

Thomas B. Brooks was born on June 15, 1836 in Monroe, NY, near the New Jersey border, and died nearby on November 22, 1900. In 1852 at the age of 16, he joined a surveying crew of the Erie Railroad and rapidly advanced from woodsman to instrument man. In 1853 he was employed with the New York Topographic and Geological Survey and then entered the Engineering Department of Union College of Schenectady, NY in 1856, graduating in 1858 in civil engineering. He remained at Union College as an instructor for a year and then took part in topographical surveys in New York, New Jersey, Pennsylvania and the U.S. Gulf Coast. In

¹ Quoted from an article by Chas. A. Lawton in the Daily Mining Journal, November 29, 1900 entitled *The Late Major Thomas Benton Brooks: Biographical Sketch of a Man Whose Name is Intimately Associated With the Early Development of Michigan's Iron Mines*. The Mining Journal, the predominant daily newspaper of Marquette, Michigan and the Northern Peninsula of Michigan, was founded in 1841.

² As quoted by Bailey Willis of the U.S. Geological Survey in an obituary for Major Brooks in the Proceedings of the American Association for the Advancement of Science, New Series, Volume 13, No. 325(March 22, 1901), 460-462.

1860 he attended a series of lectures on geology given by Prof. J.P. Lesley former state geologist of Pennsylvania and Professor of Geology at the University of Pennsylvania. This was his only formal education in geology. He volunteered for the Union Army in 1861 and organized an engineering company that had a distinguished record during numerous Civil War campaigns. He retired from the Union Army in 1864 as a brevet colonel after being wounded in the battle of Denly's Bluff, but referred to himself after the war as Major Brooks.

In 1865 after leaving the Union Army he accepted a position with the Geological Survey of New Jersey where he conducted magnetic surveys with a dip needle to locate iron ores and was put in charge of mines and furnaces. Shortly thereafter, he was induced to take charge of the mines of the Iron Cliffs Company in the Marquette Iron Range as vice-president and general manager. He moved to Negaunee, Michigan, where his practical knowledge of geology and engineering, leadership skills, originality, keen powers of observation and deduction, and intense work ethic served him, the company, and the Lake Superior region well. This is where his extensive geological studies began and where he developed the instruments and methodology to exploit the iron ores of the Lake Superior region. He brought the dip needle to the Lake Superior region and was among or possibly was the very first, to use it in iron ore exploration and geologic mapping in the region. He also pioneered the dial (Sun) compass, which he modified for geologic use from the surveying solar compass developed by W.A. Burt.

In 1869 he resigned from the Iron Cliffs Company and was given the responsibility of mapping and reporting on the Marquette Iron Range and was placed in charge of the Economic State Geological Survey of the district by the Michigan Geological Survey, essentially becoming the State Geologist of the Northern Peninsula. He received no salary for this position, but he was allowed to receive private funds from numerous iron ore companies and mines. Unfortunately, his intense work schedule took a toll on his health that caused him to leave Marquette with his family in the winter of 1872-73 for London, England and eventually Dresden, Germany, where he hoped to regain his health, but failed to do so. During this period he prepared reports on his iron range geologic studies for publication by the Michigan and Wisconsin Geological Surveys (Brooks, 1873 and 1880), articles on the geology of the region and magnetic surveying instruments and their use published in various journals including the American Journal of Science and Arts (Brooks and Pumpelly, 1872; Brooks, 1875), and co-authored the book "Iron Ores of Missouri and Michigan" (Pumpelly, Brooks, and Schmidt, 1876).

During his years involved with the geology and ores of the Lake Superior region Major Brooks made numerous advances in the geological knowledge of the region that have served as a foundation for future studies and developed methods and instruments that proved useful for exploiting the ores of the region for many years. The following are a list of his major lasting accomplishments:

- He with the assistance of R. Pumpelly and R.D. Irving developed the dial (Sun) compass for geologic studies based on the principal of Burt's surveying solar compass which together with the dip needle that he brought from the Geological Survey of New Jersey were used in the Lake Superior region for nearly a century to locate and outline iron-rich rocks and ores. His publications on these instruments led to their extensive worldwide use.
- He established procedures for conducting magnetic surveys for geological purposes in the Lake Superior region and methods of interpreting the observations of the surveys based on empirical studies.

- He was the first to describe the magnetic characteristics of the minerals and rocks of the Lake Superior region.
- He (Brooks, 1872a) recognized that magnetic anomalies observed in the area of non-magnetic Paleozoic (then Silurian) sedimentary rocks of the eastern part of the Northern Peninsula of Michigan were likely derived from the basement Precambrian rocks that crop out to the west. Accordingly, these anomalies could be used to trace the basement rocks and their structure beneath the sedimentary rocks. Furthermore, he realized that anomaly characteristics could be used to determine the depth to magnetic sources and thus, the thickness of the sedimentary rocks. In a similar manner he understood that perhaps the depth of Lake Superior could be determined from analysis of the lake magnetic anomalies.
- He founded the first assay facility for iron ores in the Lake Superior region in the city of Marquette which facilitated iron ore mining in the region.
- He conducted one of the first geological surveys of the Marquette, Menominee, Crystal Falls, and Gogebic Iron Ranges. He was the first to understand that the Marquette Iron Range occurs within a 75-km long syncline extending to the west from near Marquette, Michigan (Allen and Martin, 1922).
- He recognized the stratigraphic position of the copper-bearing rocks of the Northern Peninsula of Michigan and suggested the name Keweenawian (note his spelling) for the age of these rocks in American Journal of Science and Arts articles of 1872 and 1875. Subsequently, the term Keweenawan has been used for these rocks.
- He had an important role in developing safe, efficient methods of mining iron ores of the Lake Superior region (Brooks, 1972b).
- He was intensely interested in the education of his children and supported the studies of his son, Alfred Hulse Brooks, a famed geologist of the U.S. Geological Survey, Alaska Branch, who is honored by naming of the Brooks Range of Alaska after him.

These are all significant contributions that have had a profound role in understanding of the geology of the Lake Superior region and the exploitation of its ores. They have largely gone unrecognized for the past century and a half, but they clearly distinguish Major Thomas Benton Brooks as a Pioneer of Lake Superior geology.

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William J. Hinze,
Purdue University

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In Memoriam

Stephen Allard

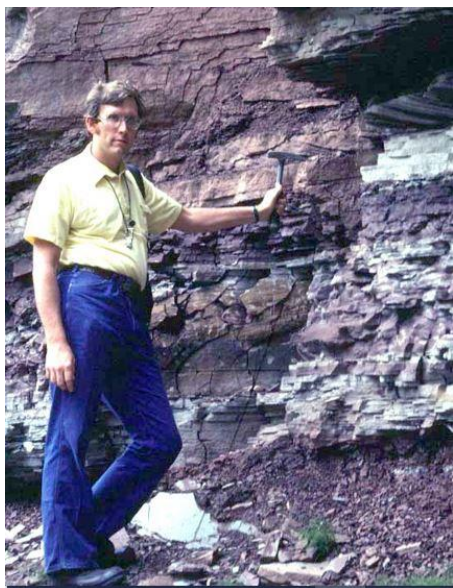


Stephen Thomas Allard, 59, of Winona, MN, passed away on Friday, September 16, 2022. He was born May 2, 1963, in Manchester, New Hampshire and graduated from Manchester Central High School before going on to receive both his bachelor's and master's degrees from the University of New Hampshire, and his doctorate from the University of Wyoming. In 2002, Stephen moved to Winona, MN to begin his career as a professor at Winona State University. After serving for 19 years as a faculty member in the Department of Geoscience, Stephen retired from the university in December of 2021. During his tenure at WSU, Stephen served on several committees and taught 13 different courses drawing on his expertise in hard rock and structural geology. Stephen was dedicated to teaching and mentoring students through field-based research, leading courses and field trips throughout the United States, notably the many summers spent in the Black Hills of South Dakota.

(modified from Hartford Courant newspaper)

In Memoriam

Steven A. Hauck



This Fall the Institute on Lake Superior Geology lost a dedicated geologist and friend, Steve Hauck, who was a regular attendee of ILSG (since at least 1984) and worked on countless projects in the Lake Superior Region while employed at the Natural Resources Research Institute (NRRI) in Duluth, MN. During that time, Steve was a mentor to numerous geologists in the region throughout their early and continuing careers. Steve Hauck had just recently moved from Duluth to Euclid, OH where he passed away on October 6, 2022 at the age of 73.

Steve was born on May 16, 1949, in Rochester, NY, where he graduated from Gates-Chili High School prior to attending Albion College where he earned a BS in geology. He enlisted in the US Army where he was trained as a Chinese translator and married fellow Albion student and the love of his life Barbara Horsley

to whom he was married for 50 years. Steve loved to talk about geology on car trips and impressed his future father-in-law with his knowledge and enthusiasm. Steve later earned a MS degree in geology from the University of North Carolina before embarking on a geology career that eventually led him around the globe. He was first employed by Union Carbide in Grand Junction, CO, where he was responsible for exploration for uranium in the 4-corners region. While at Union Carbide he was also responsible for developing a world-wide exploration program in search of IOCG deposits (as they were later called) and visited many similar deposits including Olympic Dam, Pilot Knob and Pea Ridge in Missouri, and Kiruna iron deposits in Sweden to name a few. Steve's first ILSG talk (1984) pertained to the distinguishing characteristics of these types of deposits and was titled "Comparison of Middle Proterozoic Iron Oxide Rich Ore Deposits, Mid-Continent, USA, South Australia, Sweden, and the Peoples Republic of China."

Steve was then hired as the second employee of the Minerals Division of the NRRI in 1984 as Research Director and Manager where he worked for over 30 years. He was initially responsible for building and equipping the division, focusing on economic geology, and initially hired graduate students from the University of Minnesota Duluth (UMD). During his tenure at the NRRI, Steve hired well over 30 UMD students (both undergraduate and graduate students) as well as many geologists in their early career years. Projects that he and his co-workers researched ranged from clay deposits in SW MN, to Cu-Ni and Fe-Ti deposits in the Duluth Complex, to the Biwabik Iron Formation, to geochemistry on a wide range of rocks spanning from the Archean to the Cretaceous. He worked closely with fellow geologists at the Minnesota Geological Survey, Minnesota Department of Natural Resources Lands and Minerals, and the U.S. Geological Survey, and collaborated with many geologists across the U.S. and overseas in academia and industry.

Steve was a Co-chair of the ILSG meeting for its 50th Anniversary in Duluth in 2004 and served on the Board of Directors for three years. Overall, Steve participated in three ILSG talks (one as primary author) and ten posters (four as primary author). Steve loved to talk about rocks and encouraged his co-workers to give talks and poster presentations at many of the ILSG meetings.

Steve was an avid birder, cultivator of native plants, and shutterbug. He was predeceased by his youngest son, Davis, and his parents Arthur and Jean (Doron). He is survived by wife Barbara, son Steven (Danette), sisters Carlin Eagan (Daniel), Sandra Doron, and Mary McGuire (Mark), and two grandchildren Levi and Abigail.

(modified from Duluth Tribune newspaper)

In Memoriam

Manfred Kehlenbeck



Manfred was born in Bremen, Germany in 1937 to parents Emma and Theodor. This is where he spent his childhood, amidst the horrors of World War II, like so many of Europe's children.

At age 14, Manfred immigrated with his parents to the U.S., landing in New York in July of 1952 and settling with relatives in Long Island until they could become established. Here he completed his high school education, then attended Hofstra University for his undergraduate degree. It was there that he was introduced to the science of geology, which became his life-long interest and focus of his future education and career. It was also on Long Island that he met Elenore, who would eventually become his wife of 53 years.

Manfred went on to Syracuse University in upstate New York to attain his M.Sc. in Geology and gain field experience in the beautiful Adirondack Mountains. And then, moving even further north, he attended Queen's University in Kingston, Ontario where he achieved his Ph.D. Since he has always planned to teach, he then accepted a position at the young Lakehead University in Thunder Bay, Ontario. Here he soon became fascinated with the Precambrian geology of the area and greatly enjoyed his teaching duties. He was a born teacher, winning Teacher of the Year awards both at Lakehead and in the Province.

He served five terms as a Geology Department Chair, guiding the department into its M.Sc. program. His years at Lakehead were productive and happy ones.

Upon his retirement, Manfred was able to expand on other interests and travel widely. In addition to trips in Canada, the U.S. and Germany, there were four “special” ones – professionally to Russia and China, and then the most fascinating ones, to the Arctic and Antarctic. His other areas of interest and hobbies were in watercolour and pen and ink drawings of local scenes, especially forests, lakes, rocks, and old buildings of NW Ontario

and many views of Old Fort William. Many of his works hang in Thunder Bay homes. He became an avid gardener, curler and opera lover, and spent many hours volunteering for various causes.

It was a happy and fulfilling retirement for Manfred and Elenore until his last illness and unexpected passing in the early morning hours of July 7, 2022 when he drew his last breath at the Thunder Bay Regional Health Sciences Centre after emergency surgery. Our thanks to the I.C.U. staff and especially to Katie and Michaela who were so kind and thoughtful during those last terrible hours, and to N.P. Crystal Kaukinen for the many years of care she had provided.

Thanks also to all who have been so kind with phone calls, cards, offers to help, food and rides. Special thanks to Barb Morriss for always checking in, to Sam and Georgina Spivak for all the rides, and to Vince and Frieda DeSa who have been here for me everyday with their help and support – without them, I don't know how I would have survived this devastating time.

Manfred was a good, kind, generous man, and loving and devoted husband. He is sorely missed.

Auf Wiedersehen mein lieber Manfred.

Published by The Thunder Bay Chronicle Journal on Aug. 13, 2022.

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 annual banquet.

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

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

Successful applicants will receive their awards during the meeting.

Joe Mancuso Student Research Awards

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

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

The 2012 Board of Directors approved modification of the fund's name, adding "Mancuso" to reflect the many contributions of Joseph Mancuso to the organization and sizeable donations made in his name. "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 2022, the ILSG Board of Directors selected two students to be granted research funding of \$1000.00 each from the Joe Mancuso Student Research Fund. The awardees were:

Itai Bojdak-Yates

Lawrence University
Department of Geosciences
TOPIC: *Detrital zircon provenance study of Paleozoic sandstones from Wisconsin*

Lillian Glodowski

University of Wisconsin- Eau Claire
TOPIC: *Petrogenesis of the Lynne Zn-Cu-Pb Deposit, Oneida Co., Wisconsin*

Evan Weber

University of Wisconsin- Eau Claire
TOPIC: *U/Pb Geochronology and Zircon Trace Element Geochemistry of the Pembine-Wausau Terrane of the Proterozoic Penokean Orogen, 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.

Board of Directors

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

The terms of Board members were extended 2 years because of cancellation of the 2020 meeting, and the difficulties of virtual voting by the membership during the 2021 meeting.

Mike Easton, Chair (2022-2025) — Ontario Geological Survey

Mark Smyk (2019-2024*) — Lakehead University

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

Peter Hollings — Secretary (2019-2024*) — Lakehead University

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

Field Trip Leaders and Guidebook Authors

Field trips have been the mainstay of the ILSG since its inception 69 years ago. We want to give a special thanks to the field trip leaders and guidebook authors who volunteered their time and talent in carrying that tradition forward.

1) Precambrian geology of the Chippewa River Valley

Rob Lodge- UW- Eau Claire

Bob Hopper- UW- Eau Claire

2) Wisconsin's Paleozoic stratigraphy and tour of Crystal Cave

Carsyn Ames- Wisconsin Geological and Natural History Survey

Esther Stewart- Wisconsin Geological and Natural History Survey

William Batten- Wisconsin Geological and Natural History Survey

Eric Stewart- Wisconsin Geological and Natural History Survey

Ian Orland- Wisconsin Geological and Natural History Survey

3) Precambrian geology of the Eau Claire River Valley

Rob Lodge- UW- Eau Claire

Evan Weber- UW- Eau Claire (*student*)

4) Quaternary geology and geomorphology of the Eau Claire Region

Doug Faulkner- UW- Eau Claire

Elmo Rawling- Wisconsin Geological and Natural History Survey

REPORT OF THE 68th ANNUAL MEETING OF THE INSTITUTE ON LAKE SUPERIOR GEOLOGY

The Ontario Geological Survey (OGS), with support from the Geological Survey of Canada (GSC), hosted the 68th Annual Institute on Lake Superior Geology on May 07 – 12, 2023 in the “Cavern” at Science North in Sudbury, Ontario. The meeting consisted of two days of technical sessions with pre- and post-technical session field trips.

First, we would like to thank the meeting sponsors for their generous support, either through direct funding or in-kind support, namely: the Centre for Excellence and Sustainable Mineral Exploration in Thunder Bay, Gel Exploration Limited, the Northwestern Ontario Prospectors Association, Vale Canada, and the Ontario Geological Survey. We also thank the Individual Contributors to the Student Travel Scholarship fund: Mary Kay Arthur, Mike Beauregard, Ben Berger, Terry Boerboom, Jim DeGraff, Michael and Monica Easton, Dick Heglund, Joanna Hodge, Bob Mahin, Jim Miller, Dean Peterson, Mark and Laurie Severson, Al MacTavish and Graham Wilson.

The 2022 meeting was the first *in-person* meeting held since the 2019 Terrace Bay meeting. An ILSG meeting questionnaire, which ran from January 20 to February 20, 2022, was key to shaping the format and venue of the meeting during a period of rapidly changing COVID-related regulations, with most responses favouring an *in-person* meeting. For technical reasons, a hybrid meeting was not possible.

Total meeting registration was 80, including 12 students. This registration is about 80% of the attendance of the last two Sudbury area meetings (Sudbury 1997; Sault Ste. Marie 2006), and was a great turnout given the COVID-related travel restrictions still in place at the time of the meeting. Attendance from the United States was excellent, with attendance from the Sudbury area lower than expected, for unknown reasons. Despite the somewhat lower attendance, the technical program was nevertheless excellent, with a strong focus on Midcontinent Rift geology and mineralization in the Lake Superior region. In addition, four presentations focused specifically on Sudbury area geology. There was also time in the schedule for several impromptu presentations on a variety of topics on Wednesday afternoon prior to the announcement of the student awards.

Proceedings Volume 68 was published in two parts. Part 1 – Program and Abstracts, compiled and edited by Michael Easton (OGS), contains 28 published abstracts for 21 oral and 8 poster presentations (one poster did not have an abstract). Students presented 5 oral and 5 poster presentations. Part 2 – Field Trip Guidebooks, also was compiled and edited by Michael Easton. It contains descriptions of three pre-meeting and two post-meeting field trips. Hard copies of the Abstract Volume and Field Trip Guidebooks for trip participants were printed by Johanne Roux and Carlo Castrechino (OGS) after it proved impossible to find a commercial printer who could produce the volumes in time for the meeting. Both volumes are available for download from the Institute on Lake Superior Geology website. Monica Easton is thanked for assisting in preparing the digital versions of both volumes.

The 68th ILSG marked only the second time in the Institute’s long history that its annual meeting was held in Sudbury, the last time being in 1997. Since the discovery of distal ejecta

from the Sudbury impact in the western Lake Superior area in 2005, many members of the Institute had suggested that the time was right for another Sudbury meeting. The meeting location enabled organizers to offer five field trips that showcased a variety of Proterozoic rocks in the Sudbury area itself, as well as along the north shore of Lake Huron. Three field trips focussed on the geology and mineralization related to the Sudbury Structure, and the organizers wish to thank the local exploration companies that graciously provided information and access to their properties. Parts of the other two of the field trips had been offered at previous ILSG annual meetings (e.g., Sudbury 1997; Sault Ste. Marie 2006), but both greatly benefitted from the new mapping, research, discoveries and interpretations that had taken place in the intervening years. COVID-related shortages of rental vehicles and/or drivers led to pre-meeting trips being held over several days, which unexpectedly, provided more opportunities for attendees to take in several field trips if they wanted. All the field trips, and the meeting itself, were blessed with sunny weather and a minimum number of pesky insects. Total field trip participation was 96 (excluding leaders and volunteer drivers). A list of field trips is provided below (numbers correspond to trip numbers in the Guidebook volume):

Pre-meeting field trips (and leaders) on Saturday, May 07; Sunday, May 8, and Monday, May 9.

- 5) A cross-section through the Huronian Supergroup at Elliot Lake, Ontario
(Michael Easton, Ontario Geological Survey) (May 7)
- 2) Geology of the Grenville Front in the Sudbury area
(Michael Easton, Ontario Geological Survey) (May 8)
- 1) Traverse across the Sudbury Impact Structure
(Wouter Bleeker, Geological Survey of Canada, and Sandra Kamo, University of Toronto;
Michael Leshner and Henning Seibel, Laurentian University) (Two-day trip, May 8 and May 9)

Post-meeting field trips (and leaders) on Thursday, May 12

- 3) Magmatism and brecciation in the Footwall Rocks of the southwestern Sudbury Structure
(Caroline Gordon, Ontario Geological Survey; Carol-Anne G  n  reux, Laurentian University
and Terrane Geoscience; and Brad Clarke, SPC Nickel Corporation)
- 4) An overview of the geology of the Sudbury Structure
(Shirley P  loquin, Ontario Geological Survey)

Many registrants attended the welcoming reception on Monday evening, which included an IMAX theatre presentation on “Dinosaurs of Antarctica”. Furthermore, the vast majority of registrants and invited guests attended the annual ILSG banquet on Tuesday night. Although a Homer Award overview presentation was given, no “recipients” were identified during the 2022 annual meeting, or in the previous 3 years!

As always, a highlight of the post-banquet activities was presentation of the 2022 Goldich Medal. This year’s very deserving recipient was Terry Boerboom. The Goldich Medal citation was presented by Mark Jirsa, his colleague for many years. Mark described Terry’s contributions to the ILSG and to the greater understanding of Minnesota’s geology over several decades during his time as a student and his 35 years with the Minnesota Geological Survey. Terry is indeed a worthy recipient of this prestigious award. The 68th ILSG saw a return to the usual post-banquet guest speaker tradition. Andy Parmenter

of the Canadian Nuclear Waste Management Organization (NWMO) travelled from Toronto to give an overview of NWMOs *Geoscience site characterization of the Revell batholith in the Ignace area of northwestern Ontario*. His talk provided detailed insights into the 3-D character of a Neoarchean granodioritic to granitic intrusion, based on detailed mapping and geophysical, seismic, and geochemical studies, as well as from multiple 1 km-long research cores obtained from the batholith.

In 2022, the student paper committee had its usual difficult job of selecting the best among five excellent oral presentations and five poster presentations for the Doug Duskin Student Paper Awards. The committee awarded four prizes, with the best talk award going to Rebecca Price for her talk on “*Mineralogy and Petrology of the Good Hope Carbonatite Complex, Marathon, ON*” and the best poster award going to Khalid Yahia for his poster on “*Geochemical and isotopic composition of Midcontinent Rift-related intrusions of the Thunder Bay North Igneous Complex, northwestern Ontario, Canada*”. Runner-up prizes went to Audray Hinkenmeyer for her talk on “*Characterizing Late Wisconsinan Rainy Lobe till from the Hudson Bay Lowlands to SW Minnesota: Insights on provenance and ice sheet behavior during Late Wisconsin glaciation*” and to Katherine Langfield for her poster on “*Slip Kinematics of the Hancock Fault in the Midcontinent Rift System, Keweenaw Peninsula, Michigan*”. Eisenbrey Student Travel Grants were given to three students: Connor Caglitoti (Lakehead University), Katherine Langfield (Michigan Technical University), and Miles Harbury (University of Wisconsin, Milwaukee).

The Institute’s Board of Directors met on Tuesday, May 10, 2022, and a brief overview of the meeting notes is provided below:

1. Accepted report of the Chairs for the 67th ILSG, Virtual Meeting; as published on the ILSG web site, and minutes of last Board meeting in May 2021.
2. Received, discussed, and accepted 2021-2022 ILSG Financial Summary.
3. Received, discussed, and accepted 2021-2022 report of the Secretary (Hollings).
4. Approved Michael Easton as on-going ILSG Board member
5. Discussed and approved renewal of Mark Jirsa as Institute Treasurer (end of term 2022). This was later approved by a vote of the membership.
6. Discussed and approved replacing Dan England as the “member from industry” on the Goldich Committee (end of term 2022) with Dean Peterson.
7. Approved Eau Claire as the site for the 69th annual ILSG meeting. The meeting will be hosted by Robert Lodge and Esther Stewart.
8. Reviewed and approved the guidelines for the Honouring the Pioneers of Lake Superior Geology with the charge that the document will be reviewed as needed.
9. Future meeting locations were discussed. Ted Bornhorst offered Houghton in 2024, Peter Hinz has offered Kenora as a future site and Mark Jirsa is keen to host the Mountain Iron meeting that was cancelled in 2020 because of the pandemic. In a subsequent discussion, Bernie Saini-Eidukat expressed a willingness to organize a meeting in St. Cloud.
10. The cost of insurance was discussed and it was agreed that the Board of Directors insurance and field trip insurance should be maintained for future meetings and that the costs would be included in the cost of each meeting. The fact that the Institute meets in both the US and Canada is an added complication.

11. Jirsa advised the board of the donation of polar bear carvings from Mike Beauregard, and it was agreed that a silent auction would be held during the meeting with funds going to support student travel. Dan England later donated two samples with visible gold and, combined, these items raised \$395 for the Eisenbrey fund
12. Bornhorst advised that there are a small number of hard copies missing from the MTU archives and that he will work to fill these. It was agreed that the ILSG would make a donation of \$1 per member (minimum \$100) each year to the library as a “thank you” for their efforts
13. The 68th ILSG meeting was a great success and we wish to thank all the people who contributed to that success, including staff of the Ontario Geological Survey who were pressed into action as editors, field trip leaders and drivers. Patty Cobin and Ted Bornhorst (A.E. Seaman Mineral Museum, Michigan Technological University) handled the pre-meeting registration. Ted also supplied the poster boards. Thanks go also to the staff at Science North who helped the meeting run smoothly as well as Bryston’s on the Park in Copper Cliff who provided a first-class banquet dinner, as well as lunches and snacks during the technical sessions.

Michael Easton (OGS) and **Wouter Bleeker** (GSC)

Co-Chairs, 68th Institute on Lake Superior Geology

TECHNICAL PROGRAM

TECHNICAL PROGRAM

SUNDAY APRIL 23, 2023

All field trips begin and end at The Lismore Hotel

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

1) Precambrian geology of the Chippewa River Valley

Rob Lodge and Bob Hooper – UW- Eau Claire

2) Wisconsin's Paleozoic stratigraphy and tour of Crystal Cave

Carsyn Ames – Wisconsin Geological and Natural History Survey

4:00 pm - 10:00 pm **Registration** (Wilson Hall Lobby)

7:00 pm - 10:00 pm **Welcoming Reception** (Wilson Hall A/F)

MONDAY APRIL 24, 2023

7:30 am – 11:30 am **Registration** (Wilson Hall Lobby)

8:00 **OPENING REMARKS** (Wilson B)

Rob Lodge and Carsyn Ames, Co-Chairs, 2023 ILSG

TECHNICAL SESSION I

Session Chair: James DeGraff- Michigan Technological University

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

+ denotes author that will present abstract, if different than the first author.

8:10 **William J. Hinze, and +William Cannon**

2023 Pioneer of Lake Superior Geology: Thomas Benton Brooks

8:30 **Erika Vye and William Rose**

Geoheritage as an educational tool to explore relationships with land and water in the Keweenaw

8:50 **William Rose**

New work developing Keweenaw geoheritage awareness

9:10 **Matt Carter and Donald Elsenheimer**

Workshop Outcomes and Updates for the Minnesota Department of Natural Resource's Drill Core Library

9:30 **Dean Peterson**

On the Importance of Geologic Maps for Mineral Exploration

9:50 **END OF TECHNICAL SESSION I**

9:50 **COFFEE BREAK**

TECHNICAL SESSION II

Session Chair: Ben Drenth- USGS and Amy Radakovich Block- Minnesota Geological Survey

- 10:00 **Dana Peterson, Paul Bedrosian, and Carol Finn**
Subsurface characterization of the Duluth Complex and related intrusions from 3D modeling of gravity and magnetotelluric data
- 10:20 **Paul Bedrosian, Tien Grauch, Laurel Woodruff, William Cannon, Benjamin Drenth, Esther Stewart, Dana Peterson, and James Jones**
Interpreted geophysical cross-sections through the Lake Superior region: Investigating three billion years of geologic history in sixteen lines of data
- 10:40 **Tien Grauch, Sam Heller, Esther Stewart, and Laurel Woodruff**
Exploring the geology of the Midcontinent Rift under western Lake Superior using a preliminary velocity model of seismic line GLIMPCE C
- 11:00 **Jennifer Smith, Victoria Tschirhart, Loughlin Tuck, Randy Enkin, and David Roy-Guay**
Exploring the application of full tensor magnetic gradiometry to better define conduit type Ni-Cu-PGE targets
- 11:20 **END OF TECHNICAL SESSION II**
- 11:20-1:00 **LUNCH BREAK and LSG BOARD OF DIRECTORS MEETING**
- lunches not provided to conference attendees-
- 11:20-1:00 **Student Career Panel- (L.E. Phillips Memorial Public Library- 400 Eau Claire St. in the Riverview Room (Room 306))**

TECHNICAL SESSION III

Session Chair: Marcia Bjørnerud- Lawrence University

- 1:10 **Wouter Bleeker, Jennifer Smith, Michael Hamilton, Sandra Kamo, Pete Hollings, Michael Easton, and Robert Cundari**
The Midcontinent Rift System: Neither triple junction nor failed rift?
- 1:30 **Matthew Brzozowski, +Pete Hollings, Jing-jing Zhu, and Robert Creaser**
Contributions of diverse mantle sources during the early stages of Midcontinent Rift formation — Implications for a passive rifting model
- 1:50 ***Daniel Lizzadro-McPherson, James DeGraff and Ian Gannon**
Structural analysis and slip kinematics of the Keweenaw fault system between Bête Grise Bay and Gratiot Lake, Keweenaw County, Michigan
- 2:10 ***Katherine Langfield, James DeGraff, and Nolan Gamet**
Slip Kinematics of the Keweenaw and Hancock Faults within the Midcontinent Rift System, Upper Peninsula of Michigan
- 2:30 **END OF TECHNICAL SESSION III**

2:30 COFFEE BREAK

TECHNICAL SESSION IV

Session Chair: Pete Hollings- Lakehead University and 2023 Goldich Medalist

- 2:50 ***Tianna Groeneveld, Peter Hollings, Wyatt Bain, and Lionnel Djon**
Petrography, geochemistry, and mineralization of the Archean Titan (Roaring River) intrusion, Northwestern Ontario
- 3:10 ***Sam Ghanous, Noah Phillips, Alex Lusk, Julie Newman, and Shaocheng Ji**
Are serpentine fault mirrors an indicator of seismic slip? A microstructural analysis
- 3:30 ***Blaize Briggs and Mary Louise Hill**
Quetico-Wabigoon Subprovince Boundary in the Superior Province north of Thunder Bay, Ontario, Canada
- 3:50 **Margaret Upton, Phillip Larson, Allan MacTavish, and Peter Hinz**
Summary of the 2022 ILSG Field Trip to Iceland
- 4:10 **END OF TECHNICAL SESSION IV**
- 4:10 **POSTER VIEWING - AUTHORS WILL BE PRESENT AT THEIR POSTERS**
-
-

6:00 **RECEPTION AND CASH BAR** (Wilson Hall A/F)

7:00 **ANNUAL BANQUET AND AWARDS** (Wilson Hall A/F)
SPEAKER: Curt Meine- *Adjunct Professor at UW- Madison and Senior Fellow with the Aldo Leopold Foundation and Center for Humans and Nature*
IMAGINING “CONSERVATION GEOLOGY”: LESSONS FROM THE DRIFTLESS AREA

TUESDAY APRIL 25, 2023

8:00 **INTRODUCTORY REMARKS AND UPDATES** (Wilson Hall B)
Rob Lodge and Carsyn Ames, Co-Chairs, 2023 ILSG

TECHNICAL SESSION V

Session Chair: Allan MacTavish- Consulting Geologist and 2021 Goldich Medalist

- 8:10 ***Justin Jonsson, Pete Hollings, Matthew Brzozowski, Wyatt Bain, and Lionnel Djon**
Petrogenesis of the mineralized horizons in the Offset and Creek zones, Lac des Iles Complex, N. Ontario
- 8:30 **Pete Hollings, Jacob Hanley, Mark Smyk, Larry Heaman, and Brian Cousens**
Copper-rich melt inclusions from the St. Ignace Island Complex: Implications for magma mixing and mineralization

- 8:50 **Alex Steiner, Dean Peterson, and Gabriel Sweet**
Magma Recharge and the distribution of Copper and Nickel in the Keweenaw Large Igneous Province
- 9:10 **David Good**
Identifying regional exploration domains for Ni-Cu-PGE deposit types in the Midcontinent Rift
- 9:30 **Julia Steenburg and Anthony Runkel**
Record of an Ancient Meteorite Impact Buried Beneath the Twin Cities, MN
- 9:50 **COFFEE BREAK**
- 10:10 **Benjamin Drenth, Amy Radakovich Block, George Hudak, Kate Souders, and Stacy Saari**
Geophysical architecture of the Neoarchean Mentor anorthosite intrusive complex, northwestern Minnesota
- 10:30 **Paul Weiblen**
The Use of Electric Pulse Disaggregation Technology to Recover Nickel Metal from Nickel Sulfide Ore Deposits
- 10:50 **END OF TECHNICAL SESSION V**
- 11:00 **ADDITIONAL POSTER VIEWING – AUTHORS ARE ENCOURAGED TO BE AT THEIR POSTERS (Wilson C & D)**
- 11:30-12:30 **LUNCH BREAK**
- lunches not provided to conference attendees-

TECHNICAL SESSION VI

Session Chair: Laurel Woodruff- USGS and 2014 Goldich Medalist

- 12:40 ***Margaret Upton, Howard Mooers, and Philip Larson**
Alteration Geochemistry Characterization and 3D Modeling of the Back Forty Volcanogenic Massive Sulfide (VMS) Deposit Stephenson, Upper Peninsula of Michigan, USA
- 1:00 **Robert Lodge**
Re-evaluating the tectonics and metallogeny of terranes in the Paleoproterozoic Penokean Orogen, Wisconsin
- 1:20 **William Cannon and Benjamin Drenth**
Eastward transition from banded iron-formation to ferruginous clastic rocks across the central Upper Peninsula of Michigan
- 1:40 **Jamey Jones, William Cannon, Benjamin Drenth, and Paul O’Sullivan**
Provenance patterns and tectonic styles of ca. 2.3–1.8 Ga metasedimentary strata in northern Michigan based on regional mapping and detrital zircon U-Pb geochronology

- 2:00 ***Audray Hinkemeyer, Howard Moores, and Phillip Larson**
Determining Provenance of Rainy Lobe Till using Geochemistry and Detrital Zircon Geochronology.
- 2:20 **COFFEE BREAK**
- 2:40 **Gordon Medaris Jr. and Steven Driese**
Secular Changes in the Magnitude of Terrestrial Weathering
- 2:40 **END OF TECHNICAL SESSION VI**

TECHNICAL SESSION VII

Session Chair: Carsyn Ames- Wisconsin Geological and Natural History Survey

- 3:00 **Caroline Rose**
Tips from a GIS Specialist: Moving maps to GeMS, and a utility for georeferencing quadrangles
- 3:20 **Matthew Rehwald, Carsyn Ames, Sarah Bremmer, William Fitzpatrick, Eric Stewart, Bill Batten, and Stephen Mauel**
Mobile geologic mapping at the Wisconsin Geological and Natural History Survey
- 3:40 **Roger Schulz**
Outcrop Scale Mapping Utilizing High-Accuracy GNSS with MnDOT's Virtual Reference Station (VRS) Network: Minnesota Examples
- 4:00 **Stephen Mauel, Eric Stewart, Matthew Rehwald, Esther Stewart, Carsyn Ames, Sarah Bremmer, and William Fitzpatrick**
3D geologic mapping at the Wisconsin Geological and Natural History Survey
- 4:20 **END OF TECHNICAL SESSION VII**
- 4:20 **BEST STUDENT PAPER AWARDS**
STUDENT TRAVEL AWARDS
CLOSING REMARKS
- 4:40 **END OF TECHNICAL SESSIONS**

WEDNESDAY APRIL 26, 2023

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

Field trips begin and end at The Lismore Hotel

3) Precambrian Geology of the Eau Claire River Valley

Rob Lodge and Evan Weber– UW- Eau Claire

4) Quaternary Geology and Geomorphology of the Eau Claire Region

Doug Faulkner – UW- Eau Claire

J. Elmo Rawling III– Wisconsin Geological and Natural History Survey

POSTER PRESENTATIONS

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

***Zsuzsanna P. Allerton, Anita Hall, Françoise Roger, and Christian Teyssier**

Geochronology and Geochemical Analysis of the Giants Range Batholith in Northern Minnesota

Carsyn Ames

The Wisconsin Geological and Natural History Survey's (WGNHS) 2020 and 2021 National Geological and Geophysical Data Preservation Program (NGGDPP) Projects

***Ryan Barkley, Noah Phillips, and Pete Hollings**

The geologic setting, structural controls, and geochemical signature of the Eagle River Au deposit in Northwestern Ontario

Marcia Bjørnerud, Buchholz, T., Falster, A.U, And Simmons, W.B.

Deformation, metamorphism, fluid flow and pegmatite emplacement history of the post-1630 Ma Waterloo Quartzite of southern Wisconsin

Amy Radakovich Block, Kate Souders, Benjamin Drenth, George Hudak, Stacy Saari, and Aaron Hirsch

New geologic mapping in the Superior Province of northwestern Minnesota, USA: Pennington and Red Lake Counties

***Itai Bojdak-Yates, Marcia Bjørnerud, David Malone, and Esther Stewart**

A revised provenance model for the Elk Mound Group in south-central Wisconsin based on detrital zircon analysis

James DeGraff and William Rose

Digital Image Capture and Database Compilation of Historic Mining Data from the Keweenaw Copper District, Michigan: A Progress Update

Benjamin Drenth and William Cannon

Geophysical mapping of the Great Lakes Tectonic Zone and surrounding Precambrian geology in the central Upper Peninsula, Michigan

William Fitzpatrick and Eric Stewart

Multiple overlapping features spatially associated with lead-zinc-copper mineralization in the Highland quadrangles, southwest Wisconsin, USA

***Lillian Glodowski and Robert Lodge**

Characterizing volcanic host stratigraphy and syn-volcanic intrusions at the Lynne Zn-Pb-Cu deposit, Oneida Co., Wisconsin

***Kaine Johnson and Robert Lodge**

Hydrothermal Alteration Facies of the Eisenbrey Zn-Cu Deposit, Rusk County, Wisconsin

***Matthew Leahy and Robert Lodge**

Petrology and Geochemistry of the Paleoproterozoic Eau Claire Volcanic Complex, Eau Claire, WI

***Francisca Nuñez-Ferreira, Lucas Zoet, and J. Elmo Rawling III**

Morphometry and formation process of eskers developed under the Chippewa Lobe of the Laurentide Ice Sheet

***Jordan Peterzon, Noah Phillips, Peter Hollings and Lionnel Djon**

Fault zone architecture in mafic protoliths at the Lac des Iles mine, northwestern Ontario

Caroline Rose, J. Elmo Rawling III, Eric Carson, John Attig, David Mickelson, William Mode, Mark Johnson, and Kent Syverson

Quaternary Geology of Wisconsin at a scale of 1:500,000 (in review)

Allison Severson, Eric Nowariak, and Phillip Larson

Geology and geochemistry of the basal North Shore Volcanic Group and Midcontinent Rift Intrusive Supersuite, Cook County, MN, USA

Eric Stewart, William Fitzpatrick, and Carsyn Ames

Relay zones in weakly folded and faulted Paleozoic strata and their role localizing Mississippi Valley-type mineralization, southwest Wisconsin, USA

***Madeline Taylor and Marcia Bjørnerud**

Deciphering the metamorphic and deformational history of the Hardwood Gneiss, Felch District, Michigan: Anomalously high-pressure rocks in the heart of the Penokean orogen

***Evan Weber, Robert Lodge, and Jeffrey Marsh**

U/Pb geochronology and zircon petrochronology of Paleoproterozoic magmas from the Marshfield terrane Penokean Orogen, Wisconsin

BANQUET PRESENTATION

IMAGINING “CONSERVATION GEOLOGY”: LESSONS FROM THE DRIFTLESS AREA

Curt Meine

Adjunct Professor at UW- Madison and Senior Fellow with the Aldo Leopold Foundation and Center for Humans and Nature

The field of *conservation biology* emerged in the 1980s when scientists became increasingly alarmed about the loss of biodiversity, and decided that they had a responsibility to put their science to work to address the issue. This required not only new interdisciplinary research, but new ways to put knowledge to work in our human and natural communities. Can we imagine a field of *conservation geology* that similarly seeks to integrate geological knowledge with history and culture, and addresses our concerns for our landscapes and for future generations? The Driftless Area provides ample examples and opportunities to explore that question.

ABSTRACTS

Geochronology and Geochemical Analysis of the Giants Range Batholith in Northern Minnesota

ALLERTON, Zsuzsanna¹, HALL, Anita¹, ROGER, Françoise², and TEYSSIER, Christian¹

¹Earth and Environmental Science Department, University of Minnesota, 150 Tate Hall, 116 Church St. SE, Minneapolis, MN 55455

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The Giants Range Batholith (GRB) is a ~2.7-billion-year-old (2.7 Ga) granitic unit in northern Minnesota striking SW-NE from east of Ely to Grand Rapids (Figure 1). It is located N-NW of the 1.8 Ga Mesabi Iron Range and the 1.1 Ga Duluth Igneous Complex (DC). During emplacement, the GRB was situated at the southern edge of the Superior Craton, the Archean core of the North American Continent. At its eastern end the GRB is in contact with the Mesoproterozoic DC (1.1 Ga), which is the intrusive segment of the Mid-continent Rift System, and to the west the GRB flanks the Lower Member of the Ely Greenstone Formation. This project has two main goals: (1) better understanding the origin of the GRB; and (2) using the GRB to track the thermal and hydrothermal history of the rocks from the contact with the DC outward.

The project included the compilation of existing data, such as geochronology and geochemistry, that have been collected to date on the GRB, based on Allison (1925), Griffin & Morey (1969), Viswanathan (1971), Boerboom & Zartman (1993), Boerboom (1994), and Southwick (1994). The Minnesota Geological Survey (Jirsa, 2016) acquired U-Pb zircon age dates on selected samples. Only Boerboom & Zartman (1993) and Boerboom (1994) have completed trace element analysis. Their eight samples are from the central section of the GRB (red circle in Figure 1) and were collected along the northern margin. The samples from the GRB main body have not been analyzed for trace elements, and geochronological data are scarce.

Our sampling campaign so far has concentrated on the northeastern part of the GRB (white dashed box in Figure 1) and builds on the work of Boerboom & Zartman (1993) and Boerboom (1994). Thin sections were cut and used in transmitted-light petrography to determine mineralogical composition, analyze textures, and identify accessory minerals for radiometric dating.

Radiometric dating involved Laser-Ablation Inductively Coupled Plasma Mass-Spectroscopy (LA-CPMS) performed at the University of Clermont-Ferrand, France. We obtained zircon and titanite age dates for samples located within 1000 meters from the DC contact. The zircon grain separates from one sample produced a concordant age date of $\sim 2690 \pm 10$ Ma. *In-situ* zircon analysis of another sample displays some discordia (Pb loss) that may be associated with hydrothermal alteration related to DC emplacement. The mounted titanite grains and *in-situ* analysis yielded ages (approx. 2450-2500

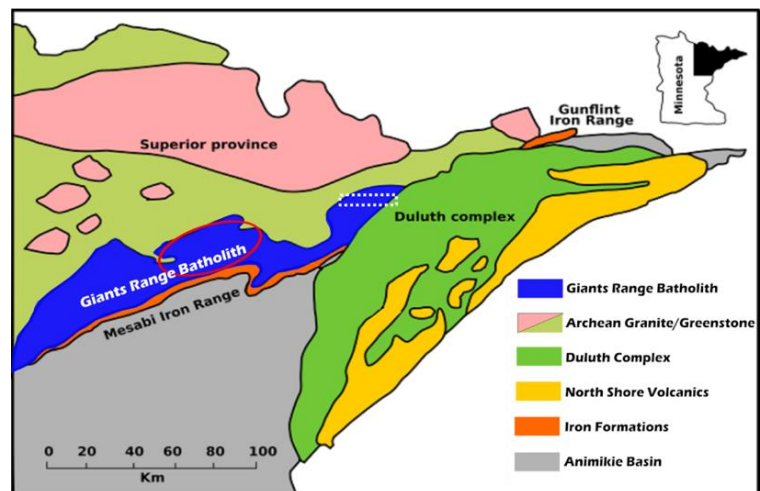


Figure 1. Simplified geologic map of Minnesota's arrowhead region showing the Giants Range Batholith in blue. Prior studies have been done in the area circled in red. The white dashed box shows the current and proposed area of this project. Modified from Jirsa, M.A., Miller jr., J.D., & Morey, G.B. (2008).

Ma) that are consistently younger than zircons from the same samples.

Current and future work include further sample collection in the study area (white dashed box in Figure 1) to obtain additional U-Pb dates on titanite and zircon to the thermal and hydrothermal history of GRB at the contact with the DC. The GRB samples also contain abundant apatite grains, some primary and some recrystallized, that will be dated using the U-Pb method to provide new data on the thermal and hydrothermal history of the GRB near the DC contact. Additionally, we will pursue acquiring bulk composition and trace element data in order to better understand the source of magma and the likely tectonic setting in which the GRB was emplaced.

References

- Allison, I.S., 1925. The Giants Range Batholith of Minnesota. *The Journal of Geology*, 33(5): 488-508. <https://doi.org/10.1086/623215>.
- Boerboom, T.J. and Zartman, R.E., 1993. Geology, Geochemistry, and Geochronology of the Central Giants Range Batholith, Northeastern Minnesota. *Canadian Journal of Earth Sciences*, 30(12): 2510-2522. <https://doi.org/10.1139/e93-217>.
- Boerboom, T., 1994. Short Contributions to the Geology of Minnesota: Alkaline Plutons of Northeastern Minnesota; Report of Investigations 43. Minnesota Geological Survey, ISSN 0076-9177.
- Frost, B.R. and Frost, C.D., 2008. A geochemical classification for feldspathic igneous rocks. *Journal of Petrology* 49.11.
- Griffin, W.L. and Morey, G.B., 1969. Geology of the Isaac Lake Quadrangle, St. Louis County, Minnesota. Published in Cooperation with Minnesota Department of Iron Range Resources and Rehabilitation. Minnesota Geological Survey 5 P-8 Special Publication Series. University of Minnesota.
- Southwick, D.L., 1994. Short Contributions to the Geology of Minnesota: Assorted Geochronologic Studies of Precambrian Terranes in Minnesota: A Potpourri of Timely Information. Report of Investigations 43. Minnesota Geological Survey, ISSN 0076-9177.

The Wisconsin Geological and Natural History Survey's (WGNHS)'s 2020 and 2021 National Geological and Geophysical Data Preservation Program (NGGDPP) Projects

AMES, Carsyn¹, GOTTSCHALK, Brad¹, ROSE, Caroline¹, SIBLEY, Dave¹

¹*Wisconsin Geological and Natural History Survey, University of Wisconsin- Madison, 3817 Mineral Point Rd. Madison, WI 53705*

The Wisconsin Geological and Natural History Survey (WGNHS) received grants from the United States Geological Survey (USGS)'s National Geologic and Geophysical Data Preservation Program (NGGDPP) for FY2020 and FY2021. This program promotes the preservation and public accessibility of geoscience collections and data.

Projects completed during the 2020 grant were 1) to preserve 130 boxes of hand samples, and 2) to convert 10 WGNHS maps to the standard Geologic Map Schema (GeMS) format. The majority of hand samples for this project came from a donation by Gene LaBerge (UW-Oshkosh) who worked extensively in and around Marathon County, and whose work resulted in a Marathon County bedrock map (LaBerge and Myers, 1983) published by WGNHS. The collection includes more than 1500 specimens from 583 separate outcrops. Successfully preserving these samples is of importance as Marathon Co. continues to urbanize and many of the outcrops these samples represent are being demolished due to land development. The 10 maps converted to GeMS format during the project include Pleistocene maps from northwestern Wisconsin and bedrock maps from southern and northeastern Wisconsin. Converting legacy maps to GeMS format is important because the digital use of WGNHS maps allows for wider and broader use by both internal and external stakeholders. Additionally, a survey of WGNHS external partners showed that a majority prefer digital versions of maps and data.

Projects for the 2021 grant included 1) expanding the WGNHS data viewer's capacity to deliver photos of bedrock cores, 2) digitizing borehole data from the Mineral Development Atlas (MDA)- a joint project between the USGS, United States Bureau of Mines (USBM), and state surveys of Wisconsin, Iowa, and Illinois- that gathered information related to metallic mineral exploration and mining in the lead-zinc district, and 3) photograph, log, and permanently archive seven cores from the Lynne Deposit, a volcanogenic massive sulfide deposit in Oneida County. WGNHS's data viewer, created in 2018, saw its capacity expanded to include photos of cores in their collection. The 2021 project used almost 300 donated Wisconsin Department of Transportation (WisDOT) cores to test pilot this new ability and results are available here: <https://data.wgnhs.wisc.edu/data-viewer/>. An additional part of this project included the correlation of 3300 scanned logs to the boreholes and updating location data for logs and cores. The MDA portion of the 2021 project focused efforts on mine workings in Lafayette Co., WI. Staff at the Survey geolocated more than 17,000 boreholes and corrected polygons for surface workings such as quarries, prospecting sites, and lead diggings. Lastly, WGNHS permanently archived seven cores from the Lynne Deposit, Oneida Co., WI in 2021. These cores were transferred to WGNHS's samples repository from the University of Wisconsin- Eau Claire where they had been stored temporarily for student study. The cores (totaling approximately 2500 ft) were then logged and photographed by UW-Eau Claire students. These photos were also added to the WGNHS data viewer.

References

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<https://wgnhs.wisc.edu/catalog/publication/000295/resource/ic45>.

The geologic setting, structural controls, and geochemical signature of the Eagle River Au deposit in Northwestern Ontario

BARKLEY, Ryan¹, PHILLIPS, Noah¹, HOLLINGS, Pete¹

¹Department of Geology, Lakehead University, 955 Oliver Road, Thunder Bay, ON P7B 5E1 Canada

The Eagle River orogenic gold deposit is hosted in the Mishibishu greenstone belt of the western Superior craton, approximately 50 km west of Wawa, Ontario. The deposit, an active underground mine, has been in continuous production since 1995 and produced 1.485 (Moz) of Au through to the end of 2021 (SRK, 2022). The average grade is 9.7 g/pt and Au is primarily hosted in highly strained, milky white to grey quartz veins that dip to the north and strike east to west. The shear zones are hosted in an elliptical quartz diorite pluton, extending into iron rich mafic volcanic rocks. The Mishibishu greenstone belt is dominated by granitic plutons, mafic to felsic volcanics, and lesser amounts of metasedimentary packages. U-Pb zircon dates in the belt range from 2.6 to 2.8 Ga, indicating a Neoarchean environment (Keller, 1989). To understand the geological setting, structural controls, and the geochemical signature of the Eagle River deposit, we completed detailed structural field mapping, petrography, and whole rock geochemistry analysis of the rocks in and around the deposit.

A total of 41 whole rock geochemistry samples were collected from the area north of the mine. Two suites were identified; suite one consists of calc-alkaline basalt, andesite, dacite, rhyolite, diorite, tonalite and granite. This suite is characterized by enriched La/Sm_n ratios of 2.06 to 6.83 and negative Nb anomalies (Nb/Nb* of 0.09 to 0.43), consistent with magmas formed in a supra-subduction environment. Suite two consists of tholeiitic basalt, andesitic-basalt and gabbro. This suite is characterized by flatter trace element patterns with La/Sm_n ratios of 0.83 to 1.48 and minor Nb anomalies (Nb/Nb* of 0.40 to 0.85), consistent with primitive arc tholeiites (Fig. 1).

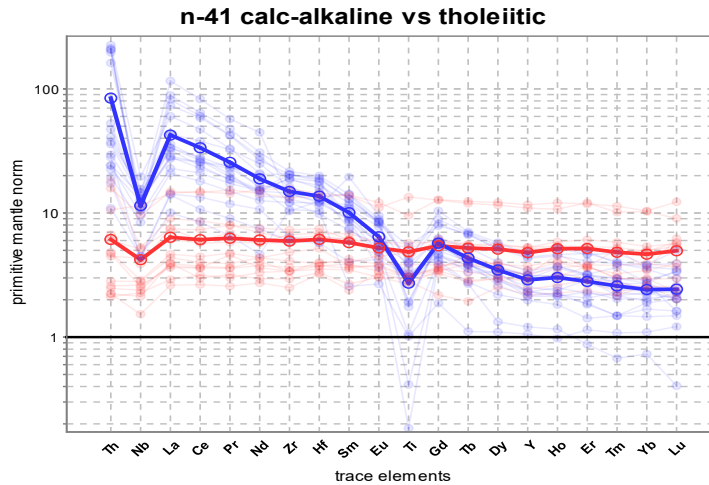


Figure 1. Primitive mantle normalised diagrams for the calc-alkaline (blue) vs tholeiitic (red) rocks of the study area. Normalising values from Sun and McDonough (1989).

Shear zones for this study appear to be ductile. The white to grey, boudinaged quartz veins are highly strained and flattened, indicating a ductile environment. Gold accumulates in areas of high strain. Quartz veins exhibit chessboard extinction patterns and lobate grain boundaries indicating that the veins have recrystallized through grain boundary migration dynamic recrystallization (Fig. 2; Stipp et al, 2002). Deformation therefore occurred at high temperatures in a low stress environment.

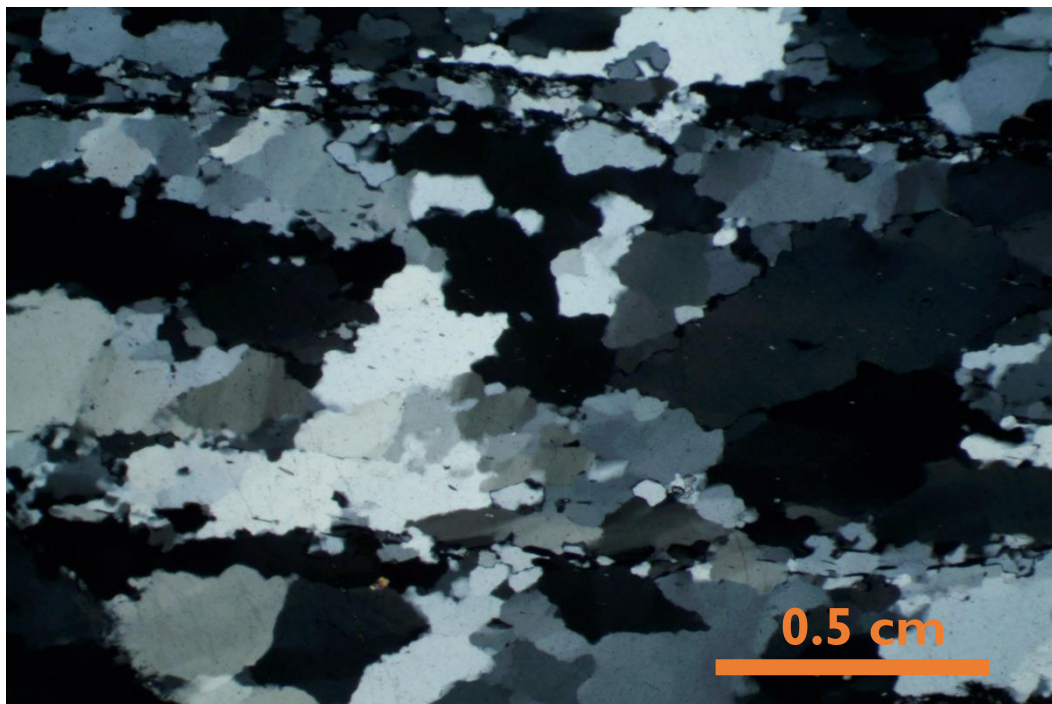


Figure 2. Recrystallization of quartz veins via grain boundary migration.

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Interpreted geophysical cross-sections through the Lake Superior region: Investigating three billion years of geologic history in sixteen lines of data

BEDROSIAN, Paul A.¹, GRAUCH, V.J.S.¹, WOODRUFF, Laurel G.², CANNON, William F.³, DRENTH, Benjamin J.¹, STEWART, Esther K.⁴, PETERSON, Dana E.¹ and JONES, James V.⁵

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³U.S. Geological Survey, 12201 Sunrise Valley Dr., MS 954, Reston, VA 20192

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The northern midcontinent is a window into an Archean-Proterozoic continent, and the Mesoproterozoic Midcontinent Rift System (MRS) that nearly tore it apart. This complex tectonic collage has been largely unmodified during the last billion years yet is poorly exposed except in the Lake Superior region. The area is rich in mineral resources, including native and sedimentary copper deposits, iron formations, volcanogenic massive sulfide deposits, and nickel-copper-platinum-group element sulfide mineralization.

In 2016, 2,710 line-km of airborne electromagnetic (AEM) and magnetic data were collected along sixteen regional transects spanning parts of three states and more than three billion years of geologic time (Bedrosian, 2019). The transects range from 100 to 300 km in length and cross parts of the Wisconsin Magmatic Terrane, the Penokean fold and thrust belt, the MRS, and the Archean Superior Province (Figure 1). Data modeling was challenging due to poor control on system height and the prevalence of induced polarization effects (Bedrosian et al., 2018).

The final electrical resistivity models derived from the AEM data have been translated into interpreted geophysical cross-sections through an iterative, consensus building approach. A team was assembled with varied expertise in the geology, geophysics, and mineral resources of the MRS, Penokean, and Archean assemblages within the region. Over a period of two years, a series of interpretation sessions worked line-by-line through the transects, culminating in a workshop to synthesize and finalize interpretations. Geologic maps, potential-field data, and drill hole logs were examined alongside the AEM resistivity models and incorporated into the resulting interpretations. Constraints from seismic reflection and refraction studies, magnetotelluric models, geochronology, and detrital zircon studies were also considered where available.

The resulting annotated geophysical cross-sections are a resource to be drawn and built upon for geologic and tectonic investigations. Some aspects these sections touch upon include:

- Internal structure of the Animikie basin and the basal contact of the Duluth Complex
- Geometry and deformation of MRS-flanking sedimentary basins
- Structure of the MRS Ashland syncline
- Geometry and extent of post-magmatic MRS clastics (Oronto and Bayfield Groups)
- Geometry, internal variability and provenance of the Jacobsville Sandstone
- Geometry and extent of Archean, Penokean, and MRS faults
- Extent and dismemberment of Penokean-deformed metasedimentary units
- Iron formations and Penokean structures along the early Proterozoic gneiss dome corridor
- Patterns of reverse polarity dikes
- Phanerozoic cover and underlying structure (e.g., eastern arm of the MRS)
- Distribution, thickness, and variability in glacial cover

New insights and refinements are many but include (a) a restricted areal extent for Bayfield Group clastic rocks, (b) multiple distinct subunits within the Jacobsville sandstone, (c) a close stratigraphic relation between Penokean iron formations and conductive sulfide-rich metasediments, and (d) complex deformation and alteration of the main bowl Animikie basin.

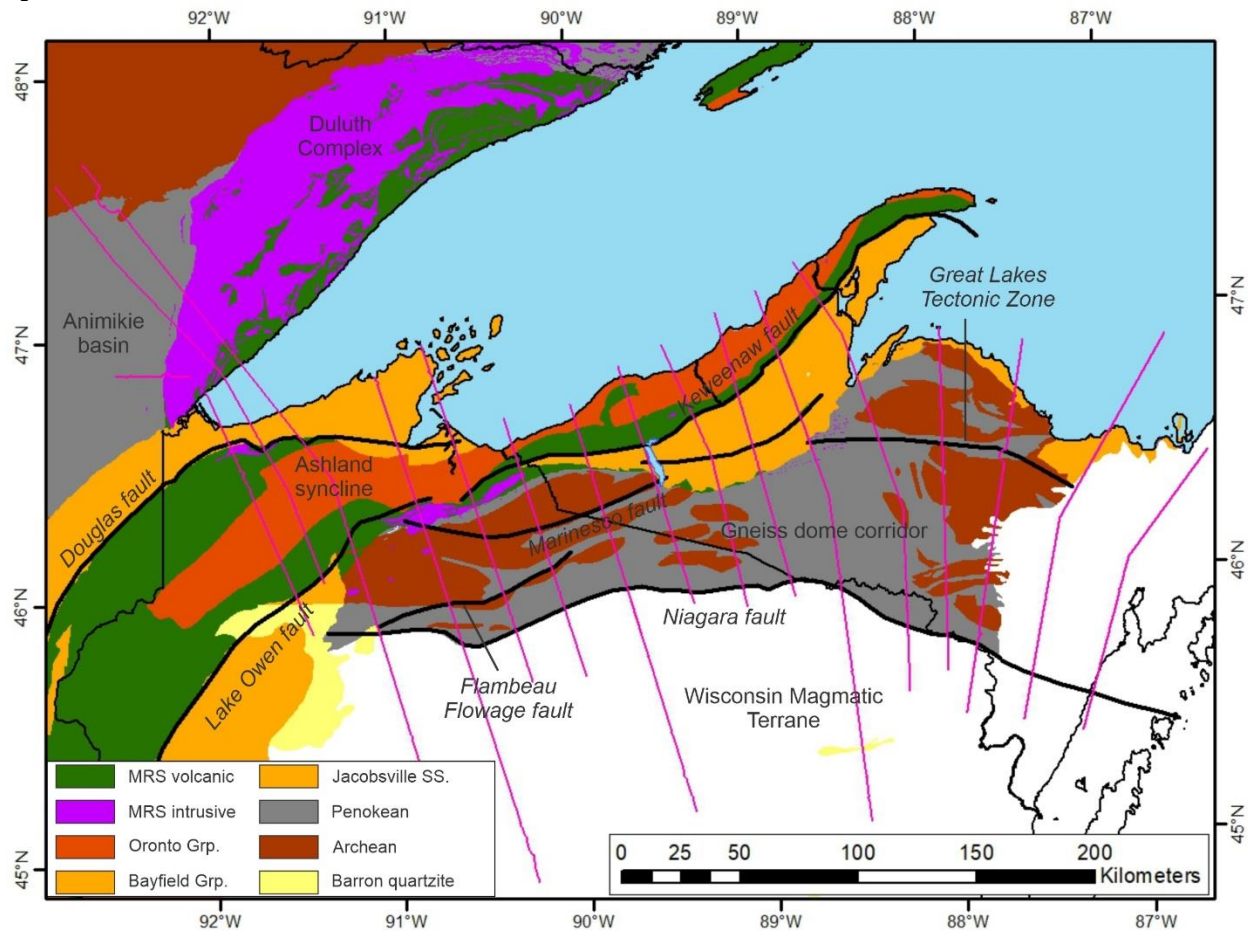


Figure 1. Location of AEM and magnetic profiles (magenta). Background geology is from a USGS MRS GIS compilation from published sources of the region.

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Deformation, metamorphism, fluid flow and pegmatite emplacement history of the post-1630 Ma Waterloo Quartzite of southern Wisconsin

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The Waterloo Quartzite, one of the upper Paleoproterozoic ‘Baraboo Interval’ quartzites of the southern Great Lakes region (Medaris *et al.*, 2003), experienced a more complex structural history and higher-grade metamorphism (amphibolite facies) than any of the other quartzite units in this group. It is also distinctive in being intruded by bodies of granitic pegmatite. Natural outcrops of the Waterloo quartzite are limited, but a major quarry near the town of Waterloo (43.210 N, 88.450 W) provides three-dimensional exposures and access to a large volume of fragmented rock. This study is based on observations and samples taken at the quarry over several years as it was deepened and enlarged by blasting.

The youngest detrital zircons in the Waterloo Quartzite date to 1634 Ma, younger than the 1710 Ma maximum depositional age of the Baraboo Quartzite, and an indication that sediment transport directions changed from southward to northward (modern coordinates) between the times of deposition of the Baraboo and Waterloo units (Schwartz *et al.*, 2018). The protolith of the Waterloo quartzite was primarily pure quartz sandstone but also included pelites and quartz pebble conglomerates with clasts of jasper (Stewart, 2021).

The earliest deformational feature in the Waterloo quartzite is a penetrative foliation (S1) defined by aligned grains of sub-mm muscovite in the pelitic layers; this muscovite has yielded an ⁴⁰Ar/³⁹Ar age of 1452 +/- 7 Ma and has been interpreted as evidence of a pervasive fluid flow event that introduced potassium into the supermature sediments, in which K was originally absent (Medaris *et al.*, 2003). In the quarry, the S1 foliation is nearly parallel to bedding; both surfaces strike toward the northeast (045° to 055°) and dip moderately (35°-55°) southeast, suggesting that the rocks lie on the SE limb of a tight NW-verging anticline. In places, mm- to cm-scale quartz veins with Ti-rich hematite masses on their margins lie parallel to the foliation and have fibers oriented perpendicular to the foliation. This points to another episode of fluid infiltration under a stress regime distinct from the one that formed the foliation. These early quartz veins are commonly folded and/or boudinaged.

The S1 foliation is overprinted by porphyroblasts of andalusite, typically about 0.5 cm in size. Most of these have been altered to muscovite and/or kaolinite, indicating another episode of fluid infiltration. The kaolinite occurs mainly on the margins of the andalusite crystals, giving them a zoned appearance. In many specimens, the retrograded andalusites have a rusty red color that may be related to the presence of hematite in the kaolinitic rims (Geiger *et al.*, 1982). The next structural feature to develop in these rocks are kink-like crenulations in pelitic horizons, seen abundantly in blocks in the quarry waste piles. At two sites where this crenulation cleavage (S2) was observed in place, it strikes N to NNW and dips steeply east. The geometry of the crenulations is strongly influenced by the presence of the andalusite porphyroblasts/ pseudomorphs, many of which have small, asymmetric pressure shadows of quartz and muscovite that seem to be related to the development of the crenulations.

Sometime after the formation of the crenulation cleavage, the quartzite was intruded by K-feldspar-dominated pegmatite dikes ranging in width from 1 cm to 3 m. Pegmatites have been known from the NW portion of the Waterloo Quarry for some years and have been discussed by

Buchholz *et al.* (2016). The pegmatite dikes have sharp boundaries and granitic textures, with K-feldspar, quartz and muscovite crystals of equal and uniform size. Blasting of a phyllitic horizon in the NE part of the quarry has recently exposed additional thin (< 5 cm wide) pegmatite dikes, with mm-scale chilled margins at contacts with the host rock. Heavy mineral separates from these thin dikes contain fluorapatite, monazite-(Ce), ilmenite, columbite-(Mn), tantalite-(Mn), evidence of significant enrichment of Ta/Nb and Mn/Fe.

In addition to the pegmatite dikes, coarse-grained pegmatite-like patches occur in the necks of boudinaged quartz veins and quartzose layers enclosed by phyllites, primarily in the NE corner of the quarry. Unlike the clearly igneous dikes, these patches have irregular boundaries with the host rock and their crystal size is variable. In thin section, K-feldspar and quartz in these patches show a micrographic texture. Muscovite in pelitic layers surrounding the boudins is coarser than in the rest of the rock, and rusty andalusite pseudomorphs are smeared and flattened in the vicinity of the boudins, suggesting that they had already been altered and softened by the time the boudins formed. Although they occur in the same area of the quarry, the pegmatite-like boudin patches do not seem to be physically connected to the pegmatite dikes. The patches are presumably older since they formed during the process of boudinage, while the dikes apparently postdate deformation. The pegmatite-like material in the boudin necks could either be hydro- thermal or produced by *in situ* melting related to influx of fluids or perhaps a local drop in pressure (mean stress) during boudinage.

Examination of heavy mineral separates from the pegmatite-like bodies associated with boudins revealed fluorapatite and monazite-(Ce). One specimen of the boudin material contains small beryl crystals in a pocket-like void. This may be similar to beryl occurrences in regionally metamorphosed rocks in Austria (Franz *et al.*, 1986), believed to have formed between 500- 550°C -- slightly higher than maximum metamorphic temperature estimates of 500°C for the Waterloo rocks (Medaris *et al.*, 2003). Small crystals of greenish to light brown dravitic tourmaline are also present locally; analysis shows that these are Li-bearing, as are nearby muscovites. Additional mineral phases include chloritoid, spessartine garnet, fluorapatite, and gahnite, all pointing to the introduction of fluids with a rich mix of ions.

Although the Waterloo quarry lies only 20 km in the across-strike direction from the south limb of the Baraboo syncline, it is not easy to correlate either the chronology or the orientations of structures at Waterloo with those in the more famous Baraboo Quartzite. Our observations from the Waterloo quarry suggest that the 1470-1450 Ma “Baraboo Orogeny” (Medaris *et al.*, 2021) was a complex, multi-stage tectonic event whose details have not yet been fully documented.

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The Midcontinent Rift System: Neither triple junction nor failed rift?

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The Midcontinent Rift System has often been described in terms of i) a failed intracontinental rift system; with ii) a basic ‘triple junction’ architecture, the three arms of the triple junction being represented by the SW arm of Lake Superior, the SE arm of Lake Superior, and a less developed rift structure reaching up into the Lake Nipigon area. Here we challenge both views.

Although it is certainly true that on a local scale, i.e. the North American midcontinent, the rift system failed and inverted, it is likely that on a more global scale the system did not fail but led to ocean opening at ca. 1103 Ma, i.e. the waning phase of the “**Early Magmatic Stage**”³ of the Midcontinent Rift. This led to a global reorganization of plate stresses. The majority of robust structural indicators suggest that this early stage rifting, initiated at ca. 1110 Ma and waning towards ca. 1103 Ma, was oriented on an NW-SE axis or trend (present orientation), from Lake Nipigon to the SE arm of Lake Superior and beyond. The significant gradient in rifting and lithospheric stretching, from Lake Nipigon (minor rifting followed by sagging) to the SE rift arm (major rifting), requires that the rotation pole for this early phase of rifting was situated to the northwest, somewhere in northwest Ontario. At larger distances from this rotation pole, up to 90° of arc away(?), to the southeast (present orientation), lithospheric spreading may have reached ~1000 km and thus likely led to ocean opening. This early phase of rifting with its NW-SE axis came to a close with a marked hiatus of ~4-5 Myr (the “**Magmatic Hiatus**”), represented in most sections by a distinct unconformity of conglomerates and more shallow dipping basalt flows on top of older, more steeply dipping basalt flows.

When rifting resumed, after this significant hiatus, it opened up the SW arm of the Midcontinent Rift organized on a SW-NE trending rift system. This phase was accompanied by the “**Main Magmatic Stage**” and was initiated at 1099-1098 Ma, the emplacement age of the Duluth Complex (e.g., Paces and Miller, 1993). The marked gradient in rifting and lithospheric stretching on this SW-NE rift system, with major crustal stretching in the central part of Lake Superior, and less stretching farther to the southwest, indicates that the rotation pole for this younger phase of rifting was situated well to the southwest, perhaps in Texas or on the future western margin of Laurentia. This SW-NE rift system shows marked jogs, and may have stepped over to the south, through the eastern arm of Lake Superior, and continued to the northeast in the area now obscured by final accretion and collision of the Grenville orogen at ca. 1 Ga. As for the first phase of rifting, we observe locally (in North America) only one proximal end (relative to the rotation poles) of the larger rift systems—systems that may well have been global in scale. Clearly the later SW-NE rift system is distinct from the earlier NW-SE rift system, with completely different rotation poles, and rift axes that are essentially perpendicular to each other.

Relevant to the early NW-SE rift phase, the extent of the rifting and the location of its rotation pole, are occurrences of carbonatite complexes in northwest Ontario, and large diabase sills at the base

³ We use here the magmatic stage terminology of Miller and Nicholson (2013) but with modified age boundaries.

of the Athabasca Basin (the Moore Lakes sills), the latter with an age exactly equivalent to those of the Nipigon diabase sills (see Bleeker et al., 2020 and references therein). At a larger scale, there are 1108 Ma magmatic provinces on several other continents (e.g., the Umkondo sills in South Africa; Hanson et al., 2004). And relevant to the younger SW-NE rift phase is the major diabase sill magmatism of the SW USA Diabase Province at 1095-1085 Ma (e.g., Bright et al., 2014; Heaman and Grotzinger, 1992). Clearly, we need to zoom out to develop a broader understanding of the Midcontinent Rift System and see it in a more global context.

The GSC-funded project to refine our knowledge of this major rift system started with an attempt to better define the ages (both precision and accuracy) of some of the major events and many of the mineralized intrusions. We currently have ~30 U-Pb samples in various stages of progress and some early results were reported in Bleeker et al. (2020) and Smith et al. (2020). Several others will be discussed as part of this presentation. Our initial focus was to resolve many of the problematic age ‘outliers’, the majority of which were based on extrapolations from sparse and discordant data. Most of these outliers are now gone. Based on our current data and review of the published literature, major age divisions may be summarized as follows:

Initiation: ca. 1111-1110 Ma, as best defined by the large Echo Lake subvolcanic layered intrusion (a robust zircon age, reported in Cannon and Nicholson, 2001).

Early Magmatic Stage: 1110-1103 Ma, with emplacement of regional diabase sill complexes (ca. 1108-1106 Ma) following early rift intrusions and regional plateau basalt building (1110-1107 Ma). The Tamarack intrusion, still organized on a NNW-SSE dyke-like system, is ca. 1104 Ma.

Hiatus: 1103-1099 Ma, in many places marked by an angular unconformity.

Main Magmatic Stage: 1099-1092 Ma, initiated with emplacement of the Duluth Complex and later characterized by the very extensive flood basalts of the Portage Lake Volcanic Group.

Late Magmatic Stage: 1092-1084 Ma, waning volcanism and intercalated rift-fill sediments.

Sagging and Rift-Fill Stage: 1084 to ca. 1060 Ma, final rift fill sedimentation, Oronto Group.

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New geologic mapping in the Superior Province of northwestern Minnesota, USA: Pennington and Red Lake Counties

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The Earth Mapping Resources Initiative (Earth MRI) is a partnership between the USGS and state geological surveys/science agencies that funds data collection and geologic mapping in order to better characterize areas of potential critical mineral resources. Earth MRI recently funded a high-resolution airborne geophysical survey (Allen Langhans and Drenth, 2023; Fig. 1, blue box) and acquisition of new geochronologic (Souders, A.K., in review), petrologic, and geochemical data in a part of the Superior Province in northwestern Minnesota that is prospective for numerous critical-mineral-producing systems. Previous geologic mapping of the area (Jirsa et al., 1999; Jirsa et al., 2011) was limited by an absence of outcrop, limited drill hole data, and only one geochronologic age. Newly acquired data support ongoing bedrock mapping across a large area (Fig. 1, red box); This map highlights the geology of Pennington and Red Lake Counties (Fig. 1, orange box). The map area comprises three conterminous subprovinces of the Archean Superior Province which are situated in unusually close proximity to one another; in the map area, the Quetico metasedimentary province pinches to as little as 5 km of thickness in map view where it separates the Wabigoon and Wawa volcanoplutonic subprovinces on either side.

Ages from a biotite tonalite in the Snake River batholith (ca. 2758 Ma), a diorite in the Grygla pluton (ca. 2771 Ma), and a biotite-hornblende tonalite in the Red Lake Falls pluton (ca. 2701 Ma) (Souders, in review) define multiple Neoarchean episodes of intermediate to felsic intrusive activity within the Wabigoon subprovince. Interpretation of the improved aeromagnetic data suggests a revised, more southerly position of the Wabigoon-Quetico subprovince boundary, as well as modifications of numerous other geologic contacts across the map area. Finally, new geochronologic ages confirm an Archean (ca. 2737 Ma) age for the Mentor Anorthosite Intrusive Complex (MAIC) (Souders, in review), and new geophysical interpretations reveal that the MAIC is as much as twice as large and much more structurally complex than previously thought (Drenth et al., this volume). Both findings regarding the MAIC are consistent with what is known of other Archean anorthosites in the Superior Province (Sotirou & Polat, 2020; Polat et al., 2018).

Work in the larger Earth MRI mapping area is ongoing. Additional geochronologic data will shed light on the depositional history and timing of mineralization of volcanic strata in both the Wawa and Wabigoon subprovinces. Geochemical analyses will supplement petrographic observations and help refine tectonic provenance of all rock units. A new geologic map of the entire area (Fig. 1, red box) will be completed, and a comprehensive mineral potential model will better assess the potential for critical minerals in the area.

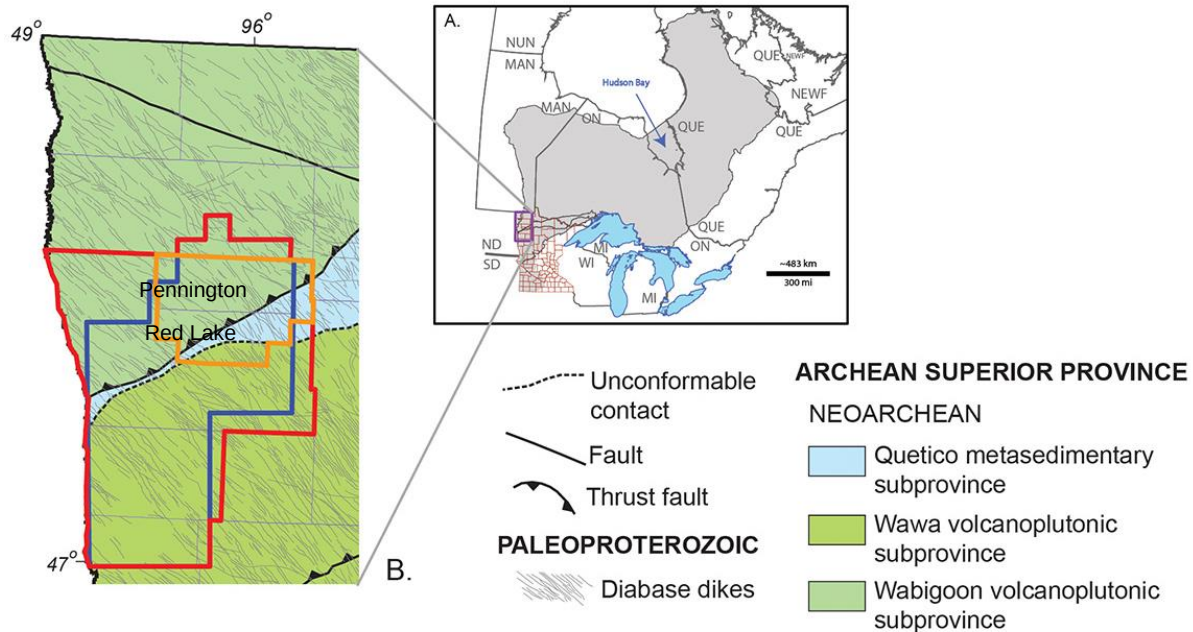


Figure 1. Generalized subprovince map of the Superior Province in northwest Minnesota, USA, showing the location of both the recent geophysical survey (blue outline), ongoing new mapping (red outline) for the EarthMRI project, and the map area for this poster (orange outline).

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A revised provenance model for the Elk Mound Group in south-central Wisconsin based on detrital zircon analysis

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The Late Cambrian Elk Mound Group consists of three sandstone formations deposited in a shallow tropical sea: the Mount Simon, Eau Claire, and Wonewoc formations, in ascending order. The formations underlie much of the upper Midwestern United States in vast, thin sheets, which thicken toward the Illinois Basin further south. These formations have long fascinated geologists due to their extraordinary physical and chemical maturity, but they have often eluded explanation thanks to those same qualities. Recent studies have employed detrital zircon (DZ) U-Pb analysis to constrain the sources of the sand, and workers have begun to build regional provenance models that describe the origins of the sand and the routes it took to arrive at its present location.

Our study builds upon these models with new samples from the Mount Simon Sandstone, a quartz arenite deposited in terrestrial and shoreface environments (Dott et al. 1986). We analyzed samples from outcrops of nonmarine deposits high on the Wisconsin Arch near Wisconsin Dells, WI, as well as a drill core taken 26 miles east of the Dells (the Triemstra core, near Belle Fountain, WI). We place these samples in the context of previous DZ work in this area, especially a study by Konstantinou et al. (2014). The formations of the Elk Mound Group are poorly defined in central Wisconsin, and the samples reveal a transition from Mesoproterozoic source provinces towards Late Archean source provinces as one moves up section and to the west (Figure 1). This transition is understood to represent a shift from sediments derived from the more local Wolf River Batholith (ca. 1470 Ma) and Penokean orogenies (ca. 1830 Ma) to more distal sediments derived from the Superior Province (ca. 2650 Ma). However, other sedimentary basins such as the Animikie and Huronian basins and the Midcontinent Rift may have contributed sediments as well. The physical maturity of the sand grains supports a recycled origin, as multiple cycles of weathering and erosion would have been necessary to produce such rounded grains (Dott, 2003).

Sedimentological details of the sandstone reveal additional information about shifts in provenance. A pair of samples from the Wisconsin Dells area (upper Chapel Gorge and lower Mirror Lake) show relatively high proportions of Penokean-age sediments. The sedimentology of the outcrops sampled records a transition from a dune environment to a braided river environment, and these rivers may have brought sediment from the Penokees. Additionally, the proportional increase in Archean-age sediments correlates with a rise in sea level as one rises through the Elk Mound Group. This correlation suggests that local sediment sources were drowned by sea level transgressions, while the distal Superior Province remained high enough to continue eroding and contribute sediment to a shallow sea already rich in Archean-age sand. Paleocurrent indicators derived from optical borehole image logs from wells across central Wisconsin add to the regional provenance picture with evidence of predominant currents flowing toward the west and southwest, giving some indication of the more immediate source and final transport of these sediments.

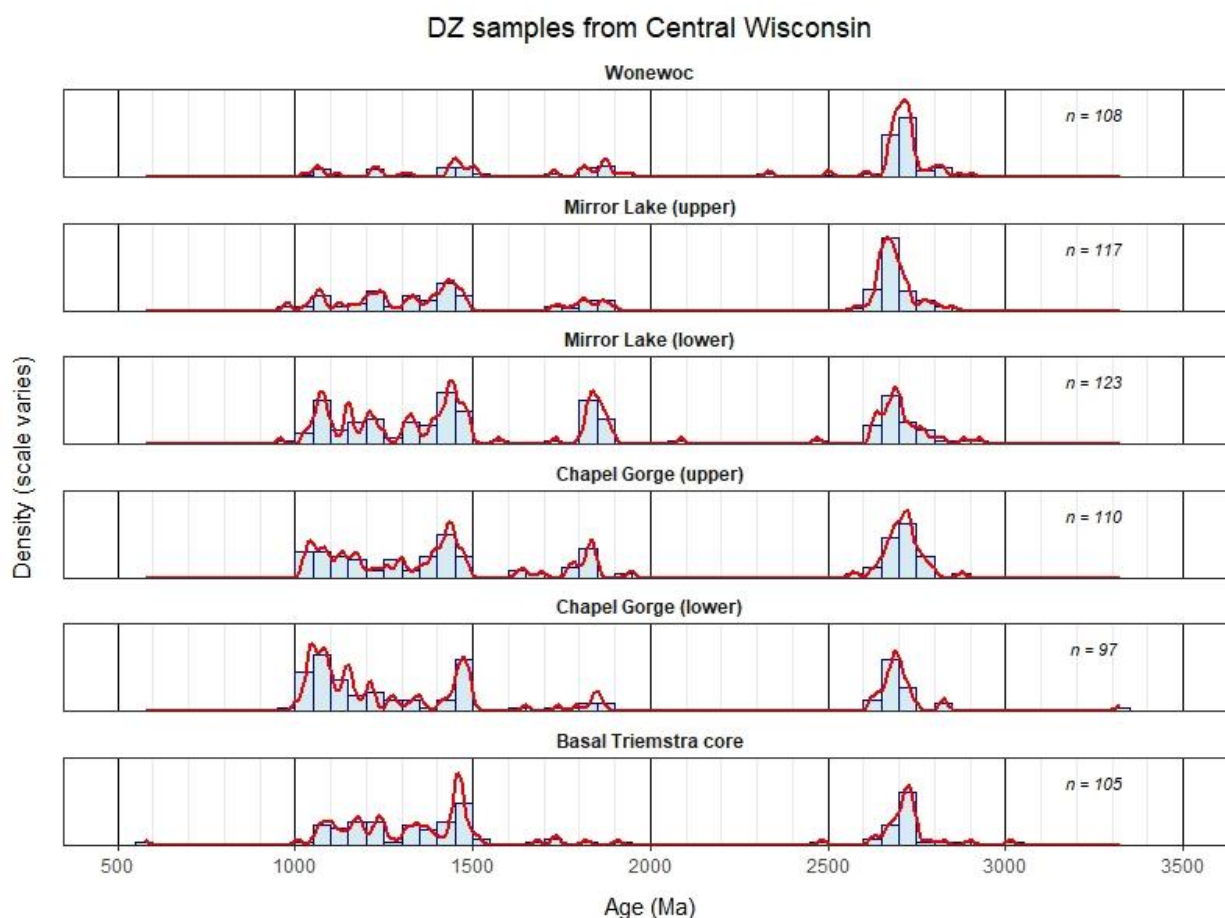


Figure 1. DZ data from six samples gathered in central Wisconsin, organized in ascending order through the section and from east to west. (The Triemstra sample is the oldest and furthest east; the Wonewoc sample is the youngest and furthest west.) The Chapel Gorge samples came from the east bank of the Wisconsin River about 1.5 miles north of Wisconsin Dells. The Mirror Lake samples came from the northwest shore of Mirror Lake about 3.5 miles south of Wisconsin Dells. The Wonewoc sample was collected near Wonewoc, WI, about 21.5 miles west of Wisconsin Dells, and was analyzed by Konstantinou et al. (2014).

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Quetico-Wabigoon Subprovince Boundary in the Superior Province north of Thunder Bay, Ontario, Canada

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The boundary zone between the Quetico and Wabigoon subprovinces is a complex zone of deformation and metamorphism that historically has been described as a fault, change in metamorphic grade and/or change in lithology. This boundary zone is exposed along Highway 527 within a roughly 23km stretch of highway. At the south end of this zone the DeCourcey Lake outcrop is a strongly foliated, mylonitic gneiss containing quartz, feldspar, garnet, sillimanite, muscovite, and biotite with pegmatites and boudinaged quartz veins that is interpreted to be part of the Quetico subprovince. The north end of the zone is marked by weakly foliated Max Lake conglomerate that displays primary sedimentary textures and is interpreted to be part of the Wabigoon subprovince. Cataclasite was discovered 9.8km north of the DeCourcey Lake outcrop and marks a sharp change from the high-grade amphibolite to granulite facies Quetico lithologies south of the cataclasite to sub-greenschist to greenschist facies Wabigoon lithologies to the north. This cataclasite is characteristic of brittle deformation and evidence for a fault that has not been reported in previous studies. The fault is mapped parallel to the foliation of the cataclasite (Fig. 1). This cataclasite is interpreted to be a boundary fault marking the abrupt transition between the Quetico and Wabigoon subprovinces along Highway 527.

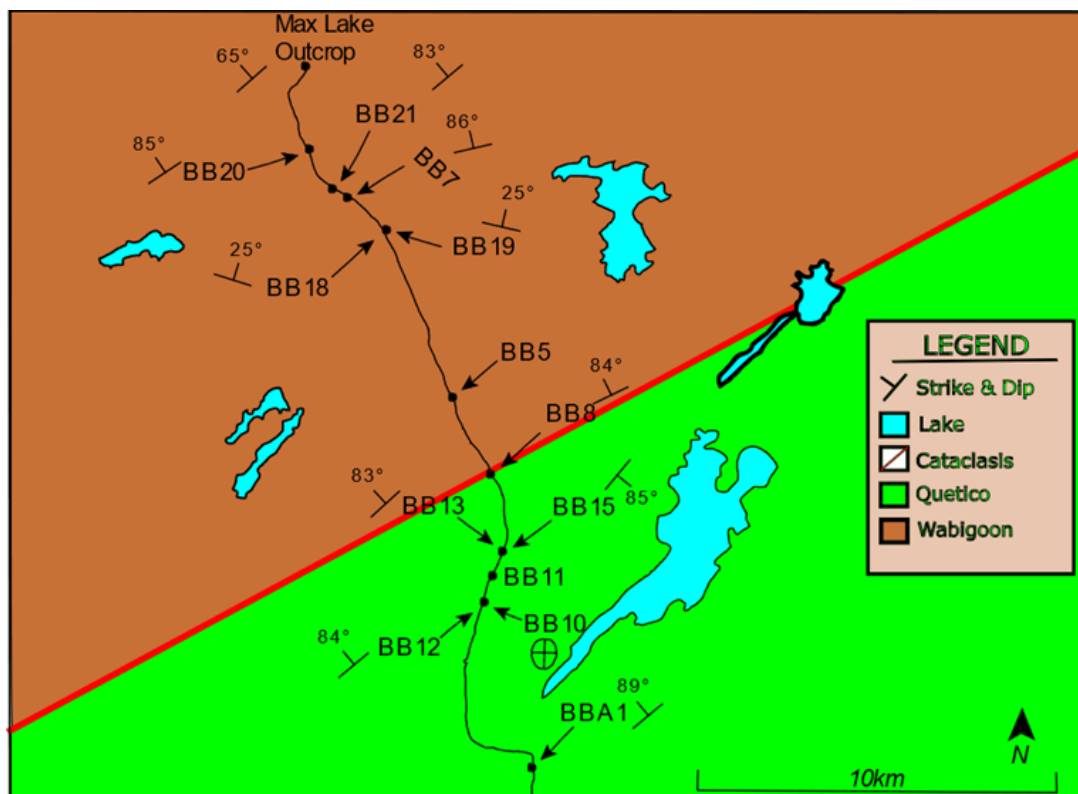


Figure 1. Map of study area along Highway 527 showing sampled outcrops and new subprovince boundary.

Thirteen outcrops along Highway 527 were mapped and sampled for microstructural analysis.

Thin sections created from these samples were used to identify deformation microstructures in quartz and feldspar. Feldspar deformation microstructures are particularly useful and can be used as a proxy for temperature since feldspar needs higher temperatures than quartz to deform internally. Identifying deformation regimes for feldspar is important as most of the rocks within the study area are dominantly composed of quartz and feldspar.

Metamorphic Grade	Temperature	Textures/Deformation Structures
Low	400 °C	-Patchy undulose extinction -Fracturing and cataclasis -Angular grains -Grain size faults with bent cleavage plane/twins
Low-Medium	400-500 °C	-Internal fracturing (minor dislocation glide) -Bulging recrystallization (BLG) -Tapered deformation twins -Bent twins -Undulose extinction -Deformation & kink bands
Medium	450-600 °C	-Core & mantle texture -Fine grain recrystallization/uniform grain size -Micro-kinking -Less abundant deformation twins
High	600 °C	-Sub-grain rotation (SGR) -Bulging recrystallization (BLG) -Core and mantle texture -Myrmekite along foliation planes

Table 1. Feldspar deformation structures and corresponding temperatures/metamorphic grade based on descriptions from Passchier and Trouw (2005).

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Contributions of diverse mantle sources during the early stages of Midcontinent Rift formation — Implications for a passive rifting model

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It is generally accepted that the Midcontinent Rift System (MRS) and associated magmatism originated as a result of the impingement and melting of the Keweenaw Plume beneath the crust ca. 1.1 Ga (Hutchinson et al. 1990). This interpretation is based largely on Sm–Nd and Re–Os isotope data, and the need for a heat source to explain the large volumes of magma generated (Cannon 1992; Nicholson et al. 1997; Shirey 1997). This view has recently been challenged, however, given the long duration of magmatism associated with the MRS (Hollings and Heggie 2014) and paleomagnetic evidence that is indicative of rapid plate motion during the formation of the MRS (Swanson-Hysell et al. 2014). Alongside these ambiguities are uncertainties in the nature of the sources that fed the MRS with magma (e.g., plume vs. subcontinental lithospheric mantle)? Clarifying these ambiguities has remained challenging given that many of the earliest magmas in the MRS were variably contaminated by crustal material (e.g., the Nipigon sills), masking potential contributions from distinct mantle sources. Development of a robust genetic model for the early history of the MRS and the critical mineral resources associated with this magmatism requires a firm understanding of these contributions. To address this, we integrated new Os isotope data of Initiation (>1,109 Ma), Early (1,109–1,104 Ma), and Hiatus (1,104–1,098 Ma) stage rocks with variations in their bulk-rock trace-element and Nd isotope geochemistry (Brzozowski et al. 2023).

Early MRS rock suites are characterized by highly variable γOs_i values of -10 to 3857, with Early Stage melts exhibiting the greatest variability (-10 to 3857) and Initiation Stage melts exhibiting the smallest variability (4 to 50). Given that the γOs_i values do not correlate with La/Sm, Gd/Yb, and MgO, this variability could not be due to variable degrees of partial melting, retention of garnet in the mantle, or fractional crystallization, respectively. Several of the rock suites of interest exhibit elevated Th/Nb–Th/La and radiogenic ϵNd_i – Sr_i values that are indicative of crustal contamination and/or contributions from a subcontinental lithospheric mantle (SCLM) source. Based on numerical modeling, the radiogenic ϵNd_i and γOs_i values recorded by the mafic–ultramafic intrusions and sills are indicative of their crystallization from hybrid melts (enriched SCLM-derived melt > plume-derived melt) that assimilated <10% crustal material during emplacement (Fig. 1). In contrast, the melts that fed the diabase sills and subaerial lavas likely originated from depleted portions of the Keweenaw Plume based on their variably negative to positive γOs_i values, and were contaminated during emplacement (Fig. 1). Although contamination can explain the range of ϵNd_i values exhibited by the rock suites, it cannot independently account for the range of γOs_i values because i) this would require unrealistically high degrees of contamination and ii) not all of the rock suites were contaminated (cf. Wolfcamp Basalt). Rather, it is likely that fractionation of sulfide liquid and/or Os-bearing platinum-group minerals also contributed to this variability. Together, these results indicate that i) not all of the rock suites in the MRS crystallized from plume-derived melts, ii) melt contributions from the SCLM were greatest during the early stages of rift formation, and iii) the MRS likely initiated passively, with plume impingement being a coincidence that provided the energy and material necessary for voluminous

magmatism.

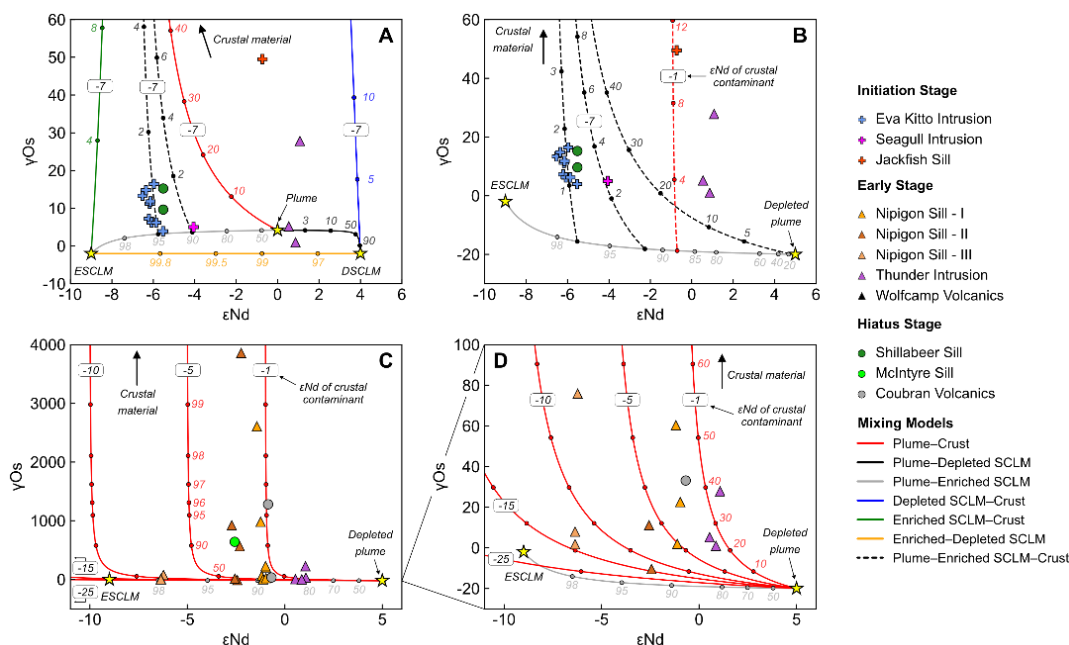


Figure 1. Variation in γOs_i and ϵNd_i in hybrid magmas generated by mixing of melts from various mantle reservoirs. The numbers along the mixing curves are the mixing percents. The numbers in rounded boxes are the ϵNd_i values of the contaminant.

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Eastward transition from banded iron-formation to ferruginous clastic rocks across the central Upper Peninsula of Michigan

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The classic Paleoproterozoic iron-formations of the Lake Superior iron ranges are predominantly banded cherty chemical sedimentary rocks characterized by centimeter-scale interbedding of chert and various iron minerals. New observations from legacy iron exploration drill cores that sampled Precambrian rocks below Paleozoic sediments to the east of the exposed iron ranges in the Upper Peninsula of Michigan show that highly ferruginous fine-grained clastic sedimentary rocks are predominant in that area, and that true cherty iron-formation is a subordinate component of the ferruginous sedimentary section. Most of our information is derived from a collection of cores from proprietary exploration holes held by Cleveland-Cliffs Iron Company, who has allowed us to examine, sample, and describe the rock units. Those holes were drilled to test five large-amplitude magnetic anomalies (Figure 1). Cores from four additional anomalies that are publicly available at the Michigan Geologic Sample Repository were also studied.

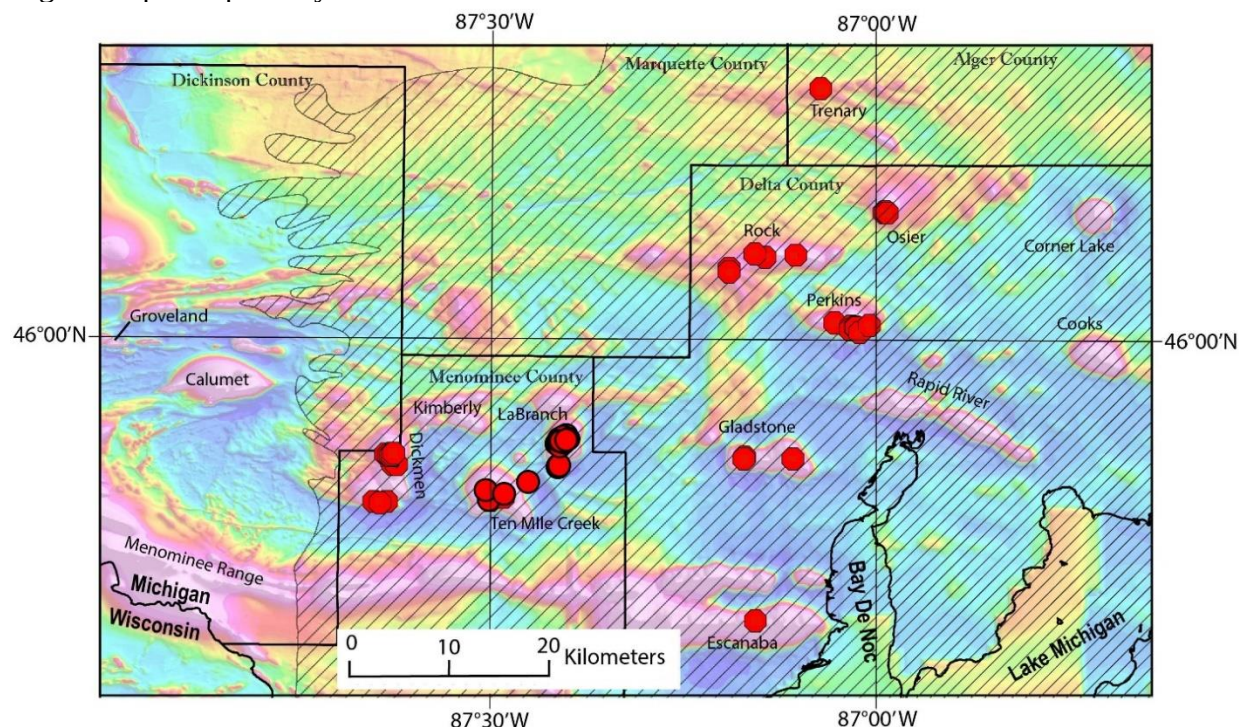


Figure 1. Reduced to pole aeromagnetic anomaly map showing anomalies sourced in sub-Paleozoic Precambrian basement, names assigned to each magnetic anomaly, and drill holes used in this study. Cross-hatched pattern is the area of Paleozoic cover.

The ferruginous clastic rocks examined in this study are generally laminated at centimeter- to millimeter-scale and range from fine-grained quartzite to siltstone. Most are even-bedded. Laminae alternate between quartzo-feldspathic and ferruginous; some of the latter are nearly 100% iron minerals. Average iron mineral content of individual short core segments is as much as 50% by visual estimates. All are metamorphosed to varying degrees, but unambiguous relict clastic textures are preserved widely. The combination of textures and mineral content leaves no doubt that these are

clastic rocks that accumulated very anomalous concentrations of iron.

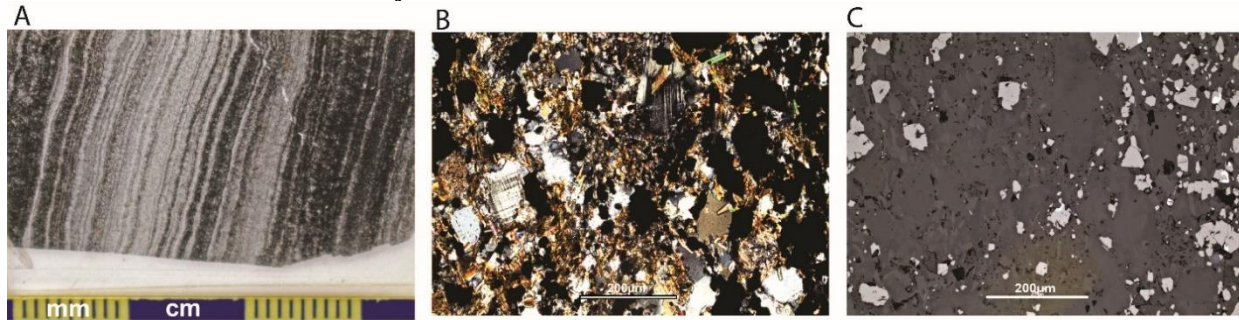


Figure 2. A. Whole thin section of thinly interlaminated fine sandstone and siltstone from the LaBranch deposit. Light layers are quartzo-feldspathic fine sandstone. Darkest layers are nearly all magnetite. B. Crossed polars view of quartz, microcline, biotite, and magnetite in fine sandstone from the Gladstone deposit. C. Same view as B in reflected light showing numerous magnetite grains. Bright partial rims on some grains are martite.

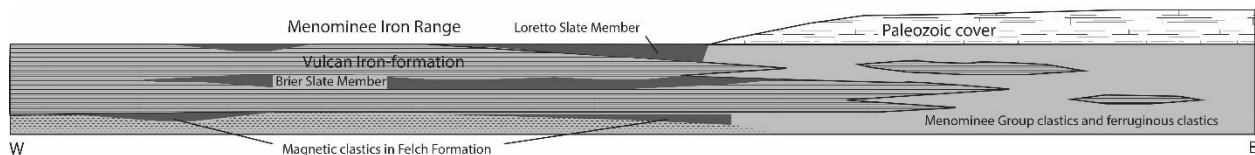


Figure 3. Schematic section of approximately 100 kilometers showing the transition from Vulcan Iron-formation in the west, as exposed on the Menominee Range (Bayley et al., 1966) and Felch Trough (James et al., 1961), to ferruginous clastic-dominated sedimentary rocks in areas covered by Paleozoic sediments in the east.

We interpret these ferruginous clastic rocks as the lateral equivalent of the Menominee Group, which includes the major banded iron-formations of the Menominee and other iron-ranges of the western Upper Peninsula of Michigan. They record a gradation from the purely chemical and clastic-starved true banded iron-formations to the west, to a more shoreward facies where fine clastic sedimentation predominated and overwhelmed slow precipitation of chert beds. Intermittent periods of diminished clastic input allowed sporadic deposition of layers of cherty banded iron-formation, some of which are granular, indicating deposition in shallow water. These relationships show that the lateral disappearance of true banded iron-formations resulted from suppression of chemical chert precipitation by the input of fine-grained clastic sediments. However, intense iron deposition persisted into this more proximal fine-clastic-dominated facies resulting in abundant ferruginous clastic rocks.

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Workshop Outcomes and Updates for the Minnesota Department of Natural Resource's Drill Core Library

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The Minnesota Department of Natural Resources (DNR) provides public access to more than one million meters of drill core from over 9,000 locations across the state at its Hibbing Drill Core Library (DCL). This archive opened in 1967 and has been an invaluable resource for bedrock mapping, mineral exploration, and research, including numerous ILSG presentations.

In November 2022, the DNR convened a workshop to gather stakeholder input on DCL policies and procedures (Carter et al., 2023). A need to update these policies and procedures was identified by DNR staff after conducting a 2022 inventory of DCL holdings and determining its current storage capacity, an assessment of projected core submissions, participation in a National Geological and Geophysical Data Preservation Program (NGGDPP) data management workshop, and a review of the policies and procedures of the United States Geological Survey (USGS) and peer repositories. Workshop participants were affiliated with the mining/mineral exploration industry, government agencies, academic institutions, and consulting firms.

Feedback was gathered through exercises and participant surveys that focused on the mission of the DCL, prioritization of storage for various materials, sampling and related policies, and desirable enhancements to DCL databases. DNR staff used input from the workshop and reviewed the mission statements from the USGS, the DNR, and peer repositories to create a mission statement for the DCL.

DCL curatorial decisions on what to add or retain in its collection have not previously been constrained by storage capacity. Given anticipated core submissions, participants were encouraged to consider submission and retention priorities, even with a planned addition of a fourth DCL storage building. It was recommended that prioritization should be given to materials that are costlier to replace, are more difficult to access (present and future) as well as complete (i.e., non-skeletonized) diamond drill hole cores that have economic and/or geologic significance. Suggestions were made in favor of retaining pulp and reject samples derived from bedrock core, while acknowledging the potential for the materials to degrade over time. It was suggested that unless surficial materials (e.g., outcrop, glacial sediments) have historical significance or were from areas with restricted access then they should be given a low storage priority. Participants encouraged the DNR to consider strategies that might optimize storage capacity or lower retention costs, such as standardized containers for unconsolidated materials or off-site storage of lower priority samples within the collection.

Established DCL policies for facility visits, sampling protocols, and derivative thin sections and dataset submissions are comparable to peer repositories. While reviewing these policies, workshop participants expressed concerns about missing or oversampled intervals and suggested improving communication about the allowable sample size based on the proposed analyses. It

was generally accepted that samples, unused materials, and thin sections should be returned within a year. Yet, it was recognized that multi-year projects may need accommodations, that regular communication and updates must be provided by visitors who want to retain materials for over a year, and that consequences need to be established and enforced for those that do not follow policies. In general, the DCL could improve the communication of its policies to ensure visitors are better able to follow them.

Participants also offered ideas on enhancing online access to DCL holdings and associated datasets. These included improving the accuracy of some drill hole collars as well as the link between historical and other publicly available data to drill holes. Digital images of cores boxes were also desirable and the DNR is conducting a pilot program to evaluate digital image collection. The importance of the DCL and the value it offers to researchers, the local mining and mineral exploration community, and the citizens of Minnesota was emphasized by workshop participants. DNR staff are currently using workshop feedback and relevant policies and procedures at peer repositories to make preliminary curational decisions that support the DCL's mission on topics such as storage prioritization, development of operational policies, enhancements to associated databases, and future decision-making. Discussions and input on preliminary policy ideas at venues such as ILSG will help craft a published update to DCL policies and procedures.

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Digital Image Capture and Database Compilation of Historic Mining Data from the Keweenaw Copper District, Michigan: A Progress Update

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The Michigan copper rush starting at Copper Harbor in 1843 (Fig. 1) led to 150 years of mining that produced $\sim 7.5 \times 10^6$ MT of copper (Bornhorst, T.J. and Barron, R.J., 2011), attracted $\sim 100,000$ persons from 40 countries, and profoundly influenced understanding of Lake Superior geology, advances in mining technology, and the region's pattern of life. Many companies invested significantly in trenching, coring, and mining operations that generated an enormous body of geologic information. USGS efforts in the 1940s and 1950s to map bedrock geology and to assess mineral resources have compiled much of this information as bedrock geology maps with supporting cross sections and reports. Though available online in various formats, these map products are the tip of an iceberg of original detailed source data that is not easily accessed. Significant exploratory drilling that postdates map publication has not been utilized for later geologic investigations because of the same difficulty of access. Paper records and microfiche that decay with time are stored at various locations, which further complicates their use. Many groups could benefit from improved access to this vast amount of information. Therefore, we began a 'skunk-works' project to identify and gather information into a digital image repository, to extract it into tabular databases, and to explore how to make it available to scientists, industry, land-use planners, and the general public.

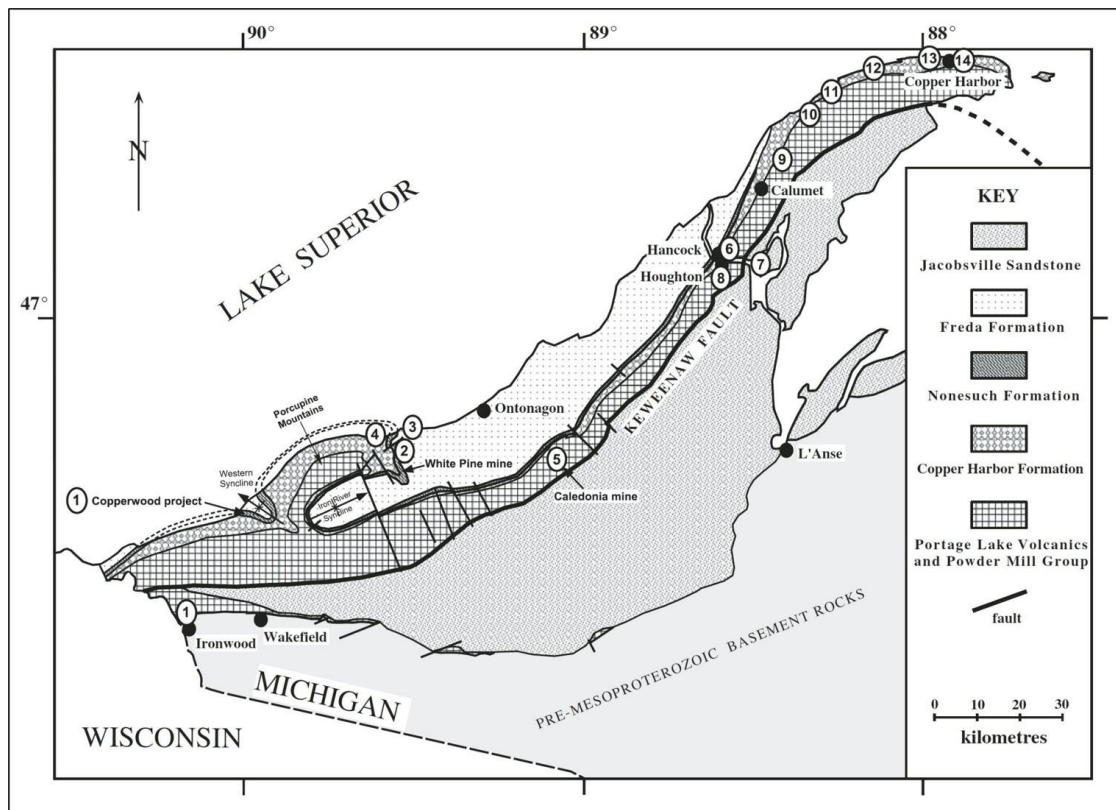


Figure 1. Michigan's copper mining district with generalized bedrock geology. Figure modified from (Bornhorst, T.J. and Barron, R.J., 2011). Numbered field trip stops generally define the extent of copper mining and exploration between 1843 and present. Limited mining also occurred on Isle Royale just off the map to the

north.

The initial phase of the project was to identify sources, access data, establish procedures, and demonstrate feasibility. We started with drill holes, trenches, and mine openings posted on USGS geology maps of the Keweenaw Peninsula. Features were symbolized in Google Earth from georegistered maps, assigned unique codes, and recorded with their data in tables having a common layout (Stage 1). Derivative tables contain data unique to a class, such as azimuth and inclination of drill holes found on core logs (Stage 2). Data captured up to this stage are useful for positioning and orienting features on maps and in subsurface models. Stage 3 captures geologic data as a function of location in a feature, e.g., distance along a drill hole. Such information, available from core descriptions at the Keweenaw National Historical Park (Keweenaw National Historical Park, 2016), the USGS/Denver Archives (White, W.S., 1985), old reports and plates, often requires careful transcription to extract it from image records. Other potential sources of such mining data include early reports of the Michigan Geological Survey, university archives, and private collections. Besides preserving and making these data available to others in an easy-to-access format, we hope to build subsurface models that can benefit research, mineral exploration, and land-use planning (Fig. 2).

Potential Uses

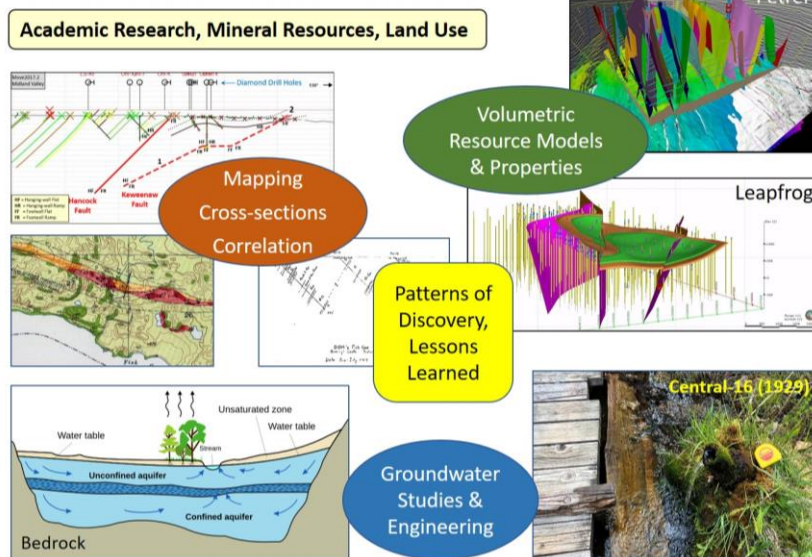


Figure 2. Possible uses of the database once it is further developed.

Acknowledgements: We thank Ted Bornhorst (MTU), Jeremy Mason (KNHP), Bill Cannon (USGS), and Jenny Stevens (USGS) for making us aware of and facilitating access to the two archives that currently are being digitally captured and tabulated. This work is possible because of the foresight of many late geologists who gathered and preserved the original paper records.

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Geophysical mapping of the Great Lakes Tectonic Zone and surrounding Precambrian geology in the central Upper Peninsula, Michigan

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The Great Lakes Tectonic Zone (GLTZ) forms the boundary between the Wawa-Abitibi subprovince (north side) and Minnesota River Valley subprovince (south side) within the Archean Superior Province. The GLTZ is concealed for all of its 1100 km length, except south of Marquette in the central Upper Peninsula of Michigan (Sims, 1991; Sims and Day, 1993). Near KI Sawyer, it is exposed as a NW-striking, 2.3 km wide mylonite zone along a strike length of about 11 km, with a mylonitic foliation that dips steeply to the SW (Sims, 1993). The location extent of the GLTZ is unknown to the east where it is concealed beneath Paleozoic sedimentary rocks. We use legacy aeromagnetic data (Daniels et al., 2009) in combination with modern aeromagnetic data (Drenth and Brown, 2020) and ground gravity data to geophysically characterize the GLTZ and map its eastward extent under cover and map additional nearby covered Precambrian tectonic elements.

Discontinuous NW-striking aeromagnetic gradients observed over the mylonite zone are interpreted to be produced by structurally juxtaposed rocks with varying magnetizations, and such relations are observed locally in outcrops. Mapping of similar gradients across the region shows that they are widely distributed, but have highest concentration within 3 km of the center of the GLTZ. Gravity data show a steep regional gradient along the GLTZ trend, which is likely produced by the juxtaposition of a dense greenstone belt on the north against lower-density gneisses and granites on the south. Using the distribution of aeromagnetic gradients, broader aeromagnetic patterns, and the regional gravity gradient, the GLTZ is interpreted to extend about 55 km under cover to the east, where it changes to an E-W strike and possibly NE strike (Fig. 1). Interpretations are less detailed and less certain east of the area covered by high-quality aeromagnetic data.

Interpreted Paleoproterozoic features have similar strike as the GLTZ. This includes an undated dike swarm and an elongated trough of variably magnetic and dense Paleoproterozoic strata that extends from the Gwinn district southeast under Paleozoic cover. The trough is truncated on its southeastern margin by an interpreted extension of the Norway Lake fault.

The GLTZ is terminated on the east by broad aeromagnetic and gravity highs produced by rocks of the buried eastern arm of the 1.1 Ga Midcontinent Rift. The intersection of the rift and the GLTZ is the location of a change in the strike of the rift from crudely N-S north of the GLTZ to NW south of the GLTZ.

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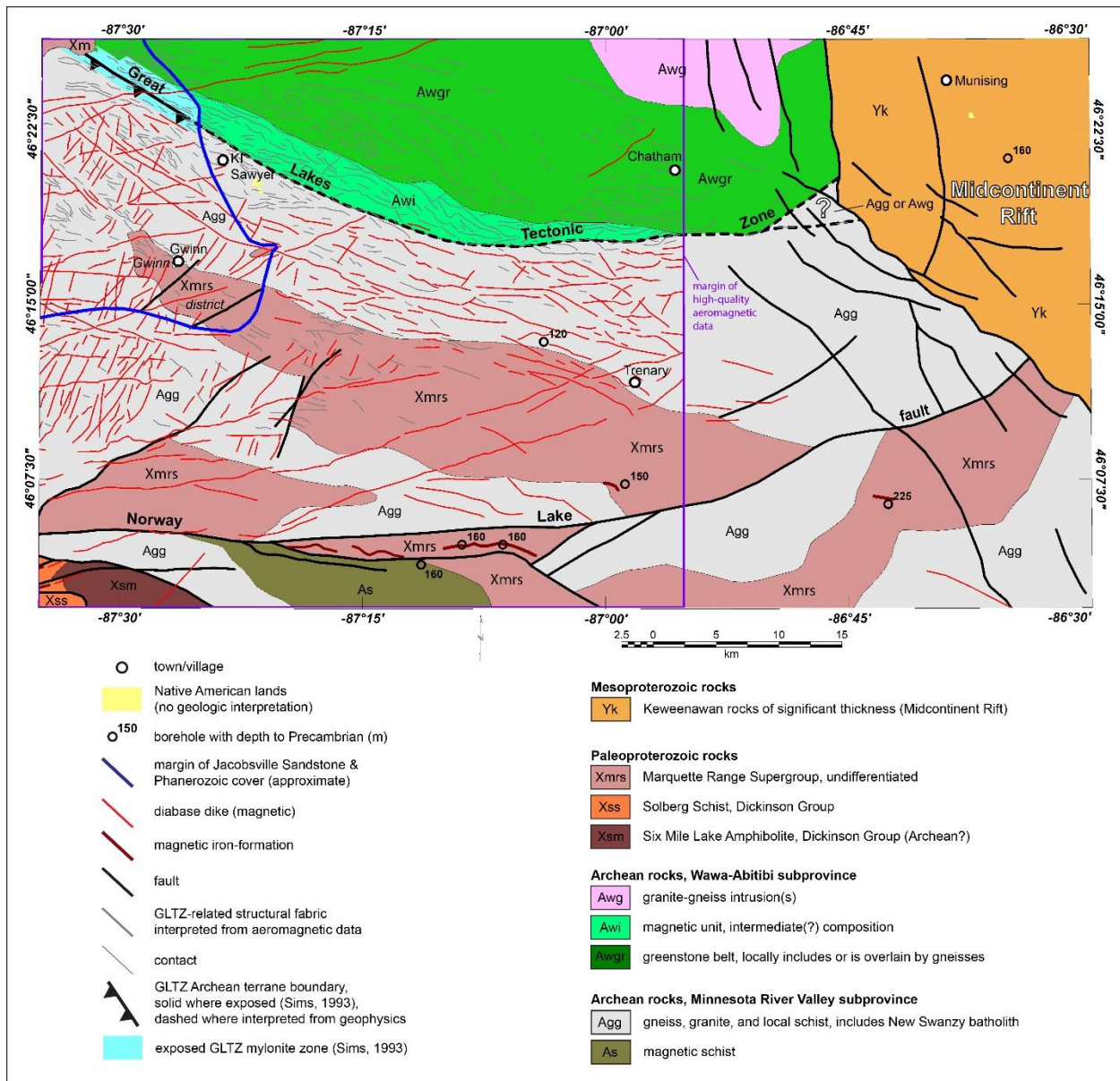


Figure 1. Preliminary interpretations.

Geophysical architecture of the Neoproterozoic Mentor anorthosite intrusive complex, northwestern Minnesota

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The ca. 2737 Ma (Souders, 2023) Mentor anorthosite intrusive complex (MAIC) lies near the northern margin of the Wawa subprovince of the Archean Superior Province, in an area of northwestern Minnesota where the Wawa, Quetico, and Wabigoon subprovinces are juxtaposed in close proximity (Fig. 1). The rocks of interest are entirely concealed by 10s to >100 m of unconsolidated Quaternary sediments and localized Cretaceous strata and saprolite. The MAIC comprises a large volume of megacrystic anorthosite, with a lesser volume of oxide-rich gabbros. The gabbros are known, from a single borehole intersection at ~70 m depth, to be enriched in vanadium (see <http://minarchive.dnr.state.mn.us>), and have further potential for chromium and titanium mineralization. New interpretations are based on data from an Earth Mapping Resources Initiative (MRI)-sponsored aeromagnetic survey flown in 2021 and pre-existing ground gravity data, constrained by approximately ten boreholes in the area.

The anorthosite is weakly magnetized and dense, with a mean measured density of 2940 kg/m³, producing a 10-60 mGal gravity high. Pervasive epidote alteration is a suggested explanation for the high density of the anorthosite (the density of unaltered anorthite is 2730 kg/m³). The oxide-rich gabbros are strongly magnetized, producing aeromagnetic anomalies as large as 6000 nT, making them readily mappable across the complex. New geophysical interpretations (Fig. 1) suggest that the MAIC is significantly broader in extent than previously interpreted (Jirsa et al., 1999) and can be traced along strike for approximately double its originally interpreted length. The MAIC covers an area of about 640 km² along a strike length of about 85 km, and forward modeling suggests a depth extent as great as 7 km. The MAIC is here interpreted to be the largest known anorthosite complex in the Superior Province, as measured by preserved extent in map view (cf. Sotiriou and Polat, 2020).

The MAIC is observed in drill core to intrude a package of basalt flows at its northwest boundary and is itself intruded by multiple low-density felsic plutons that produce 10-20 mGal, 4-20 km wide gravity lows. The large felsic pluton along the southeastern margin of the MAIC is dated at 2702 ± 6.5 Ma (Souders, 2023), and is here called the Fertile pluton after the nearby town. This tectonomagmatic setting is consistent with other anorthosite complexes of the Superior Province, that commonly intrude packages of mafic volcanic flows and are themselves commonly intruded by felsic plutons (e.g., Polat et al., 2018). Disrupted trends and patterns of geophysical anomalies indicate that the MAIC was variably deformed, likely via both faulting and folding, in a complex fashion.

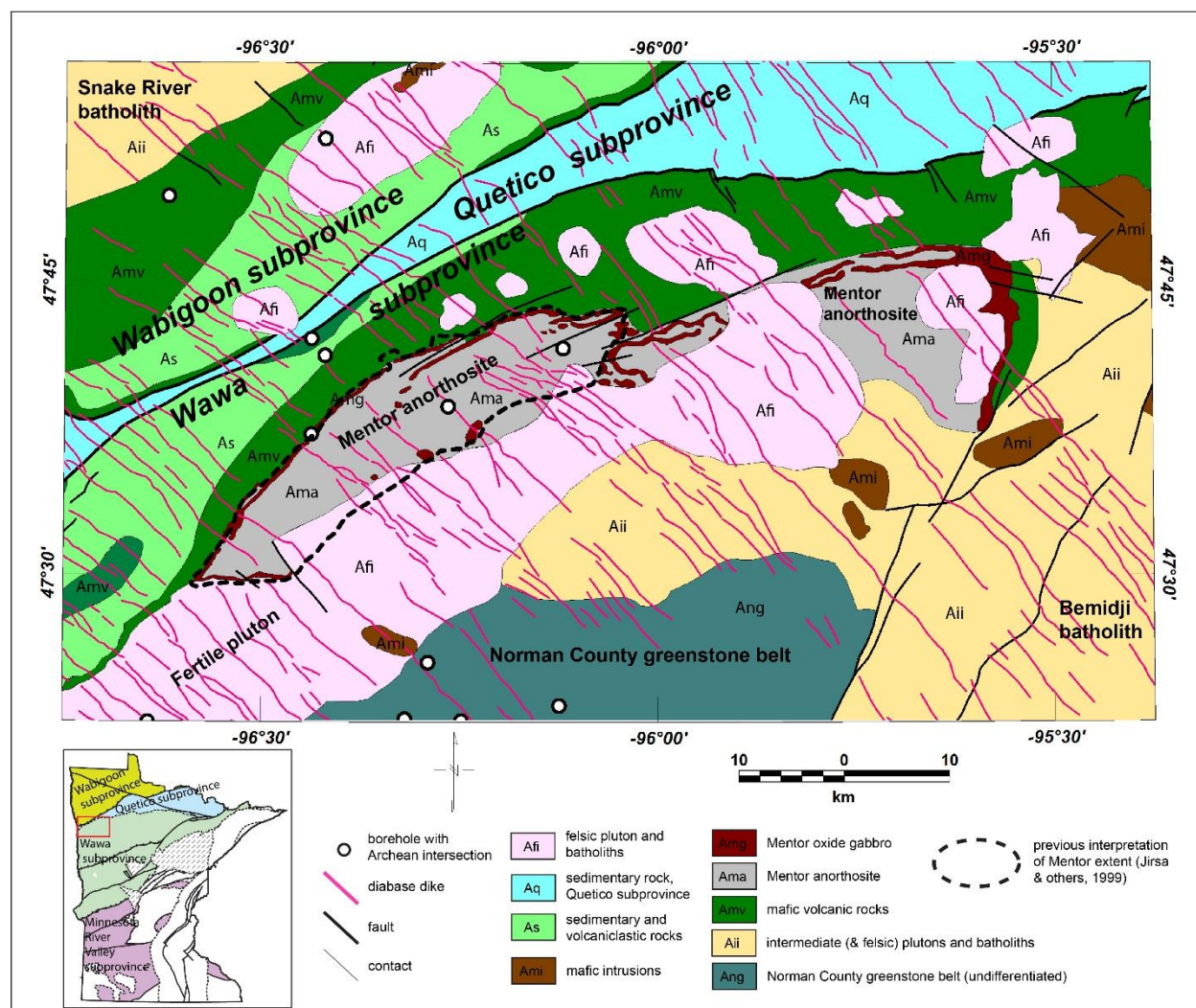


Figure 1. Preliminary geophysical interpretations of geology surrounding of the Mentor anorthosite intrusive complex and surrounding area. Inset shows location of study area.

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Multiple overlapping features spatially associated with lead-zinc-copper mineralization in the Highland quadrangles, southwest Wisconsin, USA

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Several features of the Paleozoic bedrock units of the Upper Mississippi Valley (UMV) lead-zinc district have been spatially correlated with sulfide mineralization in the Sinipee Group including folds and faults (e.g. Heyl et al., 1959) and paleovalleys in the base St. Peter unconformity surface (e.g. Mai and Dott, 1985). The significance of these features in creating fluid pathways with sufficient flow to explain the temperature anomalies associated with ore deposition has been justified by the modeling of Arnold et al. (1996). New detailed 1:24,000 scale mapping of two quadrangles in the Highland area created a detailed structural and stratigraphic framework for this area at the northernmost margin of the UMV district, with the results providing a case study allowing the precise geometry of factors such as fold zones and paleovalleys relative to lead zinc mineralization to be revealed.

Numerous E-W and N-S trending fold zones with amplitudes of 20-60 ft were identified during mapping of the Highland quadrangles (Fig. 1). Lead-zinc mineralization as defined by the digitized mineral development atlas (MDA) mine maps (Pepp et al., 2019) is clustered on the margins of the synclines, most commonly found on gently sloping ramps below the crest of adjacent structural highs. The largest deposits in the Highland area are spatially associated with pit zones where the base Platteville drops for an additional 40-80 ft below the trough of the synclines over restricted elliptical areas. These pit zones are the site of the steepest folding observed in the mapped area, and may have been important for compromising the integrity of the overlying Maquoketa formation, providing a fluid pathway for migrating brines through this regionally important aquitard (Arnold et al., 1996).

Numerous paleovalleys filled with St. Peter formation were identified during mapping (Fig. 2), with the largest in the southeast and southwest corners of the quadrangles mapped continuing down to the Jordan formation with the Prairie du Chien group entirely removed. By removing the Prairie du Chien group, these paleovalleys provide connectivity between the thick, lower Cambrian sandstone aquifer and the upper St. Peter aquifer, allowing large volumes of migrating brines to migrate upward in section towards the favorable ore host units in the Sinipee Group (Arnold et al., 1996). In the Highland district, the likely flow paths from these paleovalleys to the places where the Maquoketa aquitard was compromised at the pit zones directly correspond to areas with known lead-zinc mineralization.

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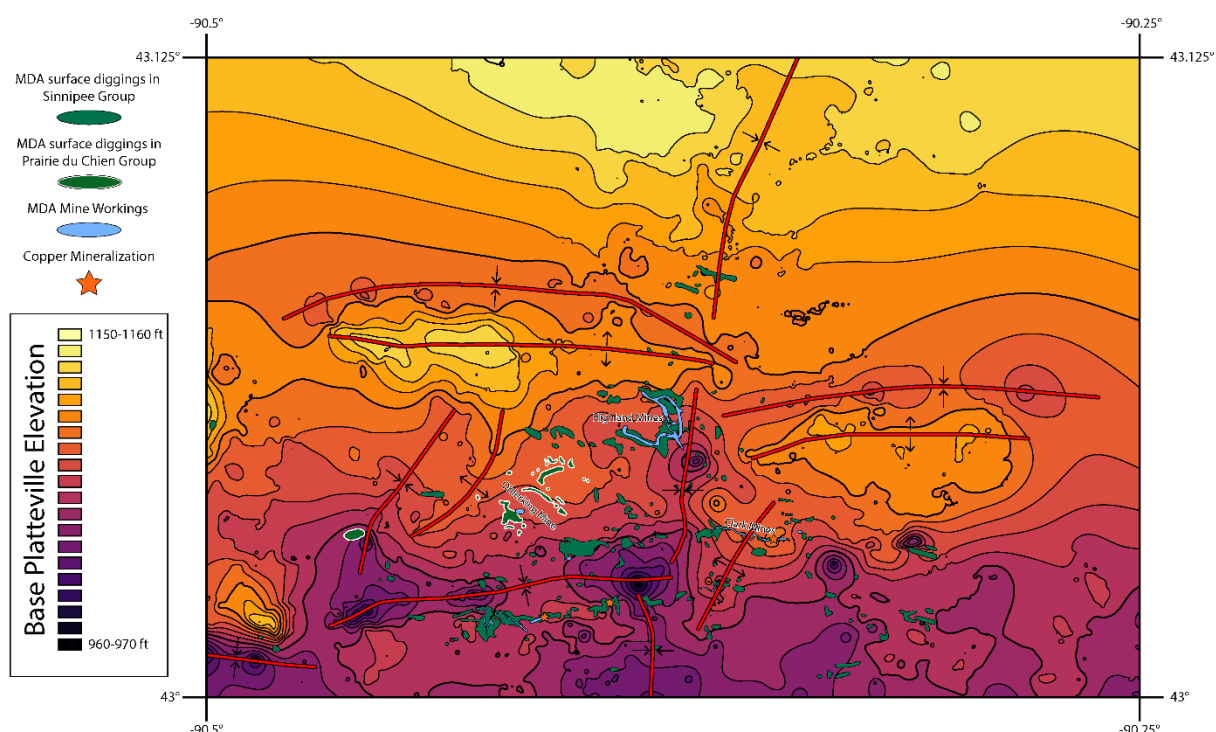


Figure 1. 10ft structure-contour map for the base of the Platteville formation with interpreted fold axes marked by red lines with black outlines with arrows denoting synclines and anticlines. Green polygons mark surface diggings and blue polygons mark underground mine workings from the MDA data digitized by Pepp et al., 2019.

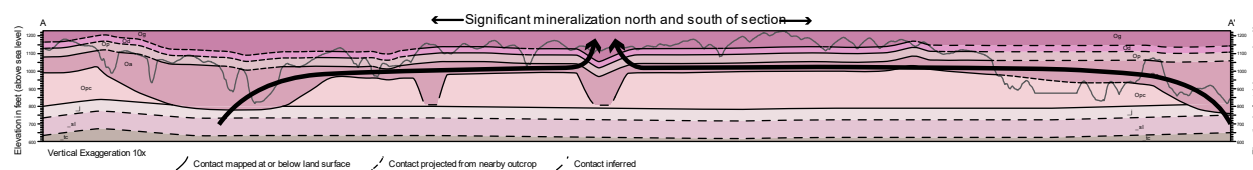


Figure 2. Cross section running E-W through the southern part of the Highland quadrangles. Large black arrows mark likely flow paths for mineralizing fluids ascending from St. Peter paleovalleys (Oa) to pit zones which locally breach Maquoketa aquitard.

Are serpentine fault mirrors an indicator of seismic slip? A microstructural analysis

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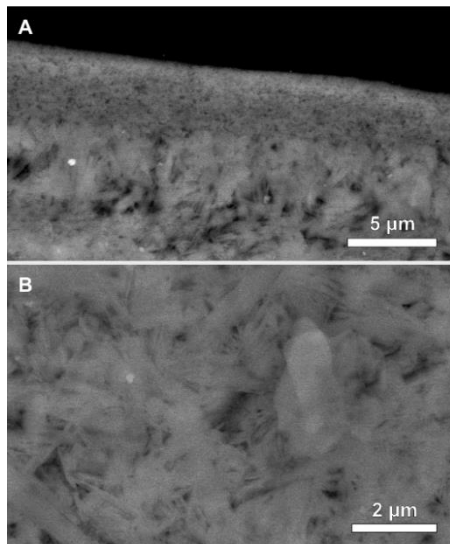
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Fault mirrors are smooth, sheened surfaces along a fault plane. An array of microstructures may produce a fault mirror which each have respective formation mechanisms and associated slip velocities. Fault mirrors in certain compositions may be an indicator of ancient earthquakes with seismic slip velocities, but not all fault mirrors are associated with seismic slip. We study the microstructures of two serpentine mirror surfaces, which have not yet been described in the literature, to determine their formation mechanisms and to assess whether they serve as indicators of paleo-seismic slip. One sample is a medium green mirror surface from a late normal fault cutting dunites from the Twin Sisters complex, Washington State, USA. The second mirror surface is pale green and cuts a serpentinite from the Thetford Mines ophiolite in Quebec, Canada. Both fault mirrors have slickenlines on their surfaces indicating that they formed during slip. The mirror surface from the Twin Sisters complex consists of a ~2 micron thick, potentially amorphous, low asperity serpentine layer which may have formed during seismic slip. The mirror surface from the Thetford Mines ophiolite consists of a ~0.5 centimeter-thick layer which is composed of radiating serpentine microcrystallites which are ~ 1 micrometer in length and 10's to 100's of nanometers in width. These serpentine microcrystallites are interpreted to have crystallized from a serpentine gel phase during slip. While we hypothesize that these samples are both indicative of seismic slip, similar structures may form if serpentine gels crystallize during aseismic creep. Serpentine fault mirrors may represent paleo-seismic slip, but a microstructural examination of the mirror surface is required to establish a seismic origin.

Figure 1. SEM photomicrographs of radiating serpentine microcrystallites from the Thetford Mines ophiolite fault mirror.



Characterizing volcanic host stratigraphy and syn-volcanic intrusions at the Lynne Zn-Pb-Cu deposit, Oneida Co., Wisconsin

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The Lynne Zn-Pb-Cu deposit in Oneida County, Wisconsin is one of several volcanogenic massive sulfide (VMS) deposits located within the understudied Paleoproterozoic (1.8-1.9 Ga) Penokean Volcanic Belt (PVB). The PVB formed as the Marshfield and Pembine-Wausau terranes collided and accreted onto the Superior Craton during the Penokean orogeny (Schulz and Cannon, 2007). VMS deposition in Wisconsin has been interpreted to be associated with continental back-arc rifting in a submarine environment. However, little data is available on the deposit-level at Lynne and other deposits in the PVB to test this model. Volcanic and tectonic variability in VMS forming environments and the effect of basement inheritance on metallogeny are important for district-scale exploration. This study constrains the volcanic and tectonic setting at the Lynne deposit via trace element systematics and aims to improve regional metallogenic models in the PVB.

Historically, the Lynne deposit was subdivided by Adams (1996) based upon their relative stratigraphic position to the ore horizon into upper and lower “Rhyolite”, “Dacite”, and “Volcaniclastic (VCS)” with mineralized zones occupying the lower VCS unit (**Figure 1A**). This study relogged seven drill holes from the Lynne deposit and sampled for petrographic and geochemical analyses. The new geochemical data presented in this study reveals there are no petrochemical differences between the upper and lower host strata (**Figure 1B**). There were also no petrochemical differences observed between the volcanic host rocks and the intruding footwall granodiorite. Therefore, the rocks in this study have been subdivided based simply upon composition and petrography.

The volcanic rocks which host the Lynne deposit are comprised primarily of medium to dark grey felsic to intermediate lapilli and crystal tuff. The sedimentary rocks at the Lynne deposit are observed to be very fine-grain, dark grey siltstones with thin parallel laminations and are assumed to be volcanically derived. The Lynne deposit is intruded by a pluton of medium-grained granodiorite which disrupts the lower massive sulfide lenses. The granodiorite appears in a variety of colors ranging from pink and orange to grey and white. Smaller mafic and felsic dikes also crosscut the Lynne deposit. The mafic dikes are dark grey to green with a fine-grain mafic matrix and feldspar phenocrysts. Felsic dikes are commonly light to medium grey with a fine-grain felsic matrix.

The geochemical data indicates that VMS deposition at the Lynne deposit occurred in a bimodal-felsic petrochemical assemblage consistent with a continental setting. The shared FII-type lithogeochemistry of the felsic volcanic rocks, granodiorite pluton, and felsic dikes suggests these rocks formed under similar extensional, shallow crustal conditions and originated from the same magmatic system. Combined with the lack of a metamorphic aureole around the pluton, the intruding footwall granodiorite is likely the syn-volcanic intrusion which eventually intruded its own volcanic pile (Galley et al., 2003). Improved geochemical and petrographic data on the Lynne deposit will allow for more accurate and improved models which can be compared to other deposits throughout the PVB and around the world.

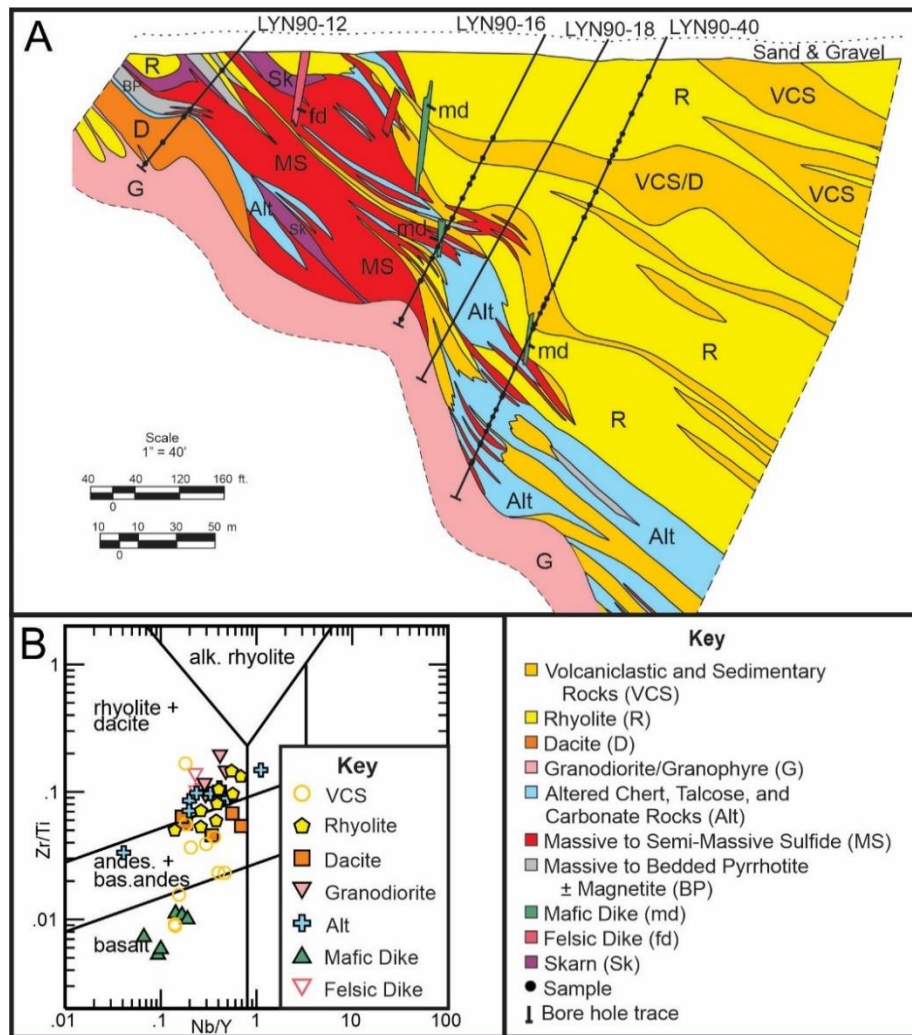


Figure 1. A) Geologic cross section of the Lynne deposit highlighting host stratigraphy, bore hole traces, approximate sample locations, and mineralized zones. Modified from Kennedy (1997). B) Rock type classification diagram of the Lynne. Diagram from Pearce (1996).

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Identifying regional exploration domains for Ni-Cu-PGE deposit types in the Midcontinent Rift

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A new classification strategy for Midcontinent Rift basalts and associated gabbro and ultramafic rocks is proposed, the main objective being to identify magmatic suites associated with known Ni-Cu-PGE occurrences and their spatial distribution across the rift. The study is based on the idea that units with similar incompatible trace element signatures formed under similar conditions in a similar mantle source region and had been subjected to similar contamination or fractionation processes. Elements used in this study are REE, Th, Nb, and Zr. The approach taken is to identify point cloud clusters (magmatic suites) on contoured point density plots for REE represented by ‘lambda’ parameters which emphasize slope and curvature of REE patterns. The resultant groups are checked in Gd/Yb vs. Th/Nb and Gd/Yb vs. La/Sm diagrams which identify influence by crustal contamination or clinopyroxene fractionation, respectively. Melts produced in a metasomatised mantle source are a special case and are distinguished from contaminated melts in a Zr-Th-La diagram.

The data set comprises a total of 1815 samples, 343 of which are basalt, from 70 mafic units. Data are carefully screened for discrepancies and extreme outliers removed. Results indicate a total of eight distinct magmatic suites (Groups 1 to 8). The groups are not listed in stratigraphic order because many units appear simultaneously, and a few are active for long time periods during the MCR event. Highlights of the study with respect to Ni-Cu-PGE mineralized intrusions include: a) Group 1 includes the Current, Seagull and Thunder Intrusions and the Lower Suite basalts of the Osler Volcanic Group; b) Group 2 is the most voluminous and includes the Duluth, Tamarack and Crystal Lake deposits, the Pigeon, Cloud and Arrow intrusions, and basalts of the Greenstone Flows, Upper Suite at Black Bay (OVG) and Upper Groups A and B at Mamainse Point; c) The Eagle deposit is intermediate between Groups 2 and 5 but overlaps the field for all flows in Lower Mamainse Point Group A; d) Group 7 includes the Two Duck Lake (Marathon deposit), Abitibi Dykes and metabasalt unit 3a; e) Group 8 includes the Geordie Lake deposit, Wolfcamp basalt, Copper Island dykes and a few of the Pukaskwa dyke swarm; and f) Groups 3 and 4 are not, as yet, associated with mineralized intrusions and includes the Nipigon sills and basalts of the Centre and Upper Suites of OVG. A map of the Midcontinent Rift showing regional domains for each Group is presented, highlighting the extent of igneous rock domains for each of the known Ni-Cu-PGE deposit types, and their locations relative to the central axis of the MCR.

Exploring the geology of the Midcontinent Rift under western Lake Superior using a preliminary velocity model of seismic line GLIMPCE C

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Seismic-reflection data were collected in the 1980s as part of the Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE) to investigate the 1.1 Ga Midcontinent Rift System (MRS). GLIMPCE Line C crosses western Lake Superior from north to south shores (Fig. 1 inset). Many previous workers have interpreted the MRS in Line C as an asymmetric central graben filled with 10–20 km of subaerial basalt flows, overlain by 7–10 km of sedimentary section, and underlain by magmatic underplating. The central graben was interpreted to have formed from extensional normal faults, later reactivated as high-angle reverse faults. The northern part of Line C crosses over a prominent gravity low called the Grand Marais Ridge (GMR; Fig. 1 inset), previously interpreted as an Archean granitic basement high.

Line C interpretations are commonly shown on a section plotted against two-way travel time along with a crudely estimated depth scale. We are undertaking a more rigorous approach by developing a detailed velocity model for time to depth conversion. The modeling for Line C is guided by velocities resulting from a pre-existing seismic refraction study, intervals defined by seismic horizons, and correlation with velocity models from neighboring seismic-reflection lines. Velocities are verified using common-reflection point gathers from pre-stack depth migration. Several salient points about the MRS can be gleaned from the preliminary velocity model alone (Fig. 1). The north and south sides of the model are dissimilar, reflecting the disparate geology of the north and south shores. On the south side, we identify an outline reminiscent of a bird (Fig. 1) that helps focus discussion without implying any geologic significance.

Aided by a land-based seismic line near the southeast end of Line C, we can tentatively identify the geologic units under the lake within the bird outline (Fig. 1) and interpret a sag basin rather than a graben. The basin contains inferred Porcupine Mountains Volcanics (PM; 6.1 km/s), Portage Lake Volcanics (PLV; 5.9 and 6.5 km/s), with older, possibly reversed magnetic polarity, volcanic units at the base (6.9 km/s). A thick gabbroic sill (6.8 km/s) is inferred within the PLV section. We interpret the truncated PLV (5.9 km/s) and PM (6.1 km/s) intervals at the bird's head to represent an eroded cliff face of the tilted northern limb of the sag basin.

Sheet-like mafic intrusions (7.1 km/s) arise from the lower crust/upper mantle (7.2 km/s) and diverge upwards, following the geometry of the central sag basin. The interpretation that these 7.1 km/s units represent discontinuous or only partially evident magmatic feeder zones is based on their high velocities and sheet-like forms, which in part are constrained by neighboring industry seismic sections.

The sedimentary section above the sag basin includes the Oronto Group (3.4, 4.7, 5.2, and 5.6 km/s) and likely Bayfield Group (3.0 km/s). An angular unconformity between Oronto Group (5.6 km/s) and underlying PM (6.1 km/s) at the bird's head indicates the north limb of the sag basin was tilted prior to deposition. In contrast, the units on the south limb appear conformable.

Using aeromagnetic patterns that lead from the north shore into the lake, we tentatively identify a highly reflective (not shown) 4.7 km/s interval as rhyolites of the upper northeast sequence of the North Shore Volcanic Group (NSVG). This unit is interpreted to be angularly unconformable with overlying sedimentary rocks of the same velocity (4.7 km/s). The 5.6 km/s and 6.5 km/s intervals

beneath the interpreted rhyolites are likely older NSVG volcanic rocks that form a carapace over the GMR. The 6.1 km/s velocity of the GMR corroborates its interpretation as a granitic basement high. The model indicates that a 5.6 km/s unit (NSVG?) dives below the bird outline to depths below 15 km. Whether this unit is connected to deeper parts of the sag basin or separated by faulting is obscured by the 7.1 km/s sheet-like intrusions.

The sedimentary section on the north side of the model tilts to the south, unconformably overlies volcanic rocks (4.7 and 5.2 km/s) and is truncated by the overlying 3.0 km/s interval (Bayfield Group or equivalent). The sedimentary package on the north side collectively has lower velocities and is thinner than the sedimentary package on the south side. It is unclear if the northern section is correlative with the Oronto Group or represents less consolidated, younger rocks, possibly eroded from the NSVG or basalts at the bird's head.

Identification of velocity intervals and their relations at and under the bird's head are key to understanding the tectonomagmatic picture but remain somewhat obscure. Suffice to say for Line C that magmatism and syn-magmatic subsidence played a greater role in the origins of the MRS than previously realized. Moreover, unconformable relations within the sedimentary package may be evidence of multiple post-magmatic tectonic events.

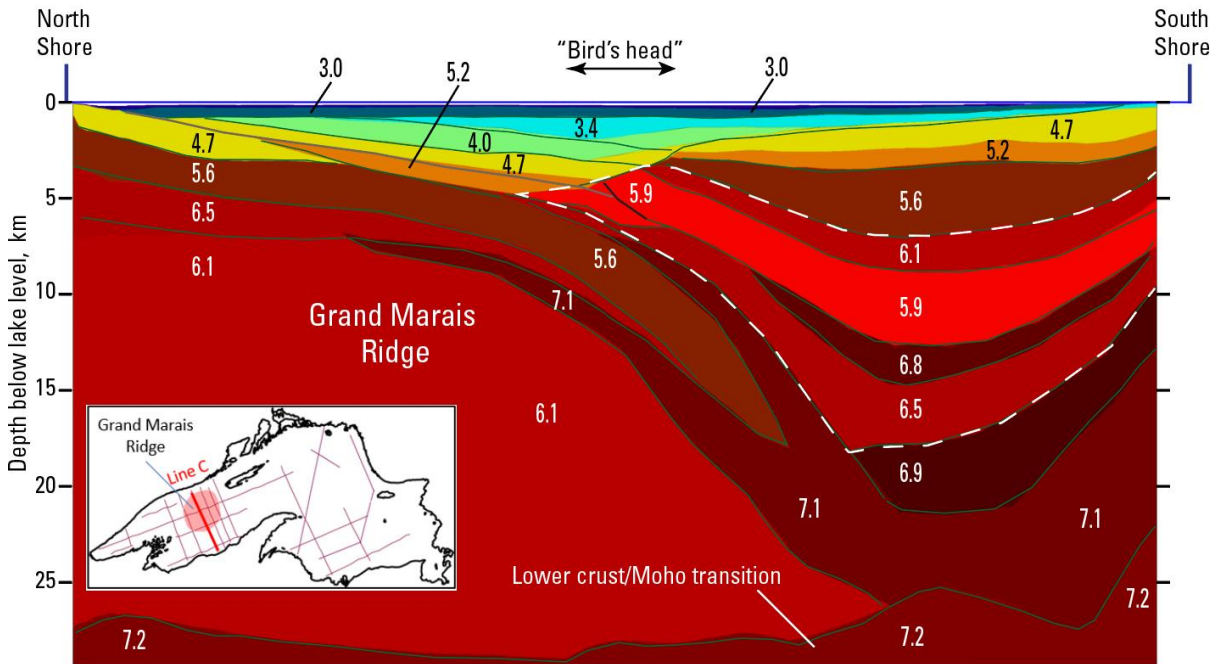


Figure 1. Preliminary velocity model for GLIMPCE Line C showing velocity intervals in km/s. Inset map shows Line C in relation to the Grand Marais Ridge and neighboring seismic lines in Lake Superior. The white dashed line outlines a bird-like pattern to guide discussion. Velocities near the bird's head are interfingered only to provide a smooth transition for the depth migration; lines are drawn to better represent the form of the depth-converted seismic horizons, which are not shown for simplicity. Vertical exaggeration=2.

Petrography, geochemistry, and mineralization of the Archean Titan (Roaring River) intrusion, Northwestern Ontario

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The Archean Titan intrusion, formerly known as the Roaring River mafic intrusion, is one of several mafic-ultramafic complexes in northwestern Ontario that are currently the focus of ongoing PGE exploration. The Titan intrusion is located ~145 km North of Thunder Bay, Ontario, in the Winnipeg River terrane of the western Superior Province and is part of the Roaring River Complex (Figure 1).

The Titan intrusion was identified as an underexplored area during a lake sediment survey in 2000 (Ontario Geological Survey). In the following five-year period, there were several periods of prospecting and soil surveys carried out in the area as well as one diamond drilling project, which aimed to determine the extent of the Titan intrusion within the Roaring River Complex and assess the potential for economic Ni-Cu-PGE mineralization. This early exploration revealed petrologic and geochemical similarities between the Titan intrusion and the mineralized mafic-ultramafic rocks in the Lac des Iles (LDI) Complex, which lies ~60 km to the south of the Titan intrusion (Figure 1). The LDI Complex is the largest of a series of mafic and ultramafic intrusions known as the LDI suite, all within the Marmion terrane, and hosts the world-class LDI palladium mine. An unpublished U-Pb age for zircons from the Titan intrusion yielded an age of 2690 ± 3.2 Ma, broadly coeval with the LDI Complex, dated at 2689 ± 1.0 Ma (Heaman and Easton, 2006).

Outcrop across Titan is sparse, due to the presence of pervasive glacial till and Proterozoic diabase sills. Samples were collected in the summer of 2021 and analyzed for whole rock and PGE geochemistry, sulphur and Sm-Nd isotope analysis, and detailed petrographic characterization. The intrusion consists of a mix of lithologies, ranging from pyroxenites to gabbros to leucogabbros. The lithologies are distributed throughout the intrusion and suggest a simple magma body, where one pulse of magma underwent fractional crystallization within a closed system. Sulphide mineralization is generally confined to pyrite and chalcopyrite, though inclusions of pyrrhotite were observed occasionally. Sulphide mineralization is typically fine-grained and disseminated, though larger blebs do occur, usually of either pyrrhotite or chalcopyrite. The pyrite is considered to be a hydrothermal phase, likely formed from secondary precipitation while the larger blebs of pyrrhotite are considered to be a primary magmatic phase. The Titan intrusion is characterized by enriched LREE's and fractionated HREE's, with negative Nb, Zr, Hf, and Ti anomalies (Figure 2). Titan samples have a range of $(La/Sm)_N$ from 0.7 to 3.8, a range of $(Gd/Yb)_N$ from 2.3 to 7.4, and a range of Nb/Nb* values from 0.02 to 0.47. The geochemistry behavior is consistent with formation in a supra subduction zone setting, which fits with the regional setting of the Winnipeg River and Marmion terranes during this time period (~2.74-2.69 Ga). Only small amounts of crustal material appears to have been incorporated, based on ϵ_{Nd} values of 0.70 to 1.82, compared to an estimated depleted mantle at 2.7 Ga which would have a ϵ_{Nd} value of +3. Titan appears to be a simple intrusion when compared to intrusions of similar size in the LDI suite and many of the similarities between Titan and the LDI suite appear to occur from regional characteristics of the area in this time period (~2.74-2.69 Ga).

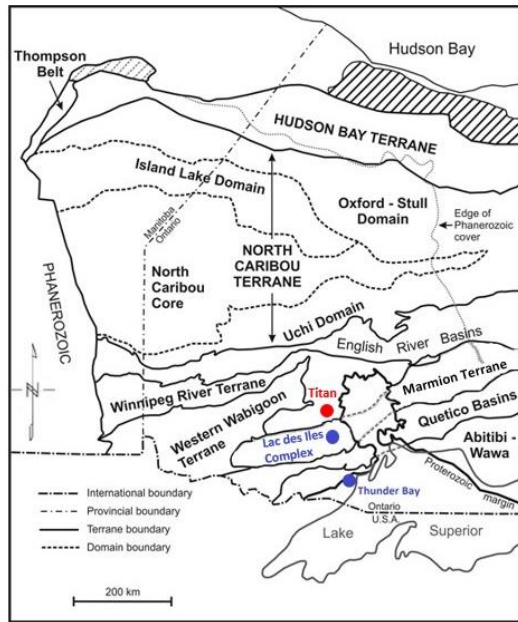
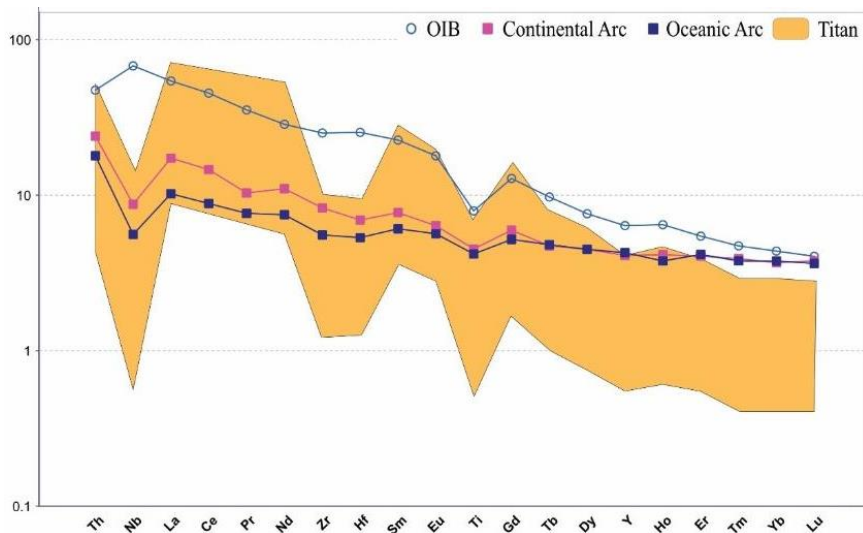


Figure 1. (left) A regional geology map of the western Superior Province highlighting the approximate locations of the Titan intrusion, the Lac des Iles Complex, and the city of Thunder Bay, modified from Stott et al., 2010.

Figure 2. (below) Primitive mantle normalized spider plot, showing representative values for oceanic island basalts (OIB), continental arc, oceanic arc, and the span of values for Titan. Concentrations normalized to primitive mantle from Sun and McDonough (1989) OIB from Sun and McDonough (1989), continental and oceanic arcs from Kelemen et al. (2014).



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Determining Provenance of Rainy Lobe Till using Geochemistry and Detrital Zircon Geochronology.

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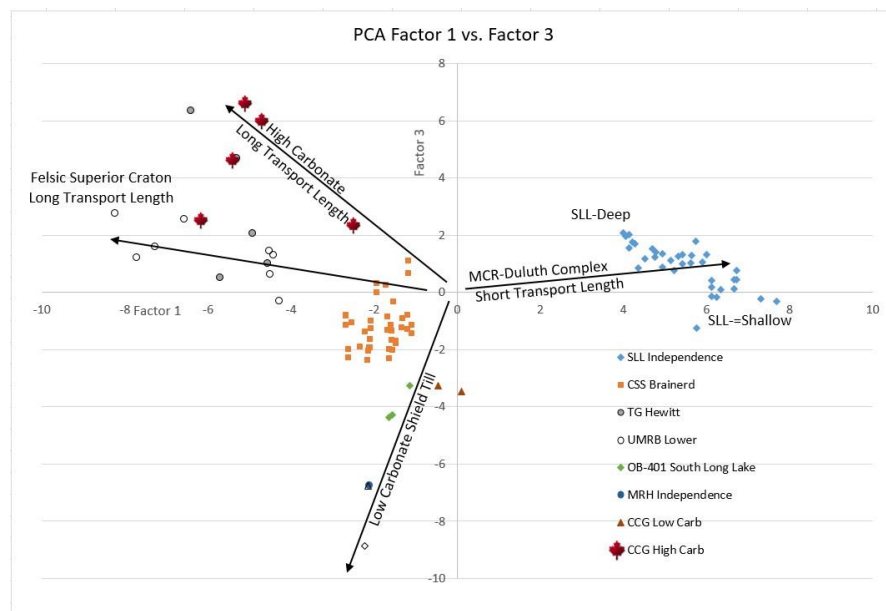
Till of the Late Wisconsin Rainy lobe (RL), which emanated from the Labradoran sector of the Laurentide ice sheet, is exposed at the surface from SW Minnesota to the extreme NE part of the State. The RL advanced to its maximum limit in southwestern Minnesota well prior to the Last Glacial Maximum (*ca.* 27-30 ka BP) and retreated into Ontario by 17.9 ka BP. This till exhibits dramatic spatial and temporal changes in provenance from the Hewitt till of SW Minnesota to the Independence till in the NE. While texture, fabric, and physical properties are similar, lithologic changes include a decrease in carbonate and greywacke of the Omarolluk Fm. with an increase in mafic rocks of the Duluth Complex as the ice retreated. The observed change in lithology reflects changes in the mean transport length (MTL) of the till. The MTL is the average distance of transport defined by the indicator lithology abundance. The Hewitt till has a mean transport length of > 1000 km, whereas the Brainerd and Independence tills have mean transport lengths of approximately 400 and 100 km, respectively (Berthold, 2015).

Two models have been proposed to explain the lithological differences (particularly carbonate) in RL tills. Goldstein (1989) postulated that the downglacier increase in carbonate in the Hewitt till was the result of progressive incorporation, by regelation or deformation, of older underlying till that was rich in carbonate. However, Goldstein also postulated an accretionary origin for the Wadena drumlins, which would imply continuous deposition rather than erosion. This subglacial erosional vs. depositional paradox remains unresolved.

Larson (2008) concluded that the changes in sedimentology and landforms record systematic changes in provenance related to changing basal boundary conditions in the interior of the LIS. As the RL advanced early in the last glacial cycle, a continuous till sheet composed of sediment from Hudson Bay and the Hudson Bay lowlands (HBL) extended to SW MN. As the ice approached its maximum limit, much of this till sheet was then eroded exposing Canadian Shield bedrock along the central portion of the flow path (Fig. 1). Early in this phase of glaciation, the sediments reflect long-distance transport from Hudson Bay, and later phases reflect increased proportions of felsic shield lithologies and Duluth Complex rocks.

These two models of Rainy lobe till sedimentology are evaluated using mixing models, till matrix geochemistry, and detrital zircon geochronology. The tills underlying the Hewitt till are typically finer textured and contain significant concentrations of Cretaceous age carbonates and shales. Therefore, a multicomponent mixing model is developed to examine sedimentological variability by incorporation of older, underlying tills (*e.g.* Goldstein, 1989). To evaluate the model of Larson (2008), which implies long vs. short transport distances, twenty-eight samples collected along a transect from SW to NE Minnesota, and six samples collected from the HBL, were processed and sent for geochemical analysis. Fifteen of these samples were processed and analyses for detrital zircon geochronology using laser-ablation, ICPMS.

Results of a 48-element analytical suite along with latitude, longitude, and depth were run through a principal component. The first 3 factors were retained for analysis. Factors 1 and 3 distinguished mafic vs felsic igneous rock geochemical signatures and carbonate content, respectively. Factor 1, felsic vs. mafic lithologies, can be used as a proxy for MTL and shows locally vs distally derived lithologies. Factor 3 distinguishes tills based on carbonate content.



Core SLL (Independence till) plots positively on factor 1 indicating a short MTL. Core CSS (Brainerd till) represents an intermediate MTL, while cores UMRB and TG (Hewitt till) SW of the Wadena drumlin field have the longest MTL. In addition, the samples with the longest MTL plot in high carbonate space, positive on Factor 3. Detrital zircon age populations represented on probability density plots show that the shortest MTL samples have the highest signature of local 1.1 Ga Mid-Continent Rift zircons. A

Kolmogorov-Smirnoff (K-S) test statistically compares age populations and determines if they are statistically different. Results from the K-S test reveal that HBL ages are statistically similar to samples from central Minnesota (core CSS). The mixing model, indicates that the Hewitt till is not a mixture low-carbonate RL till and older underlying tills. Geochemistry, and detrital zircon analyses support the model of Larson (2008). Early deposits of the RL in SW Minnesota are geochemically similar to the high-carbonate HBL samples, indicating a distal provenance. This similarity is also observed in the detrital zircon results from the K-S test. Subsequently younger deposits lose the HBL signature and start to incorporate more felsic craton and eventually mafic signatures of the Mid-Continent rift system.

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Copper-rich melt inclusions from the St. Ignace Island Complex: Implications for magma mixing and mineralization

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The St. Ignace Island Complex (SIC) comprises volcanic and intrusive rocks that were emplaced the upper portions of Midcontinent Rift-related, *ca.*1008 Ma Osler Group volcanic rocks (Davis and Sutcliffe 1985; Fig. 1). The St. Ignace Island complex is a ~26 km² stock with a core of quartz-feldspar-phyric rhyolites and dacites and an outer ring of anorthosite and gabbro (Sutcliffe and Smith 1988; Giguere 1975). The petrology and geochemistry of the SIC has been described by Smyk et al. (2006) and Hollings et al. (2023).

The pink to grey, felsic rocks at the center of the complex are quartz-phyric, with rare pyroxene and feldspar phenocrysts. Textures at a variety of scales show evidence of the mingling and mixing of partially crystallized mafic and felsic liquids in SIC rocks.

Mafic and felsic liquids may be incipiently mixed, resulting in partially disaggregated mafic enclaves hosted in a felsic matrix. With progressive mixing, the felsic volcanic domains in the rock become darker and phenocrysts of quartz and alkali feldspar appear embedded in the mafic domains. In the most intensely mixed samples, small, mafic crystalline clots are dispersed throughout a felsic matrix, and as rare mafic enclaves, consisting of only a thin rind of mafic rock surrounding coarse-

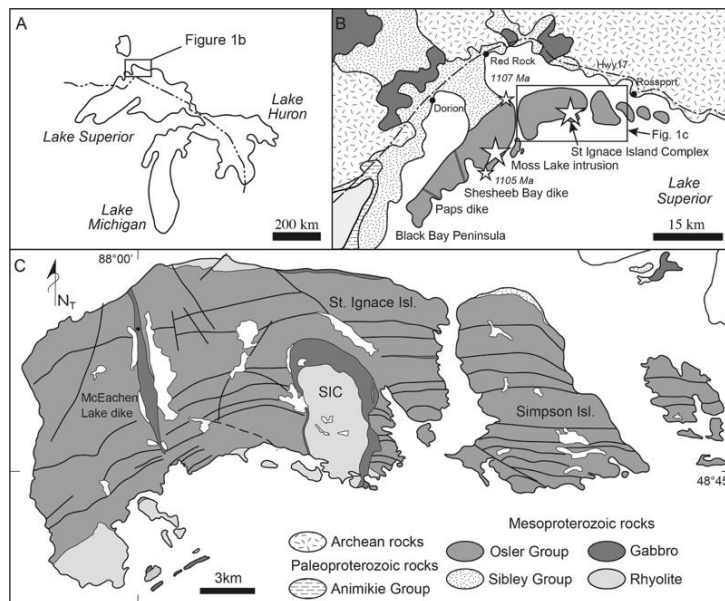


Figure 1. (A) Map of upper Great Lakes. (B) Regional geology of the St. Ignace Island complex. Age data (black stars) from Davis and Sutcliffe (1985) and Davis and Green (1997). (C) Geological map of St. Ignace Island, modified after Giguere (1975).

grained plagioclase phenocrysts.

Well-preserved silicate melt inclusions (MI), many completely glassy, were observed in quartz, clinopyroxene and some plagioclase phenocrysts from the felsic and mafic rocks of the SIC, representing some of the oldest unrecrystallized silicate melt inclusions recognised to date. Melt inclusions from quartz from the felsic rocks are broadly rhyolitic in composition whereas those from

plagioclase in the mafic rocks range from basalt to basaltic andesite. The melt compositions are interpreted to represent the end-member liquids in the system with direct evidence of mixing of the two. Concentrations of Cu and Ag (in both mafic and felsic MI), and Mo (in felsic MI), are up to an order of magnitude higher in both the mafic and felsic MI than in continental crust and the host bulk rock concentrations. We propose that the melt inclusions have preserved pre-eruptive metal tenors that were subsequently modified by sulfide saturation, degassing, or post-solidus hydrothermal alteration. The elevated Cu and Ag contents are similar to those noted in arc-related and extremely oxidized early Midcontinent Rift-related rocks and may account for the world-class volcano-sedimentary-hosted Cu-(Ag) deposits within the Rift as well as the presence of small, porphyry-style deposits.

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Hydrothermal Alteration Facies of the Eisenbrey Zn-Cu Deposit, Rusk County, Wisconsin

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This study focuses on the hydrothermal alteration zones surrounding the volcanogenic massive sulfide (VMS) Eisenbrey Zn-Cu deposit in Rusk County, northwestern Wisconsin. The Eisenbrey deposit is hosted within the Paleoproterozoic Pembine-Wausau terrane and is a part of the Penokean volcanic belt, along with many other VMS deposits including the Crandon, Lynne, and Flambeau deposits. The goal of this research is to develop a petrographic and geochemical categorization of alteration types and complete a geochemical mass balance to produce specific alteration trends. Data collected on the hydrothermal alteration at the Eisenbrey deposit is being compared with other Wisconsin VMS deposits to produce a better depositional framework for VMS mineralization.

The Penokean Orogen is the culmination of various accretionary events and volcanism. The Penokean Orogen began around 1.88 Ga along the southern margin of the Superior Craton. The collision and subsequent accretion of the Pembine-Wausau terrane resulted in subduction moving to the south and began back arc basin development. Most VMS deposits within the Penokean volcanic belt formed within this back arc extensional environment (Shultz and Cannon 2007). Arc magmatism continued until roughly 1.85 Ga. when an Archean crustal fragment, known as the Marshfield terrane, accreted to the Pembine-Wausau terrane & Superior Craton.

VMS systems are characterized by volcanic-sedimentary hosted massive sulfide deposits that form at or near sea floor. Formation is associated with convection of metal rich hydrothermal fluids rising through the crust and mobilizing elements. These deposits are commonly poly-metallic with common mineralization of Zn-Cu-Pb-Ag-Au rich sulfides. Hydrothermal alteration in VMS environments results in mobilization of major elements during modification of primary minerals. The style of alteration varies based on the volcanic setting and fluid chemistry, but commonly are noted by gains in MgO, Fe₂O₃, K₂O, and/or SiO₂ and losses in Na₂O and CaO (Galley et al., 2007).

The Eisenbrey deposit (Figure 1) is relatively poorly understood. Regional metamorphism at the Eisenbrey deposit is lower amphibolite facies and has completely recrystallized the alteration zone at the deposit. Eisenbrey deposit is the only known VMS occurrences associated with Algoma-type iron formation and formed within the “Main Arc Sequence” (DeMatties, 2022). Therefore, improving our understanding of the Eisenbrey hydrothermal system can aid in identifying new exploration criteria in non-typical VMS environments for the Penokean Orogen.

Samples of the hydrothermal alteration zone at the Eisenbrey deposit were analyzed across twelve drill holes from both the structural hanging wall and footwall to the ore horizon. These samples were initially divided into alteration mineral assemblages based on petrography. Alteration types include chlorite-cordierite-anthophyllite, quartz-anthophyllite-biotite, quartz-white mica, quartz-biotite. These alteration types were then characterized using major and trace element geochemistry and mass balance calculations. The alteration at Eisenbrey has notable gains in Fe₂O₃ and MnO; with losses in SiO₂, MgO, and Na₂O. This contrasts alteration at Flambeau, which has gains in K₂O and SiO₂ (Lodge et al., 2022).

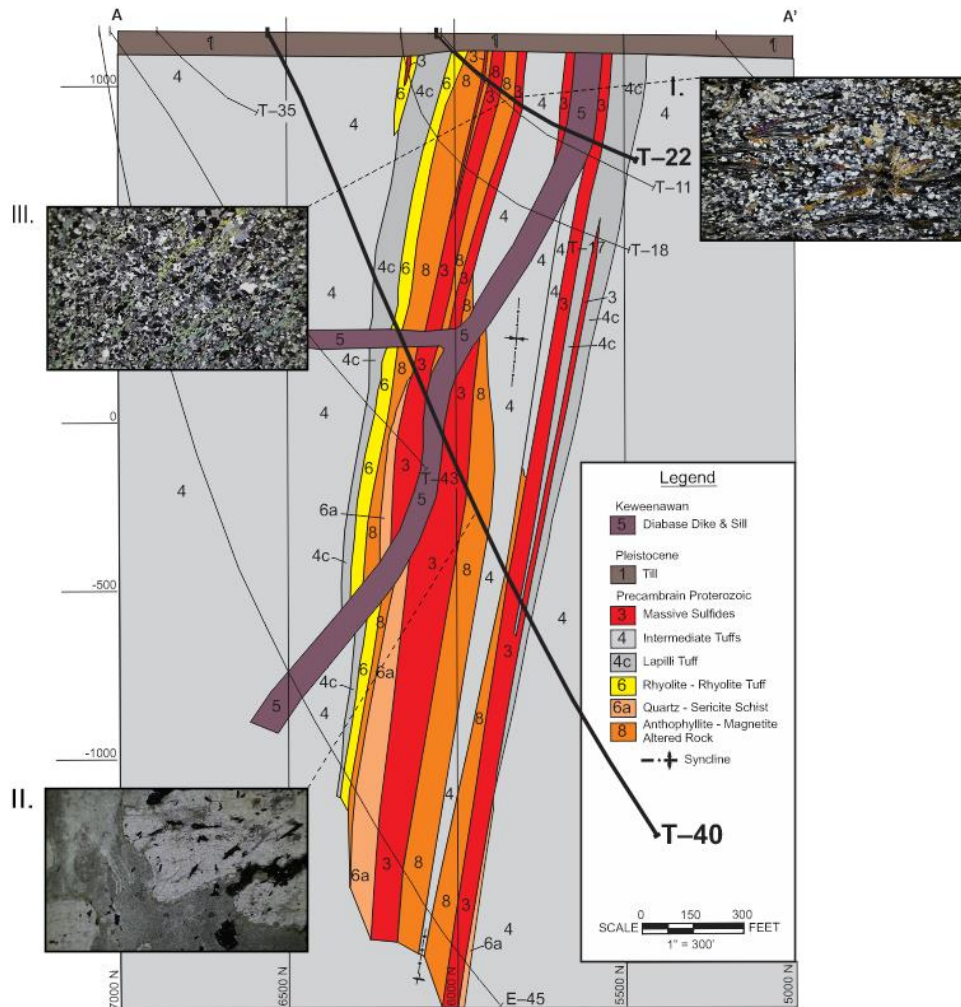


Figure 1. Representative cross-section of the Eisenbrey deposit with representative photomicrographs of common alteration types (right). I. shows Quartz-Anthophyllite alteration (T-22), II. shows Chlorite-Cordierite alteration (T-40), III. Shows Quartz-White Mica alteration (T-22)

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Provenance patterns and tectonic styles of ca. 2.3–1.8 Ga metasedimentary strata in northern Michigan based on regional mapping and detrital zircon U-Pb geochronology

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Detrital zircon U-Pb data from ca. 2.3–1.8 Ga metasedimentary successions in northern Michigan are used to test regional stratigraphic correlations and yield key insights into provenance and tectonic styles along the southern Superior craton. Circa 2.3–2.2 Ga Chocoley Group turbiditic strata and quartzite record initial rifting and basin formation along the southern Superior margin. Unimodal ca. 2.7–2.6 Ga age populations were derived from abundant Archean batholiths in the surrounding region. Distinctive ca. 2.3 Ga populations are rare but present in some samples, but the source(s) of these grains is not well understood. Chocoley Group detrital zircon data are very similar to upper Huronian Supergroup strata to the east and with other global ca. 2.3–2.2 Ga glaciogenic successions. The ca. 2.1 Ga Dickinson Group contains bimodal ca. 2.9 and 2.7 Ga age populations in the East Branch Arkose and Solberg Schist that are distinctive in the region and suggest a mixture of recycled 2.3 Ga Chocoley Group quartzite and more diverse regional Archean basement sources. Minor ca. 2.1 Ga grains indicate derivation from nearby plutonic sources or eroded volcanic equivalents of the same age, consistent with magmatism, regional uplift, and final rifting of the southern Superior craton ca. 2.1. After a ca. 100 Ma hiatus, the Ajibik and Siamu Formations of the ca. 1.90–1.85 Menominee Group have unimodal ca. 2.7–2.6 Ga age populations that suggest continued derivation from ca. 2.7–2.6 Ga batholiths and (or) recycling of older underlying strata. The Goodrich Formation of the basal Baraga Group (ca. 1.85–1.83 Ga) shows similar patterns. A provenance shift to prominent ca. 1.85 Ga populations occurs in turbiditic strata of the Michigamme Formation (upper Baraga Group), indicating arrival of the outboard Wisconsin magmatic terrane to the south. Michigamme strata record basin evolution between the southern Superior Province and the exotic terrane as it approached and collided during the ca. 1.87–1.83 Ga Penokean orogeny, but the relative role of Penokean versus younger ca. 1.78–1.76 Ga tectonism in regional folding and metamorphism remains uncertain. Additional mapping and geochronology focused on Michigamme strata will better constrain regional depositional ages, facies relationships, and tectono-metamorphic patterns.

Petrogenesis of the mineralized horizons in the Offset and Creek zones, Lac des Iles Complex, N. Ontario

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The Lac des Iles Complex is a Neoproterozoic (2.69 Ga; D.W. Davis cited in Stone et al., 2003) polyphase mafic-ultramafic complex located in the Marmion terrane of the Superior Province, 85 km north of Thunder Bay, Ontario, Canada. The intrusive complex can be subdivided into two discrete subcomplexes: the ultramafic-dominated North Lac des Iles Complex and the mafic-dominated South Lac des Iles Complex (SLDIC). The SLDIC has been subdivided into four intrusive series, termed the gabbro-norite, breccia, norite, and diorite series (Decharte et al., 2018). To date, economic Pd-rich mineralization has been discovered in both the breccia and norite series, and occurs proximal to the contacts between the breccia and gabbro-norite series and between the breccia and norite series. The objectives of this study are to i) evaluate the mechanisms of formation of the mineralized horizons near the contact between the breccia and norite domains in the Offset and Creek zones of the SLDIC, ii) evaluate the role that crustal contamination played in this process, and iii) assess the tectonic setting in which the SLDIC formed.

The breccia and norite series are both composed of varitextured, brecciated, and equigranular leucocratic-melanocratic norites and gabbro-norites, and their altered equivalents. The breccia series contains a greater proportion of brecciated and varitextured rocks, while the norite series contains a greater proportion of equigranular rocks. All pre-alteration lithologies are essentially plagioclase-orthopyroxene cumulates with varying minor quantities of interstitial clinopyroxene, biotite, magnetite, chalcopyrite, pentlandite, and pyrrhotite. Variable degrees of hydrothermal alteration are indicated by the presence of tremolite-actinolite and talc (after pyroxenes), chlorite and sericite (after plagioclase), and pyrite (after pyrrhotite). Although the breccia and norite series are mineralogically similar, the breccia series is generally more leucocratic (i.e., higher plagioclase/pyroxene ratio) than the norite series.

Neodymium isotopic evidence indicates that the Offset and Creek Zone magmas were crustally contaminated. ϵ_{Nd} values of 19 analyzed samples range from +0.38 to -3.47 (median = -2.13), which is consistently more negative than the ϵ_{Nd} value of +2.24 expected in an uncontaminated mantle-derived magma that crystallized at 2.69 Ga. The crustal contaminant that imparted the negative ϵ_{Nd} values is unlikely to be the tonalitic gneiss that hosts the SLDIC, as the ϵ_{Nd} value of one reported tonalitic gneiss sample is -1.77 (Brugmann et al., 1997). The lack of correlation between ϵ_{Nd} and geochemical or spatial variations suggests that variable crustal contamination was not the cause of the geochemical variability observed within the Offset and Creek Zones. Samples from both the breccia and norite series have similar trace-element chemistry, including enriched LILE/LREE patterns, flat HREE patterns, and pronounced negative Nb anomalies. Although these characteristics can be caused by assimilation of crustal material, it is more likely that they are the result of formation of the parental magma in a magmatic arc. Evidence for this interpretation includes low Nb/Yb ratios, high Ba/Th ratios, low Th content, and the lack of correlation between geochemical variability and Nd isotopic variability.

Evidence from S isotopes of sulfide minerals and whole-rock geochemistry suggests that the addition of crustal S was not necessary in the formation of the Pd-rich mineralization within the Offset and Creek zones. $\delta^{34}S$ values of 54 crystals from 17 samples range from -0.37‰ to +3.28‰ VCDT

(median = +1.11‰), with values from 52 of 54 crystals falling in the expected range of mantle-derived sulfur ($0 \pm 2\%$; Seal, 2006). Based on the association of low Cu/Pd ratios with high Pd values, Offset and Creek zone ores formed at high R factors, which were likely high enough to cause the PGE enrichment without incorporation of crustal sulfur. The higher degree of Pd enrichment in the Offset Zone compared to the Creek Zone was likely due to a greater amount of sulfide liquid in the Offset Zone that also underwent higher R factors; the distribution of sulfide liquid and magma flow may have been influenced by primary structural constraints on the geometry of the intrusion. No evidence was found for significant low-temperature remobilization of chalcophile elements, including the PGEs.

The compositional variability observed within the breccia and norite domains suggests that both domains formed via multiple pulses of compositionally similar magma. The proximity of mineralization to the interpreted feeder conduits suggests that the distribution of mineralization is largely the result of PGMs/Pd-rich pentlandite crystallizing as the magma transitioned from the feeder structure outwards into the periphery of the intrusive complex. This process may have repeated several times as successive magma pulses infiltrated the partially crystallized intrusive complex, resulting in the redistribution of ores in brecciated zones.

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Slip Kinematics of the Keweenaw and Hancock Faults within the Midcontinent Rift System, Upper Peninsula of Michigan

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The Keweenaw fault is a major compressional structure along the center of the Keweenaw Peninsula and positioned near the southern edge of the Midcontinent Rift System (MRS). The smaller Hancock fault connects with the hanging wall of the Keweenaw fault and, together, the two faults define a thrust slice. The MRS formed ~1.1 billion years ago when a major extensional event split a significant portion of the ancient North American continent across the Upper Midwest. The rifting produced large volumes of basaltic lava, roughly ending with the Portage Lake Volcanics that have an exposed thickness of 3-5 km along the Keweenaw Peninsula (1). A common interpretation of the Keweenaw fault is that it originally formed as a normal fault during MRS extension and then inverted to become a reverse fault during a post-rift compressional event, most likely the Grenville Orogeny (2,3). Another interpretation is that the Keweenaw and Hancock faults are parts of a detached fault system that was initiated during the Grenville Orogeny (4).

Until a few years ago, ideas about these and similar faults in the region considered only dip slip with an either normal or reverse sense of motion. Recent bedrock mapping and measurements of fault-slip lineations, however, have revealed a significant component of right-lateral strike-slip on the Keweenaw fault system near its northeastern end which is about twice the magnitude of north-side-up reverse slip (5, 6). To clarify the slip kinematics of this region we utilized bedrock mapping and fault slip measurements between Hancock and Mohawk, MI to clarify the geometry and slip kinematics of the NE-trending Keweenaw and Hancock faults and to relate their characteristics here to what is observed along the more easterly trending portion of the fault system previously studied (Fig. 1).

Rose diagrams of slickenlines rakes found along the Hancock and Keweenaw Faults show that both faults have roughly equal dip-slip versus strike-slip components (Fig. 2). This bimodal distribution of rake data differs from previous EDMAP projects, possibly due to the overall curvature of the Keweenaw Peninsula. The strike-slip to dip-slip component ratio was 2:1 (Mueller, 2021). The resulting map from this project indicates that the Keweenaw Fault isn't a single fault trace, but instead connected fault segments (Fig. 3) The updated map and cross-section from this project proposes a new model for the Keweenaw Fault system kinematics.

Acknowledgements

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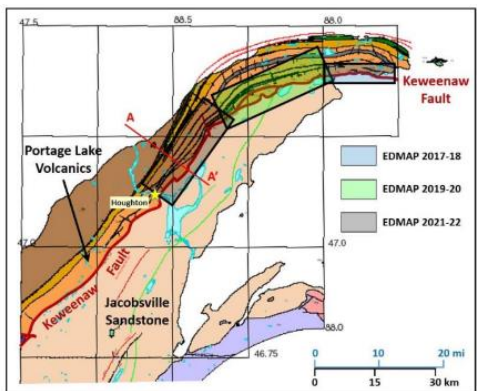


Figure 1. Map showing geology of the Keweenaw Peninsula. The boxes show the areas for the previous and current EDMAP project. (Cannon and Nicholson, 2001).

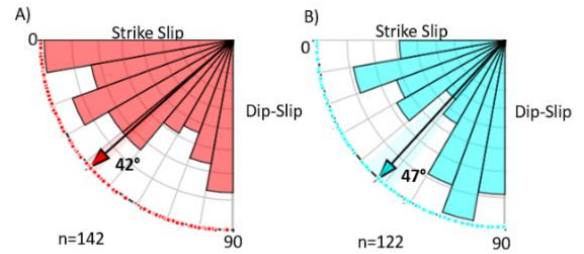


Figure 2. Rake histograms showing the distribution of low and high angle rake on the Keweenaw fault (A) and Hancock fault (B). Arrows indicate mean rake of each dataset.

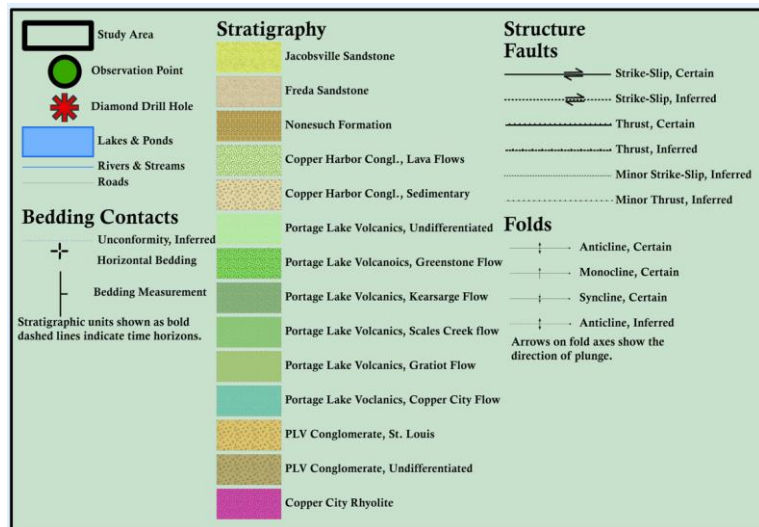


Figure 3. Updated bedrock geologic map and legend of study area.

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Petrology and Geochemistry of the Paleoproterozoic Eau Claire Volcanic Complex, Eau Claire, WI

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The 1.8 Ga Eau Claire Volcanic Complex (ECVC) is located in the northwestern portion of Wisconsin primarily exposed in the Eau Claire River valley. The complex is part of the Marshfield terrane of the Penokean Orogen which developed along the southern margin of the Superior craton (Schulz & Cannon, 2007). Following the accretion of a juvenile ocean island arc, now known as the Pembine-Wausau terrane (PWT), with the southern margin of the Superior craton, opposing subduction zones closed the ocean between the accreted PWT and MT resulting in coeval magmatism on both terranes prior to collision around 1850 Ma. The origin of the MT is uncertain but is believed to be a small Archean craton that is either a rifted fragment of the Superior Province (Zi et al., 2021) or Wyoming Province (Malone et al., 2019). The suture between these terranes is the Eau Claire Shear Zone.

Paleoproterozoic subduction-related volcanism began to develop along MT's northern margin, resulting in arc volcanism and back-arc spreading with associated calc-alkaline felsic magmas (DeMatties, 2022). This volcanism continued until the terrane collided with the subduction trench, resulting in a major compressional event along the Superior craton (Sims et al., 1989; Shultz and Cannon, 2007). This comprehensive interpretation of the tectonic setting fits well with the eastern portion of the MT where rocks are more abundantly exposed. However, the lack of outcrop exposure due to extensive Cambrian sedimentary strata has restricted research and mineral exploration in western parts of the orogen (DeMatties, 2022). This includes the ECVC, which is based on geophysical data, and has high potential for supergene-enriched VMS-style mineralization (DeMatties, 2022).

The main objective of this study is to map and sample volcanic, metamorphic, and intrusive packages of the ECVC exposed along the North Fork of the Eau Claire River (**Figure 1A**) and Chippewa River for whole-rock geochemistry and petrographic analysis. Trace element geochemical data can be used to determine magmatic and tectonic settings of these rocks and improve regional tectonic models for the ECVC and MT. Twenty-four samples were analyzed for major elements via XRF and trace elements via ICPMS. Rock classifications were given in the field, reevaluated during petrographic analysis, and grouped into suites based on geochemistry. The majority of the suites were separated into four main categories: felsic gneiss (**Figure 1B**), mafic gneiss (**Figure 1C**), amphibolite (**Figure 1D**), and granitoid (**Figure 1E**).

Each suite was diagnosed with a tectonic signature using multiple trace element diagrams. Th/Yb versus Nb/Yb displayed geochemical characteristics of deep crustal recycling for the majority of the samples, related to the active subduction that occurred during the advancement of the MT. The only suite that differs from this trend is the amphibolite group, which has a lower Th-Yb-Nb concentration, insinuating magma-crustal interactions with the protolith basalt. A tectonic classification ternary diagram using La-Y-Nb solidified the theory that calc-alkaline arc magmatism dominated the MT region, while the amphibolite suite trends towards a more tholeiitic arc composition. This interpretation is backed by a magmatic affinity diagram as well using Th-Yb-Zr-Y percents.

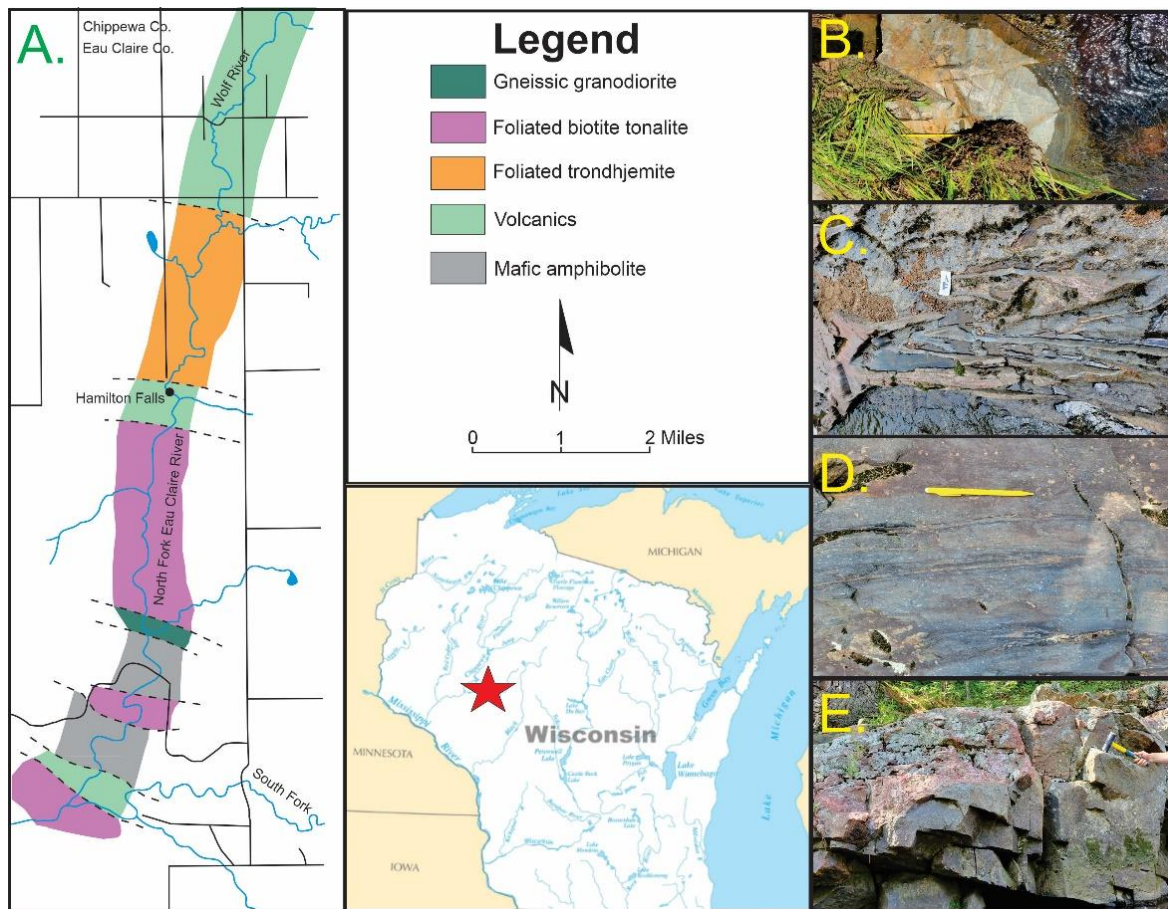


Figure 1. (A) Regional map of the Eau Claire River with the North Fork and relative location in Wisconsin, (B) Poorly exposed bedrock of a felsic gneiss, (C) Isoclinal folded trondhjemite at Hamilton Falls trending east-west, (D) Elongated pipe vesicles on an amphibolite outcrop near Knights Pool, (E) Intrusive contact between pegmatite and amphibolite.

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Structural analysis and slip kinematics of the Keweenaw fault system between Bête Grise Bay and Gratiot Lake, Keweenaw County, Michigan

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The Keweenaw fault is perhaps the most important geologic structure on the Keweenaw Peninsula, with an estimated 7-11 km (1) of reverse slip juxtaposing Cu-bearing volcanic strata of the ~1.1 Ga Portage Lake Volcanics above ~1.0 Ga Jacobsville Sandstone. The fault has been interpreted as a rift-bounding normal fault later inverted by compressional pulses of the Grenville Orogeny (2) and, more recently, as part of a detached thrust fault system unrelated to an earlier normal fault (1). The fault is shown on published maps as a nearly continuous fault trace whose sinuosity implies multiple fault segments and complex slip dynamics. Recent mapping has revealed that the Keweenaw fault at its most northeastern exposure on land is better characterized as a network of interconnected, left-stepping fault segments with easterly strike and exhibiting a 2:1 ratio of dextral strike slip to reverse slip (3).

This project focused on the eastern half of a 2019-2020 EDMAP project (Fig.1) to map the Keweenaw fault system between Bête Grise Bay and Gratiot Lake. New mapping combined with

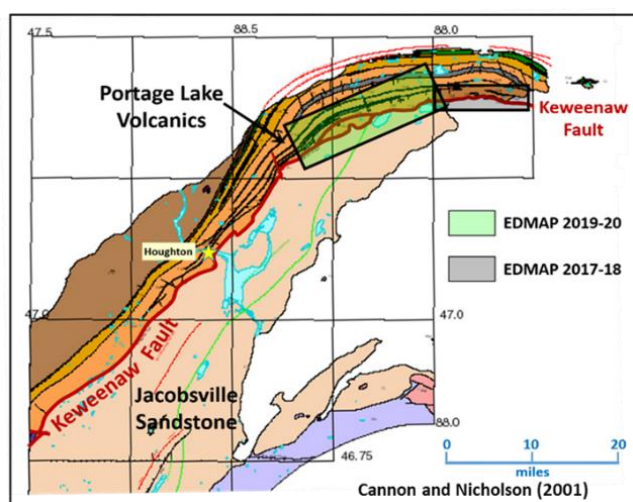


Figure 1. Bedrock geology of the Keweenaw Peninsula (4), showing the 2017-2018 (grey box) and 2019-2020 (green box) EDMAP study areas.

structural and fault-slip analyses produced a revised bedrock geology map (Fig. 2) and a 3D-model (Fig. 3) that better constrain the geometry of the fault system, revealing folds and fault-bounded blocks in the main fault's footwall. Analyses of fault slip data indicates a strike-to-dip slip ratio of 1.7:1 and a local shortening direction of 083°-263°. Slip along faults is a function of their strike relative to the shortening direction. Eastward transport of fault-bounded blocks relative to the distal footwall was facilitated by mostly strike slip on longer EW-trending faults and reverse slip on shorter NE-trending faults, coupled with layer-parallel detachments along weak layer boundaries. The fault network defines a complex multistranded transpressional system with overall dextral strike slip and north-side-up reverse slip. Footwall folds in Jacobsville strata adjacent to mostly strike-slip

faults are considered to be cogenetic drag folds that formed during the Rigolet phase of the Grenville orogeny. These findings are consistent with recent mapping projects adjacent to the study area and investigations that relate far-field compressive pulses of the Grenville Orogeny to deformation of Keweenaw strata.

Acknowledgements

Funding provided by the USGS EDMAP program (Award No. G19AC00140) with a matching contribution from the Department of Geological and Mining Engineering and Sciences, Michigan Technological University and additional support from the Keweenaw Community Forest Company. Sponsored by the Michigan Geological Survey.

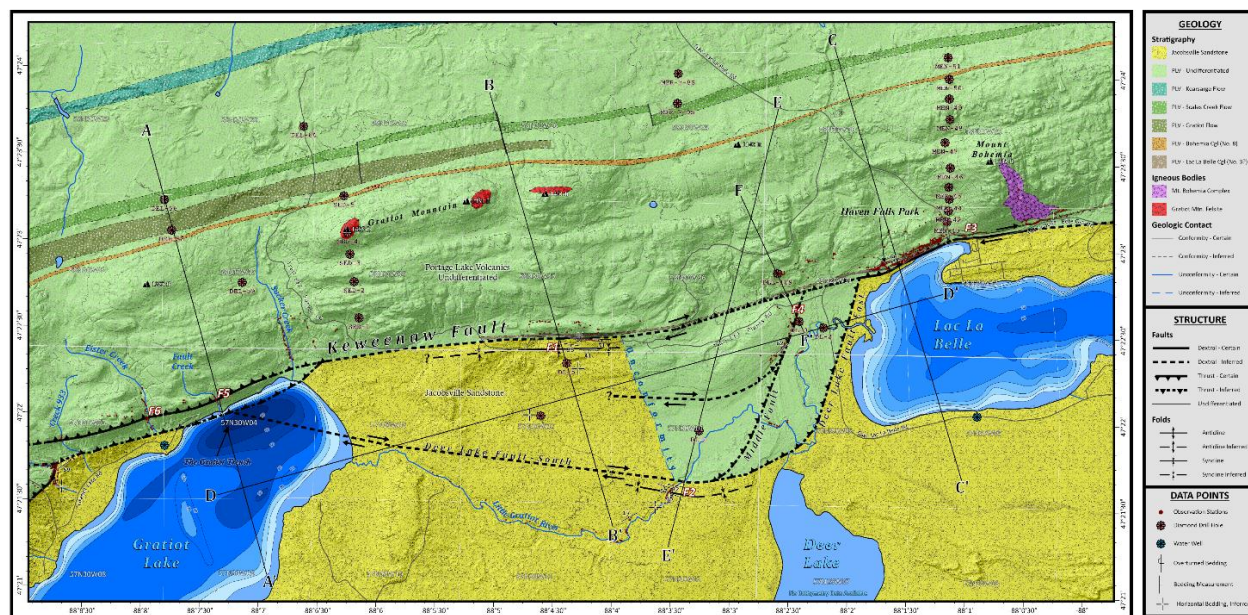


Figure 2. Keweenaw fault system between Lac La Belle and Gratiot Lake. Deer Lake fault block is in the Keweenaw fault's footwall between the lakes. Cross-sections shown by thin black lines labeled A - F.

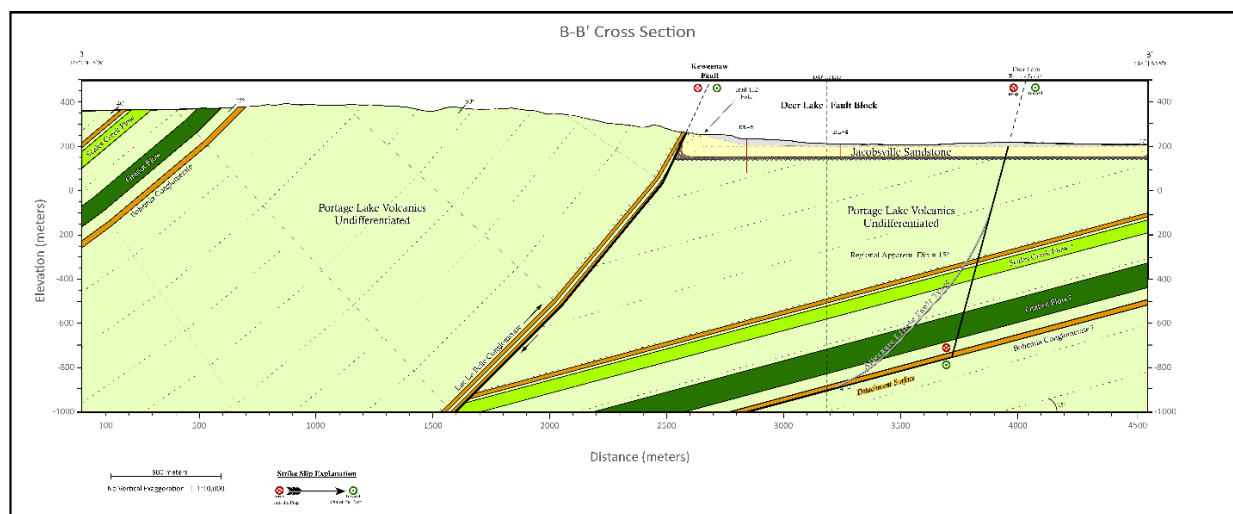


Figure 3. Cross-section B-B' showing modeled hanging-wall and footwall structural and stratal relationships across the Deer Lake fault block.

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Re-evaluating the tectonics and metallogeny of terranes in the Paleoproterozoic Penokean Orogen, Wisconsin

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The tectonic model for the development of the Penokean orogen was synthesized in a classic paper by Schutz and Cannon (2007) that compiled decades of mapping, sedimentology, U/Pb geochronology, and geophysical surveys. The orogen started at ca. 1880 Ma with the accretion of Pembine-Wausau terrane, an oceanic arc complex, onto the margin of the Superior Province. A subduction flip after accretion resulted in overprinting continental arc volcanism and rifting (**Figure 1A**) until the collision of an Archean crustal block, known as the Marshfield terrane, at ca. 1850 Ma. Several undeformed intrusions, interpreted as post-tectonic intrusions, constrain the end of the Penokean orogen at ca. 1835 Ma (**Figure 1B**).

Perhaps the most important event during the orogen was the formation of the ~150 million tonnes of volcanogenic massive sulfide (VMS) deposits in the Pembine-Wausau terrane at ca. 1875 Ma (Sims et al, 1989; Quigley, 2016). This event was widespread across multiple VMS deposits. This presents a clear episode of submarine rifting and was assigned to a period of continental back-arc tectonism by Shultz and Cannon (2007). This is supported by the presence of inherited Archean zircons at the Lynne and Back Forty VMS deposits (Quigley, 2016) indicating the presence of Archean crust during the formation of Pembine-Wausau magmas. However, new U/Pb data has documented a second VMS forming event at ca. 1835 Ma at the Back Forty (Quigley, 2016) and Eisenbrey (Weber and Lodge, 2022) VMS deposits. Recognition of this extensional event has led to an alternate tectonic model wherein back-arc extension reactivated multiple times during ridge subduction (Zi et al., 2021).

One of the principal issues that needs to be resolved with the classic Penokean tectonic model is the regional setting of Penokean VMS mineralization. VMS deposits formed in continental settings have different petrochemical associations than those formed in oceanic settings. New lithogeochemical data from mafic and felsic rocks at several VMS deposits (Flambeau, Eisenbrey, Lynne, Wolf River) suggest that most of the deposits hosted in rocks that are consistent with oceanic settings, while some suggest a continental setting. This suggests that the continental setting for the VMS mineralization does not apply to all deposits and that the extent of Archean basement needs to be better defined.

Zircon petrochronology provides a mechanism to better resolve the nature of continental basement and its influence on metallogeny by providing a link between age of magmatism and tectonic setting and/or crustal inheritance. Once again, some deposits within the Pembine-Wausau terrane provide evidence for Archean basement, while others do not. However, in the process of discovering new ages, we also discovered that VMS forming environments continued until ca. 1835 Ma in a juvenile, oceanic setting. It was also discovered that some of the rocks from the Eau Claire volcanic complex of the Archean Marshfield terrane were mantle-derived, oceanic magmas that were ~1875 Ma with no evidence for Archean inheritance and seems eerily similar magmas from the Pembine-Wausau terrane. While Penokean magmas are known to intrude Archean rocks in the Black River Falls region of Wisconsin (Weber and Lodge, 2022), they clearly show Archean inheritance. As the hunt for domestic critical minerals makes its way to Wisconsin, the Penokean terranes and their metallogenic setting needs to be re-evaluated.

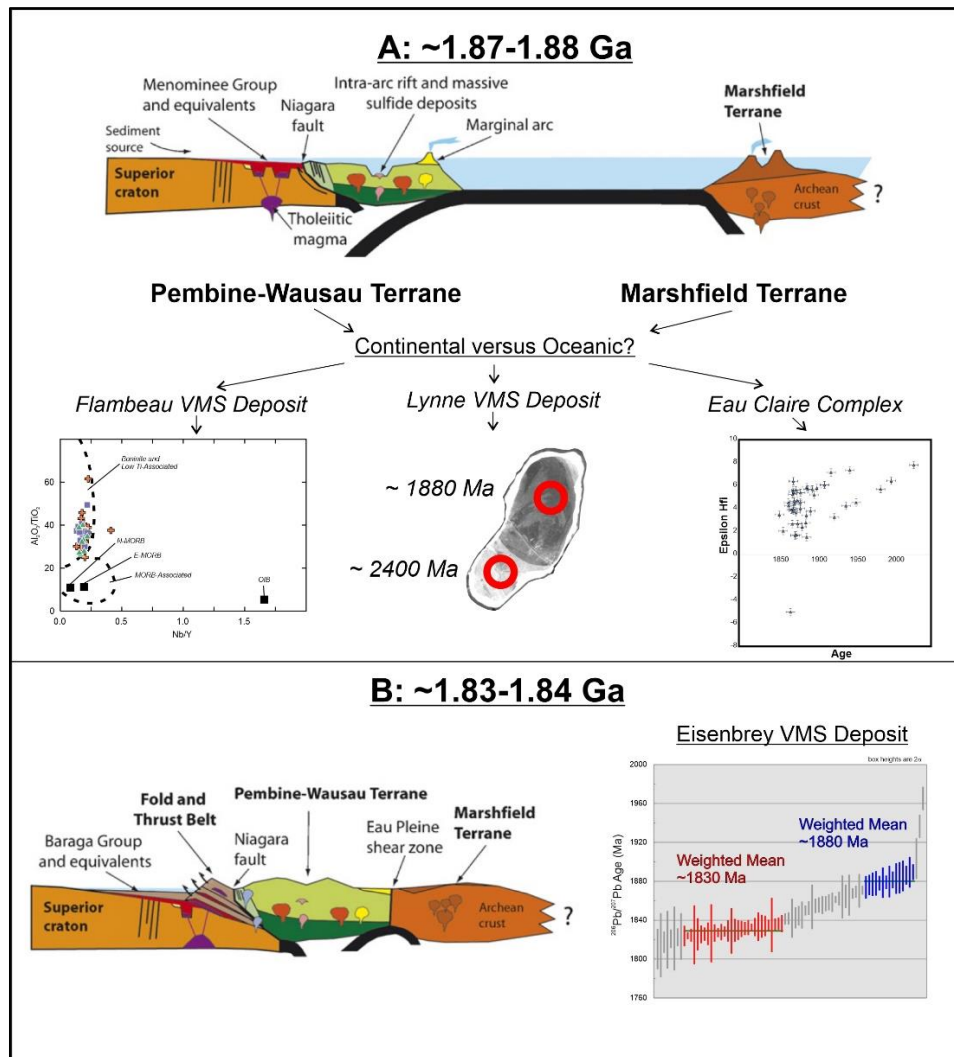


Figure 2. Illustration of tectonic models proposed by Shultz and Cannon (2007) and various new petrochemical or zircon petrochronology datasets that highlight some inconsistencies in the model.

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3D geologic mapping at the Wisconsin Geological and Natural History Survey

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The Wisconsin Geological and Natural History Survey has constructed a preliminary 14-county 3-D geologic data model across southern Wisconsin. The model was constructed primarily from well construction reports (WCRs) that have been refined for several WGNHS projects, as well as data from the Mineral Development Atlas, borehole geophysics, and data from previous mapping performed at various scales.

Well Construction Reports (WCRs) from digital and analog sources were assembled in a GIS geodatabase. The land surface elevation for each well was extracted from a DEM, and the elevation was then used to “hang” each well’s downhole lithology. By displaying and exaggerating the data in 3D, the different lithologies were carefully selected and assigned to geologic formations. Prior to interpolation, statistical outliers were identified, inspected, and edited when appropriate. The elevation for each formation contact was used to interpolate a raster. The resultant raster was inspected to identify obvious outliers, and after the outliers were edited or removed, a “final” raster of each contact was generated. The formation contact rasters can be intersected with a bedrock elevation raster to produce a geologic map. New data can be added to the model when available, and a new updated map can be generated.

The products derived from this type of 3D geologic modelling are useful to the public in many applications. Harmful minerals or metals dissolved in groundwater are a realistic concern in Wisconsin, and determining the geologic formation in which a well terminates can help to avoid or resolve water quality issues. 3D geologic modeling can help to inform decision making about land use and land practices, land conservation, zoning and planning, identification of natural hazards, and the construction & engineering of wells, roads, railways, and buildings.

Secular Changes in the Magnitude of Terrestrial Weathering

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In a recent investigation of paleosols in the Lake Superior region, the magnitudes of weathering in six Proterozoic paleosols were found to be less than those in four Phanerozoic paleosols and four modern soils (Medaris et al., 2022). However, in view of this relatively small database, the apparent age distinction in the magnitudes of weathering might be spurious, and thus we have expanded the database to test the veracity of secular changes in the magnitude of terrestrial weathering. Twenty-one first-cycle paleosols in igneous and metaigneous rocks with well-characterized and relatively homogenous protolith compositions were selected for comparison. These paleosols occur world-wide, vary in age from 100 Ma to 2960 Ma, and have protolith compositions ranging from gabbro to granite. This expanded database confirms that the magnitude of weathering in Phanerozoic paleosols and modern soils is greater than that in Precambrian paleosols.

Potassium metasomatism is a common phenomenon in paleosols (Rye and Holland, 1998), and among the 17 Cambrian and Precambrian paleosols investigated here, 14 experienced potassium metasomatism, which is recorded by the presence of neoblastic muscovite, illite, or microcline. The effect of such K-metasomatism is illustrated in a plot of $\text{Al}_2\text{O}_3\text{-(CaO*+Na}_2\text{O)-K}_2\text{O}$, where compositional trends for modern soils and unmetasomatized paleosols are oriented subparallel to the A-C*N join (Fig. 1A), and those for K-metasomatized paleosols are rotated towards the K apex (Fig. 1B).

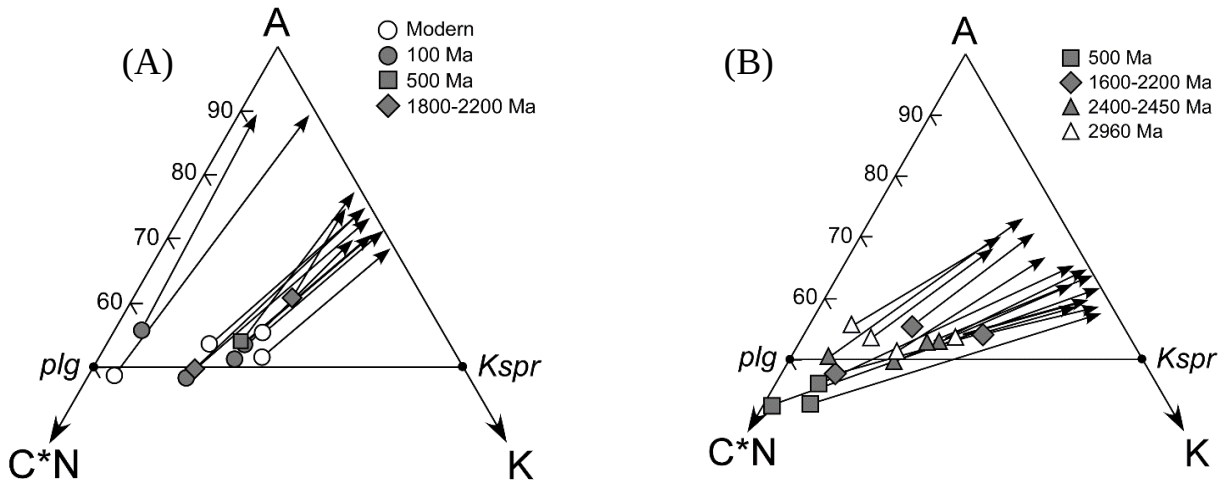


Figure 1. Protolith compositions and paleosol trends in the system, $\text{Al}_2\text{O}_3\text{-(CaO*+Na}_2\text{O)-K}_2\text{O}$. A: Modern soils and paleosols without K-metasomatism; B: Paleosols with K-metasomatism.

In K-metasomatized paleosols, the amount of K_2O removed by weathering is unknown, but may be estimated by comparison to an average for the depth variations of K_2O and Na_2O in modern soils, for which:

$$(\% \text{ change } \text{K}_2\text{O}) / (\% \text{ change } \text{Na}_2\text{O}) = -1.40z^3 + 0.95z^2 - 0.31z + 0.75$$

where z is normalized depth. Following this approach, the removal of K_2O is estimated to be $47 \pm 4\%$ for the combined Cambrian and Precambrian paleosols and observed to be $54 \pm 21\%$ for the Cretaceous paleosols and $47 \pm 21\%$ for modern soils (Fig. 2A). Interestingly, no correlation exists between the percentage of K_2O removed and age (or protolith composition; not shown). In contrast, the total

addition of K₂O to the weathered profiles, expressed in terms of Depth-Normalized Mass Flux, progressively increases with decreasing age, *i.e.* 0.74 ± 0.29 at 2960 Ma, 0.96 ± 0.18 at 2450 Ma, 1.04 ± 0.52 at 1600-2200 Ma, and 1.62 ± 0.36 at 500 Ma (Fig. 2B).

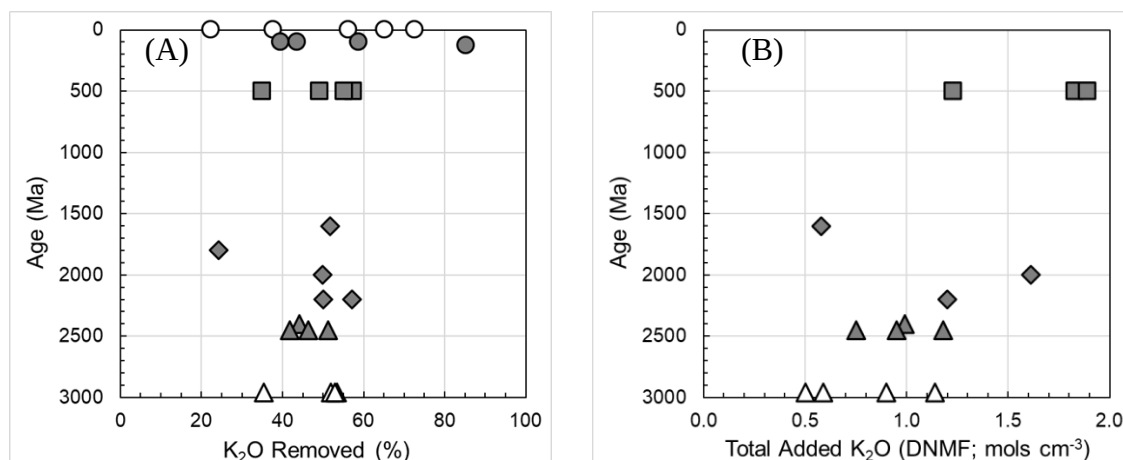


Figure 2. A: Percentages of K₂O removed from soils and paleosols;
B: Total K₂O added to paleosols, expressed as Depth-Normalized Mass Flux (DNMF).

The percentage removal by weathering for the sum of SiO₂, CaO, Na₂O, and K₂O_(est or meas) progressively increases from Archean ($17.3 \pm 1.5\%$) to Proterozoic ($21.0 \pm 3.7\%$) to Cambrian ($25.1 \pm 3.1\%$) to Cretaceous ($37.1 \pm 10.8\%$) paleosols. In comparison, the percentage of mass removed from five modern soils is $36.0 \pm 3.7\%$, which lies within the values for the Cretaceous paleosols. We suggest that the greater magnitude of weathering in Phanerozoic soils compared to Proterozoic ones is due to higher concentrations of organic acids during Phanerozoic soil formation, which resulted from the emergence of sparse cryptophytes in biological soil crusts in Cambrian time and subsequent greening of the continents with vascular plants from Devonian time to the present.

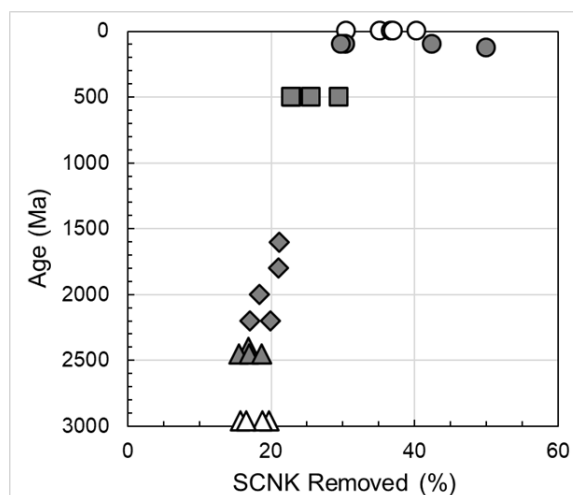


Figure 3. Percentages of the total mass of SiO₂, CaO, Na₂O, and K₂O removed from modern soils and paleosols.

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Morphometry and formation process of eskers developed under the Chippewa Lobe of the Laurentide Ice Sheet

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Eskers are an important indicator of paleo subglacial hydrologic conditions and a good alternative to direct glaciological observations because they are one of the few landforms that record those processes. Esker morphology and sedimentology is useful to gain insight into how sediment transport relates to subglacial hydrology along channels, which in consequence provides understanding on ice dynamics. However, large discrepancies in the formation mechanisms of eskers still exist and there are even fewer attempts to investigate the influence of soft bed conditions on this process. To address this, we analyzed the morphometry and distribution of eskers formed under the Chippewa Lobe of the Laurentide Ice Sheet (Figure 1). This includes mapping the sinuosity and spatial distribution with 2m resolution LiDAR, comparing these to sediment thickness derived from a water well data base, and examining the sediment sequence of one large esker exposed to sand and gravel extraction (~20 m tall) (Figure 2).

The LiDAR analysis revealed a direct relation between sinuosity and length of eskers formed in soft bed conditions, with a mean of 1.07 that is very similar to eskers formed under hard bed conditions. Eskers spacing over the soft bed of the Chippewa Lobe appear closer than over hard beds in Canada (e.g Storrar et al, 2014). The spacing of eskers decrease when the ice margin retreats, meaning that melt rates increase (Boulton et al, 2009; Hewitt, 2011). Moreover, the relation between the distribution of eskers and till thickness indicates that eskers formed preferentially over thin layers of sediment, specifically near 18 meters for the Chippewa Lobe. The results from the grain size distribution of the large esker showed that the critical shear stress changed nonmonotonically throughout the formation of the esker. As such, we can assume that the water velocity or depth of the channel likely changed sporadically with time while the esker formed.

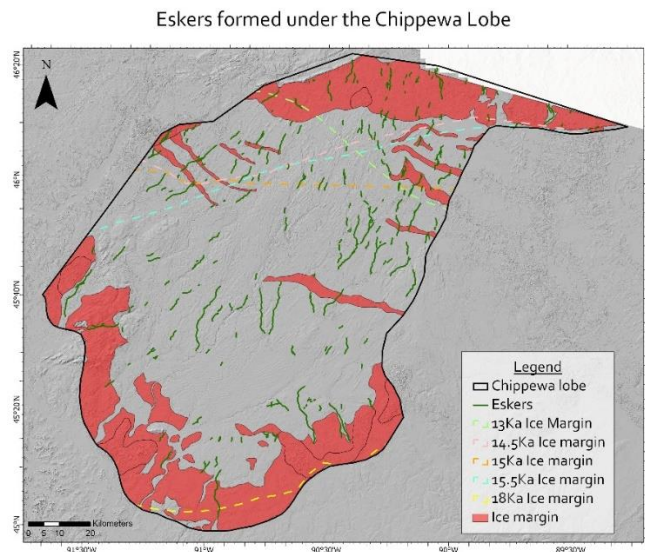


Figure 1. Distribution of eskers formed under the Chippewa Lobe during the Last Ice Age.

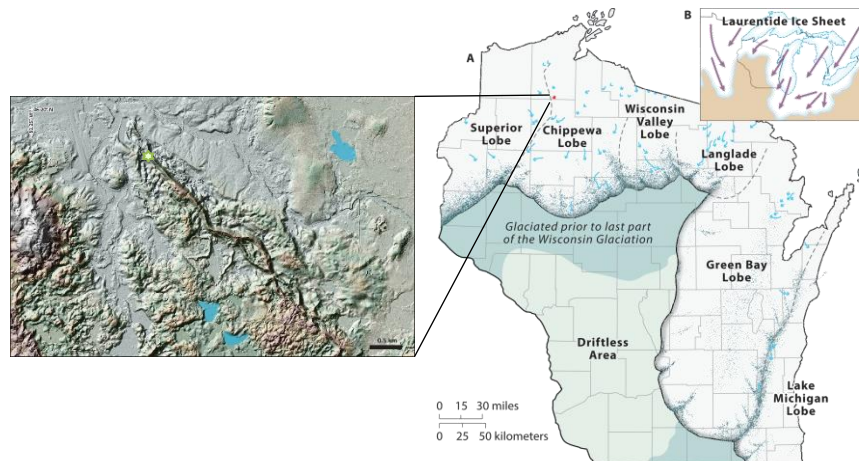


Figure 2. Location of the selected esker for sediment analysis. The yellow star shows the location of a pit where the samples were extracted for the analysis.

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Subsurface characterization of the Duluth Complex and related intrusions from 3D modeling of gravity and magnetotelluric data

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The Mesoproterozoic Duluth Complex and related intrusions in northeastern Minnesota make up the second largest exposed mafic intrusive complex in the world, second only to the Bushveld Complex in Africa. It is one of the major plutonic components of the Midcontinent Rift System and hosts a variety of copper-nickel sulfide and platinum-group-element deposits. Given the complex geology of the area, 3D modeling is necessary to provide a complete picture of the variable densities and geometries of intrusive suites throughout the Duluth Complex as well as their extent at depth.

In this study, we use Bouguer gravity data collected over the past ~60 years and magnetotelluric data collected in 2019 to create new 3D models of density, resistivity, and subsurface structure of the region constrained by geologic data. We use the results of these models to calculate the total volume of the Beaver Bay Complex, Duluth Complex, and onshore North Shore Volcanic Group, and estimate preliminary intrusion and emplacement rates using age estimates from Swanson-Hysell et al. (2021).

We model both thickness and density of intrusive and volcanic rocks in the region using Oasis GMSYS-3D. The igneous layer in our starting model is 11 km thick with a constant density of 2,941 kg/m³. Other surfaces in the model include topography, near surface glacial deposits, a high-density lower crustal layer, and the base of the crust. We start our inversion by allowing the basal surface of the igneous units to vary and then invert for density within the igneous layer, within a range of 2,630-3,180 kg/m³. Our gravity modeling indicates that intrusive and volcanic rocks reach a maximum thickness ~23 km, or half the crustal column, with densities ranging from ~2,730-3,030 kg/m³ and a mean density of 2,940 kg/m³. The thickest, highest density areas of the model are beneath the Beaver Bay Complex and other mapped diabase intrusions. We interpret the two thickest areas in our gravity model as feeder zones for the Beaver Bay intrusive complex and possibly also for the Duluth Complex, in-line with interpretations arising from previous gravity studies in the area (Allen, 1994; Miller et al., 2002).

Preliminary volume estimates from 3D gravity modeling indicate the present-day Duluth Complex, Beaver Bay Complex, and onshore volcanic rocks constitute ~92,100 km³ of igneous material. We calculate the volume of separate mapped units by extending the mapped geologic boundaries at the surface to depth within our 3D model. Three major geologic groups each comprise ~30% of this total volume: 1) the North Shore Volcanic Group, 2) diabase units of the Beaver Bay Complex and intrusions to the northeast and southwest of it, and 3) the Duluth Complex Layered and Anorthositic series. The older Early gabbro series and Felsic series of the Duluth Complex make up the remaining ~10% volume. ²⁰⁶Pb/²³⁸U zircon ages for the Anorthositic and Layered series from Swanson-Hysell et al. (2021) indicate that rocks of these units were emplaced contemporaneously over a period of 500,000 ± 260,000 years, suggesting an emplacement rate of ~0.06 km³/year, assuming a constant rate on magma input.

Using recently acquired magnetotelluric data, we invert for resistivity in the study area using ModEM (Kelbert et al., 2014). Our magnetotelluric model highlights an arcuate low resistivity anomaly at depths of ~9-20 km, westwardly adjacent to the high-density and high resistivity feeder zones (Figure 1). This anomaly may represent a plane of weakness along which magma intruded to form the Beaver Bay Complex and the Duluth Complex. Low resistivities in this case would be attributed to sulfide or graphitic mineralization that developed along the contact between intruding magma and country rock. These resistivities are also similar to values observed in the Paleoproterozoic metasedimentary rocks of the Animikie Basin, located to the southwest of the Duluth Complex. The

spatial and temporal relationship between the Animikie Basin and Duluth Complex raises a tantalizing hypothesis that the basin structure may have preferentially localized magma intrusion. If this was the case, entrainment of conductive metasedimentary rocks of the Animikie Group along a pre-existing fault could also explain the arcuate low resistivity anomaly observed adjacent to the highly resistive feeder zones.

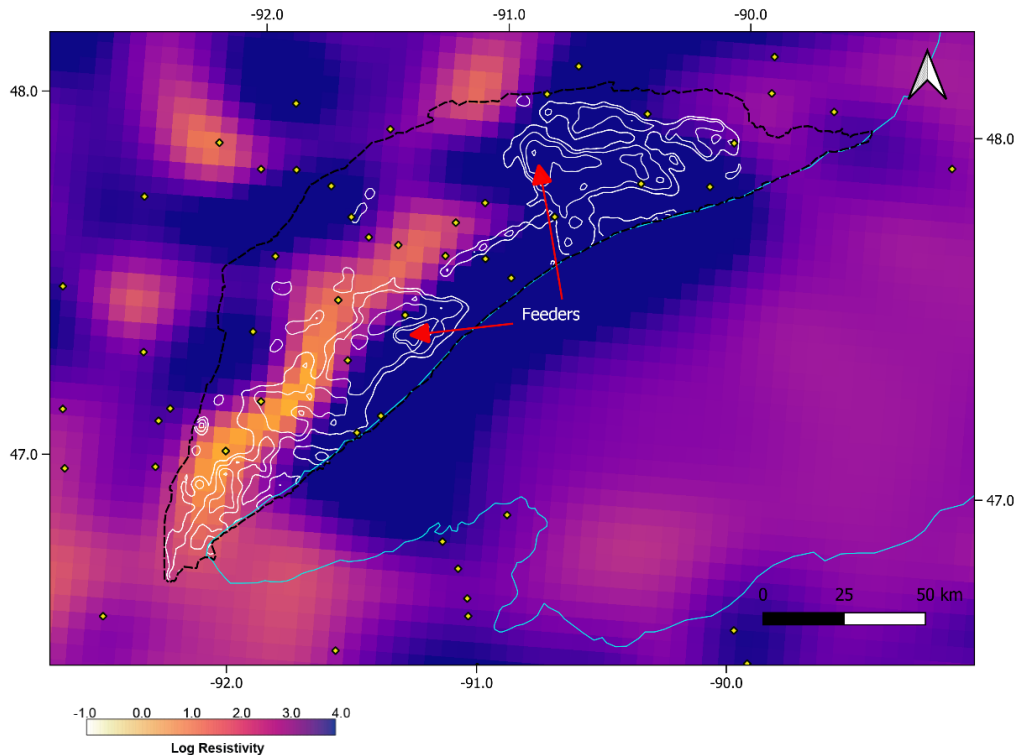


Figure 1. Depth slice through the 3D magnetotelluric resistivity model at ~14 km depth. Black dashed line is the surface extent of the Duluth Complex and related intrusive and volcanic rocks. White lines are 5 km contours of Duluth Complex thickness extracted from our gravity model, starting from 10 km. Cyan line is the outline of Lake Superior.

Acknowledgements

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. government.

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On the Importance of Geologic Maps for Mineral Exploration

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The basis for most types of geologic investigations is fundamentally rooted in geologists' observations and interpretations made of landscapes, exposed rocks, and surficial materials in their natural habitat: "in the field". Coherent geologic maps, which may take many years to create, represent assembled collections of observations in context of space and geologic time, requiring teams of geologists who are usually employed by federal or state/province geological surveys. The outcomes of these concerted efforts in the field are published geologic maps at various scales. It is these works of publicly funded geologic mapping that form the foundation upon which mineral exploration programs and mineral resource developments are built (Figure 1). These early endeavors are key components in national goals to define domestic resources of critical minerals.

In decades past, many university geology students in the USA (including the author) were employed as summer interns assisting geological survey geologists in the bedrock geologic mapping of 1:24,000 scale quadrangles. This type of early professional experience can have profound implications for the careers of these students. Student knowledge gained includes the understanding of what it takes to systematically map bedrock exposures and structural zones, categorize the various rock types into lithologic map units, write out detailed descriptions of these map units, generate geologic cross sections and correlation diagrams, and putting all of these components together into a map that the geologic survey will subsequently publish.

In today's mineral industry, geologic maps are largely digital compilations of publicly available regional/district scale GIS data (downloaded and/or digitized from geological survey websites) merged/overlain with detailed industry geologic mapping of prospects and/or project areas. For the most part, the mineral industry quickly compiles digital data into geologic databases and is seemingly always searching for new ways to quickly capture data in the field digitally. The ease with which the mineral industry can generate digital geologic map products today can be good, bad, or ugly. The state of such geologic map outcomes by industry entities rests largely on the knowledge and experience of the company geologists.

The US Geological Survey's (USGS) Earth Mapping Resources Initiative (Earth MRI) program is a partnership of the USGS, the Association of American State Geologists (AASG) and other governmental, Tribal, and private-sector entities to update the nation's surface and subsurface mapping to improve our knowledge of the geologic framework in the United States and to identify areas that may have the potential to contain undiscovered critical mineral resources. In November 2021, the US government passed the Infrastructure Investment and Jobs Act, one outcome of which is an investment of \$320 million into Earth MRI to develop a better understanding of sustainable mineral production and mine waste options. An industry appeal to Earth MRI programs is to reinvigorate the education of future professional geologists by employing hundreds of geology student interns in upcoming geologic mapping projects.

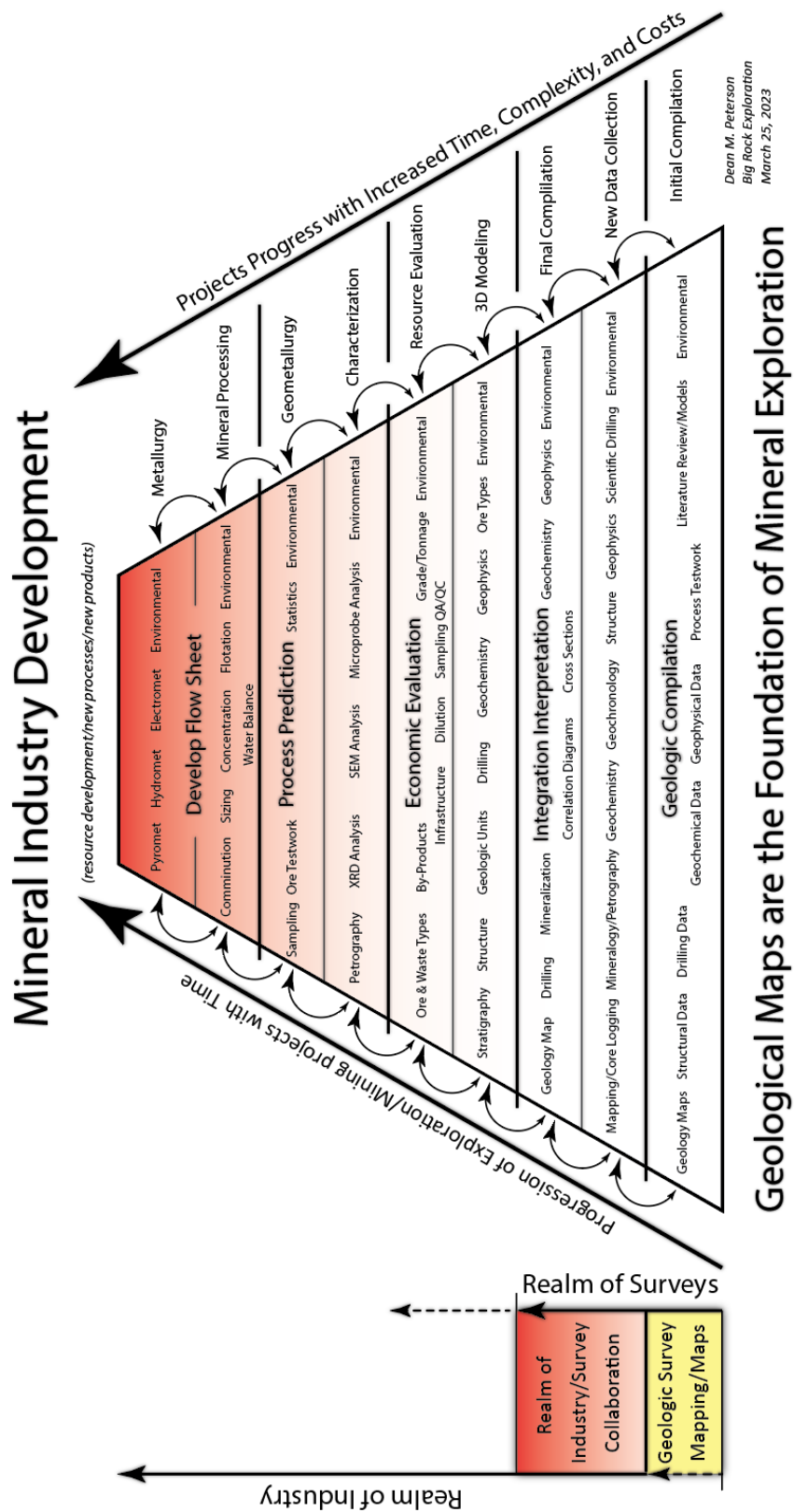


Figure 1. The mineral development trapezoid.

Fault zone architecture in mafic protoliths at the Lac des Iles mine, northwestern Ontario

PETERZON, Jordan¹, PHILLIPS, Noah¹, HOLLINGS, Peter¹, DJON, Lionnel²

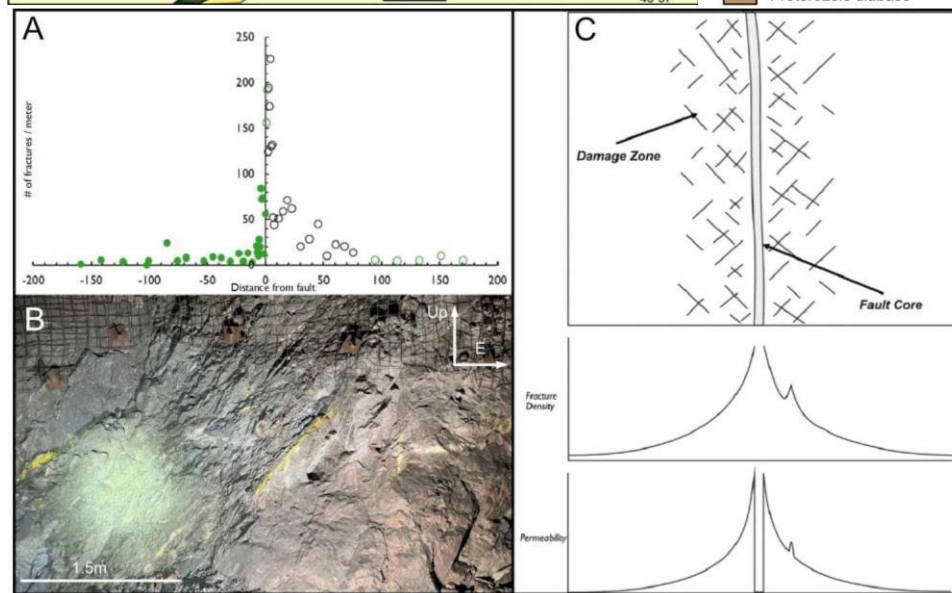
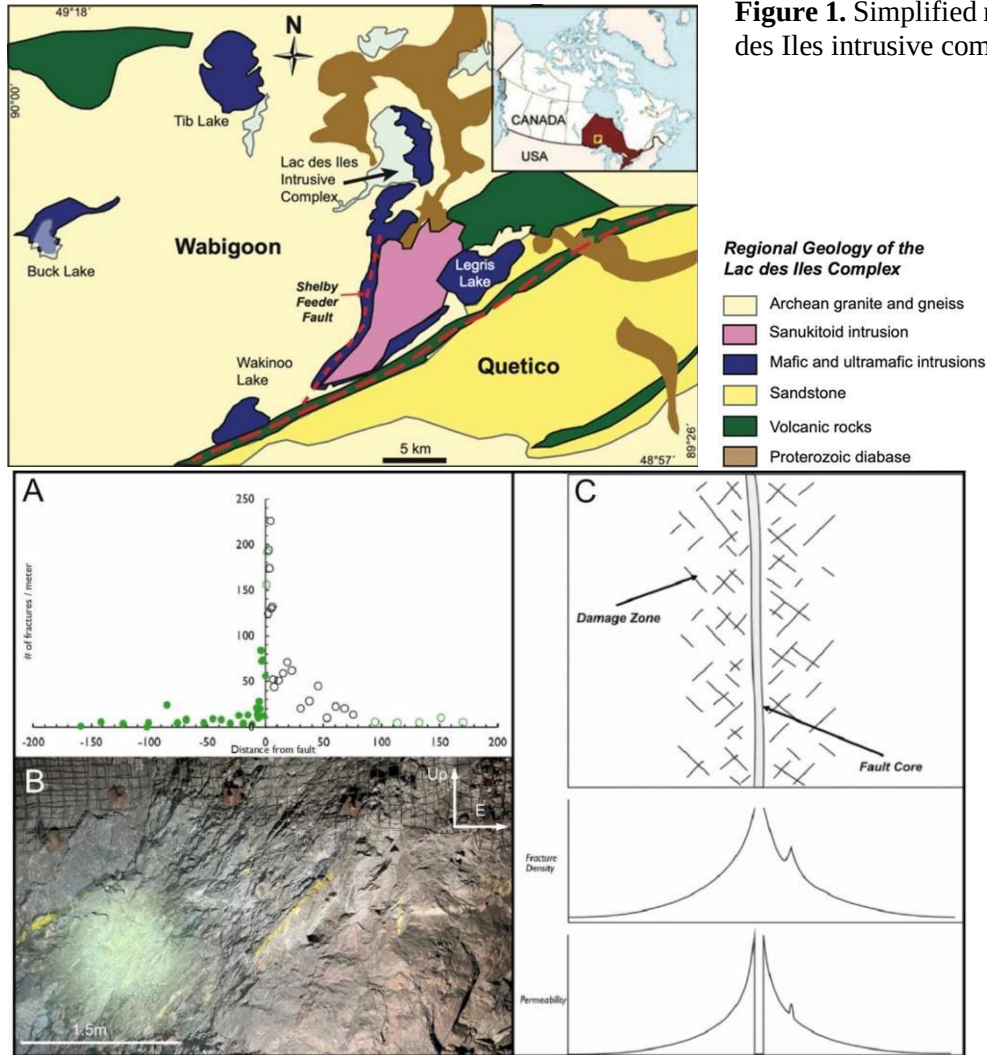
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Faults are important geologic structures that host earthquakes and serve as permeable pathways through the upper crust. From an economic perspective, faults may transport and trap mineralized fluids. In turn, trapped mineralization may be offset or remobilized by later faulting. Fault zones are complex structures that produce an array of fault rock fabrics and architectures. Fault zone architecture typically consists of three components: 1) a fault core where most of the slip has been accommodated, 2) a damage zone bounding the fault core where fracture density increases with proximity to the fault core, and 3) an undeformed and less altered protolith. (Faulkner et al., 2010). Permeability is significantly enhanced in damage zones due to the high density of fractures and is diminished in fault cores due to the presence of clay-rich fault gouges. Faults may therefore act as conduits or barriers for fluid flow depending on the proportion of fault core to damage zone (*i.e.*, the fault zone architecture; Caine et al., 1996). Fault zone architecture has been well studied in felsic to intermediate protoliths but studies on mafic protoliths are lacking. Here, we examine late faults within the mafic Lac des Iles complex to characterize fault zone architecture in mafic protoliths.

The Lac des Iles complex is a series of mafic-ultramafic intrusive bodies occurring within the Marmion terrane of the Superior Province. The complex has been dated at 2689 ± 1.0 Ma and was emplaced into a $\sim 3.01 - \sim 2.68$ Ga granite-greenstone terrane (Djon et al., 2018). The Lac des Iles mine, owned and operated by Impala Canada, is a working Pt-Pd mine which is classified as a structurally controlled magmatic sulfide deposit. Extensive Ni-Cu-PGE mineralization has been offset by two late reverse faults in the high-grade zones (>4 g/t Pd): the Camp Lake fault and the Offset fault. A depletion in Pt-Pd mineralization is observed surrounding the late Camp Lake fault which extends ~ 180 m into the hanging wall and ~ 145 m into the footwall.

Five drill holes that cross the late faults were logged and sampled in detail, with a fracture density counting program conducted systematically in the hanging wall and footwall. Fracture density increases as a power law function with proximity to the fault core and correlates with alteration. Tonalite has a higher fracture density and fracture density decay rate than gabbro near the fault. Fracture density and hematite/epidote alteration are more intense in the damage zone when faults cut through tonalite than when faults cut through gabbro. Fault cores in tonalite display a range of textures, from chlorite-rich gouges to fault breccias with calcitic matrix, while fault cores in gabbro only display chlorite-rich gouges. In this study, felsic protoliths have a higher fracture density than mafic protoliths indicating that fluid flow was more effective in felsic protoliths which may have contributed to depleted mineralization. This implies that host rock lithology strongly affects fault zone structure, including alteration assemblages, fracture densities, and permeabilities.



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Mobile geologic mapping at the Wisconsin Geological and Natural History Survey

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The Wisconsin Geological and Natural History Survey (WGNHS) currently collects and analyzes data using a number of mobile applications for different purposes. Field data collection has become a tool for collection of new data and the verification of existing data. It has allowed the survey to create an automated pipeline to capture photos, notes, as well as record location information into one central location for a respective project. We had 4 objectives to implement while incorporating mobile applications. The application had to be 1) easy to use, 2) efficient, 3) easy to update, and 4) capable of displaying many datasets in the field.

At the WGNHS we utilize mobile field applications for the collection of new data and the verification of existing map data. A mobile field application has the advantage of making many different data sets available to the user in the field within the flexible scale of a mobile GIS application. The incorporation of other mobile applications (FieldMove Clino) for data collection can increase efficiencies and are a vital to aid interpretations. Mobile field applications allow for field reconnaissance from almost anywhere.

When considering a large project with a lot of data, increasing efficiency in field mapping techniques without compromising quality is important. Automating much of the data collection and data transfer eliminates the need for individuals to spend time cataloging digital pictures, copying field notes, and uploading field data. It's a great advantage to be able to easily update or add additional map layers and data, and to see the data already collected. A visual display of data collection progress is useful in time management and project planning. The ease of which an application can be updated consumes time and affects project budget. Ease of use is also important, Accessibility and technical expertise should not be barriers to data collection. The ease of use of a mapping application has positive impacts the project participants, the project budget, and the project output.

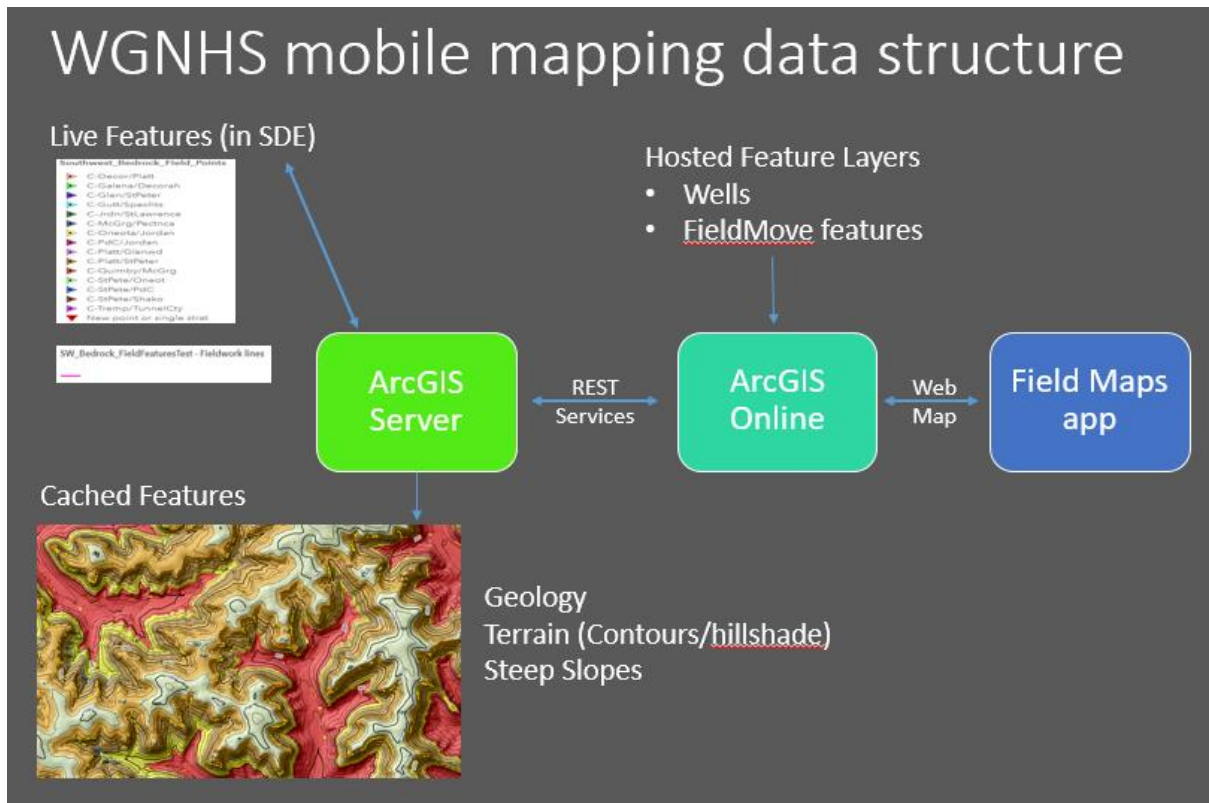


Figure 1. Diagram of the flow of geologic data from the source to and from the mobile application. Managing the data allows for customization of the functionality and the display of the data.

Quaternary Geology of Wisconsin at a scale of 1:500,000 (in review)

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In 2023 the Wisconsin Geological and Natural History Survey staff expect to publish a new statewide compilation map of Quaternary geology at a scale of 1:500,000. A preliminary version is presented here by the principal cartographer. Pre-existing statewide coverages of the surficial geology are limited to Chamberlin's 1881 map of Quaternary formations and Hadley and Pelham's 1976 map of glacial deposits at 1:500,000, which differentiates only six map units. No modern compilation of the surficial geology of the state at a scale of 1:500,000 or larger has been completed before.

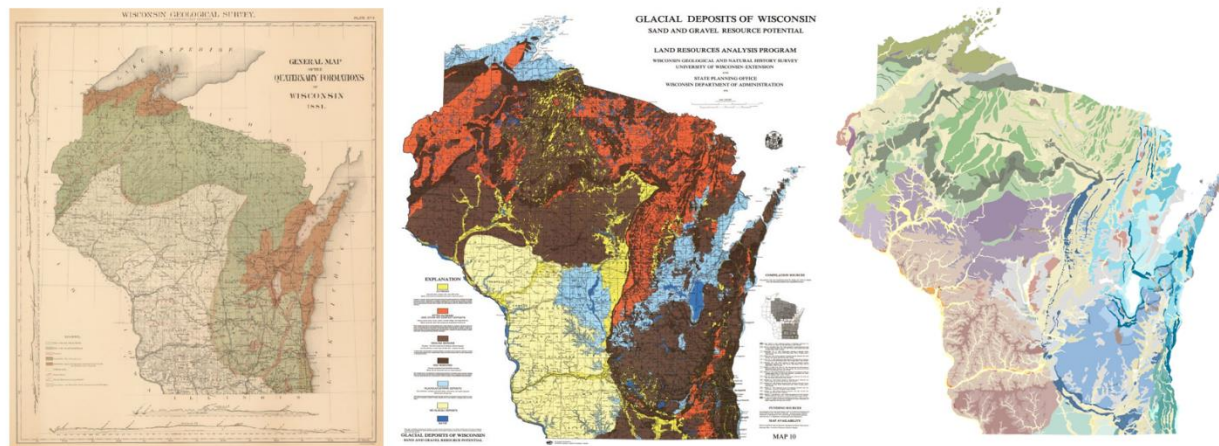


Figure 1. Statewide Quaternary geologic mapping in Wisconsin: Left: Chamberlin's 1881 "Quaternary Formations of Wisconsin". Center: Hadley and Pelham's 1976 "Glacial Deposits of Wisconsin". Right: Draft polygons of 1:500,000 scale surficial geologic map being compiled by WGNHS geologists.

This effort began in 2019 due to a one-time funding opportunity from the US Geological Survey's National Cooperative Geologic Mapping Program. Authors compiled previous mapping at 1:100,000 scale for 44 of Wisconsin's 72 counties, along with partial mapping at the 1:100,000 scale and/or mapping at the 1:250,000 scale for 13 additional counties. Some areas had no prior mapping available at detailed scales. New map units have been developed for the 1:500,000 scale and are divided into glacial and nonglacial sediment that is characterized by lithology and subdivided by geomorphology. Glacial deposits are mapped at the formation level following the WGNHS Lexicon of Pleistocene Stratigraphic Units. We use color hue to differentiate among the various glacial formations by source areas with green groupings derived from the Superior basin, blue groupings from the

Michigan basin. We assign the darkest colors to the strings of moraines and hummocky till marking the extent of glacial lobes of the most recent Wisconsin Glaciation.

Nonglacial Quaternary units are generally shown in warm colors, including modern alluvium, colluvium, lake deposits, and meltwater stream deposits, with small pockets of terraces which are highlighted along major river valleys. The Driftless Area in southwestern Wisconsin shows the dendritic patterns of eroding colluvium along branching alluvial tributaries with windblown silt on the uplands. Some large deposits of organic sediment and areas of exposed or thinly covered bedrock are included at this scale.

This map layout is being produced entirely in ArcGIS Pro, which is a relatively new layout process for our office. We are organizing the GIS data according to the USGS standard Geologic Map Schema (“GeMS”), and we make use of this data structure to draw the unit description text in the Explanation of Map Units (legend) directly from a table in the geodatabase using a dynamic text element. This saves us from the extra work of synchronizing the layout text with the database text. Although ArcGIS Pro does not natively offer an easy solution for geologic map legends, we have been able to find a series of work-arounds to achieve the desired legend layout.

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Tips from a GIS Specialist: Moving maps to GeMS, and a utility for georeferencing quadrangles

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The USGS has recently been requiring that geologic mapping deliverables use their new standard database format, called the Geologic Map Schema, or “GeMS.” The Wisconsin Geological and Natural History Survey (WGNHS) began converting geologic maps into the GeMS format four years ago. I will offer a brief overview of GeMS and will use the GIS data for the Geology of LaCrosse County map (available for download on our website) to demonstrate how GeMS captures the components of a geologic map in geodatabase format. We have created several documents to facilitate the process of migrating maps into GeMS, and we have made them available in this Github repository: <https://github.com/wgnhs/gems>.

My advice to anyone beginning this process is to first consult our “Workflow Overview” document for a high-level summary of the steps. When completing the GeMS-specified attributes, the “Quick-Reference Sheets” are a convenient arrangement of the GeMS documentation, with each layer or table printed on a separate reference sheet, to put focus on one layer or table at a time. To help verify that a GeMS database is complete, the “GeMS Fields Checklist” is designed to help in confirming completion of GeMS attributes.

Two of our documents address the process of authoring metadata for a GeMS geodatabase. The document titled “Metadata For GeMS Maps - Step by Step in ArcCatalog” is a guide to starting FGDC metadata in ArcCatalog before using the USGS-provided metadata script. The “Metadata Summary for GeMS Fields” is a reference to show where GeMS attributes appear in the FGDC metadata, as produced by the metadata script.

All of these documents are housed on our github page, along with other resources such as python scripts and slides from various presentations. We are making it a priority to share these with other GeMS users; we hope these resources are useful to other organizations working through the process of converting maps into GeMS.

I will also briefly summarize how we have involved the GeMS format in our map layouts in ArcGIS Pro by drawing from the Description of Map Units table to automatically lay out the legend using Dynamic Text elements.

In the second half of this talk, I will give an overview of a semi-automated utility for georeferencing maps, especially USGS quadrangles. The software is called QuadG+ and was developed by USGS and University of Wisconsin collaborators to build the Historical Topographic Map Collection. It is available for free download at <https://geography.wisc.edu/quad-g/> and has proven useful to Wisconsin survey staff for georeferencing maps with field notes.

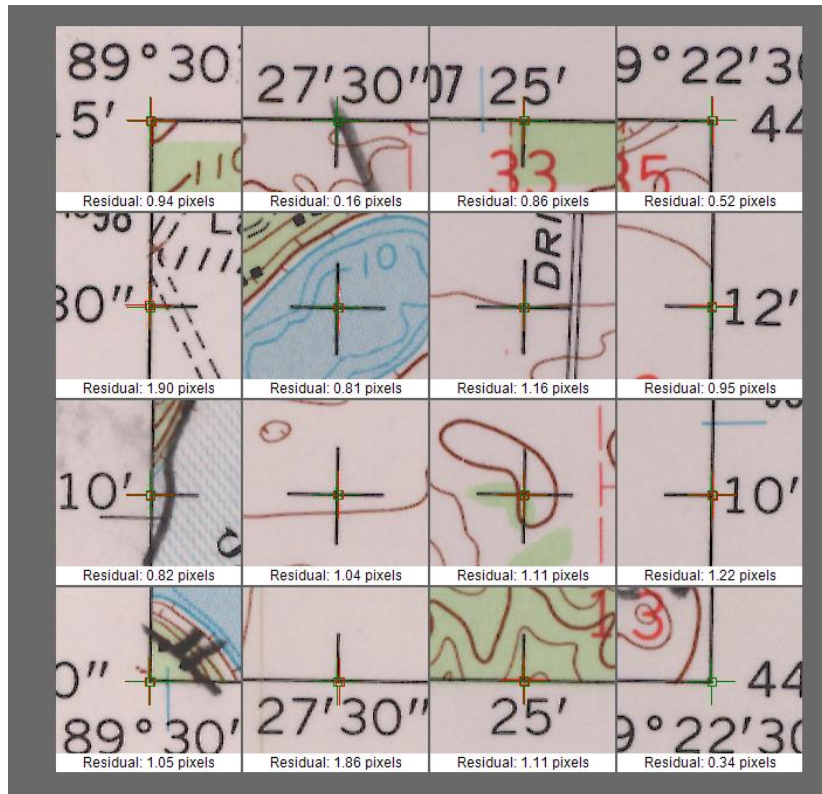


Figure 1. The free software QuadG+ automatically detects the corners and other control marks in a scan of a USGS quadrangle

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New work developing Keweenaw geoheritage awareness

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Telling Keweenaw Geostories in ~ten minutes. Old stories of Keweenaw geohistory have been made into web-based illustrated summaries meant to fill awareness of geoheritage from literature sources. About 8-15 minutes long with ~20 illustrations, these stories tell about the Ontonagon Boulder, Douglass Houghton, Louis Agassiz, Jane Schoolcraft and Hiawatha, Pasties and Keweenaw Miners, Big Annie and the 1913 Strike, Discovery of the Keweenaw Fault, the Green Rock at Copper Harbor, Ben Franklin and Lake Superior, and the Discovery of the C&H Conglomerate. The stories may be viewed online (<https://vimeo.com/showcase/9801619>). They show how local history is guided by geology. They are intended to supplement local and statewide awareness and pride.

Bringing the Boulder Home to the UP. The Ontonagon Boulder was a legendary float of native copper



which was on the west branch of the Ontonagon River until 1847 (<https://vimeo.com/showcase/9801619/video/785968264>). The word of mouth of this unusual precious rock led to widespread interest, but it was difficult to move. Dispute over the ownership of the Boulder was spirited, and eventually it ended up in Washington DC at the Smithsonian Mineral Science Museum. The Boulder is considered a sacred object by Ojibway (Erik Redix, 2017, *American Indian Quarterly*, 41 (3)). Repatriation of the boulder to the UP was applied for, but rejected by the Smithsonian in 2000. UP residents and tourists have no access to this iconic legend. Currently (for decades) the boulder resides out of public view. We propose a loan of the boulder to allow it to visit museums such as Cranbrook, Univ of Michigan and the AE Seaman Mineralogical Museum, partner of the Keweenaw National Historic Park



Building a Statue of a feminist labor leader. Anna Klobuchar Clemenc was a feminist labor leader in Calumet during the miners' strike of 1913 (<https://vimeo.com/showcase/9801619/video/748833299>). She had fame for her leadership of labor parades when she wrapped herself in the American Flag to inhibit the violent confrontations. Tall and homely, "Big Annie" used her personage advantageously and allied with the Western Federation of Miners. She worked with Mother Jones and with the women's vote efforts in Washington. She was the first member of the Michigan Women's Hall of Fame.

The Michigan legislature has officially named June 17 as "Big Annie Day". A bronze life-sized statue of her is planned for permanent display in Red Jacket, outside of the Calumet Opera House and one block away from the Italian Hall. For more info:

<https://www.facebook.com/profile.php?id=100090193837168>

Outcrop Scale Mapping Utilizing High-Accuracy GNSS with MnDOT's Virtual Reference Station (VRS) Network: Minnesota Examples

SCHULZ, Roger¹

¹*Big Rock Exploration*

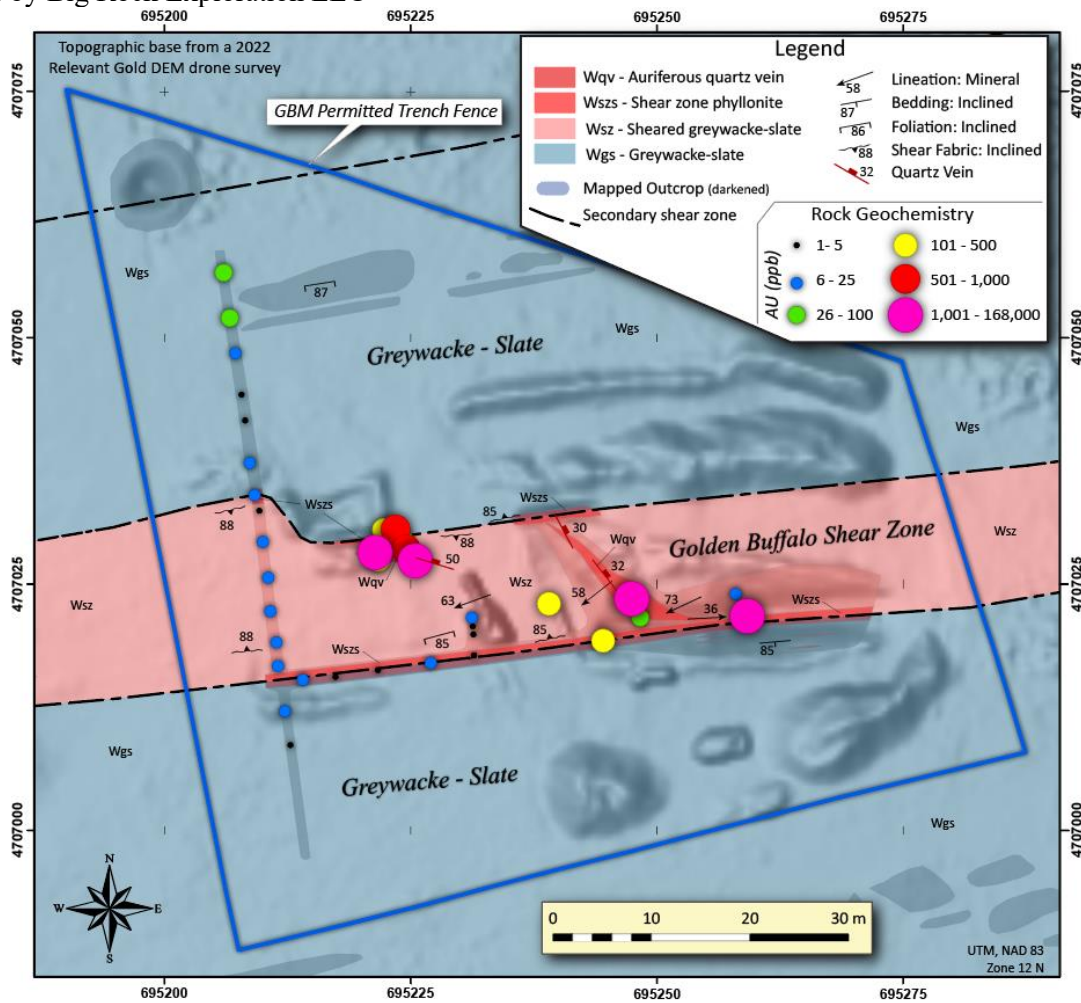
Geologic mapping has long been utilized to visualize the underlying geology of a region. An important tool used in geologic mapping are those that resolve the mapper's locations at a given time. The tools used to locate a mapper have advanced greatly since the time of pace and compass, chains, and grids. With that advancement comes ever more accurate location data. One of the most common modern mapping tools utilizes satellite networks to send a signal from which location data is calculated on a consumer grade handheld GPS unit. While handheld GPS's are useful in mapping moderate to small scale (e.g., 1:5000 or 1:24,000), the accuracy limitations of these units are not capable of resolving outcrop-size maps (e.g., <1:250 scale). Given the limited outcrop in places like the Lake Superior region, it is necessary to extract all possible data from a given outcrop, lending greater importance to small-scale maps. Attaining a level of location accuracy needed for such outcrop scale mapping requires additional real-time corrections of satellite data.

The Global Navigation Satellite System (GNSS) encompasses three major satellite networks operated by the USA (GPS), Russia (GLONASS), and the EU (Galileo). When utilized within the GNSS framework, it is possible to have reliable satellite coverage anywhere in the world, a requirement for accurate location data. GNSS functions via one-way communication of radio waves from the satellites to a receiver that calculates distance from the satellite to the receiver. Distance calculations based on the speed of the signal (c) and the time differential (Δt) between the signal being sent then picked up by the receiver ($D = c \cdot \Delta t$). To triangulate the position of the observer, this calculation must be solved by multiple satellites. This results in positional data that is generally accurate to 10m in the horizontal, at best. The reason for the inaccuracy is that the atmosphere interferes with the speed of the signal resulting in a delay. It is possible to achieve more accurate data by correcting for this differential delay using established ground-based networks.

Differential correction using Virtual Reference Station (VRS) utilizes base stations at control monuments that continually collect positional data generating an average position that can be used to determine the degree of atmospheric delay. When used in a network of base stations, the average atmospheric delay for an area can be determined. The regional delay, or differential, can be communicated to a handheld unit over an internet connection, thereby eliminating the effect of atmospheric delay. Positions can then be determined to centimeter-scale accuracy, a requirement of mapping outcrop scale features. MNDOT has implemented a statewide Virtual Reference Station (VRS) network with over 140 base stations over control monuments whose purpose is to correct for the atmospheric delay and generate high-accuracy GNSS datasets.² This network is free to use for anyone.

Figure 1 below is a case study from South Pass, Wyoming where a trench was mapped at 1:250 using a Trimble Geo 7x. The trench this study area contained auriferous quartz veins and barren quartz veins anastomose along a pair of sheared faults separated by several meters and are connected ladder veinlets. Without the decimeter-scale accuracy of the corrected positional data, it would not have been possible to accurately locate the geology, geochemical samples, or structural data within the trench and the adjacent outcrops. Such an approach could be extremely useful in visualizing complex intrusive outcrops in the Duluth Complex, tracing of the contacts of lava flows and interflow sediments along the shore of Lake Superior, and veins and stockworks within Archean rocks.

Figure 1. Trench Mapping and Sampling for Relevant Gold Corp at the Golden Buffalo Project - South Pass, Wyoming, by Big Rock Exploration LLC



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Geology and geochemistry of the basal North Shore Volcanic Group and Midcontinent Rift Intrusive Supersuite, Cook County, MN, USA

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Northeastern Minnesota preserves complex relationships between Mesoproterozoic volcanic flows and comagmatic gabbroic to granophyric intrusive rocks associated with the ca. 1.1 Ga Midcontinent Rift System (MRS), as well as Paleoproterozoic metasedimentary rocks. Over the last two years, bedrock mapping of nine 1:24K quadrangles in northeastern-most Minnesota (Fig. 1) has elucidated some of these relationships between the Rove Formation, Logan sills, Puckwunge sandstone, reversely polarized North Shore Volcanic Group (NSVG), and gabbroic and granophyric rocks of the Midcontinent Rift Intrusive Supersuite. Results described herein are based on field and thin section observations, and associated geochemistry, which will be compiled and published as part of the Minnesota Geological Survey's County Geologic Atlas Series.

Volcanic rocks lie conformably on top of the Puckwunge sandstone in the eastern map area (Fig. 1). In the western part of the map area, the Crocodile Lake Gabbro (CLG) is in contact with the Paleoproterozoic Rove Formation to the north, with the Rove being highly deformed, metamorphosed, and partially melted proximal to the contact. South of the CLG, is the coeval Cucumber Lake Granophyre (CLGp), which is in contact with the Grand Portage Lavas (GPL), Esther Lake Lavas (EL), and Hovland Lavas (HL) of the NSVG to the south.

The NSVG youngs from north to south, and transitions from mafic to more felsic from north to south which is most evident in the transition from the GPL to the overlying EL (Fig. 1). Geochemically, this sequence evolves along a strong tholeiitic trend (Fig. 2). Lithologic and geochemical patterns suggest the >1108 Ma GPL, EL, and HL were likely sourced from a long-lived, evolving magma. The basal GPL amygdaloidal basalt preserves 5 - 75 cm long pillows with somewhat enigmatic siliceous, carbonate, and glassy selvages that also preserve hyaloclastic and perlitic textures. These flows are geochemically primitive and contain abundant altered olivine, pyroxene, and oxide phenocrysts. The pillowed basal unit grades into thick, massive to ophitic basaltic and basaltic andesite flows of the EL. The transition from the GPL is also marked by a change in trace element geochemistry from an enriched mantle to a more depleted mantle signature. The base of the HL consists of a package of strongly glomeroporphyritic, amygdaloidal andesites and basaltic andesites transitioning to porphyritic rhyolite and icelandite. Porphyritic basaltic to andesitic lavas in the westernmost map area also preserve pillow structures, but these flows vary in thickness and extent, suggesting aqueous sub-basins within the HL volcanic basin. Intercalated throughout the HL are abundant dikes and sills of ultraphyric diabase containing 15-60% of >5 mm plagioclase phenocrysts within a basaltic, locally ophitic very fine-grained groundmass. These intrusives are interpreted to be hypabyssal and locally cut across volcanic stratigraphy. Though these dikes and sills are endemic to the area, temporal relationships between these intrusives, the surrounding volcanics, and the Brule-Hovland Gabbro are unknown.

The ca. 1107 Ma CLG and the CLGp comprise some of the earliest known rocks within the intrusive Duluth Complex. Basal gabbroic cumulates of the CLG grade into dioritic-monzonitic rocks of the Crocodile Lake "Mixed Zone", below the contact with the overlying CLGp. This Mixed Zone is typified by complex dikes and plagioclase cumulate rocks, rich in micrographic interstitial felsic mesostasis. Abundant quench textures and pegmatitic zones, as well as distinct geochemical patterns

suggest the Mixed Zone is a “cap” to the CLG rather than a gradual transition to the CLGp. REE patterns and Eu anomalies within these coeval intrusives suggest liquid immiscibility between mafic and felsic components of the source magma may have played a significant role in their genesis (Fig 3.). Other intrusive gabbroic rocks include the texturally varied Brule-Hovland Gabbro, which cross-cuts the HL.

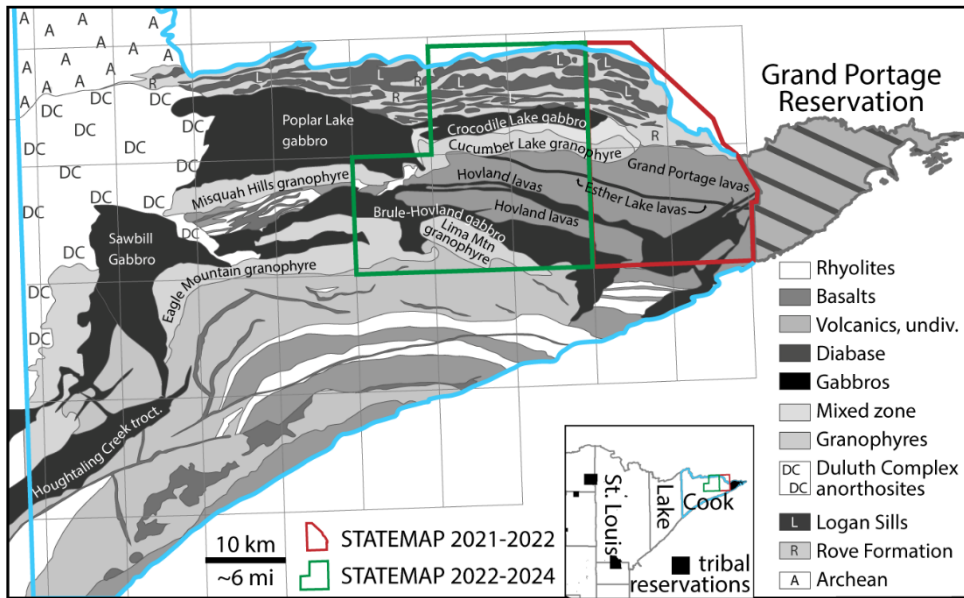


Figure 1. Regional geologic map of northeastern Cook County, MN. Ongoing partially USGS-funded STATEMAP projects outlined with bold lines. Generalized geology is from MGS miscellaneous map series M-119.

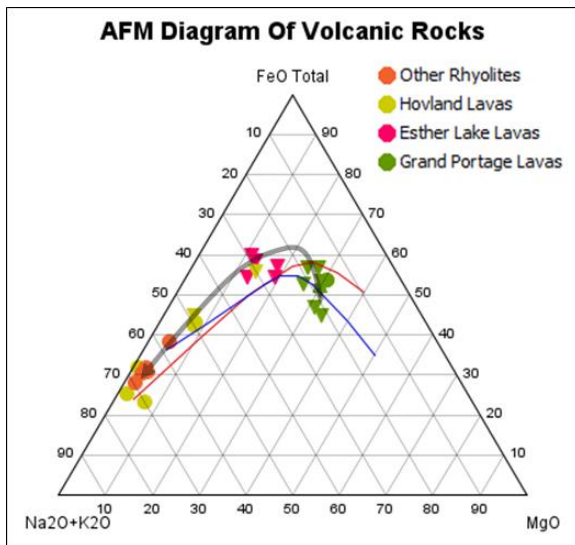


Figure 2. AFM diagram of volcanic rocks.

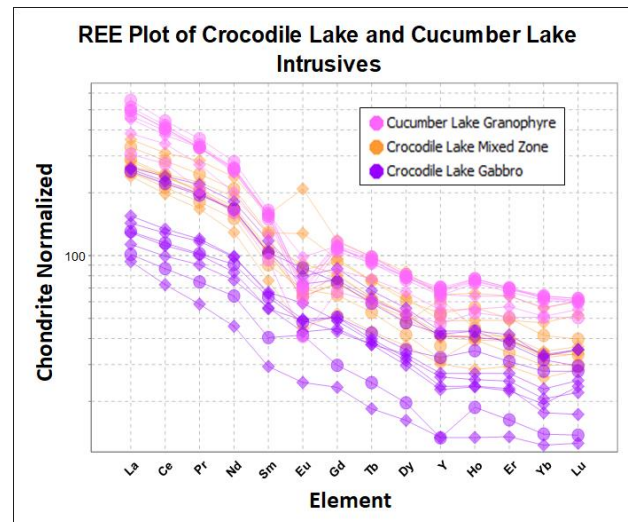


Figure 3. Chondrite-normalized REE diagram of Crocodile Lake and Cucumber Lake intrusives, based on Sun and McDonough, 1989.

Exploring the application of full tensor magnetic gradiometry to better define conduit type Ni-Cu-PGE targets

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Magmatic Ni-Cu-PGE sulfide deposits are often associated with small conduit- or chonolith-type intrusions. These deposit types are notoriously challenging exploration targets owing to: 1) their small size, 2) lack of alteration halo or distal footprint, 3) complex and variable morphology, and 4) unpredictable depositional sites of sulfides (Barnes 2023). Furthermore, mafic rocks commonly retain significant remanent magnetization which, if not detected, can result in inaccurate modelling and targeting of these deposits. With a significant increase in the global production of Ni forecasted for the transition to a low-CO₂ future, these deposit types will likely become an increasingly important source of Ni, both in Canada and globally. With fewer new discoveries being made, despite increased exploration expenditure, new methods and knowledge are needed to facilitate successful exploration at the regional and deposit scales and to ultimately secure a stable Ni supply.

Historically, exploration has traditionally relied on geophysics (gravity, magnetics, electromagnetics), to identify potential mafic and/or ultramafic host intrusions, with airborne magnetic surveying dominating due to its low cost, and ability to survey vast areas rapidly and systemically. Although there is incredible value in Total Magnetic Intensity (TMI) data there are numerous limitations to this approach (e.g. non-uniqueness, scalar measurements, can't distinguish remanence from induced field). The full tensor magnetic gradiometry (FTMG) technique, which measures the full magnetic gradient tensor at each measurement point, overcomes many of the limitations of TMI data. Advantages of FTMG include: (a) superior resolution of near-field sources, (b) enhanced detectability at low-magnetic latitudes, (c) automatic removal of the regional field and diurnal variations, and (d) additional target information from a single flight line. FTMG can provide a more complete picture of the subsurface magnetic properties and improved discrimination between magnetic sources. This leads to improved imaging of complex structures, more accurate models of the subsurface, and improved understanding of geological processes.

While quantum FTMG is in use by industry, practicalities relating to the system hamper its widespread deployment. Currently, existing quantum FTMG relies on SQUID technology for large scale airborne surveying. The application of SQUID technology has shown great benefits due to the enhanced sensitivity and fidelity of the system. However, these systems typically weigh ~270 kg and require extremely low sensor temperatures, making them impractical for ground and uncrewed aerial vehicle (UAV) surveying. These limitations have warranted the development of a complimentary ground and UAV quantum FTMG system such as the diamond-based quantum magnetometer in development by SBQuantum. This rugged and compact system leverages quantum properties of nitrogen vacancy (NV) centres in a diamond to provide highly accurate, quantum-based FTMG measurements.

The Geological Survey of Canada (GSC) is in the early stages of establishing a new collaborative partnership with Defence Research and Development Canada (DRDC), SBQuantum, and numerous other industry and academic partners. The aim of this partnership and wider project is to de-risk quantum magnetic gradiometer use across Canada with the purpose of facilitating widespread adoption by the Canadian exploration industry, academia and the military. This will be achieved

through the field testing and validation of the ruggedized quantum FTMG system developed by SBQuantum. As part of this project, SBQ's quantum magnetic gradiometer will be deployed on several Canadian critical mineral systems, allowing comparison with traditional airborne and/or ground total magnetic field systems and non-quantum FTMG systems. As part of this, a detailed study will be undertaken on the Ni-Cu-PGE bearing Escape Lake intrusion in northern Ontario, which presents as a complicated magnetic signal that is strongly affected by remanent magnetization and associated with the 1.1. Ga Midcontinent Rift. With conventional total field geophysical methods unable to address the challenging features which are often characteristic of small, conduit-type magmatic sulfide deposits, this case study will explore the use and application of quantum FTMG in the context of improving targeting of conduit type Ni-Cu-PGE deposits.

This study will be the first to generate publicly accessible quantum FTMG data over critical mineral deposits in Canada and will act to improve exploration capacity by validating tools useful for critical metal deposits whose complex geophysical expressions are not easily resolved by traditional geophysical techniques. The increased accuracy of these quantum technologies, which map the magnetic field at an enhanced scale, provide the ability to resolve the complexity of these deposits. Providing enhanced tools to facilitate exploration and delineate deposits better will aid with the identification of new Canadian deposits of critical metals needed for the lower carbon and digitized economy supply chain. This will aid Canada's Critical Minerals Strategy set forth in the 2022 Federal Budget.

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Record of an Ancient Meteorite Impact Buried Beneath the Twin Cities, MN

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An impact crater is proposed in the southeast part of the Twin Cities metropolitan area, 11 miles (18 km) south of St. Paul within an area with significant residential and industrial development. The crater lies within a predictable package of Paleozoic sedimentary rocks in the Twin Cities structural basin where near its center includes 14 formations with a total thickness of about 1,200 feet (365 meters) (Mossler, 2008; Mossler, 2013). Paleozoic formations are characterized by widespread layers of sandstone, shale, and carbonate deposited in shallow seas during the Cambrian and Ordovician Periods (500 to 450 Ma). They are underlain by Mesoproterozoic (1,100 Ma) sedimentary and volcanic rocks of the Keweenaw Supergroup associated with the Midcontinent Rift.

Paleozoic rocks in this area have limited exposure along the Mississippi and Minnesota River bluffs, roadcuts, and rock quarries, but elsewhere are buried beneath a variable thickness of Quaternary glacial sediments. Without extensive exposures, a variety of subsurface datasets are used for bedrock mapping including core, drill cuttings, geophysical logs, passive seismic stations, and driller's descriptions from water well records. While mapping the bedrock geology of Dakota County, an area of discordance with the surrounding Paleozoic stratigraphy was observed in geologic cuttings samples, and corroborated with additional cuttings, geophysical logs and water wells driller's records. Drill samples reveal as much as 575 ft (175 m) of anomalous sandstone, siltstone and shale with some intervals containing abundant cloudy and fractured quartz sand grains. The samples are from an area entirely buried by several hundred feet of glacial deposits within a deep buried channel carved into the surrounding bedrock layers adjacent to the Mississippi River near the city of Inver Grove Heights. Beneath the anomalous sequence of strata and in additional samples near the site, local Cambrian and Mesoproterozoic stratigraphic layers are recognized but are out of the usual stratigraphic order and in places entirely overturned.

Microscopic investigation has resulted in the detection of shocked metamorphic features including planar deformation features (PDFs) in the fractured quartz grains, confirming the impact origin of this structure (Fig. 1). As such, this area is referred to as the Pine Bend Impact Structure (PBIS) (Steenberg, in prep). Based on the available geologic data near the site and current models of crater formation from similarly sized structures in layered sedimentary target rocks we interpret this feature to be a *complex crater*, approximately 4 km wide with an apparent central uplift and possible terraced rims (Grieve, 1991). The total disturbed area may be as large as 9 square miles (23 square kilometers). Based on published crater- to- meteor size ratios, the size of the meteor is estimated to be several hundred meters in diameter (Grieve and Pilkington, 1996). Due to its location, within a buried bedrock valley, the upper sequence of this structure has been removed by erosion, making it difficult to precisely date the impact. It may be as old as Late Cambrian (~490 Ma), having occurred during or after deposition of the Jordan Sandstone based on the age of the overturned strata and the apparent lack of carbonate from the overlying Prairie du Chien Group in the samples. We have also collected a pebble with PDFs from strata approximating the Jordan-Prairie du Chien contact in an outcrop about 10 kilometers from the crater. If this pebble is ejecta from the PBIS, it also supports a latest Cambrian or very Early Ordovician age of impact. This would make the PBIS older than known craters in surrounding states which are Ordovician and younger (French et al., 2004; French et al., 2018).

The dynamic nature of our planet has left us with a small sample size of terrestrial impact structures, nearly 200 confirmed impact structures are currently recognized on Earth (Gottwald et al., 2020). Although Minnesota has known impact debris from the Sudbury Impact Structure, this would

be Minnesota's first documented crater, giving us a rare opportunity to better understand the important geological and biological effects of meteorite impact events on Earth.

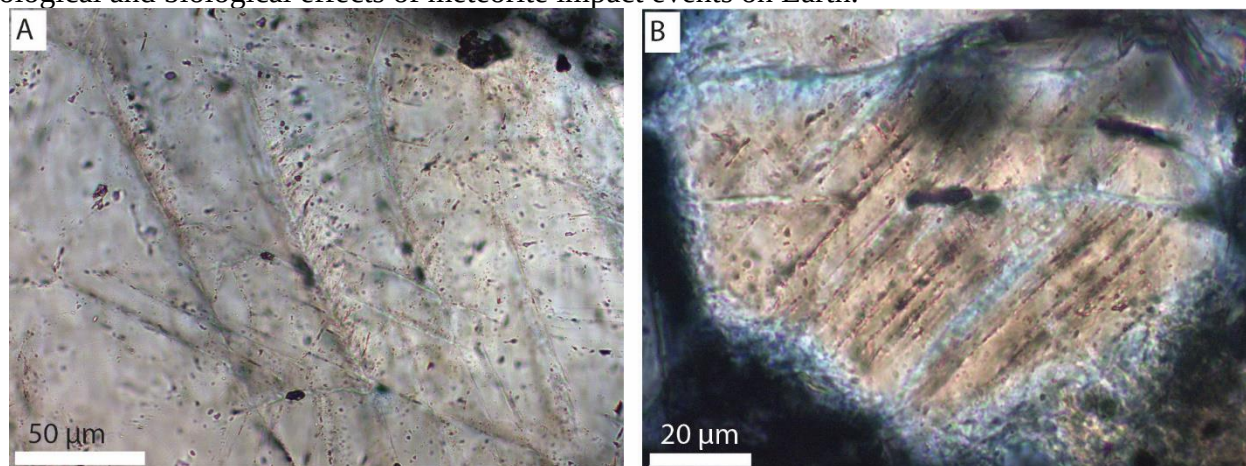


Figure 1. Photomicrographs of mounted quartz sandstone rock chips from a cuttings sample, sample depth is 525 feet. A- Two sets of planar features and feather features. B- One set of decorated planar deformation features. Photos by L. Ferriere, Natural History Museum, Vienna, Austria.

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Magma Recharge and the distribution of Copper and Nickel in the Keweenaw Large Igneous Province

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The Keweenaw large igneous province (LIP) was formed over a protracted period of magmatism that emplaced Cu-Ni-PGE bearing mafic to ultramafic intrusions along the arcuate Mid-Continent Rift system, thus creating one of the largest critical mineral resources in North America. The magmatic activity associated with the Keweenaw LIP has been divided into a series of tectonomagmatic stages extending from at least 1115 Ma to 1080 Ma. Of the six stages of formation, significant orthomagmatic sulfide deposits were formed during Stage 1 (plume impact stage; 1115-1110 Ma), Stage 2 (early stage; 1110-1105 Ma), and the Stage 4 (the main stage; 1101-1094 Ma). Stage 1 and 2 intrusions in the Minnesota and Michigan are Ni-rich while those of stage 4 in the Duluth Complex are considerably more copper-rich. Here we discuss a potential mechanism of copper enrichment via magma recharge-evacuation-fractional crystallization (RE AFC) where the parameters of differentiation are based upon a conceptual model for the formation of continental LIPs.

It has been recognized that continental LIPs form in a series of phases that reflect the conditions of magma generation and differentiation prior to the eruption and eventual formation of continental flood basalts (Jerram and Widdowson, 2005). Early phases of LIP formation are dominated by more primitive lavas, that pass through a magma plumbing system that is immature and inefficient at differentiating magmas (Steiner *et al.*, 2021). However, the magmatic plumbing system of the most voluminous eruptive phase is mature and capable of differentiating magmas to a considerable degree. The key difference between these two periods is the amount of magma recharge, which has a profound impact on the geochemical composition of the resultant magmas where compatible elements become buffered and incompatible elements become enriched (Lee, Lee and Wu, 2014).

The relative Cu-enrichment of mineralized Stage 4 intrusions compared to earlier Ni-rich Stage 1 and 2 intrusions may be explained by several mechanisms. Mechanisms such as sulfide upgrading and high-R factors have been recognized as important contributors to Cu-rich mineralization (Peterson and Boerst, 2013). However, recent chemo-stratigraphic examinations of Keweenaw LIP lavas from the Keweenaw Peninsula have demonstrated that RE AFC processes are controlling erupted lava compositions during the eruption of Stage 4 lavas (Davis *et al.*, 2021). To test the effect of RE AFC on the proportions of Ni and Cu that may be available to form an orthomagmatic sulfide deposit, RE AFC geochemical modelling utilizing the equations of Lee *et al.* (2014) were performed on a generalized basaltic composition (MgO = 10%, Ni = 250 ppm, Cu = 116 ppm (Prinz, 1967)). Figure 1 demonstrates the liquid line of descent for Cu, Ni, and MgO during RE AFC differentiation and pure fractional crystallization. During pure fractional crystallization, MgO and Ni behave compatibly, gradually decreasing in concentration with continued differentiation while Cu gradually increases. However, during RE AFC differentiation, both Ni and MgO become buffered while Cu becomes decoupled, increasing in concentration while Ni and MgO remain the constant. The consequence of this decoupling is that Cu can become considerably enriched relative to Ni, thereby producing a magma that contains greater than anticipated Cu concentrations compared to pure fractional crystallization. When this Cu-enriched magma reaches sulfur saturation, the subsequent sulfide magma would have a greater abundance of Cu to scavenge, resulting in the Cu-rich sulfide deposits observed in in the Duluth Complex.

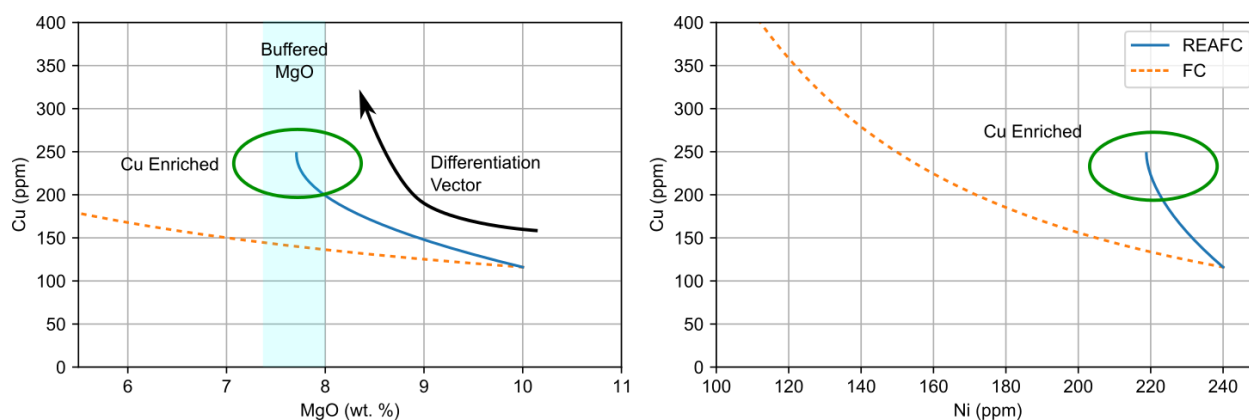


Figure 1. REAFC calculations (Lee, Lee and Wu, 2014) for a generic basalt. Model parameters are recharge/evacuation = 0.43, assimilation = 0.07, fractional crystallization = 0.5. Crystallizing phases were olivine (25%), plagioclase (65%), and clinopyroxene (15%).

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Relay zones in weakly folded and faulted Paleozoic strata and their role localizing Mississippi Valley-type mineralization, southwest Wisconsin, USA

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Folds and faults have long been known to play a role in localizing Mississippi Valley-type zinc-lead mineralization in the historic Upper Mississippi Valley base metal district (UMVD) of southwestern Wisconsin. However, a simple correlation between mineralization and map-scale structures is overly simplistic since it does not explain why mineralization often occurs only along isolated portions of folds and faults. New 1:24,000 scale geologic mapping as part of the United States Geological Survey Earth Mapping Resources Initiative (EarthMRI) in the Stitzer region of the northern UMVD was initiated to improve understanding of the relationship between folds, faults, and mineralization.

The Mineral Point anticline is the dominant structure in the Stitzer area (Figure 1). It is an asymmetric, northwest-trending gentle fold with a maximum amplitude of around 180 feet. The fold deforms platform Cambrian and Ordovician siliciclastic and carbonate strata, and contains several doubly plunging segments. Structural highs along the fold (Figure 1) correspond to aeromagnetic anomalies (Daniels and Snyder, 2002). Deformation bands in sandstone are common along the more steeply dipping northeast limb of the fold.

The asymmetry of the fold and the correspondence of structural highs to aeromagnetic anomalies suggest the Mineral Point anticline is a forced fold, forming from thrust reactivation of a buried Precambrian fault. At depth near the Precambrian basement, the segments of the Mineral Point anticline probably transition into fault segments. Simple 2D kinematic modeling suggests contraction is highest near the base of the overlying folded section. If deformation bands accommodate some of the contraction in the basal siliciclastic sequence, then significant numbers of deformation bands are probably present low in the Paleozoic section.

Mineralization and historic mining are heavily concentrated where two segments of the Mineral Point anticline overlap, and a third smaller anticline terminates (Figure 1). The area between the overlapping segments of the Mineral Point anticline is interpreted to represent the area above a relay zone between thrust segments. As mineralizing brines approached the Mineral Point anticline from the south, flow was probably altered due to the abundance of impermeable deformation bands. Flow conduits developed in the relay zone between fault-fold segments, focusing the brines upward and concentrating mineralization.

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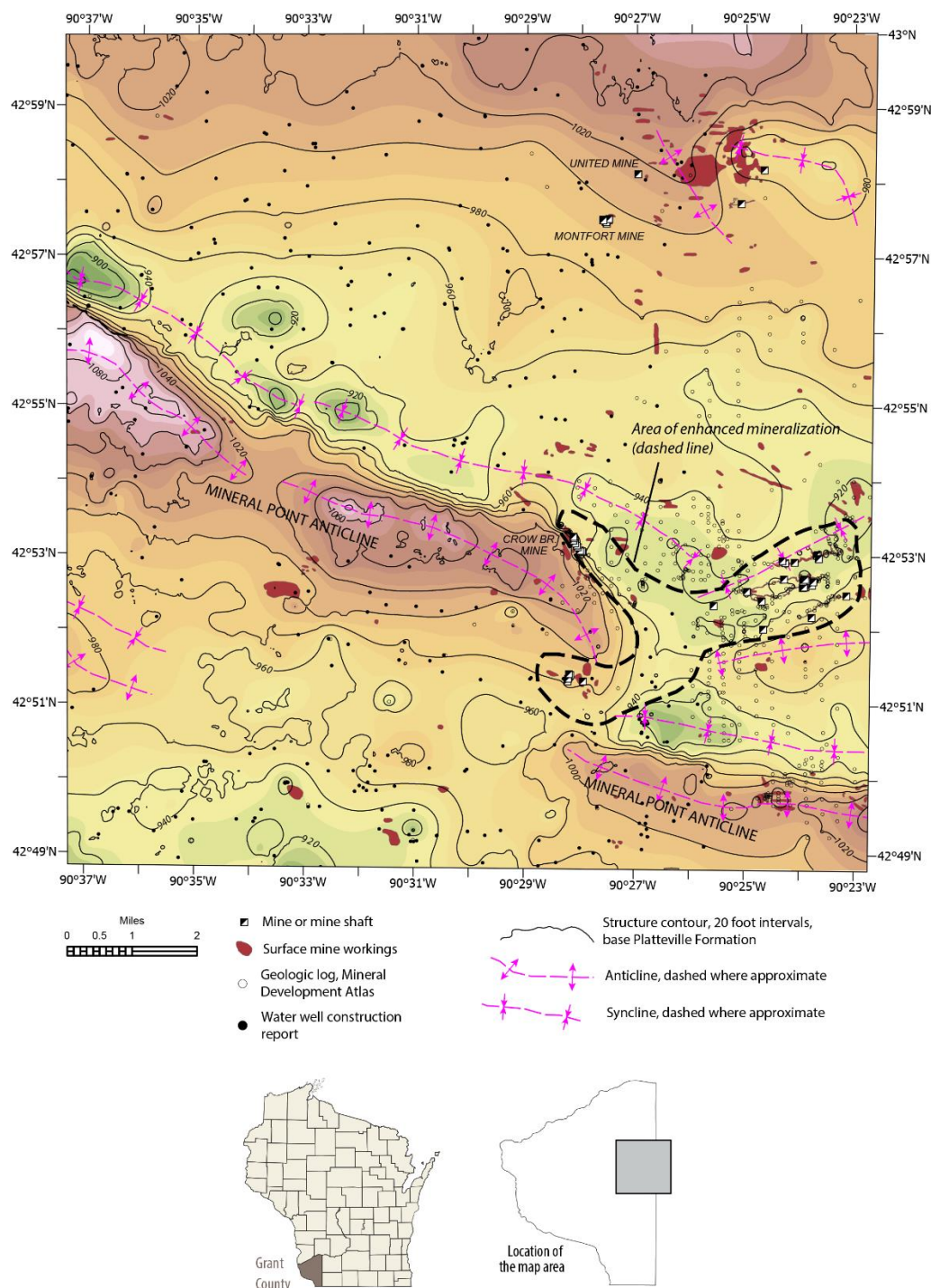


Figure 1. Simplified structure contour map of the base of the Ordovician Platteville Formation. Mines are concentrated in the SE portion of the map near the junction of three anticline-syncline pairs. Additional data sources include the Mineral Development Atlas, Carlson (1961), West (1971), and Taylor (1964).

Deciphering the metamorphic and deformational history of the Hardwood Gneiss, Felch District, Michigan: Anomalously high-pressure rocks in the heart of the Penokean orogen

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The Neoproterozoic Hardwood Gneiss is a mafic granulite with minor metapelites, exposed over an area of about 6 km² between the towns of Foster City and Hardwood, MI, 8 km southeast of the eastern end of the Paleoproterozoic “Felch Trough” (James, 1961). The area lies at the heart of the ca. 1.85 Ga Penokean orogen and within the superimposed Yavapai-age (1.75 Ga) ‘gneiss dome corridor’ (Drenth *et al.*, 2021). In contrast to the primarily felsic gneisses of the region, which contain inherited zircons with ages of 3.8-3.5 Ga, the Hardwood Gneiss is mostly mafic and yields no zircons older than 2.7 Ga (Ayuso *et al.*, 2018). Zircons from the Hardwood also record a period of growth between 2.2 and 1.9 Ga, which does not correspond to any known thermal events in the region (Cannon *et al.*, 2018). Most notably, the Hardwood experienced much higher-pressure metamorphism than any other rocks in the region. Using a variety of geo-thermometers and -barometers, Peterson & Geiger (1990) concluded that the mafic rocks underwent two distinct metamorphic events, the first, ‘M1’, at 8.2-11.6 kbar and ca. 770°C, and another, ‘M2’, at 6-10 kbar and 610-740°C, while the pelites experienced only the second.

Maximum pressure estimates for the nearby Peavy metamorphic node, in contrast, are < 5 kbar (Attoh and Klasner, 1989). It is difficult to explain how the Hardwood complex, with its distinctive geochronologic and metamorphic signatures, came to be incorporated into the Penokean orogen. This study presents detailed field, petrographic and microstructural observations that may help constrain the origin and history of the Hardwood Gneiss.

Peterson & Geiger (1990) identified three compositional units in the Hardwood: metabasite, amphibolite, and metapelite. The metapelite, a garnet-biotite schist, is clearly a distinct unit, exposed in the western end of the outcrop area, but our work suggests that the amphibolite and metabasite are both part of a heterogeneous igneous complex that included anorthositic, gabbroic and noritic horizons – perhaps a Neoproterozoic layered mafic intrusion. If this complex was of mantle origin, it could explain the absence of older Archean zircons.

In addition to their compositional variety, the metamafic rocks display a wide range of metamorphic and deformational textures. In outcrop, they have a strong, apparently mylonitic, foliation that dips mainly NE but is somewhat variable in orientation and may be folded. In thin section, microstructures show that a combination of brittle and plastic deformation mechanisms contributed to the intense fabric. In plagioclase-rich horizons, the feldspars tend to be the largest crystals, apparently surviving as porphyroclasts. These show both cataclastic fracturing and highly distorted twins, a combination usually interpreted to indicate that deformation took place at mid-crustal depths and temperatures of ca. 500°, the brittle-plastic transition for feldspars.

These intensely deformed rocks show evidence of only limited, and heterogeneous, recrystallization, either dynamic or static. This suggests that deformation was brief and that the rocks cooled quickly after deformation ceased.

Garnet-bearing horizons within the mafic complex display especially remarkable textures. Clusters and trains of garnets, apparently broken -- and in some cases, shattered -- are engulfed in a very fine-grained (<0.01mm) feldspathic matrix. The unusual shapes of some of the garnet fragments -- including crescents and splinters -- may indicate seismic fragmentation (Hawemann *et al.*, 2019). The largest garnet fragments tend to have inclusion-free cores and ‘spongy’ poikilitic rims, while smaller fragments are commonly poikilitic throughout, with a notable

concentration of opaque inclusions. In some cases, the edges of the small garnet fragments are so diffuse that they cannot be seen in plane light. Peterson & Geiger (1990) interpreted the poikilitic rims and small inclusion-rich garnets as records of a second metamorphic event, but we speculate that these are resorption features rather than overgrowths. ‘Spongy’ or ‘amoeboid’ poikilitic rims are known to form around granulite-facies garnets during the introduction of external fluids (Baxter *et al.*, 2017), or when garnets are engulfed in pseudotachylyte melts (Austrheim *et al.*, 1996). Because they form under disequilibrium conditions, such resorption rims are unlikely to yield reliable P-T results, and this could account for the large range of P-T conditions Peterson & Geiger (1990) suggested for their ‘M2’ metamorphic event. Given the shattered nature of the Hardwood garnets, we tentatively speculate that the very fine-grained material in which they occur could represent coseismic fault rock – either (devitrified) pseudotachylyte or/and ultracataclasite flushed with seismically-pumped fluids.

In this interpretation, the Hardwood complex would have experienced only one high-P/T metamorphic event, followed by mylonitization, cataclasis and seismic faulting. If the quasi- brittle deformation of the feldspars – which seems to be part of the same event that shattered the garnets -- can be interpreted as occurring at ca. 500°, the deformation would have had to happen well after the granulite-facies event. However, feldspar plasticity can be suppressed in very dry rocks (e.g. Bjørnerud & Austrheim, 2004), so it is also possible that the seismic event(s) occurred under high-temperature conditions and possibly soon after the granulite facies metamorphism that formed the inclusion-free garnets. Whether any of these events occurred during the Penokean orogeny remains unclear. One possible constraint on the timing of the main foliation-forming event comes from the occurrence of an unfoliated mafic within a feldspathic layer in the Hardwood Gneiss on the south bank of the East Branch of the Sturgeon River. If this sill could be dated or linked geochemically with known mafic magmatic units in the region, this would establish the youngest possible deformation age for the Hardwood Gneiss.

The Hardwood pelites are classic garnet-biotite schists, with asymmetric quartz-vein boudins and garnet ‘tails’ that suggest normal-sense shear along the NE-dipping foliation. Low- angle normal faulting would be the most efficient way to juxtapose deep crustal rocks like the Hardwood Gneiss against the shallower units that surround it. But the pelites, which represent supracrustal material and record amphibolite rather granulite-facies conditions, lie on the western edge of the Hardwood outcrop area, so top-to-the-east normal slip does not help explain how the high-pressure mafic units were brought up from depth. The area between the Felch Trough and the Niagara Fault is among the most structurally complex of parts of the Penokean/Yavapai orogen, with many anastomosing faults of different generations (Drenth *et al.*, 2021). The orientations of structures within the Hardwood complex have almost certainly been altered since their formation by later faulting and tilting. For now, the Hardwood Gneiss remains a micro- terrane of unknown provenance within the Penokean orogen.

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Alteration Geochemistry Characterization and 3D Modeling of the Back Forty Volcanogenic Massive Sulfide (VMS) Deposit Stephenson, Upper Peninsula of Michigan, USA

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The Gold Resources Back Forty zinc-and-gold-rich polymetallic volcanogenic massive sulfide (VMS) deposit is located near Stephenson in the Upper Peninsula of Michigan. In general, VMS deposits are created in submarine environments when heated seawater circulates through oceanic crust and precipitates base and precious metals at or near the seafloor due to both cooling and neutralization of the ore fluid. In the process, host rock mineralogy and geochemistry are modified by both downwelling and upwelling hydrothermal fluids, which produces distinct alteration mineral assemblages and metasomatic changes within the host rock (Shanks and Thurston, 2012; Galley et al., 2007). Alteration mineral assemblages and their spatial distribution can be used to unravel the geochemical evolution of the system and help locate mineralization. The relationship between host rock and alteration mineralogy is not well understood or documented at the Back Forty Deposit but essential for understanding its genesis.

This study 1) identifies the alteration mineral assemblage present at the Back Forty Deposit using lithogeochemistry results; 2) calculates the elemental gains and losses associated with hydrothermal alteration; 3) develops a working method for immediate qualitative alteration values from core logging; and 4) creates a model of the alteration zonation in coordination with the existing stratigraphy and mineralization.

Core from nine drill holes (~ 2,950 meters), were logged to observationally identify alteration mineral assemblages, intensity, and their textural characteristics. The deposit, hosted in felsic pyroclastic rocks, shows mostly sericite alteration, which was used to establish an alteration intensity scale of 1-4 (1: weak, 5: intense). Major alteration mineral assemblages observed were sericite ± silica ± chlorite. Sericite alteration is pervasive throughout the deposit (2.5-3.5) with silica alteration intensity ranging from 1-2 and a few areas of silica flooding (3.5-4.5). Weak to moderate (1.5-2.5) chlorite alteration occurred throughout the deposit within the host rhyolite crystal tuff units as spotty chlorite coarse-grained agglomerations.

Lithogeochemistry (1,300 count) was evaluated using the alteration box plot (Large et al., 2001) and the isocon mass balance method (Grant, 1986) (fig. 1), which are essential in quantitative assessment of chemical changes associated with alteration mineral assemblages and their spatial distribution, and the identification of hydrothermal fluid pathways and mineralization vectors within the deposit. In addition to using isocon results, alteration box plot results were modeled based on sericite, chlorite, and total alteration. The production of cross sections based upon this numerical modeling identify the alteration mineral zonation and its relative extent; this model is evaluated to determine the relationship between massive sulfide mineralization and alteration intensity.

From these results, downhole core logging of alteration assigned numeric values (“quick log”) is evaluated as a method to make fast-paced exploration decisions while awaiting longer lead-time lithogeochemical results. By leveraging the process and combination of core logging for alteration mineralogy and intensity paired with geochemical analysis, it may be possible to determine the origin direction of hydrothermal fluid flow associated with mineral deposition and aid in future exploration efforts to locate additional mineralization on the Back Forty Deposit property.

Results from this study show the sericite alteration is most significantly related to Zn and Cu mineralization, whereas the chlorite alteration is most associated with Ag, Au, and Pb. Distinctly depleted species associated with sericite alteration include Ba, Sr, Na₂O, Rb; with chlorite commonly depleted in Br, Ba, Sr, Na₂O.

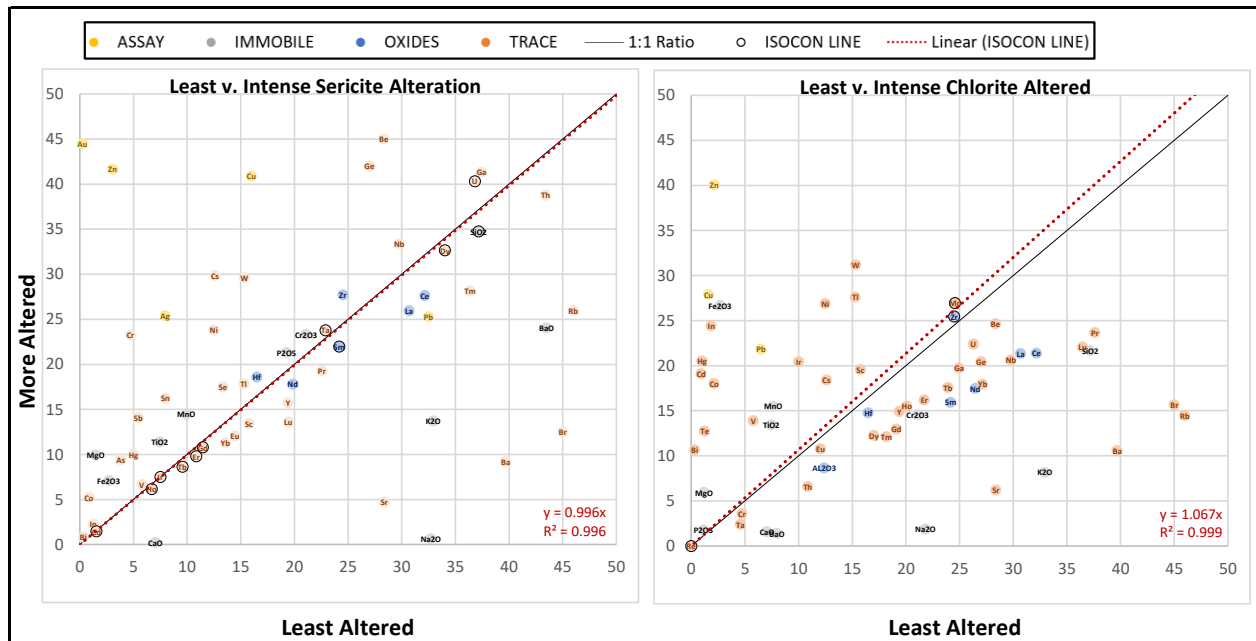


Figure 1. ISOCON plot of selected elements used to compare elemental gains and losses between least and most altered samples. Isocon line of best fit is defined by relative immobile. Species above the isocon line are enriched; below are depleted (Grant, 1986).

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Summary of the 2022 ILSG Field Trip to Iceland

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During Summer of 2022 (July 26-August 9), a group of 16 people set out to tour the diverse and awe-inspiring geology of Iceland, led by ILSG representative geologists Phil Larson, Peter Hinz, and Allan MacTavish. The 15 day trip held many surprises for all involved, including the worst stretch of weather Phil has experienced in Iceland (of 11 visits!) as well as a once-in-a-lifetime experience to see a volcanic eruption.

In addition to the trip leaders, the group of 16 people included 3.5 professional geologists, 1.5 graduate students, one retiree, one Goldich Medal laureate, and 9 members of the Minnesota Geological Society. Stops throughout the trip focused on a wide range of topics:

- Volcanism, both historical and the 2021 Geldingadalir eruption;
- Icelandic cuisine, lore, and the historical and cultural evolution of the nation;
- Environmental geochemistry of subsurface and near-surface processes;
- Volcanic flows, igneous petrology for mineralogy and volcanic textures;
- Geothermal energy and its uses;
- Hydrology and hydrologic events related to glaciers and volcanics;
- Geomorphology as it relates to ecology, volcanics, and glaciers
- Wind, water, and glacial erosional features; glacial nomenclature



Figure 1. Photo credit: Tom Hart

By special arrangement, the trip was scheduled to overlap with the onset of the 2022 Meradalir eruption (fig.1). An advance party made a midnight scouting foray to the vent site before a Force 13 gale descended on the island.



Figure 2. Generalized map of the trip route.

This presentation summarizes the highlights from the trip (fig.2). Featured locations include the Fagradalsfjall eruptions on the Reykjanes Peninsula, the Vestmannaeyjar Islands, climbing atop and viewing the Laki fissure from above, trekking to the highlands to view Askja and its pumice fields, the Jökulsárgljúfur canyon and scablands, free roadside hákarl stands, being lowered into a dormant magma chamber, a sampling of geothermal pools, plus the many epic waterfalls along the way!

GEOHERITAGE AS AN EDUCATIONAL TOOL TO EXPLORE RELATIONSHIPS WITH LAND AND WATER IN THE KEWEENAW

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Geoheritage is an evolving field in the United States that considers the protection, interpretation, and management of geologic features with significant scientific, educational, cultural, or aesthetic value (Brocx & Semeniuk, 2007; Geological Society of America, 2017; National Park Service & American Geosciences Institute, 2015; Reynard & Brilha, 2017). Geoheritage strongly emphasizes the importance of the varied personal values people have for geologic features and the wide-ranging relationships we have with landscapes. As such, geoheritage is an effective geoscience communication tool affording place-based learning experiences that nurture our sense of place, deepen our Earth science literacy, and inspire stewardship and protection of our place. This presentation explores geoheritage education and outreach initiatives in Michigan's Keweenaw Peninsula for both formal and informal learning communities.

The Keweenaw Peninsula sits at the heart of the Midcontinent Rift and is renowned for the world's largest accessible native copper deposit and Lake Superior, the largest freshwater lake on Earth. These geologic processes and features have fostered varied human relationships with the landscape, including the oldest metal workings in the Western Hemisphere and the European immigration wave of 1840-1910 triggered by the Copper Boom. This intersection of deep time, industrial, and cultural heritage has been the focus of teacher professional learning institutes and student internship experiences that explore the compelling geoheritage of our place. These programs: a) focus on complex environmental issues rooted in Earth systems processes of importance within the community, b) emphasize strong community partnerships that bring together varied values and perspectives of our place; c) explore other ways of knowing about the dynamic and interconnected geologic and human stories that serve as the foundation of the landscape's past, present, and future through equitable knowledge exchange, and d) elevate Earth science literacy for educators and students by connecting the underpinning geology to current environmental issues with wide-ranging impacts in our communities today such as cultural identity, subsistence uses, recreation, and sense of place.

The geologic formations of the Midcontinent Rift are beautifully exposed in the Keweenaw for researchers, teachers, students, and geotourists. As the Keweenaw shifts from an extractive industrial economic past, geoheritage initiatives support a future based on education, conservation, and sustainable tourism. Current initiatives in our community include a) the development of geotourism opportunities - *Keweenaw Geotours*, b) strong partnerships with local conservation groups to maintain access to world-class geosites that provide outstanding Earth science learning opportunities, and c) exploration of recreational opportunities including the concept of a shoreline hiking trail following the high water mark of Lake Superior. Geoheritage education and outreach opportunities help foster a culture of stewardship, increase Earth science literacy, and provide opportunities to share our varied relationships with land and water.



Figure 1. Teachers and students explore the geoheritage of the Keweenaw by land and water.

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U/Pb geochronology and zircon petrochronology of Paleoproterozoic magmas from the Marshfield terrane Penokean Orogen, Wisconsin

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This study presents U-Pb, Hf-Lu, and trace isotopic element data from zircons obtained from volcanic and intrusive rocks from the Paleoproterozoic Penokean magmas within the Marshfield terrane in northern Wisconsin. The Penokean Orogen hosts both the Proterozoic Pembine-Wausau and the Archean Marshfield terranes. The Eau Pleine Shear Zone is interpreted as the paleosuture zone between these two terranes (Sims et al., 1989). Both terranes host volcanic and intrusive rocks that were formed during the Penokean orogen. The Pembine-Wausau terrane is a juvenile arc system that was developed through subduction during the Penokean orogen that accreted against the Superior craton. The volcanic rocks in this terrane are tholeiitic and calcalkaline in nature (Schulz and Cannon, 2007). The Marshfield terrane is thought to be an accreted fragment of an Archean craton that collided with the Pembine-Wausau terrane and the Superior craton (Klier, 2019). The Marshfield terrane is mainly comprised of gneisses that underlie Early Proterozoic volcanic rocks (Sims et al., 1989), but due to poor exposure of these rocks this terrane is poorly understood. This study aims to provide a better understanding of the volcanic terranes in the region to improve regional models of the southern portion of the Penokean orogen.

Samples were collected from Big Falls and other locations within the Eau Claire volcanic complex, as well as from granites and gneisses exposed in Black River Falls. Zircons from these samples were then analyzed at Laurentian University (Sudbury, Ontario, Canada) via Split-Stream Laser Ablation Inductively Coupled Plasma Mass Spectrometer (LASS-ICP-MS) to obtain U-Pb, Hf-Lu, and trace isotopic element data. Results reveal complex age relationships and basement architectures. The Big Falls gneiss, part of the Eau Claire volcanic complex lying south of the Eau Pleine Shear Zone (Fig. 1), resulted in an interpreted U-Pb age of 1874.7 ± 2.1 Ma (Fig. 1) which is consistent with VMS-forming events in the Pembine-Wausau terrane. Zircon trace element geochemistry from the Eau Claire volcanic complex indicate rocks formed from a hydrated but reduced melt. This melt may have occurred in a back-arc setting where decompression occurred in a metasomatized mantle, which is characteristic of back-arc signatures. Hf-Lu isotopic data from the Eau Claire volcanic complex show the rocks here lack an Archean inheritance.

The data from the Eau Claire volcanic complex was compared to a granite intrusion in Black River falls and both the Eisenbrey and Lynne VMS deposits in the Pembine-Wausau terrane. Based on Hf-Lu data, the Black River Falls granite showed inheritance of basement, which is expected based on field relationships with Archean rocks from the Marshfield terrane. The Eisenbrey and Lynne deposit have juvenile signatures which is characteristic of an oceanic arc system. According to trace isotopic element data, the VMS deposits also formed from a more oxidized and hydrated melt which is a similar geodynamic setting seen in the Eau Claire volcanic complex. Since we would expect basement inheritance in the Eau Claire volcanic complex, these results question what is known about the Marshfield terrane and its relationship to the Penokean.

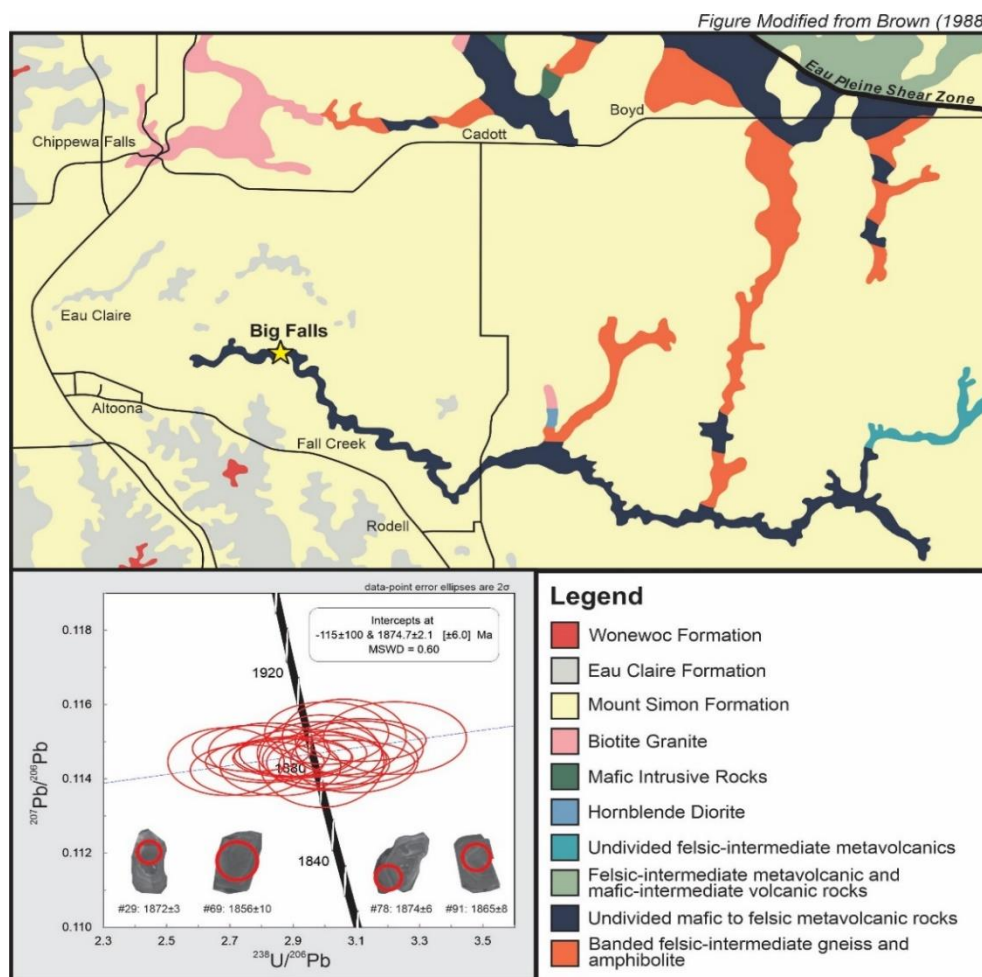


Figure 1. Geologic map of Eau Claire and Chippewa Falls area highlighting the location of Big Falls alongside a concordia diagram plotting the age of Big Falls at 1874.7 ± 2.1 Ma. Cathodoluminescence imaging of individual zircons are also shown with their corresponding ages.

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The Use of Electric Pulse Disaggregation Technology to Recover Nickel Metal from Nickel Sulfide Ore Deposits

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All metals, except for the noble metals like gold, occur in nature as metal sulfides. The chemical process “Plat Sol”¹ can be used to recover nickel metal from nickel sulfide ores. The demand for nickel metal has increased dramatically due to the need for nickel metal for electric vehicle batteries. Elon Musk, always ahead of the curve, has signed an agreement with Talon Metals to be the sole recipient of any nickel metal they produce. Similarly, the Biden Administration is encouraging a transition from fossil Fuel vehicles to electric vehicles.²

However, a particle size of less than a millimeter is required for the feed to the Plat Sol process. Electric Pulse Disaggregation Technology³ provides much more efficient and less expensive method than conventional crushing and grinding for reducing the particle size of ore samples. Figure 1 provides details on the disaggregator. Inside the 3D printed gray cap on the left below is a stainless steel hemisphere with a pointed electrode projecting upward. On the right, is a black 3D printed cap with an electrode like the one above. When the two caps are screwed together, a sphere is formed. The electrodes are separated ~ 5 mm forming a spark gap. The two hemispheres are filled with water and inch-sized sample fragments. When the 50KV power supply is turned on the discharge across the spark gap vaporizes the water, which in turn separates different minerals along their grain boundaries.

Examples of “zapped” Talon Metals nickel sulfide ore will be shown.



Figure 1. Image of the disaggregator set up.

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Google “Plat Sol”

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<https://www.researchgate.net/project/Electric-pulse-disaggregation-and-hydroseparation-for-mineral-processing>

*** Abstract Withdrawn***