



63rd Annual Meeting

Institute on Lake Superior Geology



**Wawa, Ontario
May 8 - 12, 2017**



Wawa

**Wild Goose
or
Land of the Big Goose
in Ojibway**



**Proceedings Volume 63
Part 1: Program and Abstracts**



Institute on Lake Superior Geology

63rd ANNUAL MEETING

May 8-12, 2017

Wawa, Ontario

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ONTARIO GEOLOGICAL SURVEY

MINISTRY OF NORTHERN DEVELOPMENT AND MINES

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A. E. SEAMAN MINERAL MUSEUM

MICHIGAN TECHNOLOGICAL UNIVERSITY

Meeting Co-Chairs

Anthony Pace, Ann Wilson, and Theodore J. Bornhorst

Proceedings Volume 63

Part 1: Program and Abstracts

Edited by Theodore J. Bornhorst and Margaret J. Hanson

Cover Photos: Top left, Calcite crystals on pyrite from George W. MacLeod Mine, Wawa, collection of the A. E. Seaman Mineral Museum, photograph by George Robinson; iconic Wawa goose at junction of Trans-Canada Highway and Highway 101, image from <http://www.northernontario.travel/algoma-country/fun-facts-about-the-famous-wawa-goose>; Sir James Dunn open pit iron mine on the Eleanor Iron Range, photograph by Anthony Pace.

63rd INSTITUTE ON LAKE SUPERIOR GEOLOGY

VOLUME 63 CONSISTS OF:

PART 1: PROGRAM AND ABSTRACTS

PART 2: FIELD TRIP GUIDEBOOK

TRIP 1: ARCHEAN AND PROTEROZOIC GEOLOGY OF THE MARATHON-HEMLO AREA

Day 1: Geology of the Coldwell Alkaline Complex

Part 1: Transect through the Coldwell alkaline complex

Part 2: Marathon Cu-PGM deposit

Day 2: Geology of the eastern Schreiber-Hemlo Greenstone Belt in the vicinity of
Heron Bay and Hemlo

TRIP 2: MORE UNUSUAL DIAMOND-BEARING ROCKS OF THE WAWA AREA

TRIP 3: GEOLOGY OF THE WAWA GOLD PROJECT

TRIP 4: GEOLOGY OF THE ISLAND GOLD MINE

TRIP 5: GEOLOGY OF THE RENABIE AREA

TRIP 6: KAPUSKASING STRUCTURAL ZONE AND BORDEN LAKE GOLD DEPOSIT

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<http://www.lakesuperiorgeology.org>

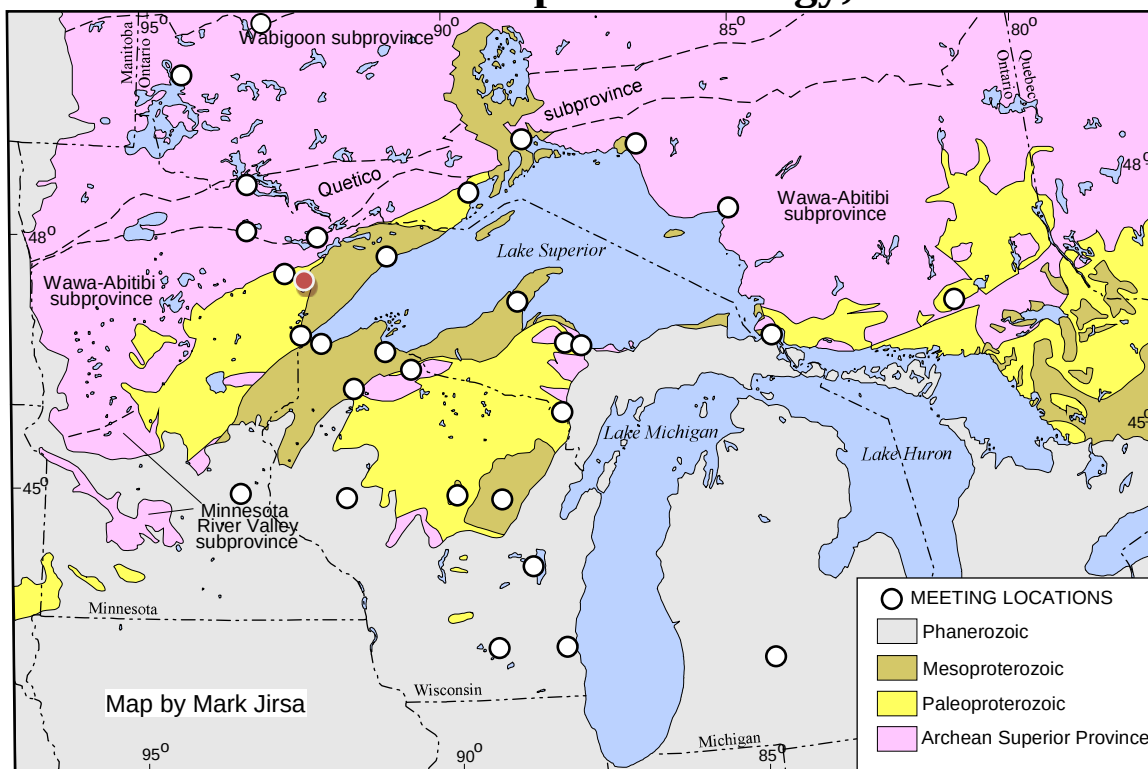
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Part 1: Program and Abstracts

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Institutes on Lake Superior Geology, 1955-2017



<u>#</u>	<u>Date</u>	<u>Place</u>	<u>Chairs</u>
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

#	Date	Place	Chairs
23	1977	Thunder Bay, Ontario	M.M. Kehlenbeck
24	1978	Milwaukee, Wisconsin	G. Mursky
25	1979	Duluth, Minnesota	D.M. Davidson
26	1980	Eau Claire, Wisconsin	P.E. Myers
27	1981	East Lansing, Michigan	W.C. Cambray
28	1982	International Falls, Minnesota	D.L. Southwick
29	1983	Houghton, Michigan	T.J. Bornhorst
30	1984	Wausau, Wisconsin	G.L. LaBerge
31	1985	Kenora, Ontario	C.E. Blackburn
32	1986	Wisconsin Rapids, Wisconsin	J.K. Greenberg
33	1987	Wawa, Ontario	E.D. Frey & R.P. Sage
34	1988	Marquette, Michigan	J. S. Klasner
35	1989	Duluth, Minnesota	J.C. Green
36	1990	Thunder Bay, Ontario	M.M. Kehlenbeck
37	1991	Eau Claire, Wisconsin	P.E. Myers
38	1992	Hurley, Wisconsin	A.B. Dickas
39	1993	Eveleth, Minnesota	D.L. Southwick
40	1994	Houghton, Michigan	T.J. Bornhorst
41	1995	Marathon, Ontario	M.C. Smyk
42	1996	Cable, Wisconsin	L.G. Woodruff
43	1997	Sudbury, Ontario	R.P. Sage & W. Meyer
44	1998	Minneapolis, Minnesota	J.D. Miller & M.A. Jirsa
45	1999	Marquette, Michigan	T.J. Bornhorst & R.S. Regis
46	2000	Thunder Bay, Ontario	S.A. Kissin & P. Fralick
47	2001	Madison, Wisconsin	M.G. Mudrey & Jr., B.A. Brown
48	2002	Kenora, Ontario	P. Hinz & R.C. Beard
49	2003	Iron Mountain, Michigan	L. Woodruff & W.F. Cannon
50	2004	Duluth, Minnesota	S. Hauck & M. Severson
51	2005	Nipigon, Ontario	M. Smyk & P. Hollings
52	2006	Sault Ste. Marie, Ontario	A. Wilson & R. Sage
53	2007	Lutsen, Minnesota	L. Woodruff & J. Miller
54	2008	Marquette, Michigan	T.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

Sam Goldich and the Goldich Medal

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

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

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

Reference:

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

Prepared by various Goldich Medal Awardees, 2007



INSTITUTE ON LAKE SUPERIOR GEOLOGY GOLDICH 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
1980	<i>not awarded</i>	1999	Tsu-Ming Han
1981	Carl E. Dutton, Jr.	2000	John C. Green
1982	Ralph W. Marsden	2001	John S. Klasner
1983	Burton Boyum	2002	Ernest K. Lehmann
1984	Richard W. Ojakangas	2003	Klaus J. Schulz
1985	Paul K. Sims	2004	Paul Weiblen
1986	G.B. Morey	2005	Mark Smyk
1987	Henry H. Halls	2006	Michael G. Mudrey
1988	Walter S. White	2007	Joseph Mancuso
1989	Jorma Kalliokoski	2008	Theodore J. Bornhorst
1990	Kenneth C. Card	2009	L. Gordon Medaris, Jr
1991	William Hinze	2010	William D. Addison & 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	2016	Mark A. Jirsa

2017 GOLDICH MEDAL RECIPIENT

Philip Fralick

Goldich Medal Committee

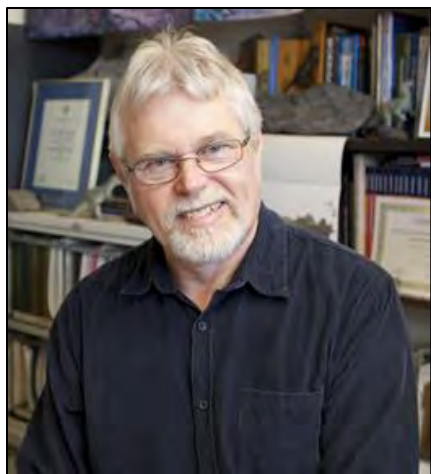
Serving through the meeting year shown in parentheses.

Hélène Lukey, Chair (2014-2017) Cliffs Natural Resources

Shannon Zurevinski (2015-2018) Lakehead University

Klaus Schultz (2016-2019) U. S. Geological Survey

Citation for the Goldich Medal Award to **Philip Fralick**



ILSG Members, fellow Goldich Medalists and guests, it is my great honour to present the citation for this year's recipient of the Goldich Medal, Dr. Philip Fralick.

Phil received his Bachelor's and Master's degrees in geology from Dalhousie University in 1977 and 1980, respectively, and received his Ph.D. from the University of Toronto in 1985. I first met Phil when he arrived as an Assistant Professor at Lakehead University in Thunder Bay in 1983. I had already taken my required undergraduate sedimentology courses and unfortunately did not have the opportunity to be one of Phil's students. However, in the 34 years that Phil has been at Lakehead, I have benefited, as have countless others, from his knowledge, enthusiasm, insight and support.

Goldich Medalists have made substantial and significant contributions to our understanding of Lake Superior geology and in doing so, advance our understanding of the science and help to put our region on a world stage. Phil has been instrumental in this regard, conducting research that has led to new concepts and interpretations that have informed other geoscientists, students and the public at large.

Phil has also been an ardent supporter of the ILSG and has been more than willing to share his ideas and findings with us in the Institute. He has been a mainstay of Institute meetings since 1985, co-chaired the Thunder Bay meeting in 2000, subsequently served on the ILSG Board of Directors and has contributed to 74 (and counting) ILSG abstracts and field guides. He has always supported his students in their participation at ILSG and has encouraged them to deliver presentations and remain active in the Institute. He is proud of the fact that many of his students have won Best Student Paper awards at our annual meetings. Clad in his signature red necktie, Phil has led countless ILSG field trips and been pressed into action on an *ad hoc* basis many times. His innate ability to describe and interpret sedimentary sequences has allowed us to better understand and appreciate the stories these rocks hold. He has also been involved with a number of other international symposia as an organizer, invited lecturer, field trip leader, editor and committee member.

Phil's research, and that of his students and collaborators at Lakehead University, has contributed greatly to our understanding of the Precambrian and Quaternary geology of the Lake Superior region. His work has focused on:

- Evolution of ocean-atmosphere geochemistry through the Precambrian;
- Tectonic influences on basin formation and development in Precambrian sequences;
- Genesis of iron formations, centering on understanding the shelf or deep marine hydrodynamic and chemical processes which led to the precipitation of these odd sediments; and
- The use of depositional environment and provenance to ascertain the basin-fill architecture of sedimentary units in Mesoproterozoic to Mesoarchean terrains.

Phil and his co-researchers have extensively studied iron formations and associated sedimentary rocks in a number of Archean greenstone belts in northwestern Ontario and in the Paleoproterozoic Animikie Basin around Lake Superior in furthering these goals. In doing so, he has improved our understanding of the formation of economic deposits of not only iron, but also gold, base metals and even diamonds. He has also explored the tectonic development of the Huronian Supergroup, the Sibley Basin and the Midcontinent Rift. Some of this research stemmed from his contributions on the Science Committee for the Lake Nipigon Region Geoscience Initiative from 2002 to 2005. His work with other researchers, including past Goldich Medallists Bill Addison and Greg Brumpton, on the Sudbury Impact Layer near Thunder Bay and in northern Minnesota garnered a great deal of interest and even generated a facies analog for distal impact deposits on Mars.

Conversant not only in sedimentology, but also in geochemistry, paleontology and tectonics, Phil manages to approach his research from a broad, informed perspective. Phil's reputation as a researcher has led to collaborations with many different organizations, including NASA's Astrobiology Institute, studying how to detect life in modern and ancient environments on Earth and other planetary bodies, such as Mars. Most recently, he was invited to join an international research team with a multi-million dollar budget to study the origins of oxygen in Earth's atmosphere by looking at Archean carbonates from the Red Lake greenstone belt and explore the fundamental question of when photosynthesis started on our planet, paving the way for the development of multicellular life.

At the request of researchers in other disciplines, Phil has also ventured into areas far beyond his usual scope of interests. He has worked and published on topics ranging from post-glacial sedimentation in the Lake Superior basin, to archaeology in the American Southwest and treatment methods for water contaminated with heavy metals. Phil's research activities garnered him the Lakehead University Distinguished Researcher Award in 2005 "for significant contributions to research and consistency in scholarly performance sustained over an extended period".

In addition to his role as a researcher, Phil has also been recognized for his teaching and his support of students. In 2007, Phil was given the Distinguished Instructor Award by Lakehead University. This prestigious teaching award recognizes an outstanding individual who has made a significant contribution to teaching excellence and educational innovation and leadership at Lakehead over a number of years. Perhaps the best endorsement of Phil's teaching abilities comes from his students, who have described him as a "great storyteller" and a "rock icon" with, as we all know, a distinctive and infectious laugh. And who among us could not confess to have felt the way this student did in stating that, "the dude makes me want to become a sedimentologist!"

I'm sure that you will agree that everyone who has had the pleasure of knowing Phil knows of his enthusiasm about geology, his research and his new collaborations. His continued contributions to the ILSG, his students and his colleagues in furthering our understanding of the geology of the Lake Superior region make him a more than worthy recipient of the 2017 Goldich Medal.

Mark Smyk *P.Geo.*
Ontario Geological Survey
Goldich Medallist (2005)

Honouring 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)

Douglass Houghton

Douglass Houghton: A Professional Scientist

Douglass Houghton, born in 1809, became a pioneer when his parents moved, around 1810, with their children some 400 miles into the wilderness to Fredonia, New York (Wallin, 2004). At age 20, in late 1829, Douglass was among the earliest graduates from Rensselaer Scientific School (now Rensselaer Polytechnic Institute) with a B.A. degree in the areas of natural history (including geology) and chemistry. As a result of his exceptional performance in early 1830 he became an assistant professor at Rensselaer. Rensselaer is the oldest technological university in North America, established 1824 in Troy, New York. Modern geology began with the publications of James Hutton in 1785, hence modern geological studies were still “young” by 1824 when Rensselaer was founded and Houghton graduated. Rensselaer was the preeminent educational institution for geology from its founding until the latter part of the 1800’s and as such many prominent American geologists were graduates of Rensselaer (Krause, 1992). Thus, by being a graduate of Rensselaer, Houghton had recognized credentials as a professional scientist.

The Territory of Michigan was organized in 1805 and in 1830, the Territorial Governor of Michigan, General Cass, asked Douglass Houghton to lecture in Detroit on geology, chemistry, and botany. His lectures were such a success that he quickly became a scientific pioneer and an important citizen of Detroit and the Michigan Territory. By 1830, Douglass Houghton was recognized as Michigan’s leading geological expert and Henry Rowe Schoolcraft asked him to be part of his federally approved 1831 expedition to the Lake Superior area. While Schoolcraft was uncertain as to the source of the copper boulders, Houghton’s report connected the copper boulder to the trap-rock bedrock (Krause, 1992). In 1831, Houghton returned to Fredonia and became a licensed physician leading to accounts of him as Dr. Douglass Houghton although he did not have a formal degree in medicine.

Michigan’s First State Geologist



Douglass Houghton life sized oil painting by Bradish, 1870's on exhibit at the A. E. Seaman Mineral Museum.

Michigan was admitted to Statehood at in January of 1837 after it yielded to Ohio a strip of land, including Toledo, for the Upper Peninsula with the copper district described by Douglass Houghton in 1831-1832. The new state legislature quickly created the state geological survey in February of 1837 and Douglass Houghton was appointed the first State Geologist of Michigan (Wallin, 2004). In 1838 the American Journal of Science published a review commending the new State of Michigan for initiating a geological survey of the state by Douglass Houghton, a recognized professional (Krause, 1992). Houghton’s geological surveys of 1837 to 1839 were focused on Lower Michigan and his 1840 geological survey focused on the Upper Peninsula (Wallin, 2004). His copper report published in 1841 was his greatest contribution to Michigan geology (Krause, 1992) and triggered the beginning of migration to the Keweenaw Peninsula in search of copper. Houghton’s national and Michigan recognition gave credibility and instant recognition to his report. While Schoolcraft previously reported on the existence of copper in the Keweenaw Peninsula a decade earlier, Schoolcraft did not have the professional credentials or recognition of Houghton.

From 1842 to 1844 Houghton's geological surveys waned although the rush to the Keweenaw Peninsula was increasing (Krause, 1992). Houghton was elected mayor of Detroit in 1842 despite being absent and his success at being mayor led people to consider him as having potential for higher political office (U.S. senate) (Krause, 1992). In 1844 Houghton presented a convincing paper in Washington and as a result was contracted by the federal government to continue his geological survey of the Upper Peninsula. In 1844 he was also lauded by Michigan newspapers for his personal geological investigations having more impact than any single person in any state (Krause, 1992). By the summer of 1845 the first mining rush in North America to the Keweenaw Peninsula was well underway. Houghton's federal geological survey began in May of 1845. However, in October of 1845, only one month after he turned 36, Douglass Houghton drowned in a boating accident in Lake Superior not far from Eagle River, Michigan.

Houghton struggled to understand the significance of predominance of native copper in glacial boulders and in surface outcrops of the Keweenaw Peninsula. He believed, consistent with scientific thought of the day that at depth there should be copper sulfides (Krause, 1992). Unfortunately, Houghton died just before native copper began being produced in significant quantities from the Cliff Mine near Eagle River (Wallin, 2004).

Epilogue

Since his death Houghton has been the subject of multiple memorials (see Wallin, 2004; Krause, 1992). In the Keweenaw Peninsula there are several geographic features named after him such as the City of Houghton, Houghton County, Mount Houghton and Douglass Houghton Falls. In the lower peninsula of Michigan, Houghton Lake (the largest inland lake in Michigan) is named after him. There are monuments that mention Houghton and in Eagle River, Michigan a stone monument stands as a tribute to Douglass Houghton. In Eagle River, near the historic bridge across Eagle River and adjacent to the former Eagle River School an official State of Michigan historic marker was dedicated September 2016.

Douglass Houghton was a nationally-recognized modern professional geologist. He was among early modern geologists of North America. He was the first official geologist of the newly formed State of Michigan. His geological investigations and copper report in 1841, 176 years ago, led to the first mining rush in North America to the Keweenaw Peninsula on the south shore of Lake Superior.

Douglass Houghton is a Pioneer of Lake Superior Geology.

References

- Krause, David, 1992, The making of a mining district: Keweenaw native copper 1500-1870: Wayne State University Press, Detroit, MI, 305 p.
Wallin, H., 2004, Douglass Houghton, Michigan's First State Geologist 1837-1845: Geological and Land Management Division, Pamphlet 1, 20p.

Theodore J. Bornhorst

A. E. Seaman Mineral Museum, Michigan Technological University

Lawrence J. Molloy

President, Keweenaw County Historical Society

This tribute to Douglass Houghton was modified with permission from "A tribute to Douglass Houghton: "Michigan's Pioneer Geologist" by Bornhorst and Molloy published in 2017 by the Michigan Basin Geological Society. We have principally relied Wallin (2004) and Krause (1992) to summarize Houghton's contributions.

James W. Trow (1922 – 2016)

With the death of James William (Jim) Trow on November 17, 2016 in Hancock, Michigan we lost a widely admired friend and mentor, and geology lost one of its more innovative scientists. Jim was a truly unique and highly creative individual, having been educated in the Socratic method of learning in the educational system established by Robert M. Hutchins at the University of Chicago. He was born April 22, 1922 in Chicago and entered the University of Chicago in 1939 where he gained the S.B. in 1943, the S.M. in 1945 under R. T. Chamberlin, and the Ph.D. in 1948 under Francis J. Pettijohn, with Norman L. Bowen as his secondary advisor and mentor. Pettijohn said he was the most talented student in the department during his, Pettijohn's, years at Chicago (1929 – 1952). He was unusual for the times in building a strong foundation in electricity and magnetism, thermodynamics, differential equations and physical chemistry, but his passion was structural geology and petrology. For his dissertation, Pettijohn assigned him the knotty problem of the structure, petrology, and depositional context of the Sturgeon Quartzite of the Lower Proterozoic in the Menominee Iron District of Northern Michigan. He meticulously solved it hands down; even Bowen went into the field to see his work.



Upon joining the faculty at Michigan State University in 1947 he immersed himself in teaching at a time when the university was dealing with a large influx of ex-servicemen whose education had been interrupted by World War II. He developed detailed graduate student research programs extending throughout the Great Lakes region, which were often directly related to problems of interest to mining companies. He taught structural geology and engineering geology courses to two generations of geologists and engineers from 1947 to 1997 and supervised the research of numerous doctoral and master of science students. In developing the dynamic and entertaining lecture style for which he became widely known, where students even from other departments came to watch, he said he was unable to emulate Pettijohn who carefully wrote everything out beforehand or J Harlen Bretz who used piles of 4x5 cards with tiny print, but it was Bowen who taught him to lecture logically, linearly, and extemporaneously “like a Baptist or Methodist preacher.” His “free thinking” intense interest in a broad variety of topics and critical thinking, coupled with his Edwardian style and bearing, brought him the everlasting admiration of multitudes of students.

Although steeped in a liberal education background, Jim considered himself a pragmatic prospector or “explorationist” using his strong intellectual abilities, powers of observation, and wide range of geological knowledge to identify sites of potential ore bodies. His thinking was always “out of the box.” As reflected in one of his many professional proficiencies, he listed: *Thinking in fundamental terms across a broad spectrum of scientific and economic disciplines focused upon the discovery of ores, the making of mines, and the creation of jobs and profits.* He consulted for a wide range of mining companies, from Anaconda to Falconbridge and Exxon, and state and federal geological surveys across North America. He continued these efforts upon retiring from MSU by moving to the copper range of the Upper Peninsula of Michigan. For many decades he was ahead of the profession and was, for example, subsequently proven stunningly correct in seeking the ultimate bedrock source of diamonds in the midcontinent glacial drift. Until physically unable he was still involved in developing and perfecting new techniques for mineral exploration.

Jim was an “old school” gentleman and a person of the highest integrity who was not reluctant about expressing his thoughts and feelings as reflected in his personal philosophy: *If you want a paper-pushing, glad-handing, elbow-bending, face-saving corporate gymnast who is attempting to build an empire of white coated labologists and theorists, then for God's sake don't hire me. But, if you want to find new mines, then you could use me.* He was predeceased by his wife and son.

William J. Hinze, Purdue University
Bruce D. Marsh, Johns Hopkins University
Milton A. Gere, DeWitt, Michigan

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 2016, the ILSG Board of Governors selected one student to be granted a research funding from the Joe Mancuso Student Research Fund. The awardee was:

Vittoria Smith

243 Carl Ave.

Thunder Bay, ON

Lakehead MsC geology vlsmith@lakeheadu.ca

TOPIC: *Comparative isotopic fractionation in pegmatites and potential applications to rare-element exploration.*

Award: \$500

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.

2017 Student Paper Awards Committee

Mark Puumala – Ontario Geological Survey

Amy Radakovich – Minnesota Geological Survey

Laurel Woodruff – U. S. Geological Survey

Board of Directors

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

Anthony Pace (2017-2020) – Ontario Geological Survey

Christian Schardt (2016-2019) – University of Minnesota Duluth

Rob Cundari (2015-2018) – Ontario Geological Survey

Jim Miller (2014-2017) – University of Minnesota Duluth

Pete Hollings - Secretary (2017-2020) – Lakehead University

Mark Jirsa – Treasurer (2015-2018) – Minnesota Geological Survey

Local Committee

Anthony Pace

Ontario Geological Survey
Ministry of Northern Development and Mines

Ann Wilson

Ontario Geological Survey
Ministry of Northern Development and Mines

Theodore J. Bornhorst

A. E. Seaman Mineral Museum
Michigan Technological University

Margaret J. Hanson

A. E. Seaman Mineral Museum
Michigan Technological University

Session Chairs

Mary Kay Arthur – Geological Society of Minnesota

Ron Barber – Barrick Gold Corporation

Bill Cannon – U. S. Geological Survey

Pam Coles – Abitibi Geophysics

Dave Good – University of Western Ontario

Mary Louise Hill – Lakehead University

Greg Paju – Ontario Geological Survey

Ann Wilson – Ontario Geological Survey

Field Trip Leaders

Field trips have been the mainstay of the ILSG since its inception 62 years ago. We want to give a special thanks to the field trip leaders who volunteered their time and talent in carrying that tradition forward.

1) Archean and Proterozoic Geology of the Marathon-Hemlo Area

Allan MacTavish - Panoramic PGMs Canada Ltd.

Mark Puumala, Mark Symk, and Tom Muir - Ontario Geological Survey

2) More Unusual Diamond-bearing Rocks of the Wawa Area

Ann Wilson

Ontario Geological Survey

3) Geology of the Wawa Gold Project

Jean-Francois Montreuil, Quentin Yarie, and Conrad Dix

Red Pine Exploration Ltd.

4) Geology of the Island Gold Mine

Doug MacMillan, S. Comtois-Urban, and Harold Tracanelli

Richmont Gold Mines Ltd.- Island Gold Exploration Department

5) Geology of the Renabie Area

Lise Robichaud

Ontario Geological Survey, MNDM

Jordan McDivitt

Laurentian University

6) Kapuskasing Structural Zone and Borden Lake Gold Deposit

Pierre Bousquet

Ontario Geological Survey, MNDM

Jason Rickard

Goldcorp Inc.

Sponsors

The following organizations and individuals made general contributions to the 63rd Annual Meeting. We thank them for their commitment to the Institute on Lake Superior Geology. All of the funds contributed this year go toward travel awards for student registrants.



ARGONAUT GOLD



INDIVIDUAL CONTRIBUTORS TO STUDENT TRAVEL SCHOLARSHIPS

MARY KAY ARTHUR

GORDON MEDARIS, JR.

With an especially generous donation provided by

RON SEAVOY

Report of the Chairs of the 62nd Annual Meeting

Duluth, Minnesota

The 62nd ILSG was held in Duluth, Minnesota on May 4-8, 2016. The meeting was organized by Jim Miller (UMD, general meeting chair), Christian Schardt (UMD, program chair), and Dean Peterson (Peterson Geoscience, field trip chair) with considerable assistance from Louise Miller, Julie Heinz, and the staff of the Duluth Entertainment and Convention Center. The meeting was attended by a total of 246 registrants, including a record 84 students. Special thanks to corporations (Teck American, Barr, Arcelor Mittal, Foth), organizations (Mesabi Range Geological Society, Richard Patelke Memorial Scholarship), and individuals (Mary Arthur, John Berkley, Dan Costello, Ryan Dayton, Henry Djerlev Eric Dott, William Everett, Steve Hoaglund, Allan MacTavish, Gordon Medaris, Jr., Daniel Romanelli, Ron Seavoy, Harvey Thorleifson) who provided financial support for students to attend the meeting at reduced cost.

A total of 44 talks (15 by student) and 47 posters (28 by students) were presented over the two-days of technical sessions. Morning session talks on Thursday, May 5th focused on the petrology and metallogensis of Archean to Paleoproterozoic igneous rocks, Precambrian geochronology, and Archean sedimentation and structure. The afternoon sessions included talks on Midcontinent Rift geology and mineralization and on environmental geology topics related to mining and exploration in the Lake Superior region. Technical talks continued through Friday morning and focused on Proterozoic tectonics and sedimentation. After lunch break, Jim Miller, Dean Peterson, Mark Jirsa, and George Hudak, gave talks reflecting on the 10 year anniversary of the Precambrian Research Center at the University of Minnesota-Duluth. This was followed by presentations of student travel grants and best student paper awards to Brigitte Gelinis and Sophie Kurucz (presentations) as well as Alexandra Kozlowski and Benjamin Hinks (posters).

Given the record number of oral and posters presentations, the organizers want to especially thank the diligent work of the best student paper award committee members – Karl Everett, Dyanna Czeck, Tim Kroeger, Michael Zieg, and Dorothy Campbell.

The annual ILSG banquet was held at the DECC ballroom on Thursday evening and was attended by 156 individuals. The 2016 Goldich Medal was awarded to Mark Jirsa of the Minnesota Geological Survey. Terry Boerboom presented the award during the annual banquet citing Mark's many contributions to the geology of the Lake Superior region and to his service to the ILSG. Mark has served as treasurer of the ILSG for over 20 years (1994-2002, 2005-present). The evening banquet speaker was Peter Clevenstine, Assistant Director of Minerals for the Minnesota Department of Natural Resources. The title of Pete's talk was: "Managing Minnesota's Mineral Resources and the DNR's Conservation Agenda".

The meeting offered one two-day field trip, five one-day field trips and two half-day field trips which were attended by a total of 211 participants. Three pre-meeting full-day field trips were offered on Wednesday May 4th, including 1) *Glacial Geology of the Laurentian Uplands* (24p) led by Phil Larson (Vesterheim Geoscience PLC) and Howard Mooers (UMD), 2) *Neoarchean Geology of the Western Vermilion District* (38p) led by Mark Jirsa, Terry Boerboom, and Amy Radakovich (MGS), and 3) *Cu-Ni-PGE Deposits of the Duluth Complex* (28p) led by Mark Severson (Teck American), Andrew Ware (PolyMet Mining), Kevin Boerst (Twin Metals Minnesota), and Steve Geerts (UMD-NRRI). A half-day trip on the *Geology of the Endion Sill, Duluth* (16p) was led by Jim Miller (UMD) on Wednesday afternoon.

Four post-meeting field trips were offered. On Friday evening, Dean Peterson (Peterson Geoscience) and George Hudak (UMD-NRRI) lead a trip on the *Geology and Fishing along Amity Creek, Duluth* (17p) followed by a picnic at George's yard. Two one-day trips, *Keweenaw Geology of the Hovland Area* (37p) led by Terry Boerboom (MGS) and John Green (UMD) and *Duluth Harbor Geologic History Boat Cruise: Quaternary to Anthropocene* (22p) led by Irv Mossberger, Meghan Blair, Eric Dott (Barr Engineering), Andy Breckenridge (UW-Superior), and Todd Kremmin (UMD) were run on Saturday. A two-day trip on

the *Archean and Proterozoic Geology of the Western Gunflint Trail* (27p) was led by Mark Jirsa (MGS) on Saturday and Sunday.

The Institute's Board of Directors met on Thursday May 5th to discuss the business of the Institute. The meeting was attended by meeting co-chair Christian Schardt, Treasurer Mark Jirsa, Secretary Peter Hollings and board members Jim Miller (2017 chair), Theodore Bornhorst (2016 chair) and Robert Cundari (2018 chair). Secretary Hollings took the minutes of the Board meeting that are as follows:

1. Accepted report of the Chairs for the 61st ILSG, Dryden, Ontario; as printed in the Proceeding Volume (Cundari), and minutes of last Board meeting, May 21, 2015 (Hollings)
2. Received, discussed, and accepted 2015-2016 ILSG Financial Summary (Jirsa).
3. Received, discussed, and accepted 2015-2016 report of the Secretary (Hollings).
4. Approved Christian Schardt as on-going ILSG Board member
5. Discussed and approved renewal of Pete Hollings as Institute Secretary (end of term 2019). This was later approved by a vote of the membership.
6. Approved Wawa as the site for the 63rd annual ILSG meeting. The meeting will be hosted by Ann Wilson, Anthony Pace, and Ted Bornhorst.
7. There was discussion as to the future meeting locations with Cobalt, Sudbury and Eau Claire being suggested as possibilities.
8. Discussed and approved replacing Mark as the "member from government" on Goldich Committee (end of term 2016) with Klaus Schulz.
9. The suggestion that we find some mechanism to Honor our Pioneers was raised by Gene La Berge. This was discussed and it was decided that the membership would be invited to nominate candidates (active prior to 1955) and then one or two would be selected each year and a presentation made during the Annual Meeting. The first two presentations will be given at the 63rd Annual Meeting. The Secretary will prepare a set of guidelines and circulate to the Board for approval.
10. Jirsa reported on the cost of Director's insurance. Preliminary discussions with one company suggests a cost of \$1000 to \$1500 per year for ~\$1million of coverage. This was considered too expensive and Board members were encouraged to enquire with their personal insurers to see if they were covered. Jirsa and Hollings to investigate further.
11. Bornhorst and Hollings to develop a set of field safety guidelines to be circulated to incoming meeting Chairs.
12. The Mancuso student paper awards were discussed and it was agreed that they would be limited to a maximum of four per year, but the exact division of the awards would be decided by the awards committee.

The 2016 meeting organizers would like to again thank all those who assisted with the meeting including the field trip leaders, session chairs, best student paper committee members, Goldich committee members, the DECC staff, and those who provided support behind the scenes. We would also like to thank the professional and student participants of the meeting, the field trip attendees, and the oral and poster presenters for their enthusiastic involvement with the Institute. Your active participation year after year is what makes the ILSG one of the best regional geoscience meetings in North America.

Respectfully submitted,
Jim Miller, Christian Schardt, Dean Peterson
Co-chairs, 62nd Institute on Lake Superior Geology

TECHNICAL PROGRAM

MONDAY MAY 8, 2017

Field trip 1 begins in Marathon, Ontario

8:00 am - 5:30 pm **PRE-MEETING FIELD TRIP**

1) Archean and Proterozoic Geology of the Marathon-Hemlo Area

Mark Puumala - Ontario Geological Survey, MNM

Allan MacTavish - Panoramic PGMs Canada Ltd.

TUESDAY MAY 9, 2017

Field trip 1 begins and ends in Marathon, Ontario; Field trips 2 and 3 begin and end at the Michipicoten Memorial Community Centre, Wawa, Ontario

8:00 am - 5:30 pm **PRE-MEETING FIELD TRIPS**

1) Archean and Proterozoic Geology of the Marathon-Hemlo Area

Mark Puumala - Ontario Geological Survey, MNM

Allan MacTavish - Panoramic PGMs Canada Ltd.

2) More Unusual Diamond-bearing Rocks of the Wawa Area

Ann Wilson - Ontario Geological Survey, MNM

3) Geology of the Wawa Gold Project

Jean-Francois Montreuil - Red Pine Exploration Ltd.

4:00 pm - 10:00 pm **Registration** (Michipicoten Memorial Community Centre)

7:00 pm - 10:00 pm **Welcoming Reception** (Michipicoten Memorial Community Centre)
Poster Session (Michipicoten Memorial Community Centre)

WEDNESDAY MAY 10, 2017

7:30 am – 11:30 am **Registration** (Michipicoten Memorial Community Centre)

8:00 **OPENING REMARKS** (Michipicoten Memorial Community Centre)
Anthony Pace, Ann Wilson, and Ted Bornhorst, Co-Chairs, 2017 ILSG

8:10 **Theodore J. Bornhorst**
Douglass Houghton – 2017 Pioneer of Lake Superior Geology

TECHNICAL SESSION I

Session Chairs:

Mary Kay Arthur – Geological Society of Minnesota

Greg Paju – Ontario Geological Survey

8:20 **Gordon Medaris Jr., Seungyeol Lee, Huifang Xu, John Fournelle, and Esther Stewart**

Precipitation of pedogenic quartz and concurrent bulk removal of silica during sub-Cambrian Weathering – a paradox resolved

8:40 **Brittany Ramsay* and Philip Fralick**

Sedimentology and geochemistry of the 2310 Ma Kona Dolomite, Huronian Supergroup, Northwestern Ontario and western Upper Peninsula of Michigan

9:00 **Luke Schranz*, Laurel Goodwin, Philip Brown, Gordon Jr. Medaris, and John Valley**

Stable oxygen isotopes, fluid inclusions, and microstructures in quartz cements and veins in the Baraboo Quartzite Breccia, north Baraboo Range, central Wisconsin

9:20 **Sophie Kurucz* and Philip Fralick**

The Espanola Formation: A Huronian Paleoproterozoic cap carbonate

9:40 **COFFEE BREAK**

10:10 **Christian Schardt**

High-technology metals in sulfide systems: In, Ge, Ga, and Tl content in the Vermilion District and Duluth Complex, northern Minnesota

10:30 **Yonghua Cao*, Robert L. Linnen, Dave Good, Iain M. Samson, John McBride, Rachel Epstein**

Igneous stratigraphy and Cu-Pd mineralization at Area 41 within the eastern gabbro, Coldwell Alkaline Complex, Canada

10:50 **Robert Cundari, Pete Hollings and Mark Smyk**

Geology and geochemistry of Proterozoic dykes in Pukaskwa National Park, Ontario: insights into the Midcontinent Rift-related Pukaskwa dyke swarm

11:10 **Dave Good, John McBride, Rachel Epstein, Rob Cundari, and Pete Hollings**

Progression from tholeiitic to alkaline basalt magmatism in the early stages of formation of the Coldwell Alkaline Complex, Midcontinent Rift, Ontario

11:30 **End of Technical Session I**

11:30 **LUNCH BREAK**

ILSG BOARD OF DIRECTORS MEETING

TECHNICAL SESSION II

Session Chairs:

Dave Good – University of Western Ontario

Ann Wilson – Ontario Geological Survey

- 1:00 **D. Nikkila*, R.H. Mitchell, and S.E. Zurevinski**
The mineralogy and petrology of layered series nepheline syenite within Center II of the Coldwell Complex
- 1:20 **V.J.S. Grauch, Morgan Sanger, Eric D. Anderson, and Esther Kingsbury Stewart**
Revisiting geophysical interpretations of the Midcontinent Rift below Lake Superior
- 1:40 **H. Gunawardana*, P.J.A. McCausland, D.J. Good, and J. McBride**
Use of anisotropy of magnetic susceptibility (AMS) to analyze petro-fabrics in Cu and PGE bearing gabbroic units of the Marathon Cu-PGE deposit, Ontario.
- 2:00 **POSTER SESSION – AUTHORS WILL BE PRESENT AT THEIR POSTERS**
- 3:00 **COFFEE BREAK**
- 3:20 **Margaret Upton*, Christian Schardt, George Hudak, and Tom Quigley**
Alteration zonation and geochemical characteristics of the Back Forty deposit, MI, a replacement-style volcanogenic massive sulfide deposit
- 3:40 **S. Losh**
Hydrothermal “natural ore” in the Fayal Reserve Mine, Mesabi Range, Minnesota
- 4:00 **Bailey Drover* and Mary Louise Hill**
Characterizing the grade of metamorphism and depth of burial of the Gunflint Formation near Thunder Bay, Ontario
- 4:20 **Matthew W. Matko* and Christian Schardt**
Microanalysis of rock and mineral textures and its relationship to mineralization
- 4:40 **End of Technical Session II**
-

6:00 **RECEPTION AND CASH BAR** (Michipicoten Memorial Community Centre)

7:00 **ANNUAL BANQUET** (Michipicoten Memorial Community Centre)

- Announcement of 64th Annual Meeting Location
- **2017 Goldich Award Presentation to Philip Fralick**
- Banquet Presentation - **Johanna Rowe** – Mining in Michipicoten

THURSDAY MAY 11, 2017

8:15 **OPENING REMARKS, UPDATES** (Michipicoten Memorial Community Centre)
Anthony Pace, Ann Wilson, and Ted Bornhorst, Co-Chairs, 2017 ILSG

TECHNICAL SESSION III

Session Chairs:

Bill Cannon – U. S. Geological Survey

Mary Louise Hill – Lakehead University

8:20 **Tyrone Rooney, Andrew Lavigne, Chris Svoboda, Mingda LV, Jacob Bonessi, Zachary Eriksen, Taylor Kelly, Kyle Noyce, Carol Stein, Seth Stein, Rob Moucha, and Eric Brown.**

The Lake Shore Traps – A terminal cycle of the Keweenaw flood basalt event

8:40 **Munira Afroz* and Philip Fralick**

Geochemistry of 2.94 Ga Mesoarchean iron formation in Red Lake Area, Ontario

9:00 **Erik Haroldson*, John Valley, Robert Bodnar, Akizumi Ishida, and Philip Brown**

Fluid history of the Reef deposit using fluid inclusions and oxygen isotopes

9:20 **Ross A. Salerno*, John W. Goodge, Jeff D. Vervoort**

Short-interval deposition, metamorphism, and intrusion in the Neoarchean Vermilion Granitic Complex, Superior Province, Northern Minnesota

9:40 **COFFEE BREAK**

10:10 **Kira Arnold*, Pete Hollings, and Seamus Magnus**

Geology and geochemistry of the Terrace Bay Batholith, N. Ontario

10:30 **Monica McCullough* and Philip Fralick**

Sedimentological Features in the Strata in and Adjacent to the Sudbury Impact Layer in the Northern Paleoproterozoic Animikie Basin

10:50 **W.F. Cannon, Laurel G. Woodruff, Mark Jirsa, and William Everett**

New observations on distal ejecta from the Sudbury impact in the central Mesabi iron range, Northern Minnesota

11:10 **James Farquharson* and Mary Louise Hill**

Microstructural analysis of the Plateau South Property, Yukon

11:30 **End of Technical Session III**

11:30 **LUNCH BREAK**

TECHNICAL SESSION IV

Session Chairs:

Ron Barber – Barrick Gold Corporation

Pam Coles – Abitibi Geophysics

- 1:00 **Dave Good, Imran Meghji, Robert Linnen, Iain Samson, and Rob Cundari**
Cogenetic relationship between the Wolf Camp basalt and the Geordie Lake intrusion, Coldwell Alkaline Complex, Midcontinent Rift, Ontario
- 1:20 **Tom Waggoner**
Trace Elements in iron oxides on the Marquette Range and Hemlock Volcanics
- 1:40 **John Esch**
Determining bedrock depths using the Horizontal-To-Vertical Spectral Ratio (HVSr) passive seismic method – examples from Michigan
- 2:00 **Michael J. Zieg, Blake M. Wallrich, and Samuel V. Hone**
Internal fractionation and phenocryst accumulation in the Black Sturgeon sill, Ontario
- 2:20 **Cody Suits, Mark Dehoog, and Steve Beach**
Directional drilling at Eagle, pros and cons, technical success, and Ni-Cu-PGE discovery in the Baraga Basin, Michigan.
- 2:40 **BEST STUDENT PAPER AWARDS**
STUDENT TRAVEL AWARDS
- 3:00 **END OF TECHNICAL SESSIONS**

* 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.

FRIDAY MAY 12, 2017

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

Field trips 4 and 5 begin and end at the Michipicoten Memorial Community Centre, Wawa, Ontario; Field trip 6 begins and ends in Chapleau, Ontario

4) Geology of the Island Gold Mine

Harold Tracanelli and Doug MacMillan - Richmond Gold Mines Ltd.

5) Geology of the Renabie Area

Lise Robichaud, Joe Walker, and Ann Wilson - Ontario Geological Survey, MNDM

6) Kapuskasing Structural Zone and Borden Lake Gold Deposit

Pierre Bousquet - Ontario Geological Survey, MNDM

POSTER PRESENTATIONS

Eric D. Anderson and V.J.S. Grauch

Aeromagnetic data yield preliminary depth estimates to magnetic sources underlying Lake Superior

Eric D. Anderson and V.J.S. Grauch

Updated aeromagnetic and gravity anomaly compilations and elevation-bathymetry models over Lake Superior

R.A. Ayuso, K.J. Schulz, W.F. Cannon, L.G. Woodruff, J.A. Vazquez, and J. Jackson

Evidence for the Presence of Eoarchean Crust in Northern Michigan

Steven D.J. Baumann, and Sandra K. Dylka

Possibility of the Dake Quartzite being younger than the Baraboo Formation

Jacob Bonessi*, Tyrone Rooney, Chris Svoboda, and Guillaume Girard

Silicic volcanism of the Porcupine Volcanics; implications for magma differentiation during the terminal stages of volcanism within the Midcontinent Rift

Thomas W. Buchholz, Alexander. U. Falster, and Wm. B. Simmons

A roadside pegmatite in the Stettin Complex, Wausau Syenite Complex, Marathon County, Wisconsin.

Dana Campbell*, Shannon Zurevinski., Amanda Diochon, and Rudy Wahl

Investigations of Target No. 6: a potential new kimberlite in the Marathon area, NW Ontario

Amy Cleaver*, Roger Mitchell, Shannon Zurevinski, and Rudy Wahl

The Mineralogy and Petrology of the Good Hope Carbonatite Occurrence, Marathon, Ontario, Canada

Samuel V. Hone*, Michael J. Zieg, and Blake M. Wallrich

Geochemical relationships between the Black Sturgeon sill and other Midcontinent Rift igneous units

Ann Hunt* and John Goodge

Field and Petrographic Evidence of Migmatite Formation near Lake Kabetogama, Voyageurs National Park, Northern Minnesota

Mark A. Jirsa, Terrence J. Boerboom, Amy L. Radakovich, Val W. Chandler, Dean M. Peterson, Mark D. Schmitz, Elizabeth L. Dengler, Kaleb G. Wagner, Richard S. Lively, and Dale R. Setterholm

Geologic mapping in the Central Arrowhead Area, northeastern Minnesota

Taylor Kelly*, Tyrone Rooney, Chris Svoboda, Andrew Lavigne, and Guillaume Girard
Probing the composition of the Lithospheric Mantle during the Initiation of the Mid-Continent Rift

Esther Kingsbury Stewart and Eric D. Stewart
New Precambrian Geologic Mapping of the Baraboo Hills, Southern Wisconsin Constrains Baraboo-Interval Sedimentation and Deformation

Stephen A. Kissin and Gregory R. Brumpton
Locally Subaerial Evaporitic Minerals (Quartz Pseudomorphs after Gypsum) in the Gunflint Limestone Member and its Relationship to the Deposition of Sudbury Impact Ejecta-Bearing Debrisites

Matthew Larson* and Marcia Bjørnerud
Seismic slip, mylonitization and fluid flow along the Penokean Twelve-Foot Falls Shear Zone, Marinette County, Northeastern Wisconsin

S. Losh, C. Huggins and D. Crane
The Magenta Zone in the Northmet Deposit, Minnesota

Carly Madge, Mark Puumala, and Philip Fralick
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Monica McCullough*, and Philip Fralick
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Morgan Sanger*, Esther Kingsbury Stewart, and V.J.S. Grauch
Seismic Interpretation of the 1.1 Ga Midcontinent Rift volcanic interval beneath Lake Superior

Gerrit VanderWaal and John B. Swenson
Sediment Provenance of Twin Ports Baymouth Bars

Blake M. Wallrich*, Samuel V. Hone, and Michael J. Zieg
Textural and geochemical analysis of a continuous drill core from the Black Sturgeon sill, Ontario

Aaron Witter* and Marcia Bjørnerud
Estimating volcanic SO₂ release from the 1.1 Ga Mid-Continent Rift through comparison with Phanerozoic flood basalt events

* 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.

ABSTRACTS

Geochemistry of 2.94 Ga Mesoarchean Iron Formation in Red Lake Area, Ontario

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Older rocks in the Red Lake greenstone belt comprise the Ball & Balmer assemblages of Uchi subprovince. The Ball assemblage consists of volcanic flows, pyroclastic rocks, chemical sediments, e.g. magnetite-chert, dolomite-chert and metasedimentary rocks, which were deposited between 2.94-2.92 Ga of the Mesoarchean Era (Sanborn-Barrie et al, 2000; Hofmann et al, 1985; Corfu & Wallace, 1986). This study focuses mainly on a magnetite-chert section.

A 3.5 m thick unit of magnetite-chert iron formation in the Ball assemblage was studied. The magnetite is interbedded with chert and contains pyrite, pyrrhotite and carbonate veins. The IF is overlain by volcanic ash and siltstone and underlain by siltstone with numerous carbonate veins. Geochemical analysis was conducted on core samples using ICP-AES and ICP-MS for whole rock and REE analysis respectively.

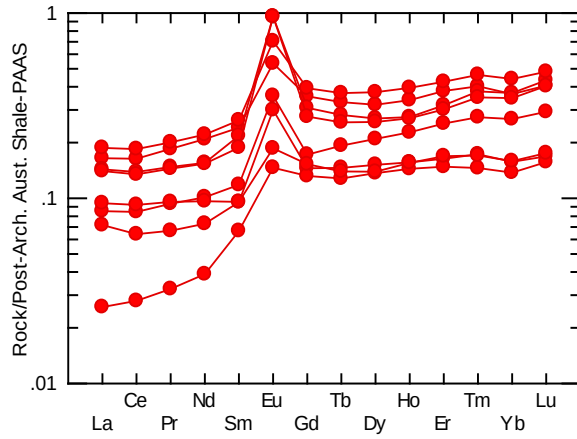


Figure 1: REE plot of Magnetite

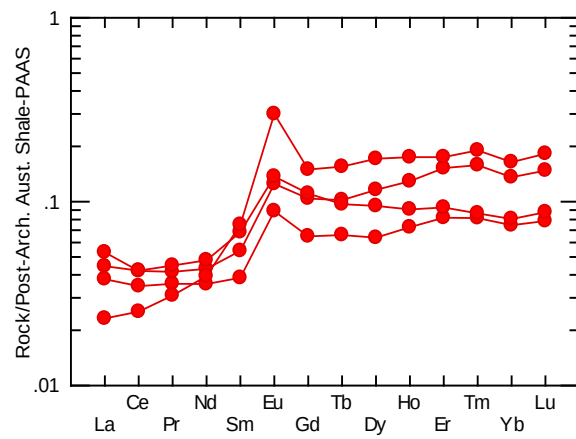


Figure 2: REE plot of Chert

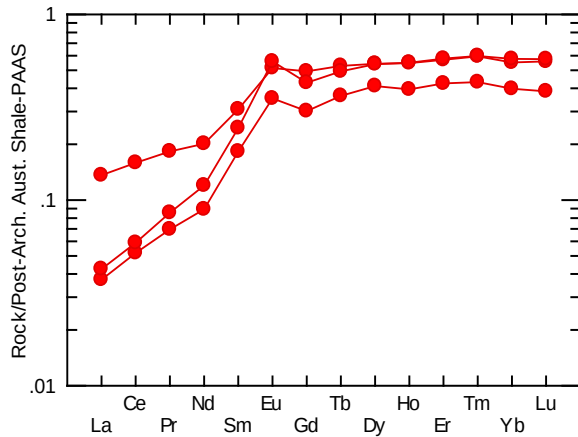


Figure 3: REE plot of Siltstone & Volcanic ash

High temperature (~250°C) leaching by hydrothermal fluids of basalt, and sediment derived from it, with +Eu anomalies (Figure 3) resulted in the Archean ocean being enriched in Eu compared to other rare earth elements. The positive Eu anomalies of magnetite (Fig. 1) and chert (Fig. 2) indicate that they inherited this +Eu anomaly as they were precipitated from the Archean ocean in a reducing environment.

Geochemistry of the siliciclastic sediments (Fig. 3) indicates they were derived from basaltic rock. The positive Eu anomalies are due to Ca^{2+} replacement by Eu^{+2} in plagioclase feldspar during crystallization in a basaltic melt (Peter, 2003).

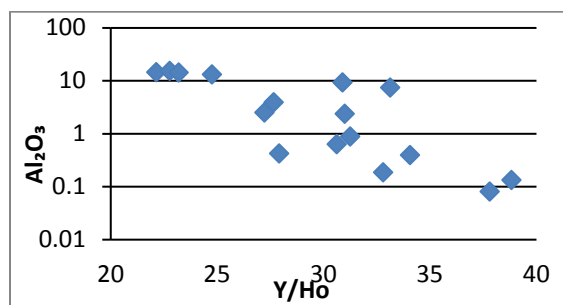


Figure 4: Al₂O₃ versus Y/Ho ratio plot

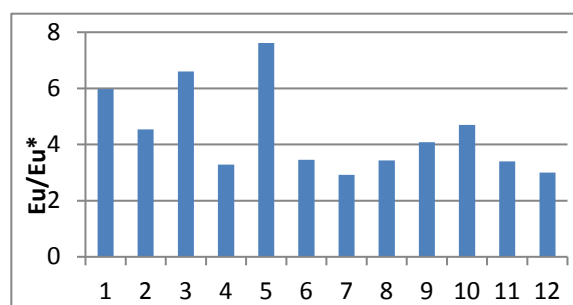


Figure 5: Eu/Eu* trend with depth

The Y/Ho ratio plotted against Al₂O₃ (Fig. 4) shows that the higher the Al concentration the lower the Y/Ho ratio and vice versa (silicic rocks have a Y/Ho in the 20s). Chert has a very low Al content, which confirms its lack of siliciclastics during deposition, and magnetite has a low to a fair amount of Al that indicates possible siliciclastic contamination of some samples. Figure 5 shows the Eu anomaly trend with position in the IF. The upper portion of the IF (at left) exhibits relatively higher Eu anomalies compared to the lower portion at the right. This trend may indicate that the hydrothermal activity increased through time or ocean currents were more favourable for bringing the hydrothermal plume into the depositional area with time.

Therefore, from the analysis, it is suggested that the magnetite bearing IF represents a typical Archean deposit with evidence in its upper portion of more direct high temperature hydrothermal influence. It was somewhat contaminated by siliciclastics derived from basalt.

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Aeromagnetic data yield preliminary depth estimates to magnetic sources underlying Lake Superior

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Aeromagnetic anomalies map lateral variations of magnetic material within the Earth's crust. The anomalies are a measure of the magnetic field produced by both the induced and remanent magnetism of underlying rocks. When remanent magnetism is significant and the magnetic polarity differs from present day, such as within early volcanic rocks associated with the Midcontinent Rift system (MRS), anomaly interpretation and modeling become more complex. The anomaly shape can also be used to estimate the depth to the magnetic source with some methods being insensitive to remanent magnetization. Magnetic anomalies over Lake Superior occur as both short and long wavelength anomalies that are generally curvilinear in form. The short wavelength anomalies reflect upturned volcanic rocks that outcrop on the north shore, Isle Royale, Michipicoten Island, and Keweenaw Peninsula. Within the Lake however, the wavelengths become longer indicating deepening sources. We present calculated estimates to magnetic material using the extended Euler deconvolution method (Phillips, 2002; 2007) which is not sensitive to remanent magnetization (Reid et al., 1990). The results help overcome ambiguity in seismic data interpretation (where layered volcanic and sedimentary rocks show similarly strong reflections) and constrain gravity modeling, both of which are proving helpful for better understanding the 3D geology and metallogeny of the Lake Superior region.

Extended Euler depth analyses (Phillips, 2002; 2007) were applied to a newly compiled magnetic anomaly grid with 400 m cells at an observation height of 300 m (Anderson and Grauch, 2017). The method analyzes the gridded data within a sliding window to obtain estimates of depth to the tops of magnetic sources. A given, idealized geometry of the sources is assumed, described by the mathematical term, structural index (SI). In practice, geologic sources of interest commonly are best represented by SI values somewhere between 0 (contact source) and 1 (sheet source). For this reason, depth analyses are commonly run with both end-member SI values to assess a range of minimum (SI=0) and maximum (SI=1) depth estimates. Window size can also be increased to better evaluate broader anomalies, which generally indicate deeper sources.

For our study, window sizes ranged from 4,400 m to 20,000 m and SI of 0 and 1 were used. For window sizes greater than 10,000 m the magnetic anomaly data were regridded to 800 m grid cell size. The short wavelength anomalies attributed to the upturned volcanic rocks on Isle Royal and to the east show magnetic source elevations above -1,000 m mean sea level (MSL) for SI of 0 and show well clustered solutions when window sizes are <10,000 m (Figure 1). Increasing the SI to 1 results in slightly deeper estimates, above around -2,000 m MSL. Circular magnetic features become apparent in solutions generated from window sizes of 10,000 m and larger. Two such magnetic features occur near White's and Grand Marias Ridges. SI of 0 indicates that the sources are around -3,000 m MSL, whereas an SI of 1 suggests the sources are deeper, around -4,000 m MSL. Linear northeast-striking clusters of solutions occur north of Grand Marias Ridge and indicate shallow magnetic sources around -1,000 m MSL. In the eastern part of the lake, circular, shallow magnetic sources occur about 25 km south of Michipicoten Island and near the southern shoreline both on and off shore. In both areas the magnetic sources

are around -2,000 m MSL with diameters reaching 30 km. East of the Keweenaw Peninsula, the magnetic sources with SI of 0 beneath the lake are relatively shallow, mostly above -1,000 m MSL. The deepest solutions imaged with window sizes >10,000 m are below -9,000 m MSL and occur throughout the lake with gradients indicating basin geometry. In general, the deep solutions in the western part of the lake are parallel to the Keweenaw Peninsula and exhibit steep gradients along the southern shore. The deep solutions in the eastern part of the lake mostly trend north-northwest and east-west.

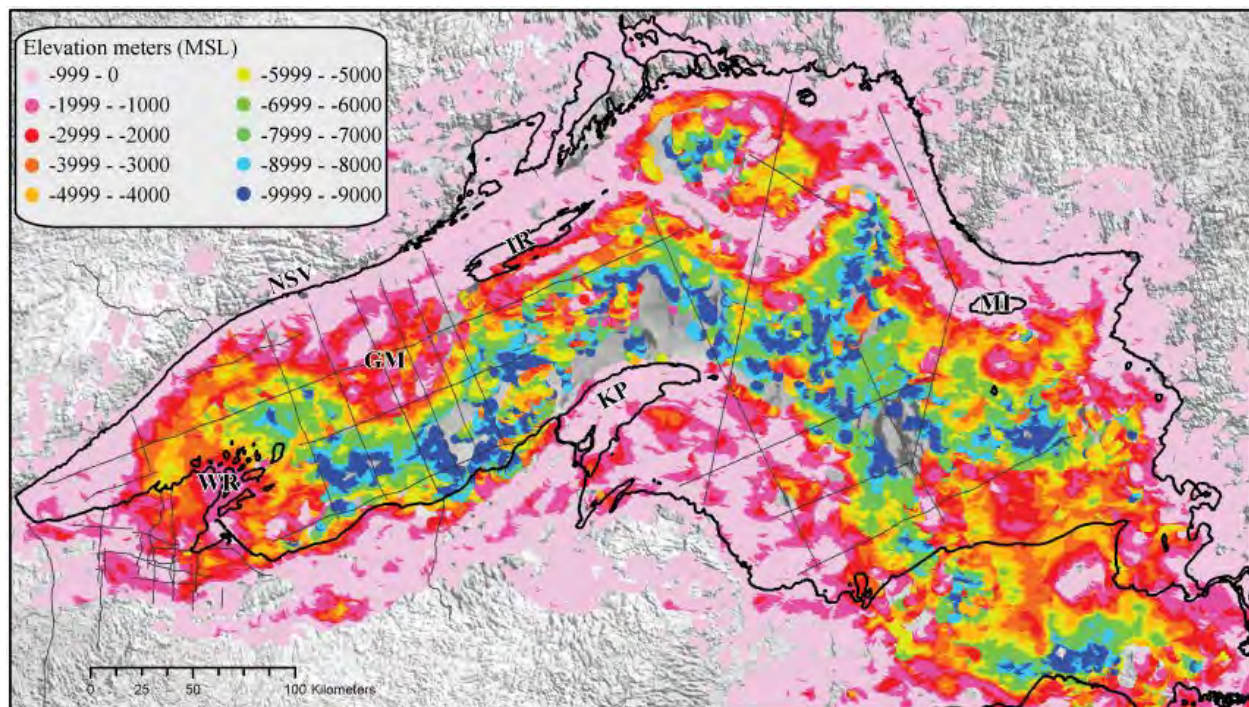


Figure 1: Results of magnetic depth estimate using SI 0 and 10,000 m window size. Lake outline shown as thick black lines. Seismic line locations are thin black lines. WR–White’s Ridge; GM–Grand Marais Ridge; NSV–North Shore volcanics; IR–Isle Royale; KP–Keweenaw Peninsula; MI–Michipicoten Island.

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Updated aeromagnetic and gravity anomaly compilations and elevation-bathymetry models over Lake Superior

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New bathymetry and gravity and magnetic anomaly data sets have been compiled for the Lake Superior region. These data provide continuous sets of observations for geologic interpretations spanning political boundaries such as US States and the US-Canada border. These data are providing constraints for on-going 3D geologic modeling of the midcontinent rift system and are helping to understand the metallogeny of the region.

Land-bathymetry and land-lake surface elevation models were produced by combining Shuttle Radar Topography Mission (SRTM) topography data with lake surface elevation and bathymetry data sets for Lakes Superior, Michigan, and Huron (Table 1). The SRTM data set was chosen because it spans the international border and has relatively high resolution at 30 m cell size. The bathymetry data were regridded from 90 m to 30 m cell size to equal that of the SRTM data. The bathymetry data sets used a shoreline reference datum equal to 0 m; therefore the lake surface elevations recorded in some gravity stations (Superior = 183.1 m, Michigan and Huron = 175.8 m) had to be added to the bathymetry data to match the SRTM datum. These data were then combined resulting in a 30 m land-bathymetry data set. An elevation model showing lake surface elevation was created by filling lake areas with constant elevation values. Both data sets were used in gravity data reduction.

The gravity compilation includes survey stations available from Natural Resources Canada, National Centers for Environmental Information (formerly National Geophysical Data Center), Minnesota Geological Survey, and U.S. Geological Survey (Table 1). Individual databases were combined and duplicates were removed using a 25 m spatial buffer for overlapping observations resulting in a database of 63,880 gravity stations across the region. The database includes the type of gravity station which is important for data reduction. The five gravity station types include: 1. land observation where land is above mean sea level (MSL), 2. lake surface observation where lake surface and lake bottom are above MSL, 3. lake bottom observation where lake bottom and lake surface are above MSL, 4. lake surface observation where lake surface is above MSL and lake bottom is below MSL, and 5. lake bottom observation where lake bottom is below MSL and lake surface is above MSL. The bathymetry and elevation models provided the necessary depth information. The gravity station data were reprocessed from observed gravity to simple Bouguer anomaly following standard methods depending on the station type and a reduction density of 2,670 kg/m³. The final Bouguer anomaly grid consists of 800 m cell size and improves upon previous US-centric compilations (Phillips et al., 1993) and seems to better resolve anomalies over eastern Lake Superior (Klasner et al., 1979).

The updated magnetic data set combines previously published aeromagnetic survey data and compilations available from the Minnesota Geological Survey, Natural Resources Canada, and U.S. Geological Survey (Table 1). The compilations and surveys were first gridded to a cell size of 100 m. Data sets were merged to the existing compilation with highest resolution (Chandler, 2007) using industry standard techniques. Some survey data showed corrugated flight line noise that was removed prior to merging. Flight line spacing and observation height

varied considerably for the individual surveys, so data were analytically continued to a surface draped 300 m above ground and regridded to 400-m cell size. The final compilation provides a consistent dataset appropriate for magnetic modeling that extends across the lake shore. Moreover, anomaly resolution is improved compared to the previous North American compilation (North American Magnetic Anomaly Group, 2002).

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Table 1 New compilation specifications and data sources.

Compilation	Resolution	Input Data Sources
Bathymetry - topography	30 m	National Geophysical Data Center, 1996a; 1996b; National Geophysical Data Center, 1999; SRTM data available from the U.S. Geological Survey
Gravimetric	800 m	Dater et al., 1999; Chandler and Lively, 2014; Gravity station data available from the Natural Resources Canada (http://gdr.agg.nrcan.gc.ca/) and the U.S. Geological Survey (www.sciencebase.gov)
Magnetic	400 m	Chandler, 2007; Aeromagnetic surveys and compilations available from the Natural Resources Canada (http://gdr.agg.nrcan.gc.ca/) and the U.S. Geological Survey (www.sciencebase.gov)

Geology and Geochemistry of the Terrace Bay Batholith, N. Ontario

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The Terrace Bay batholith is a 25 km long oval shaped granitoid intrusion located in the western portion of the Schreiber-Hemlo greenstone belt (Figure 1), part of the larger Wawa-Abitibi terrane. The batholith intrudes the Schreiber assemblage, which is composed of mafic and felsic metavolcanic and metasedimentary supracrustal rocks (Williams et al., 1991). The intrusive rocks in the region have yielded ages ranging from 2678 to 2688 Ma and the volcanic rocks have yielded ages spanning 2771 to 2695 Ma (Corfu and Muir, 1989; Fage, 2011).

This study focuses on describing and classifying the Terrace Bay batholith in order to investigate its petrogenesis and related gold and base metal mineralization. The core of the Terrace Bay pluton is a massive, homogeneous equigranular and locally potassium-feldspar porphyritic granodiorite. Mafic xenoliths are observed commonly in the core of the intrusion and are abundant proximal to the contacts of the intrusion. The granodiorite commonly has phenocrysts of quartz and potassium feldspar and up to 15% mafic minerals, typically amphibole and biotite (Figure 2a). Proximal to its outer contacts, particularly along its eastern and northern edges, the pluton comprises a pink mesocratic to leucocratic amphibole-bearing quartz syenite to syeno-granite. The amphibole quartz syenite typically contains potassium feldspar and quartz phenocrysts with 10-20% amphibole. Mafic xenoliths are more abundant in the amphibole quartz syenite than the granodiorite. The petrogenetic relationship between the syenite and the granodiorite core is currently unclear.

Quartz veins with minor carbonate components occur throughout the pluton. The veins range in width from 0.5 to 40 cm and appear undeformed. The quartz veins occur as individual veins, parallel vein sets (both horizontal and inclined) and in stockwork structures. The North Zone trench located at the eastern end of the batholith contains quartz veins and altered granitoid rocks that host minor to abundant (up to 10%) sulphide minerals including pyrite, chalcopyrite, galena, molybdenite and arsenopyrite. These sulphide-mineralized veins, especially those that are present as parallel vein sets and in stockwork structures, commonly also contain gold mineralization (Puumala et al., 2014).

The granodiorite samples plot in the granite field on a TAS diagram whereas the amphibole syenite varies from syenodiorite to alkali granite. On a primitive mantle normalized spider diagram the granodiorite samples are LREE enriched with unfractionated HREE and display prominent negative Nb and Ti anomalies characteristic of rocks formed in an arc setting (Figure 2b). The amphibole syenite displays the same trends but has undergone alteration and REE loss.

Using additional data to be collected in the summer of 2017, investigation of the petrogenesis of the different rock types and mineralized occurrences in the batholith using detailed petrographic and geochemical analyses will be continued.

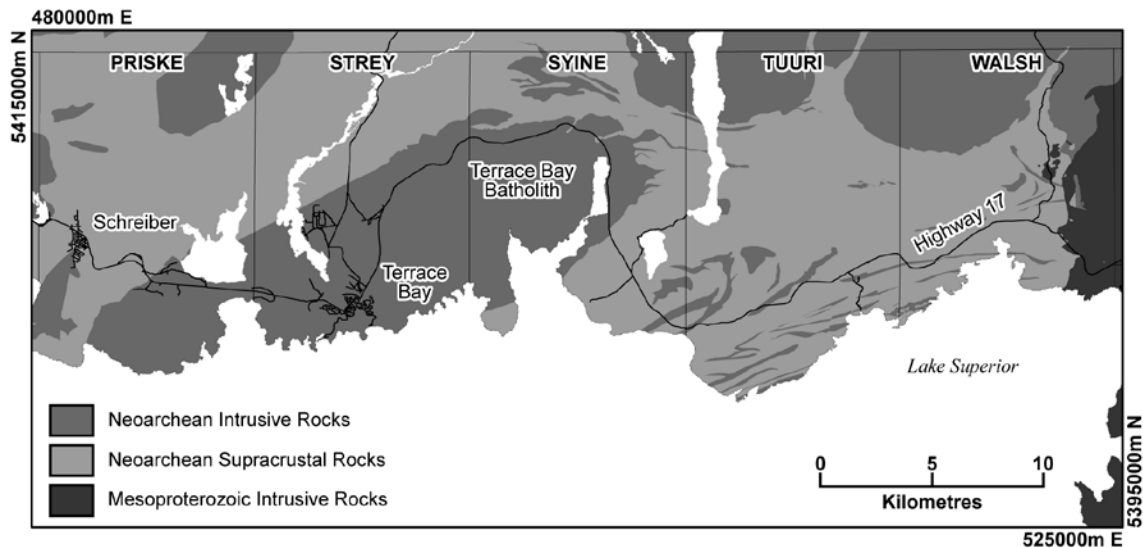


Figure 1. Simplified bedrock geology map of the western Schreiber-Hemlo greenstone belt. From Magnus and Arnold 2016.

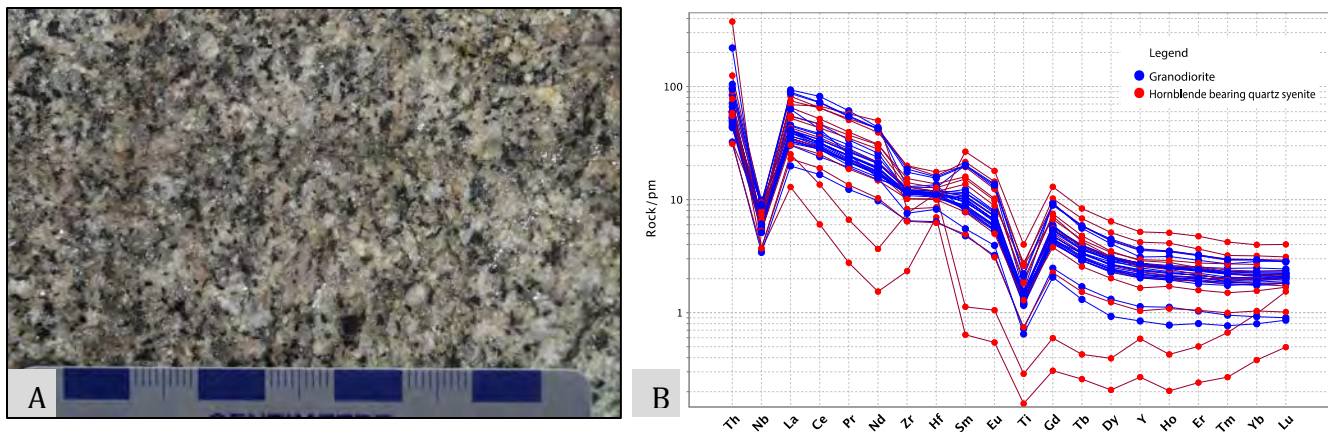


Figure 2. A. Photograph of the massive equigranular granodiorite with 10% amphibole. B. A primitive mantle normalized spider diagram showing the granodiorite and hornblende bearing quartz syenite, normalizing values from Sun and McDonough 1989.

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Evidence for the Presence of Eoarchean Crust in Northern Michigan

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Early Archean rocks are a component of the granite-gneiss terrane along the southern margin of the Superior craton. Previous zircon age data from the tonalite gneiss at Watersmeet Dome in northern Michigan indicated formation at ca. 3500 Ma, whereas granite near Thayer, MI was dated at 2745 ± 65 Ma and leucogranite dikes are ca. 2600 Ma (Peterman and others, 1980). Here we report new sensitive high-resolution ion microprobe (SHRIMP-RG) U-Pb zircon ages for two samples from the Carney Lake Gneiss in northern Michigan suggesting that an Eoarchean component ca. 3750 Ma old is present in the granite-gneiss terrane.

Carney Lake Gneiss

The Carney Lake Gneiss comprises an uplifted block of Archean basement exposed south of the Felch trough (Bayley and others, 1966). About 85 percent of the Carney Lake Gneiss is composed of granitic gneiss; of the remainder, about 10 percent is inclusions of amphibolite and biotite schist, and about 5 percent is granodiorite and syenite dikes. The gneiss is intricately folded and variable in composition and appearance, ranging from gray plagioclase-biotite gneiss to red microcline-biotite gneiss. The gray gneiss contains many amphibolite inclusions and is most abundant in the northern half of the complex. The southern half of the complex is more variable with grey to red gneiss containing many inclusions of biotite schist and lesser amphibolite (Bayley and others, 1966). The Carney Lake Gneiss is cut by metadiabase and metagabbro dikes of probable Archean and Paleoproterozoic age, as well as by Keweenawan diabase dikes.

Two samples were collected for radiometric dating from the southern half of the complex: 1) sample 1 is from a granitic K-feldspar-bearing gneiss that is locally pegmatitic; 2) sample 2 is from a banded and folded gray to red granitic gneiss. Abundant zircons were obtained from sample 1 that range from anhedral to subhedral, contain complex igneous and irregular growth zoning, and multiple growth rims; these zircons have irregular to pyramidal overgrowths. The zircons from sample 2 range from slightly rounded to subhedral and are otherwise mostly similar to zircons from sample 1.

We obtained new SHRIMP U-Pb data on zircons that were handpicked to select grains without cracks, inclusions, and alteration, and to examine whether different populations were present within each sample. The SHRIMP-RG instrument was operated at a mass resolution of ~ 8000 with an O_2^- primary ion beam, producing a spot size of 20-25 μ and 1-2 μ depth of penetration on the zircons. All peaks, including U, Th, Pb, REE, Ti, and Y, were measured sequentially for about 30 minutes per spot with an ETP multiplier. Raw data were reduced using the Squid 2 and Isoplot 3.75 programs (Ludwig, 2009, 2012).

On a Concordia diagram, U-Pb data ($n > 40$ zircons; > 80 spots for cores and rims) show clusters of data points ranging from concordant to discordant and suggest several chords and intercepts that are common to both samples from the Carney Lake Gneiss (Fig. 1A). Individual zircons have older ages near their cores (mostly discordant) and younger ages near their rims.

The predominant data cluster of nearly concordant points has an intercept ca. 2700 Ma; a smaller concentration of nearly concordant analyses at ca. 3750 Ma is taken as evidence for Eoarchean crust in the region. Nearly concordant results for zircon cores plotting in the 2700 Ma cluster have $^{207}\text{Pb}/^{206}\text{Pb}$ ages around 2750 Ma and those in the 3750 Ma cluster have $^{207}\text{Pb}/^{206}\text{Pb}$ ages around 3800 Ma (Fig. 1B). One possible chord spans the range from an upper intercept age of ca. 3750 Ma to lower intercept age of ca. 2700 Ma; a second possible chord spans a range from 2700 Ma toward an imprecisely defined intercept around 1000 Ma. The majority of the data are spread between these two apparent discordia chords although there are a number of data that suggest Concordia intercepts between 2700 Ma and 1000 Ma (Fig. 1A).

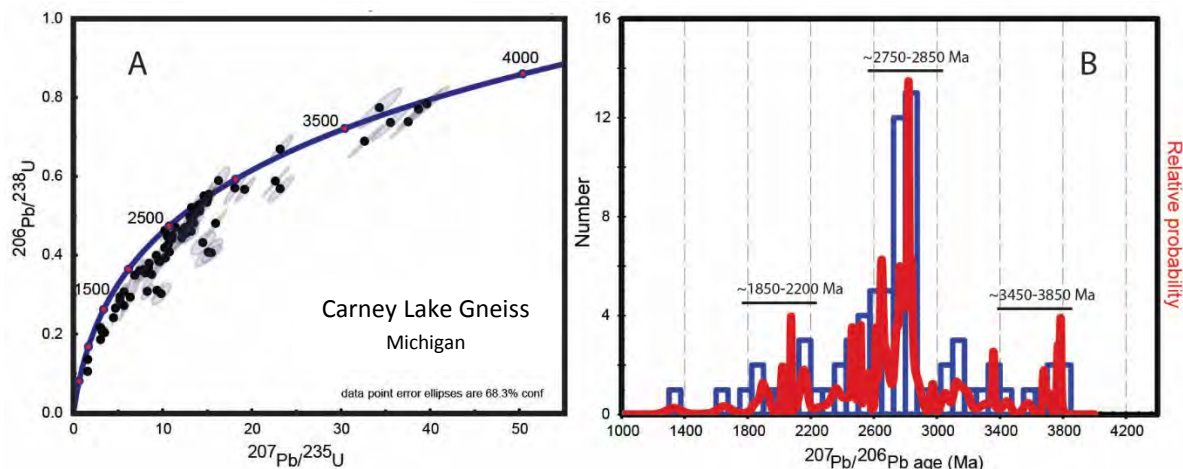


Figure 1: A. Concordia diagram for zircon ages from the Carney Lake Gneiss. B. Cumulative probability and histogram plots of the zircon ages.

The ca. 3750 Ma age of zircon cores from the Carney Lake Gneiss is the first evidence for an Eoarchean component in the granite-gneiss terrane of northern Michigan. The results suggest that the gneiss was affected by igneous and thermal events at ca. 2700, which resulted in new zircon crystallization, recrystallization, and formation of overgrowths.

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Possibility of the Dake Quartzite being younger than the Baraboo Formation

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Exposures of the Dake Quartzite within the Baraboo Syncline are limited. The best exposures are along Dake Ridge off the south side of Man Mound Road near Trapp Road (in the area of 43.48103N, 89.69099W) and along the south side of the Baraboo River west of US-12 and north of Hatchery Road (43.46993N, 89.77553W). There has been ongoing debate as to whether the Dake Quartzite overlies the Baraboo Formation or if the Dake is actually just faulted Baraboo (Clayton and Attig, 1990). Our preliminary field studies support the hypothesis of the Dake Quartzite overlying the Baraboo Formation.

The Dake Quartzite is a pale purplish gray, crystalline, thick bedded, subangular to subrounded coarse grained, quartz cemented, mature quartzite, with 20%-50% subangular to subrounded purple, white, red granules to medium pebbles of quartz and iron formation chert, with deep purple silty argillite beds. The Dake is 60 to 96 meters thick. This strongly resembles the basal part Baraboo Formation. The Baraboo is extremely thick, upwards of 1,800 meters. In the Baraboo area, ductile deformation is favored over brittle deformation. In order for the Dake to be a faulted remnant of the Baraboo and the overlying Rowley Creek Slate (Schmidt, 1951) to be equivalent to the Seeley Formation, would require faulting with a vertical displacement of >1,500 meters. These type of offsets just are not observed anywhere within the Baraboo Syncline. Geophysical work conducted by Hinze (1957) does not support the existence of any faults of the magnitude needed for the Dake to be faulted Baraboo.

The exposures along Dake Ridge show evidence of complex and tightly folded structures, such as aligned pebbles and quartz filled deformational fractures (figure 1). The strikes and dips indicate overturned and normal high angle bed within a linear distance of 300 meters. The Dake along the ridge also contains abundant red pebbles of chert not commonly found in the basal part of the Baraboo Formation (figure 2). These chert pebbles could have been derived from the banded-iron member of the underlying Freedom Formation, which is known to occur above the Baraboo Formation. This makes sense if the Dake directly overlies the Freedom Formation, instead of being a faulted part of the Baraboo. Tight folding over faulting is more plausible on Dake Ridge because the ridge is near its eastern nose within the Baraboo Syncline.

Along the Baraboo River and the railroad tracks, the Dake is conglomeratic and contains beds of deep purple argillite (figure 3). Trough cross bedding is common in the bottom of the exposure along the railroad tracks. The outcrop also contains large white quartz veins that trend differently from veins encountered in the Baraboo Formation (figure 4).

At one time there were 42 driller logs that were used to aid in the description the Dake Quartzite, which Leith (1935) used to define the formation. Unfortunately all drilling records of the Dake Formation have been lost. All that remains is Leith's (Clayton and Attig, 1990) description of subsurface relationships. Leith provided evidence that the Freedom-Dake contact was a minor erosional unconformity.

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Figure 1: Quartz filled deformational fractures at Dake Ridge



Figure 1: Red chert pebble in the Dake Quartzite at Dake Ridge (the white quartz pebble is 1.3 cm)

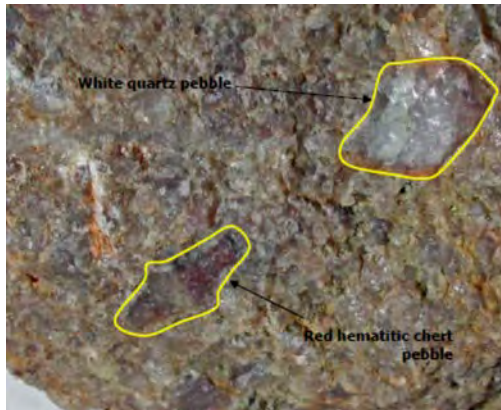


Figure 3: Deep purple silty argillite at the Baraboo River outcrop



Figure 4: Quartz filled tension fractures at Dake Ridge
(dashed-dotted lines are trough cross beds, solid lines are master bedding planes)



Silicic volcanism of the Porcupine Volcanics; implications for magma differentiation during the terminal stages of volcanism within the Midcontinent Rift

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The Midcontinent Rift and associated Keweenaw large igneous province (LIP) represent the most complete record of magmatism in a failed rift. While the Keweenaw LIP is dominated by basalt, silicic volcanism represents a significant volume of erupted material in the rift (Vervoort and Green, 2007). In contrast to basalts, which can probe mantle conditions, rhyolites can elucidate crustal magmatic processes (Arth, 1976). The genesis of silicic magmas has been a topic of considerable debate with respect to the relative importance of fractional crystallization, assimilation, partial melting of basaltic and crustal components, magma mixing, and liquid immiscibility (e.g. Nicholson, 1990; Vervoort and Green, 1997; Bachmann and Bergantz, 2008). Rhyolitic volcanism, though often viewed as a subordinate product of cyclic bimodal magmatism at rifted margins, may preserve evidence of the evolving processes that ultimately led to the termination of the Midcontinent Rift. Volcanism in the Porcupine Mountains of Michigan represents the waning stages of magmatic activity within the Midcontinent Rift (Zartman et al., 1997). Here we present a petrographic and geochemical investigation of silicic volcanism within the Porcupine Mountains.

Preliminary analysis of the silicic materials that comprise the Porcupine Volcanic group demonstrates that the samples comprise phyric rhyolite lavas and aphyric rhyolite tuffs (Fig. 1). The geochemical characteristics of the Porcupine silicic materials coincides with this textural division. Chondrite normalized REE plots show significant LREE variation with a pronounced Ce anomaly in contrast to the rhyolite lavas (Fig. 2).

Previous work on late stage silicic volcanism in the Portage Lake Volcanic group (Nicholson, 1990), which predates the Porcupine Volcanics group, identified two types of rhyolites: Type 1 rhyolites are characterized by enrichment of LREE and Rb; Type 2 are characterized by a strong Eu anomaly and enriched HREE concentrations compared to Type 1. Large volumes of Type 1 rhyolites were interpreted to be generated via partial melting of a basaltic material with minimal influence from assimilation. Type 2 rhyolites, which comprise less than five percent of the silicic material in the Portage Lake Volcanic group were postulated to have been generated by the partial melting of Archean crustal material.

When comparing the Portage Lake Volcanic group to the Porcupine Volcanics, a clear similarity exists between the rhyolite of the Porcupine Volcanics and the Type 1 rhyolite from the Portage Lake Volcanic group (Fig. 3). The parallel geochemical trends, which exist between Portage Lake and Porcupine Volcanics, imply that similar crustal processes were operating through time. The trends also suggest a cyclic nature of pulses of magmatism during the waning stages of the Midcontinent Rift. The Porcupine rhyolites, which erupted prior to the late stage Lake Shore Traps, demonstrate continuity of cyclic volcanism between the Portage Lake and the basaltic eruptions of the Lake Shore Traps. We interpret our new data within a paradigm of decreased magma flux during periods of rhyolitic volcanism.

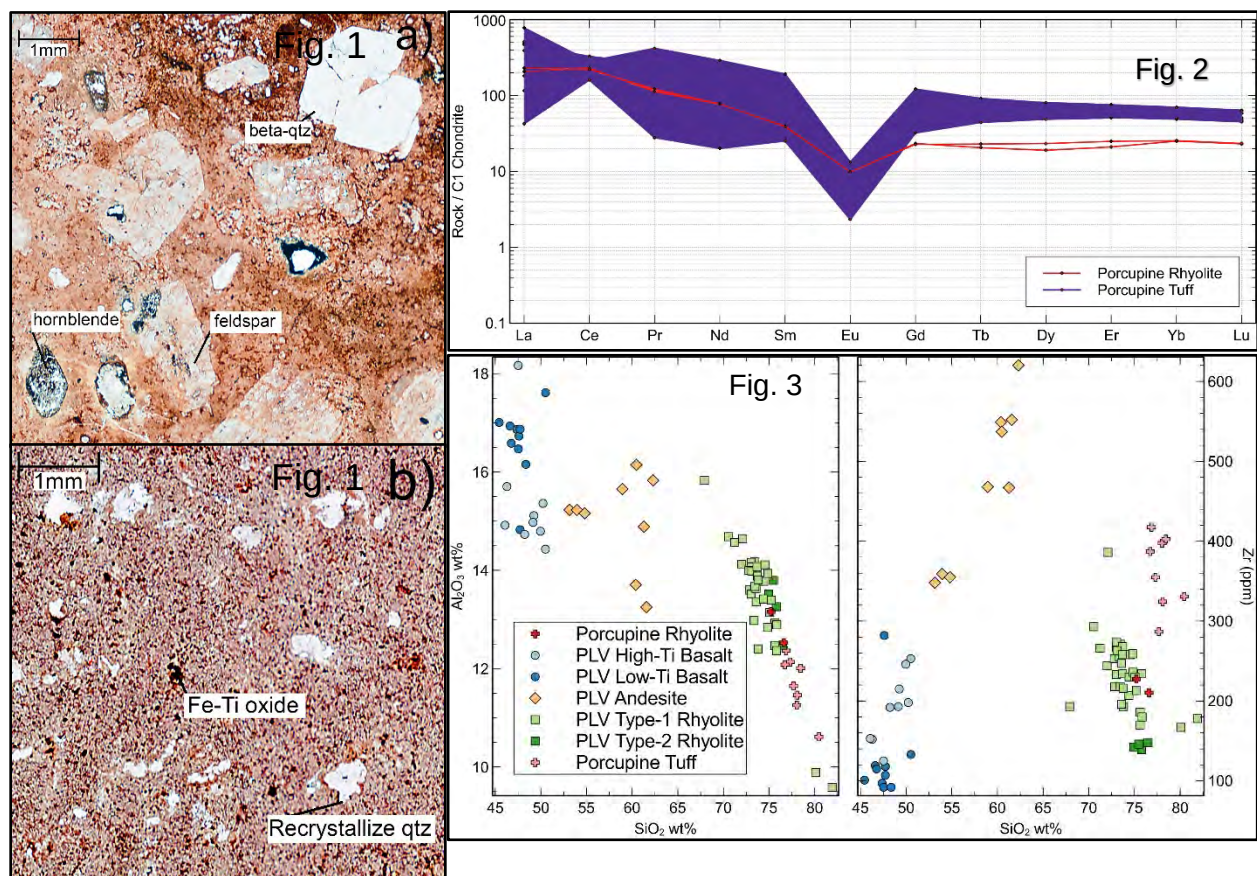


Fig. 1: Scanned and annotated thin sections that show dominant crystalline phases and general texture for a) phyric rhyolite and b) aphyric rhyolite tuff.

Fig. 2: Chondrite normalized REE diagram showing variation for aphyric rhyolitic tuff in purple and dark red trend lines of phyric rhyolite for Porcupine Volcanics.

Fig. 3: Select major and trace element Harker diagrams showing consistency between Portage Lake and Porcupine rhyolites.

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A roadside pegmatite in the Stettin Complex, Wausau Syenite Complex, Marathon County, Wisconsin.

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The Stettin Complex is the oldest (1565 ±3-5 Ma, Van Wyck 1994) and most alkalic of the four intrusions that comprise the Wausau Syenite Complex, and is primarily composed of amphibole, pyroxene, tabular and nepheline syenites, and syenite aplite. Recent roadwork along a portion of 120th Avenue in the SW 1/4 NW 1/4 of Sec. 22, T.29, R. 6E near the western margin of the intrusion has exposed a relatively large aplite/pegmatite dike exhibiting interesting mineralization and perhaps a historic connection.

The total thickness of the pegmatite is about 3 meters, with an exposure length of about 40 meters – there is no complete vertical exposure. The dike consists of thin upper and lower wall zones in contact with amphibole syenite (now gneiss, or disaggregated syenite), upper and lower intermediate zones of aplite and thin, discontinuous pegmatite bands, and a coarse core zone.

The aplite bands of the intermediate zones are largely monomineralic albite, but locally contain numerous phenocrysts of aegirine and arfvedsonite (both notably Li-bearing, 0.8 wt % Li₂O in aegirine, up to 1.8 wt. % in arfvedsonite), and in zones close to pegmatite bands small crystals of light to dark brown zoned pyrochlore and bright orange to yellow monazite-(Ce) appear, sometimes in great abundance. Aegirine, arfvedsonite, monazite-(Ce) and pyrochlore often poikilitically enclose small grains of albite, suggesting rapid, simultaneous crystallization or perhaps late metasomatic growth (post-albite).

Pegmatite bands and the core pegmatite zone contain essentially identical mineralogy, consisting largely of microcline and patches or pods of albite-rich aplite. Brown zoned crystals of pyrochlore are locally abundant, along with small patches and blebs of dark red- to yellow- to cream-colored, slightly Th-enriched, bastnäsite-(Ce). Notably, the dominant LREE-mineral in the aplites is Ca- and Th-poor monazite(Ce), whereas in pegmatitic portions it is Ca-poor, slightly Th-enriched bastnäsite-(Ce), although locally some bastnäsite-(Ce) may be found in immediately adjacent aplite, and some monazite-(Ce) in immediately adjacent pegmatite. A few examples of intergrown monazite-bastnäsite have also been observed, and probable thorbastnäsite is very rare. Notably, altered examples of bastnäsite-(Ce) may consist partially of very clean cerianite bordering sharply on unaltered bastnäsite-(Ce); the bastnäsite-(Ce) and cerianite are visually identical and require analytical work to distinguish. Virtually no xenotime-(Y) has been identified from the dike (1 tiny grain from a heavy mineral separate).

A pale yellow to colorless Li-rich mica (3.35 wt. % Li₂O), tentatively identified by EMP and DCPS as zinnwaldite (roughly mid-point of the siderophyllite-polyolithionite join), is common in pegmatite bands and the core zone, forming small fanning aggregates of flakes, reniform vug linings similar to cookeite, and sparse larger aggregates. It also forms small

crystals in late siderite-quartz-zinnwaldite replacements of an unknown mineral, possibly once a Li-rich amphibole. Zircons are abundant, and clear, gemmy reddish to yellow crystals are typically associated with quartz; opaque, pale grey to reddish crystals are also found in microcline and may represent an earlier phase of zircon crystallization; only rarely do zircons show significant enrichment in Hf, Th, and HREE. Siderite, now replaced by goethite and hematite, is abundant in pegmatitic portions. Black glassy crystals of a Ti oxide phase, probably rutile, are common in late quartz-rich pods. Partially altered pyrite is present but not common, and a few small crystals of molybdenite were found in aplite.

Columbite-(Fe) forms tiny black crystals in albite in intermediate zone aplites. Though sparse, when found it is locally abundant, and is significantly enriched in Ta relative to pyrochlore. Bismuthinite is present as rare clusters of bladed crystals coated by clays and Fe-oxide in small vugs in the core zone, generally with fluorite. Sparse clusters of small bladed crystals of astrophyllite were found in the upper margin of the dike.

Fluorite is common in small embedded roughly octahedral crystals and irregular blebs in all phases of the aplite-pegmatite, and abundant hollow voids of roughly octahedral form in aplite testify to its former abundance. Color ranges from colorless to pale green, pale blue and purple. XRF analysis of fluorite show enrichment in HREE, particularly Y and Yb (total REE content between 1-1.5 wt. % of the oxides).

Considering that this aplite/pegmatite is the only significant pegmatite exposed in the roadside in the SW 1/4 NW 1/4 of Sec. 22, T.29, R. 6E, and also the similar mineralogies, it seems likely that this aplite/pegmatite is the same roadside pegmatite described in Weidman (1907). Prior to the recent excavation work the outcrop was completely obscured by slumped soil, rock and vegetation, which may explain the absence of any work on this outcrop over the intervening 110 years.

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Investigations of Target No. 6: a potential new kimberlite in the Marathon area, NW Ontario

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A potential kimberlite known as ‘Target No. 6’ has been identified via aeromagnetic surveying 40km northwest of Marathon, ON, hosted within the Wawa-Abitibi subprovince. These units are known to host other diamondiferous rocks associated with the 1.1-Ga Midcontinent rift system and the Trans Superior Tectonic Zone (TSTZ), the closest of which being the alnoitic ‘Madonna Dyke’ located 2.5km northwest of the target. Ground prospecting revealed a botanical anomaly between a large semi-circular grassy area and its surrounding boreal vegetation (*Fig 1*). An exploration program began on the site in 2013, which led to diagnostic testing such as Soil Gas Hydrocarbon (SGH) analysis, which showed very positive indicators for the presence of a kimberlite (or related rock type). This study utilizes different investigative techniques above this potential target in an attempt to explain or exclude reasons for the botanical anomaly, and to further explore the geologic setting in order to better understand the occurrence. This includes identification techniques for the vegetation, pH analysis of the soils, grain size analysis of the soils, and indicator mineral chemistry for any potential kimberlite indicator minerals.

In order to better understand the distinct change in vegetation, samples were collected for identification. This has resulted in the grasses and sedges being identified as *Calamagrotis Stricta* and *Carex Utriculata*, respectively. These species are generally found along the edges of ponds or lakes, making their presence within Target No. 6 atypical. Other fieldwork consisted of soil sampling using a 0-30cm deep soil probe in the cardinal directions in 25m increments, as well as samples taken every 10cm with depth for a total depth of 140cm at the centre of the site from a trench. During field sampling it was noted that these soils were very sandy and the root systems of *C. Stricta* and *C. Utriculata* were between 0-40 cm depths. These sandy soil samples were used to complete a standard soil pH analysis, and the range of pH from samples taken over top of the anomaly and as well from the surrounding mixed boreal vegetation was 3.34 to 2.82-3.82, respectively, showing no evidence of pH being a control factor for distinct vegetation change. In order to determine the source of the sandy soils, grain size analysis was used to help distinguish different source environments. The sieve and pipette analysis results are in agreement with the depositional environment being that of a stream mouth bar. Surficial geology maps of the area support a stream mouth bar depositional environment, with this location at the boundary between a glacial outwash plain/valley train and a glaciolacustrine deposit where it is possible a stream entered the glacial lake and formed a stream mouth bar.

Grain sizes between 0.25mm to 0.5mm were also analysed after being selected based on their resemblance to kimberlite mineral indicators (i.e. mantle garnet and pyroxenes) using an Olympus stereoscope, then mounted in an epoxy section for subsequent SEM-EDX quantitative analysis. Minerals identified were mostly garnets and pyroxene with no mantle signature.

It is entirely possible that the vegetation above Target No. 6 is being directly influenced by an anomalous deposit below the sediment. The species present in the anomaly are generally found in wet environments such as lake shores and margins of streams. The target appears to be a depression that has been filled in by sediment from a stream mouth bar, and the porous sandy sediment may be acting as a vent for the deposit beneath it, which would explain the effectiveness of the Soil Gas Hydrocarbon analysis. Further investigation recommendations include more extensive work in the field, soil classifications, analysis of onsite drainage, and collection of a more varied plant population and tissues for chemical analysis (Haggerty, 2015; Dunn, 2012).

Target #6: Sample locations

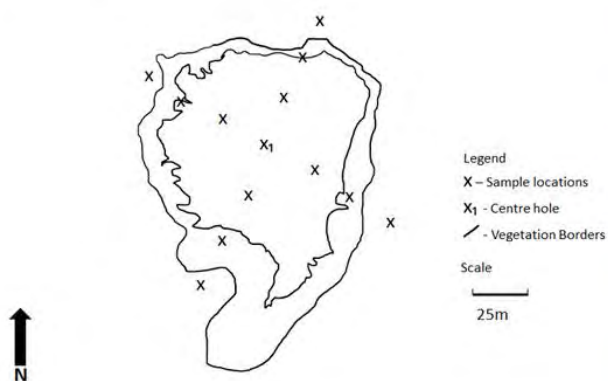


Figure 1: *Left*: Traced map of Target No. 6 showing sample locations and vegetative borders. *Centre Circle and outer Circle*: Mixed Sedges and Grasses *Outside of Circle*: Boreal Mixedwood forest. *Right*: Botanical anomaly above Target No. 6.

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New observations on distal ejecta from the Sudbury impact in the central Mesabi iron range, northern Minnesota

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The 1850 Ma Sudbury meteorite impact spread a layer of debris across the Lake Superior region (Fig. 1A). Ejecta in the Mesabi iron range, in Minnesota, has been reported previously: a) near Eveleth (Addison, et al., 2005), and b) near Coleraine (Huber, et al., 2014) (Fig. 1B). The study described here is on a new site near Nashwauk (Fig. 1B) about 930 kilometers west of the impact point. The information is derived from six drill cores, acquired during iron exploration from an area less than 2 square kilometers. The ejecta here is neither metamorphosed nor deformed and primary features are exceptionally well preserved.

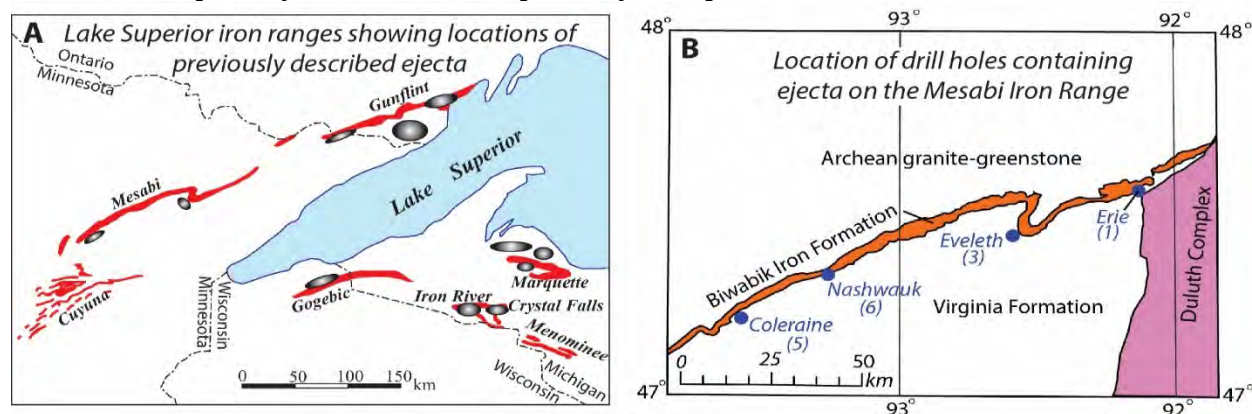


Figure 1. A. The iron ranges of the Lake Superior region and generalized location of previously described ejecta (as ovoid areas). Thirty kilometers of NW-SE extension across the Midcontinent rift has been restored to approximate the geography at the time of impact. B. Mesabi iron range showing localities where Sudbury ejecta has been documented. Numbers in parentheses are the number of drill hole intersections at each locality.

Stratigraphy. The ejecta layer lies at or very near the contact of the Upper Slaty Member of Biwabik Iron Formation and the overlying Virginia Formation. The Upper Slaty Member is mostly weakly to non-magnetic evenly laminated silicate and carbonate iron formation with varying amounts of chert beds and nodules. In some drill holes, the ejecta are overlain directly by laminated dark shale characteristic of the Virginia Formation. But in others as much as a few meters of chert and coarse-grained carbonate lies between ejecta beds and typical Virginia shale. Vestiges of ejecta particles can be seen in some of this core which is best interpreted as chemical sediment deposited soon after the impact, into which variable amounts of ejecta were intermixed. The thickness of the ejecta layer is variable ranging from zero to about 1.5 meters.

Ejecta lithology. The ejecta consists largely of particles of altered glass, generally about 1 mm diameter. Chert clasts up to several centimeters long are common in some layers. There are two distinct types of ejecta that are interlayered on centimeter scale (Fig. 2D). The most common contains fragments and lesser spheres of altered glass with varying degrees of flattening (Fig. 2B). Less common are beds composed mostly of spherical, highly vesicular microtektites and chert clasts (Fig 2C). The latter type is commonly highly replaced by coarse secondary carbonate minerals. Quartz and rare feldspar grains are present and many display well developed relict planar deformation features, clear indicators of impact shock (Fig 2A).

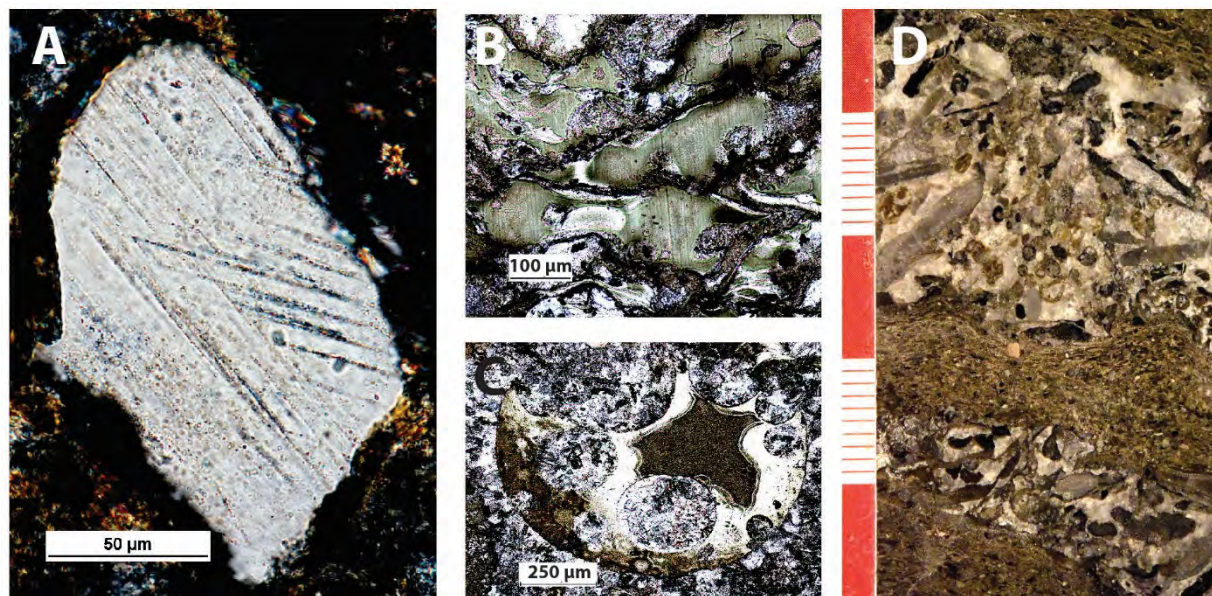


Figure 2. A-quartz grain with two sets of relict planar deformation features, B-flattened fragments of glass, C-broken highly vesicular microtektite, D-section of drill core showing three beds of flattened glassy ejecta and two beds of spherical microtektites with carbonate cement and large chert clasts. Large scale interval is centimeters.

The interlayering of distinct ejecta lithologies indicates that two very different impact-related processes are recorded in the Mesabi ejecta beds, and that the ejecta types produced by each have not been strongly intermixed. The layers of flattened glass seem best interpreted as distal parts of the ejecta curtain that had lost most of its coarser fragments closer to Sudbury and arrived as a cloud of fine particles of glass and possibly molten droplets. Some of the flattening may have occurred during deposition when particles were still hot and viscous. The microtektite layers may be products of the fireball phase of impact that formed as very high temperature vapor condensed to melt droplets during adiabatic expansion and cooling of the impact fireball. These microtektites are characteristically highly vesicular, perhaps because of boiling along a two-phase boundary as they condensed from vapor to melt droplets. In this scenario, the ejecta near Nashwauk records the transition from the more proximal ejecta curtain material to a truly distal microtektite layer. These two types of ejecta were deposited approximately simultaneously, in alternating layers, perhaps because of incomplete mixing of the two types in a turbulent cloud of hybrid ejecta.

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Igneous stratigraphy and Cu-Pd mineralization at Area 41 within the Eastern Gabbro, Coldwell Alkaline Complex, Canada

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The Area 41 occurrence is located near the northwestern margin of the Eastern Gabbro of the Coldwell Alkaline Complex (Fig. 1), approximately 18 km north-east of the Marathon Cu-Pd deposit (Fig. 1). It was discovered in 2006, and the mineralization and host rocks were characterized by Cao (2017). In order to develop a general model for mineralization in the Coldwell Alkaline Complex, the distribution of different magma series units, their relationships to mineralization, as well as the origins of mineralization need to be compared. This is a work in progress, and an initial attempt at developing a model will be accomplished by comparing Area 41 to the Marathon deposit.

Results from drill core logging, petrography and lithogeochemistry show that rock units at Area 41 are composed by three magmatic series. From oldest to youngest these are Meta-basalt, the Layered Series, and the Marathon Series, which are similar to those at the Marathon deposit. These different series can be distinguished using plots of Ce vs. Y, Nb vs. Zr, and V/Ti vs. Ba. The Marathon Series can further be distinguished from the Layered Series by comparing down-hole trends in whole-rock Zr, and the Mg numbers of olivine and clinopyroxene. These parameters vary smoothly in the Layered Series but fluctuate widely in the Marathon Series. Assay data from drill holes at Area 41 indicate that PGE mineralization is only hosted by the Marathon Series, particularly within an ophitic gabbro unit that texturally resembles the Two Duck Lake Gabbro at the Marathon deposit.

Based on differences in Cu/Pd ratios and host units, three types of magmatic sulfide mineralization are recognized at Area 41: Type 1, Cu-rich and PGE-poor mineralization (Cu/Pd > 16000) mainly hosted by a coarse- to medium-grained ophitic gabbro; Type 2, PGE mineralization (2000 < Cu/Pd < 10000) mainly hosted by an apatitic clinopyroxenite, with some within a coarse- to medium-grained ophitic gabbro; and Type 3, PGE enriched mineralization (Cu/Pd < 1500) mainly hosted by a pegmatitic to coarse-grained ophitic gabbro. The high Cu/Pd and extremely low PGE grade of Type 1 mineralization is interpreted to have likely formed by an early sulfide saturation event. Type 2 PGE mineralization has mantle-like Cu/Pd ratios, suggesting that it can be modelled by a closed-system R factor model without any upgrading process, similar to the Main zone mineralization at the Marathon deposit (Good et al., 2015). However, the variability of Cu/Pd ratios for this type of mineralization suggests that sulfide droplets may have been suspended in the turbulent magma. Type 3 mineralization has low Cu/Pd ratios corresponding to a R factor of $>10^5$. This, together with low S/Se ratios (1200 on average), which is evidence of S loss, are similar to the W-horizon mineralization at the Marathon deposit, which was explained by Ruthart (2013) to form by multi-stage dissolution upgrading. Therefore, it seems that mineralization at Area 41 shares striking similarities with that at the Marathon deposit, which appears to be conduit-related.

The topography of Area 41 has deeply eroded lineaments, which, according to Walker et al. (1993), can be related to faulting as a result of cauldron subsidence. The north-south keel-shaped trough shown in Figure 2 is close to the intersection of two major surface lineaments, indicating a fault-controlled morphology. The investigation of spatial variations in the thickness of the Marathon Series package, and the relative proportions of pegmatitic ophitic gabbro, breccia units, mineralized zones,

apatitic clinopyroxenite, and oxide melatroctolite along the longitudinal section (Fig. 2) show that all these parameters generally decrease away from the trough, which is consistent with a scenario where magma intrusions was emplaced through the feeder channel, and then flowed away as sills in different directions. Therefore, the trough is believed to represent the location of a feeder channel, and Area 41 thus is a conduit system. This discussion is also significant for exploration efforts. For example, recognition of apatite- and magnetite-rich cumulate rocks (e.g., apatitic clinopyroxenite and oxide melatroctolite) in the field are a strong indication of proximity to a conduit.

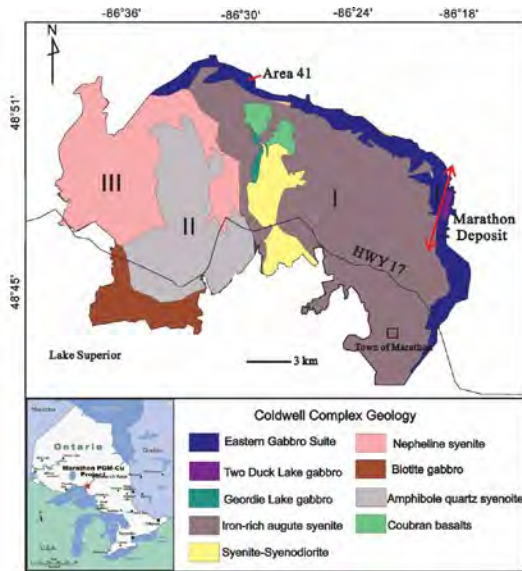


Figure 1. Geological map of the Coldwell alkaline complex (modified after Walker et al., 1993), the location of Area 41 is represented as the red dot, the location of the Marathon deposit is outlined using a double-arrow red line.

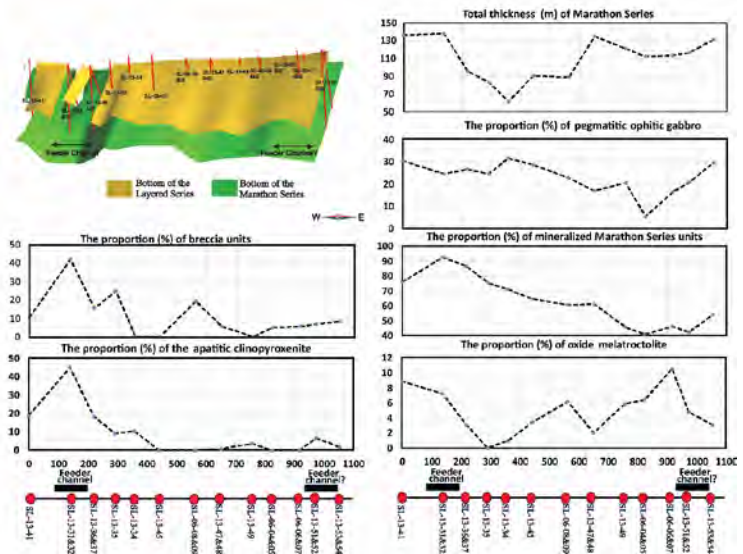


Figure 2. Spatial variations of the thickness of the Marathon Series rocks, the proportion of pegmatitic ophitic gabbro, the proportion of the breccia units, the proportion of mineralized Marathon Series units, the proportion of apatitic clinopyroxenite, and the proportion of oxide melatroctolite. The 3D model illustrates the stratigraphy of Area 41, and red lines on the cartoon represent drill holes. Drill holes are indicated using red infilled circles on the longitudinal line, potential feeder channels are indicated using the black rectangles.

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The Mineralogy and Petrology of the Good Hope Carbonatite Occurrence, Marathon, Ontario, Canada

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The Good Hope Carbonatite Occurrence is a recently discovered high grade niobium and phosphate occurrence located adjacent to the Prairie Lake Carbonatite Complex, approximately 45 kilometres northwest of Marathon and about 28km North of Highway 17 (49° 02' N, 86° 43' W). This study focuses on the paragenesis and classification of the pyrochlore-group minerals of the Good Hope occurrence. These data are used to make a preliminary paragenetic interpretation of the origin of the Nb mineralization and to evaluate if there is any genetic relationship to the adjacent Prairie Lake Carbonatite Complex. Polished thin sections of outcrop and drill core samples were investigated by optical and back-scattered electron petrography coupled with quantitative X-Ray energy dispersive spectrometry at Lakehead University.

The study revealed the presence of calcite (CaCO_3); ferrodolomite ($\text{CaFe}(\text{CO}_3)_2$); siderite (FeCO_3); apatite ($\text{Ca}_5(\text{PO}_4)_3(\text{OH}, \text{F}, \text{Cl})$); ferrocolumbite (FeNb_2O_6); fersmite ($(\text{Ca}, \text{Ce}, \text{Na})(\text{Nb}, \text{Ta}, \text{Ti})_2(\text{O}, \text{OH}, \text{F})$); and pyrochlore ($\text{A}_{16-x}\text{B}_{16}\text{O}_{48}(\text{O}, \text{OH}, \text{F})_{8-y} \cdot z\text{H}_2\text{O}$). Less common minerals include: ankerite ($\text{Ca}(\text{Mg}, \text{Fe})(\text{CO}_3)_2$); synchysite ($\text{CaCe}(\text{CO}_3)_2\text{F}$); bastnaesite ($\text{Ce}(\text{CO}_3)\text{F}$); parisite ($\text{CaCe}_2(\text{CO}_3)_3\text{F}_2$); quartz (SiO_2); rutile (TiO_2); pyrite (FeS_2); magnetite ($\text{Fe}^{2+}\text{Fe}_2^{3+}\text{O}_4$); and barite (BaSO_4). Two paragenetic varieties of carbonatite were recognized on the basis of mineral abundances and the textures. These are referred to as the pyrochlore-rich and pyrochlore-poor phases. The difference between the two phases is interpreted to suggest that the pyrochlore-poor phase represents a later stage of crystallization. The pyrochlore in the pyrochlore-rich phase are intimately intergrown with coarse-grained apatite and are interpreted as clasts derived from early-forming cumulates. The niobium mineralization is dominated by pyrochlore, which exhibits complex replacement textures involving both fersmite and ferrocolumbite (Figure 1a and 1b). On the basis of textural evidence a definitive crystallization order or relationship between pyrochlore, fersmite and ferrocolumbite could not be established. The pyrochlore is dominated by Na-Ca pyrochlore with minor amounts of Sr-pyrochlore present only in drill core samples. The compositions of pyrochlore depicted on ternary and binary plots, after Lumpkin and Ewing (1995) and Nasraoui and Bilal (2000), show a transition from magmatic to an “alteration” trend with drill core samples being more “altered” than surface samples. The latter are considered to be dominantly of a magmatic origin, whereas the drill core pyrochlores are considered to have been affected by hydrothermal processes. Our data indicate easy ore beneficiation due to the presence of only one significant niobium-bearing phase with limited compositional variations. The pyrochlore also does not contain significant amounts of U or Th which increases its economic potential as these elements can cause environmental concerns involving radioactive refinery residues.

The mineralogy of the Good Hope carbonatite occurrence is different to that of carbonatites occurring in the western and southern margins of the Prairie Lake Carbonatite Complex. The latter are dominated by olivine, calcite, fluoroapatite, Ti-magnetite and phlogopite-tetraferriphlogopite, with niobium mineralization dominated by include Na-Ca pyrochlore, latrappite, loparite, U-pyrochlore, Ce-pyrochlore and Pb-pyrochlore (Wu et al, 2016). The very different mineralogy, in addition to the different magnetic signature, carbonatite texture, weathering and topography, indicate that the Good Hope carbonatite occurrence is perhaps not directly related to the Prairie Lake carbonatite rock; however, the actual genetic relationship remains unknown.

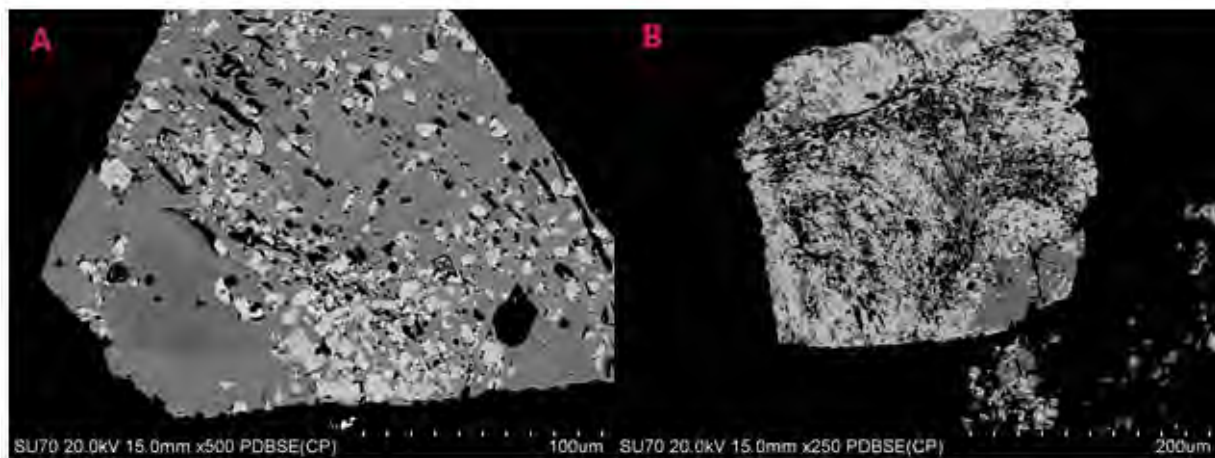


Figure 1: Representative back-scattered electron images of pyrochlores: (a) illustrates a pyrochlore grain with inclusions of fersmite; (b) a typical pyrochlore grain being replaced dominantly by fersmite with some ferrocolumbite along fractures

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Geology and geochemistry of Proterozoic dykes in Pukaskwa National Park, Ontario: Insights into the Midcontinent Rift-related Pukaskwa dyke swarm

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The Midcontinent Rift (MCR)-related Pukaskwa dyke swarm is exposed on the north shore of Lake Superior between Batchawana Bay and Marathon, Ontario. The Pukaskwa dykes have been subject to only limited research and represent a gap in our understanding of MCR rocks. Excellent exposures along the shoreline of Lake Superior in Pukaskwa National Park have allowed for further investigation of the geochemistry and petrogenesis of numerous Paleo- and Mesoproterozoic dykes of various orientations, in order to better place the Pukaskwa dykes in the context of MCR development.

The Pukaskwa dykes were noted by Green et al. (1987) and Halls and Shaw (1987) to strike in a northwest orientation, following the orientation of, and dipping at high angles (50° northeast) to, the northeastern MCR axis. Northwest-trending dykes belonging to the Paleoproterozoic Matachewan swarm are also recognized in the study area (Halls, 1991; Halls et al., 2005; Muir, 1982). The Pukaskwa dykes display strong negative, west-northwest-trending magnetic anomalies and are much more magnetic than Matachewan dykes (H. Halls, personal communication, 2017). The Matachewan dykes are characterized by a slight green colour due to the presence of chlorite and epidote compared to the deep grey colour of the Pukaskwa dykes (ibid). York and Halls (1969) conducted whole-rock K-Ar dating on four dykes in the Pukaskwa region that yielded K-Ar (minimum) ages between 1020 and 1070 Ma. Matachewan dykes have a range of emplacement from 2446 to 2473 Ma (Heaman, 1997).

Sampling efforts were supported by Parks Canada along the shoreline in Pukaskwa National Park. Thirty samples were taken from 20 locations, providing a representative sampling of dyke exposures on the shoreline. Dyke trends were variable but dominantly northwest. High-resolution air photos revealed that many of the sampled north- and northeast-trending dykes represent jogs or deflections in northwest-trending dykes. Brecciated wall rock-dyke contacts, dykelet splays, wall rock peels, anastomosing dykes and wall rock deformation were noted locally. No physical or textural differences were discernable in the field between dykes. Cross-cutting relationships were observed at four locations throughout the study area: PUK-07 cross-cuts PUK-06, PUK-022 cross-cuts PUK-021, PUK-026 cross-cuts PUK-025, PUK-30 cross-cuts PUK-29 (Figure 2, lower left). One dyke (PUK-09) was interpreted to be Archean due to the presence of significant alteration and quartz veining.

The dykes range from 46 to 53 wt% SiO₂ and from 2.6 to 5.4 wt% Na₂O + K₂O, indicating a basaltic composition. The dykes display a range of Mg# values from 0.34 to 0.57 and TiO₂ values generally range from 0.98 to 1.98 wt% with one outlier (Fig. 1A; PUK-20 = 2.26% TiO₂). Two suites of dykes can be established based on trace element characteristics: Group 1 samples (n=26) display relatively flat trace element patterns and negative niobium anomalies; and Group 2 samples (n=4) display relatively steep trace element patterns highlighted by elevated light rare earth element (REE) enrichment and pronounced negative Zr, Hf and Ti anomalies. Group 1 samples show similar trace element abundances to MCR-related Pigeon River, Cloud River and Mount Mollie dykes (Fig. 1B; Cundari 2012) but also display similar

trace element patterns to those of the Matachewan dykes (Fig. 2; Halls et al., 2005). Group 2 samples display similar trace element abundances to the Wolf Camp basalts in the MCR-related Coldwell Alkaline Complex (Cundari et al., 2016), suggesting a possible genetic relationship between the two units. It should also be noted that Group 2 samples display elevated $\text{Na}_2\text{O} + \text{K}_2\text{O}$ values verging towards those of alkalic rocks and towards the top of the range for samples collected in this study, supporting a possible petrogenetic relationship between Group 2 dykes and the alkaline Wolf Camp basalts. Two samples from dykes of Group 2 affinity (PUK-026 and PUK-030) clearly cross-cut dykes of Group 1 affinity (PUK-025 and PUK-029). The similar trace element signatures of both Group 1 samples and Matachewan dykes allows for the possibility that some Group 1 dykes may belong to the Matachewan swarm. Further work is required to establish criteria for discriminating between MCR-related Pukaskwa dykes and Matachewan dykes and also between the Groups 1 and 2 dykes evaluated in this study. Detailed petrographic work, magnetic susceptibility measurements, geochronological and further field study may aid in refining our understanding of these dykes in the context of MCR development.

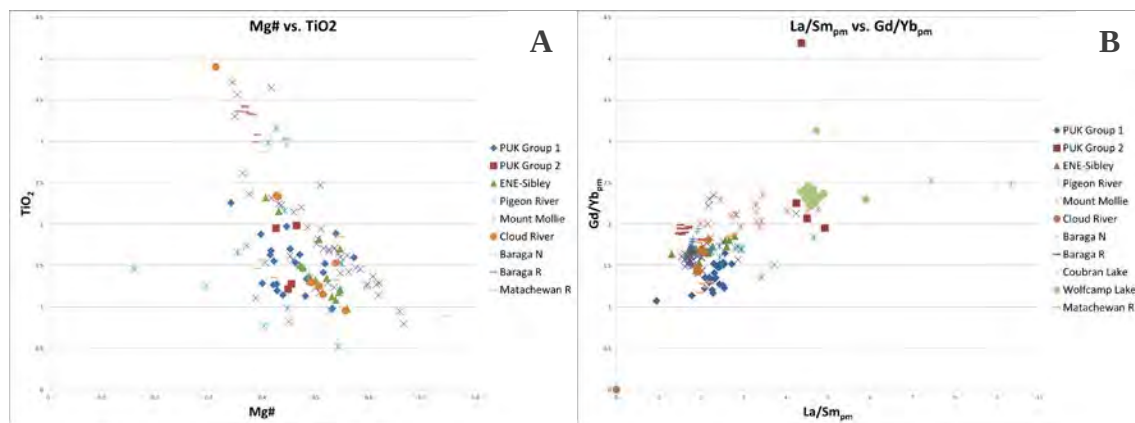


Figure 1: Major and trace element abundances for Pukaskwa National Park dykes (PUK 1 and 2) compared to other Midcontinent Rift-related units. Comparative data from Cundari et al. (2013) and Piispa (personal communication, 2012).

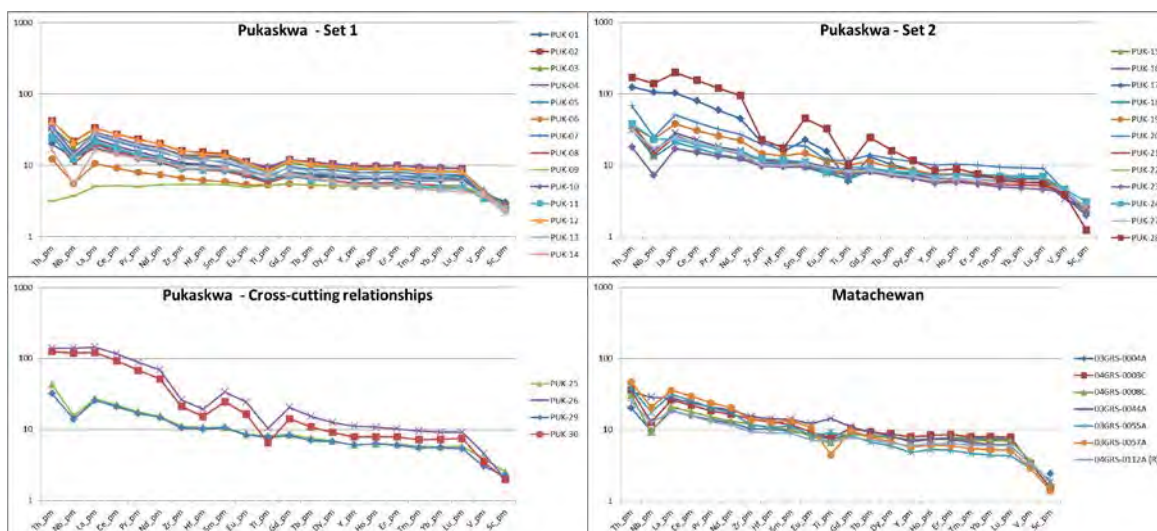


Figure 2: Primitive mantle-normalized trace element diagrams for all samples taken in this study. Matachewan data from Halls et al. (2005).

Characterizing the grade of metamorphism and depth of burial of the Gunflint Formation near Thunder Bay, Ontario

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The Gunflint Formation near Thunder Bay, Ontario, is characterized by very low grade metamorphism. The two outcrops that were studied are located on Pass Lake Road and on the old railroad tracks off Nelson Road. Both outcrops are located roughly 43 km northeast of the city of Thunder Bay, near Highway 11/17, and are dominantly folded banded chert carbonate members of the Gunflint Formation.

Microstructural analysis and semi-quantitative XRD phase analysis were completed in order to accurately classify the temperature range of the system. Parallel-trending pressure solution stylolites are common within both outcrops, and are indicative of temperatures of less than 400°C as both water and space are required for this deformation microstructure to be effective (Passchier and Trouw, 2005). Deformed calcite veins, also common in both outcrops, vary in thickness and do not have straight edges. The calcite within these veins displays undulatory extinction, evidence of intra-crystalline deformation via dislocation creep. For calcite, the lower temperature limit for dislocations to effectively move through its lattice is generally placed at 50°C. Between 50°C and 300°C, undulatory extinction is the dominant deformation microstructure within calcite (Passchier and Trouw, 2005). At 300°C, bulging recrystallization processes become dominant, and the lack of this microstructure within any of the calcite leads to a temperature range anywhere between 50°C to 300°C. Deformed quartz veins are also abundant within the Gunflint Formation, and the temperature required for dislocation creep to become efficient within quartz is greater than 150°C. Dislocation creep is then the dominant deformation process in quartz between the temperature range of 150°C and 300°C (Passchier and Trouw, 2005). Above 300°C, bulging recrystallization processes become dominant. The lack of bulging recrystallization within the quartz places the temperature range of the Gunflint Formation between 150°C and 300°C. Kinked illite-mica laths are present in the study area only within a shale unit of the Nelson Road outcrop, and are indicative of temperatures above 150°C (Passchier and Trouw, 2005).

To further assess the temperature range of the Gunflint Formation during metamorphism and deformation, semi-quantitative XRD phase analysis was completed on one powdered sample from the shale unit of the Nelson Road outcrop. The results show clinocllore, illite-muscovite 2M1, kaolinite, feldspar, quartz and likely minor interlayered illite-smectite. The presence of interlayered illite-smectite and the illite-muscovite 2M1 polytype, which is the more ordered illite-muscovite polytype, places the Gunflint Formation at a temperature range of between 200°C and 300°C (Merriman and Frey, 1999). Based on the microstructures present and the XRD phase analysis results, there is a clear temperature range that satisfies all microstructures and phases present within the unit that occurs from 200°C to 300°C. This temperature range corresponds to the very low grade of metamorphism, also known as the anchizone.

The depth of burial of the Gunflint Formation during deformation is then shown to be 6km to 10km assuming an average geothermal gradient of 30°C/km. This value is consistent with the results of Hill and Smyk (2005), Koroscil (2013) and Baird (2015), who characterize structures in the Gunflint Formation near Thunder Bay as part of a foreland thrust belt.

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Determining bedrock depths using the Horizontal-To-Vertical Spectral Ratio (HVSr) passive seismic method – examples from Michigan

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Michigan has the thickest drift on land in North America, but the thickness is quite variable and the underlying bedrock surface is very irregular. Many places have a poor distribution or quality of bedrock depth control points. The bedrock surface is a fundamental surface for many geological, environmental, and engineering investigations. Drilling to bedrock or running geophysical surveys to determine bedrock depth can often be cost prohibitive. The horizontal-to-vertical spectral ratio (HVSr) passive seismic geophysical method has been evaluated to Michigan for the last four years.

The HVSr method allows one to determine glacial drift thickness (bedrock depth) if there are strong enough acoustic impedance contrasts between the drift and underlying bedrock. The HVSr method uses naturally occurring seismic noise (wind, waves, flowing water, distant weather) and man-made noise (vehicles, industry) as an energy source. A single station, three-component seismometer (two horizontal and one vertical) is used to record the ambient seismic noise (Lane and others, 2008).

The Horizontal-to-vertical spectral ratio (HVSr) passive seismic method has a number of advantages over drilling or other geophysical methods for determining depth to bedrock including low cost, ease of use, one man operation, single station, short sampling times, minimal data processing and its specificity to a single interface (bedrock surface). Additionally it is portable, noninvasive and can be used in culturally noisy areas.

HVSr calibration readings at wells and borings of known bedrock depth have been gathered in several areas of the state. The calibration readings are compiled for a given area with the same geologic setting resulting in local and regional calibration curves and curve equations. Sixteen local and regional HVSr calibration curves as well as a statewide compilation curve have been generated from readings at wells of known bedrock depth. HVSr exploration readings are taken at locations of unknown bedrock depths and the data inserted into the local calibration equation solving for bedrock depth.

Areas where a well-defined HVSr calibration curve already exists can be used to quickly gather exploration readings, process the data and determine bedrock depth while still in the field. In areas where local HVSr calibration data isn't available yet, a statewide calibration curve is available to estimate bedrock depths at exploration readings. This not the preferred option because using the statewide calibration curve can sometimes significantly overestimate or underestimate the bedrock depths.

For small sites with a limited number of bedrock depth control points for calibration curve generation, readings can be taken at the bedrock control points available and an average shear wave velocity calculated at each reading using the equation $V_s = f_o * 4z$, where V_s =average shear wave velocity, f_o =resonance frequency, z =depth to rock. The mean of these shear wave velocities is then calculated for the site (Johnson and Lane, 2016). Exploration readings are then

collected with the resonance frequency at each reading inserted into the equation solving for z , bedrock depth.

The HVSR method has been successfully used in several parts of the state to determine bedrock depths, map bedrock topography, fill in data gaps, to confirm or deny anomalous bedrock depths, and to better define bedrock valleys, highs and scarps. The HVSR method has generally yielded good results in determining bedrock depths across Michigan. Although the HVSR method may not work everywhere and occasionally less than optimum results occur, useful data can still be gathered. Sometimes other geological inferences can be made with the data in addition to the depth to bedrock estimation.

The HVSR technique is currently being used in geological mapping, groundwater investigations, and mineral exploration. It has great potential in geotechnical and engineering investigations and utility excavations. Additionally it can be used as an independent depth calibration for modeling with other geophysical survey methods. The HVSR technique may aid in petroleum exploration by supplying an independent bedrock elevation profile along seismic reflection lines providing higher quality bedrock elevations to assist in traditional static corrections. Several examples will show its use to determine bedrock depth for different applications.

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Microstructural analysis of the Plateau South Property, Yukon

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The Plateau South Property in central-eastern Yukon hosts extensive high grade gold mineralization within the Tintina Gold Province. The property lies roughly 130 kilometers east of Mayo, Yukon within the Selwyn Basin on the western edge of ancestral North America. The purpose of this study is to identify the microstructural controls on gold mineralization at the Plateau South Property.

The Goldstack and Gold Dome zones of the Goldstrike Resources' Plateau South Project, that were analyzed for this study, show microstructural evidence of brittle-ductile deformation. Microstructures indicate moderate temperatures during ductile deformation throughout the two zones. Feldspars with undulose extinction, serrated grain boundaries, and subgrains indicate ductile deformation accommodated by dislocation creep. Deformed quartz stockwork veining is evidence of continuous brittle-ductile deformation. Quartz veins filling fractures are evidence for brittle deformation. Crosscutting relationships of older and younger quartz veins all exhibit evidence for dislocation creep. Other microstructures include kink banding and deformation twinning in feldspars. Relict devitrified pseudotachylyte in multiple areas of drill core is evidence for brittle deformation associated with seismicity and is also subsequently ductilely deformed. Abundant evidence for brittle-ductile deformation microstructures is strongly associated with increased gold mineralization at this property.

The geological microstructures found within this mineralized gold property have strong similarities to those found with in gold properties of the Archean Superior province. The strong dependence of gold mineralization on brittle-ductile deformation at the Plateau South Property in the Yukon, has been observed in the Lake Superior region. The presence of pseudotachylyte at the Plateau South might also be found in the Superior Province associated with brittle-ductile deformation. Pseudotachylyte is characteristic of this brittle-ductile transition and can be used as a macroscopic indicator when looking for these structurally controlled gold zones.

Progression from tholeiitic to alkaline basalt magmatism in the early stages of formation of the Coldwell Alkaline Complex, Midcontinent Rift, Ontario

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Early basaltic magmatism in the Coldwell Alkaline Complex is characterized by a diverse assemblage that ranges in composition from tholeiitic to alkaline of both high and low Ti types. The Eastern Gabbro Suite located around the eastern and northern margin of the complex was composed initially of a thick sequence of tholeiitic basalt that was subsequently intruded by a much larger volume of leucocratic to ultramafic intrusions that caused contact metamorphism of the basalt to pyroxene-hornfels grade (Good et al., 2015).

The tholeiitic metabasalt is subdivided into basal, middle and upper units by relative MgO, Ni, Cr, and TiO₂ contents and by La/Sm, La/Zr and Gd/Yb values (Figs. 1 and 2). In general, the basal unit is characterized by high Ti and high Gd/Yb; the middle unit by low Ti, intermediate Gd/Yb and high La/Zr; and the upper unit by low Ti and low Gd/Yb. The basal unit resembles the Mamainse Point Volcanic Group 1 (MPVG; Lightfoot, 1999; Shirey, 1994), with respect to MgO, Ni and Cr contents of up to 24%, 1325 ppm and 2120 ppm, respectively, but with higher TiO₂ content like that found in MPVG 2a. By comparison, the upper metabasalt unit is more evolved with maximum MgO, Ni and Cr of 7.7 %, 162 ppm and 230 ppm, respectively.

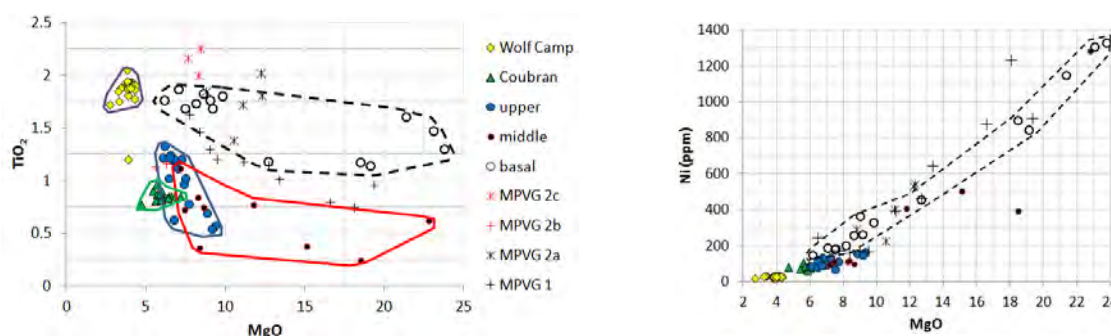


Figure 1: Plot of MgO vs. TiO₂ and MgO vs. Ni for tholeiitic metabasalt (basal, middle and upper units) and alkaline basalt (Wolf Camp and Coubran) compared to basalt from the Mamainse Point Volcanic Groups 1 and 2 (Lightfoot et al., 1999; Shirey et al., 1994).

Alkaline basalt, including the Coubran basalt (Cundari, 2012) and Wolf Camp basalt (Davis, 2016) occur as large sub horizontal sheets that are situated above thicker intrusive units composed predominantly of ferroaugite syenite of centre 1 (Mitchell et al., 1993). The basalt units were referred to as km scale xenoliths or roof pendants by Walker et al. (1993) among others. The Coubran basalt is distinguished from the Wolf Camp basalt by low Ni (63-115 ppm), low TiO₂ (0.7-1.0%), Zr/Hf of 41-43, and La/Sm of 4-7, whereas the Wolf Camp basalt contains very low Ni (17-32 ppm), high TiO₂ (1.7-2.1 %), Zr/Hf of 45-48 and La/Sm of 6.9-7.6.

A characteristic feature of tholeiitic basaltic rocks in the Coldwell Alkaline Complex is the coincident Ta-Nb and Zr-Hf depletion as indicated in primitive mantle normalized spider diagrams (not shown). The Wolf Camp alkaline basalt on the other hand has a depleted Zr-Hf signature but does not

exhibit Ta-Nb depletion. Further, Th/Nb ratios of tholeiitic metabasalt and Wolf Camp basalt are similar to that for MPVG and OIB, but Th/La values of tholeiitic metabasalt are depleted.

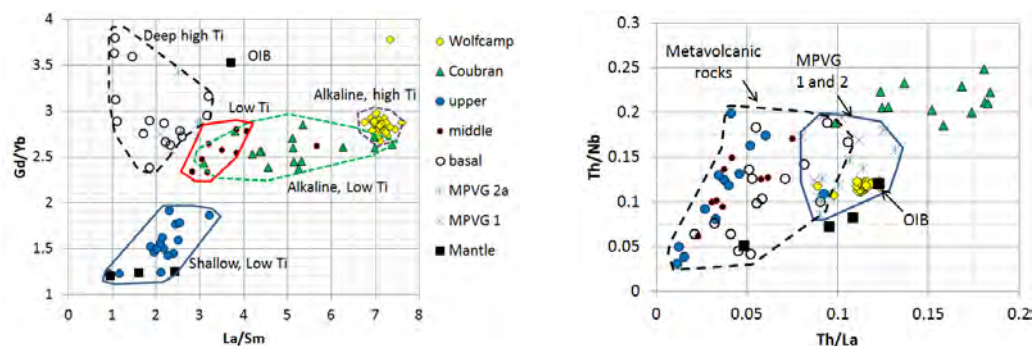


Figure 2: Plot of Gd/Yb vs. La/Sm and Th/Nb vs. Th/La for the same data set as shown in Figure 1. Filled black squares represent primitive mantle, N-MORB, E-MORB and OIB values after Sun and McDonough (1989). MPVG 1 and 2a data from Lightfoot et al. (1989) and Shirey et al. (1994).

The degree to which crustal contamination could have affected Coldwell basalt magmas was evaluated by Sm-Nd isotope analyses of alkaline basalt and by comparison of trace element ratios in tholeiitic metabasalt to MPVG 1 which is recognized to have undergone minimal crustal contamination (Lightfoot et al., 1999). The Wolf Camp basalt samples yielded epsilon Nd values of between -0.2 and 0.1 (this study) consistent with negligible contamination, and are in good agreement with Th/Nb and Th/La values that are very close to Ocean Island Basalt (Fig. 2). For tholeiitic metabasalt, abundances of LILE (Ba, Rb, K, Th) are depleted relative to OIB and MPVG 1 and imply crustal contamination did not play a significant role.

The very wide range of geochemical characteristics for the tholeiitic and alkaline basalt imply a diverse range of conditions for melt formation in the mantle source. The tholeiitic to alkaline character of the magmas can be explained by decreasing degrees of partial melting, whereas the elevated Gd/Yb can be explained by an increase in depth of partial melting. Metabasalt data suggests a LILE depleted and Sr enriched source, whereas evidence for Wolf Camp basalt suggests a normal LILE but Sr depleted source. All data except for the basal metabasalt unit exhibit significant Zr-Hf depletion. The Zr-Hf depletion is difficult to explain by a mechanism such as garnet fractionation because there is no apparent relationship between La/Zr and Gd/Yb as would be expected if garnet crystallization was important. However, the Zr-Hf depletion could be an artifact of mantle metasomatism such as that described for amphibole harzburgite from the Ronda peridotite as described by Arndt (2013). Either a partial melt derived from a similar source, or contamination of a plume derived melt with material such as this could explain some features such as Zr-Hf depletion of the Coldwell basalts.

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Cogenetic relationship between the Wolf Camp basalt and the Geordie Lake intrusion, Coldwell Alkaline Complex, Midcontinent Rift, Ontario

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The Wolf Camp alkaline basalt is located about 5 km southeast of the Geordie Lake intrusion near the centre of the Coldwell Alkaline Complex. Syenitic rocks of centre 1 intruded the Geordie Lake intrusion approximately parallel to the mineralized zone (Meghji 2016; Good and Crocket, 1994), and the Wolf Camp basalt was referred to as a large xenolith or roof pendant within syenite by Walker et al. (1993).

The Geordie Lake intrusion extends for 4 km along strike, is up to 600 m thick, and dips moderately to the west. It consists of an upper unit of homogeneous gabbro that apparently crystallized with minimal crystal sorting but with flow alignment of plagioclase in the uppermost zone. The lower zone consists of heterogeneous gabbro or magmatic breccia that consists of fragments of gabbro or olivine gabbro within cross-cutting augite troctolite. The augite troctolite is characterized by abundant skeletal olivine crystals up to 3 cm in length that presumably formed during under-cooling conditions related to breccia formation. The Cu-Pd mineralization consists of disseminated bornite and chalcopyrite concentrated mostly within augite troctolite near the base of the intrusion and is characterized by near mantle Cu/Pd but very high Pd/Ir, Cu/Ni, and Pd/Pt values.



Figure 1. Simplified geological map of the Coldwell Alkaline Complex highlights the distribution of gabbroic (dark blue) and basaltic (dark green) rocks that were cut by syenitic intrusions (beige), and locations of the Marathon and Geordie Lake deposit host intrusions (purple). Black rectangles in basalt indicate sample traverse locations. Geology after Walker et al. (1993) and Stillwater Canada Inc.

The Wolf Camp basalt is alkaline in composition and characterized by very low Ni (17-32 ppm), high TiO₂ (1.7-2.1 %), and a steep negative primitive mantle-normalized pattern (Figure 2) with depleted Sr and Zr-Hf abundances. This pattern is nearly identical to that demonstrated by the upper and lower zones of the Geordie Lake intrusion (Figure 2).

Despite the nearly identical patterns of the Geordie Lake units and the Wolf Camp basalt, there are very small differences for some trace element abundances between the upper homogeneous gabbro and the troctolite of the lower group (Figure 3). These differences could be explained by fractional crystallization, but the distinct differences between the linear regression curves for troctolite and homogeneous gabbro suggest that fractionation occurred prior to intrusion. This possibility is consistent with geological evidence for multiple intrusions and the formation of intrusive breccia by intrusion of the troctolite into the homogeneous gabbro.

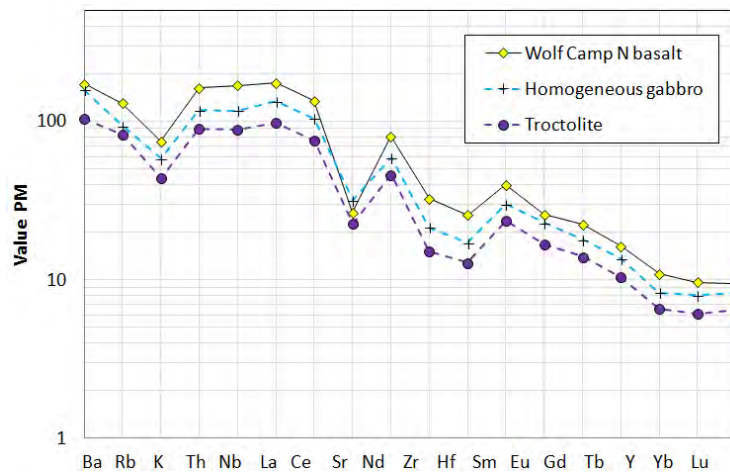


Figure 2. Primitive mantle normalized data for the Wolf Camp basalt north group (n=15) compared to the homogeneous gabbro with aligned plagioclase (n= 14) and troctolite (n=25) of the Georgie Lake intrusion.

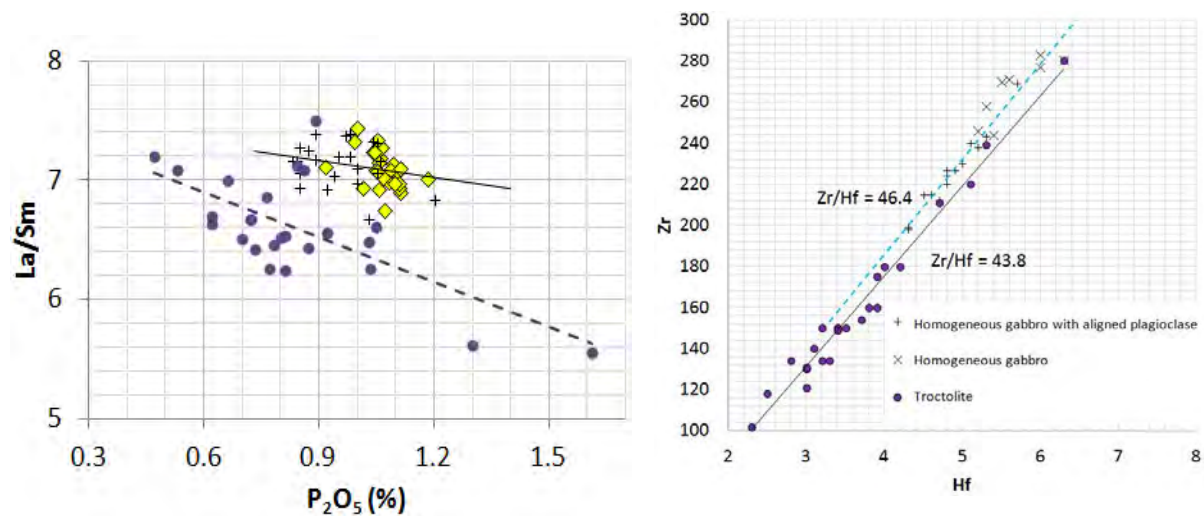


Figure 3. Comparison of troctolite (purple dots) and homogeneous gabbro (+ and x symbols) of the Georgie Lake intrusion to Wolf Camp basalt (yellow diamonds). Lines are linear regression curves. Small differences of Zr/Hf and La/Sm values between the three groups are consistent with different magma pulses of the same parentage at slightly different stages of crystal fractionation.

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Revisiting Geophysical Interpretations of the Midcontinent Rift below Lake Superior

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Efforts to construct a three-dimensional model of the volcanic basins related to the 1.1 Ga Midcontinent Rift System (MRS) in the Lake Superior region have led to a reexamination of existing geophysical data. Inconsistencies and unanswered questions from previous work, opportunities to question old paradigms, updated data compilations, and improved interpretation software provide the motivation for the reexamination. We are reinterpreting and integrating existing seismic-reflection lines (Sanger et al., 2017) and new compilations of gravity and aeromagnetic data (Figs. 1 and 2; Anderson and Grauch, 2017) with geologic constraints from onshore to build a consistent and comprehensive view of the MRS volcanic interval to about ~25 km depth below the lake, the expected depth extent of most of the seismic lines.

Color-shaded relief imaging of the new gravity and magnetic compilations for the Lake Superior region (Figs. 1 and 2) show contrasts in character between different parts of the lake. In the western lake, large-amplitude gravity lows have been interpreted previously as basement highs (White's Ridge and Grand Marais Ridge), whereas gravity highs along the shores are associated with high-density volcanic rocks, but require additional mass within the basement to explain the large amplitudes. In the eastern lake, subdued gravity values are surrounded by narrow, curvilinear gradients that are associated with uplifted volcanic rocks in seismic sections on the west side. Newly highlighted, circular gravity features interior to the eastern lake broadly correspond to a magnetic high and may indicate late-stage(?) felsic intrusive activity (label IN?). Narrow gravity gradients coincide with sharp magnetic gradients following known reverse faults in the central lake (e.g., Keweenaw and Isle Royale faults). A narrow gravity gradient diverges from the magnetic gradient interpreted as the extension of the Isle Royale fault (IRFx). Seismic data (Line A) suggest that these relations are explained by a shelf-like volcanic interval in between the gravity and magnetic gradients, which drops off and thickens into the deeper basin to the south, and is upturned abruptly at the extension of the Isle Royale fault. Similar shelf-like features are suggested by other broad magnetic gradients that follow the shores in the central and western parts of the lake. We are revisiting previous models regarding the volume of reversed-polarity volcanic layers present below normal-polarity volcanic layers at depth. In addition, we are exploring possibilities intrusive activity is more widely represented in seismic sections than previously thought.

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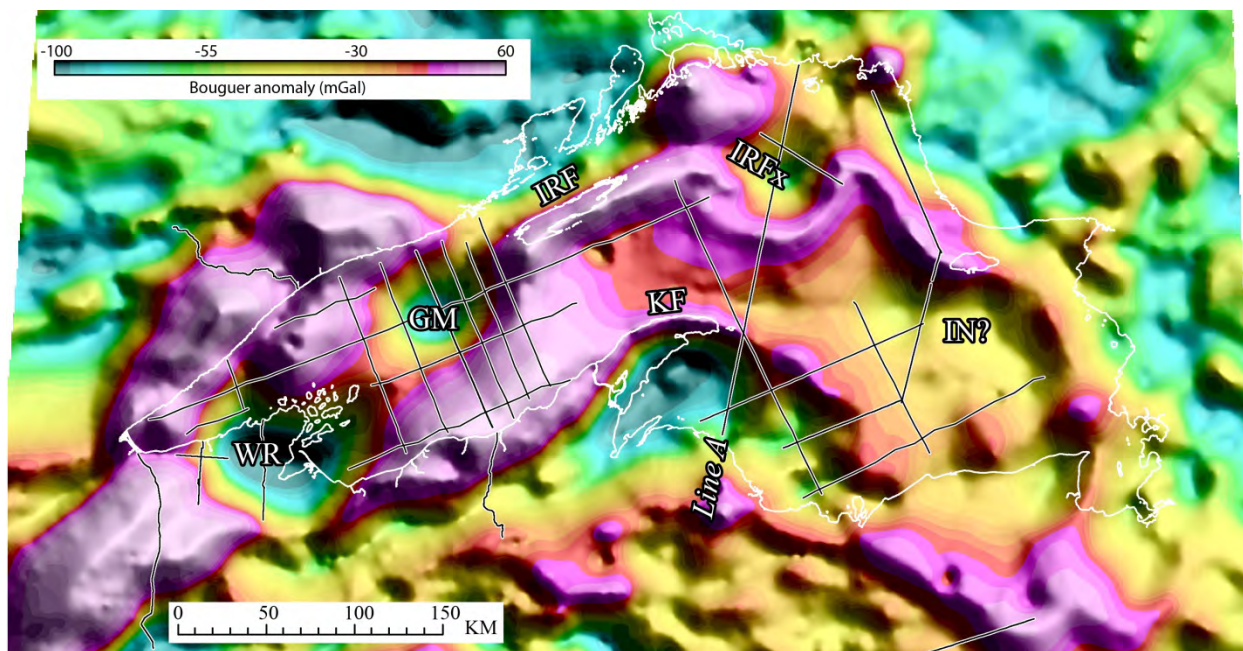


Figure 1: Compilation of Bouguer gravity data (Anderson and Grauch, 2017) shown as color-shaded relief image, illuminated from the northeast. Seismic line locations are thin black lines with white outline. Only Line A is labeled. GM–Grand Marais Ridge; IN?–Possible intrusive; IRF–Isle Royale fault; IRFx–Extension of Isle Royale fault from magnetic map; KF–Keweenaw fault; WR–White's Ridge. White outline is the lake shore.

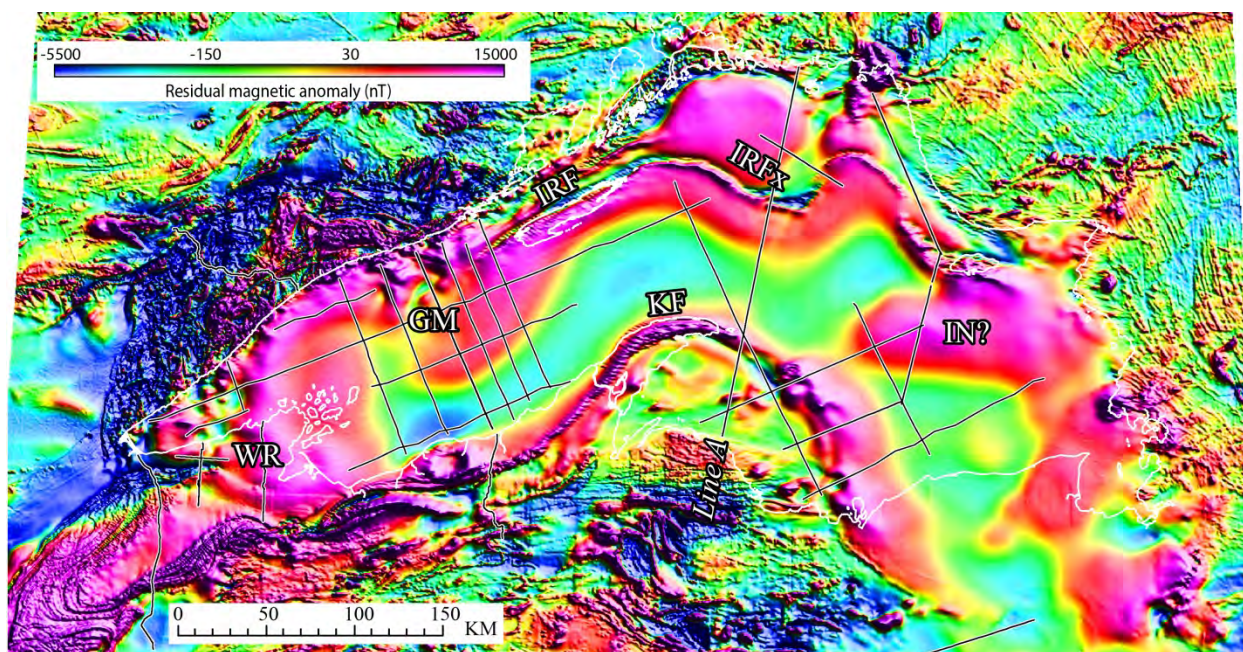


Figure 2: Compilation of aeromagnetic data (Anderson and Grauch, 2017) shown as color-shaded relief image, illuminated from the northeast. Refer to Figure 1 for explanation.

Use of Anisotropy of Magnetic Susceptibility (AMS) to analyze petro-fabrics in Cu and PGE bearing gabbroic units of the Marathon Cu-PGE deposit, Ontario.

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Petrofabric assessment of Cu and PGE bearing gabbroic units has been conducted on oriented drill core samples obtained from Marathon Cu-PGE deposit. Marathon deposit, located in the north shore of Lake Superior, is well known for its rich abundance of Cu and PGE mineralization. Marathon PGE-Cu deposits are hosted in the Coldwell Alkaline Complex composed of Late Mesoproterozoic mafic to ultramafic and syenitic intrusions that were a part of the ~1.1 Ga Keweenawan magmatic event emplaced during the North American Mid Continental rifting event along the western Great Lakes and into the Midwest U.S. (Good et al., 2014; Barrie et al., 2002; Dahl et al., 2002; Good and Crocket, 1992).

Samples taken from three oriented drill cores representing mineralized and non-mineralized zones were analyzed using Anisotropy of Magnetic Susceptibility (AMS). These drill core samples provided by Stillwater Canada Inc were carefully selected in order to best represent the main lithological units of the mineralization zones and associated lithologies. A drill press was used to drill perpendicular to the core axis of the drill core sample and oriented cylindrical specimens with an average volume of 10 cm³ were produced from each sample. These representative samples were assessed for their magnetic susceptibilities and were measured with a Sapphire Instruments SI2b desktop magnetic susceptibility meter, located in the Western Paleomagnetic and Petrophysical Laboratory (WPPL), Western University.

These magmatic Cu-PGE sulphide deposits are proposed to have formed by intrusion of a crystal mush within a magma conduit setting. Magnetic anisotropy is influenced by the preferred orientation of the long axes of grains of magnetite, which is similar to the overall petrofabric of the samples defining the flow direction of the crystal-bearing magma. Susceptibility ellipsoids constructed from analysis of AMS measurements were plotted on a Flinn diagram to investigate the dominant petro fabric textures, indicating the presence of a well-defined planar fabric. Samples that gave results of the highest degree of planar fabrics were from the Two Duck Lake Gabbro lithology; the lithological host of most of the Marathon deposit.

Stereonet projection of the directional distribution of the susceptibility ellipsoid maximum and intermediate vector directions gives orientation information of the petro fabric. As seen in Figure 1, the K max and K int directional data points of the stereonet form a well-defined girdle, while the K min data form a pole perpendicular to the girdle. The girdle can be outlined with a great circle analysis to define the planar fabric existing within the oriented drill core. A well-defined planar fabric orientation with a strike of 177 and dip 25° to the west, in excellent agreement with proposed flow direction based on 3D modeling of footwall troughs containing the higher grade mineralization, is observed in the results.

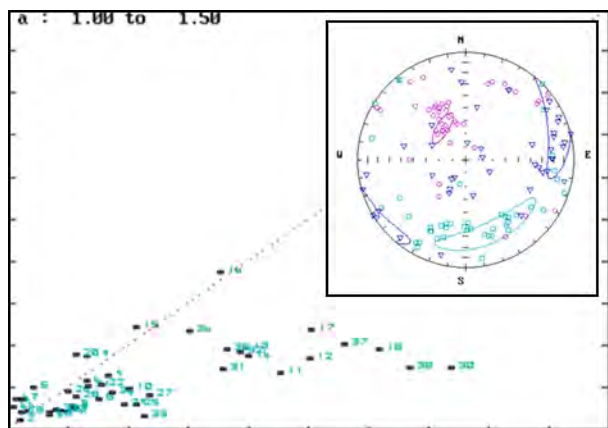


Figure 1: Flinn diagram of KP-3 drillcore specimens with AMS results displayed as numbered points. Specimens display a dominantly planar fabric, with anisotropy up to 1.4. Inset shows stereonet projection of maximum (green square), intermediate (purple triangle) and minimum (red circle) susceptibility directions in KP-3 specimens.

A fabric lineation has also been detected for drill cores obtained from the Main Zone with an average trend of 295 and a plunge of 29° reflecting the likely direction of origin for the magma. Samples obtained from W-horizon area of the Marathon deposit also indicate strong planar fabric foliations. The AMS fabric orientation is a potentially useful tool to independently quantify flow structures in magmatic systems.

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Fluid history of the Reef Deposit using fluid inclusions and oxygen isotopes

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The Reef deposit is a vein hosted Au-Cu occurrence located approximately 15 miles east of Wausau, Wisconsin. The Reef deposit consists of seven primary mineralized zones which consist of Au-Cu bearing quartz-sulfide veins that trend northeast and dip moderately to the northwest (Kennedy and Harding, 1990). The mineralized zones likely formed as the root zones of a VMS deposit as cross-cutting relationships indicate the main quartz-sulfide veins formed syn-genetically with the hosting gabbro units, but were later cross-cut by a mafic intrusion referred to as the footwall gabbro.

Gold is observed in two primary textural settings; in the earlier setting gold is encased in sulfides, and in the later setting, gold is found along quartz and sulfide grain boundaries and microfractures. Lead isotope compositions of Pb-rich phases found in the earlier textural setting are found to be similar to Pb isotope compositions for Paleoproterozoic VMS deposits located in the same terrane, to the north, whereas Pb isotope compositions for Pb-rich phases intergrown with the later gold have highly radiogenic values which match Permian-aged Mississippi Valley Type (MVT) deposits found in southern Wisconsin (Haroldson et al., 2016).

Fluid inclusion assemblages consist of multiple compositions including: H₂O-CO₂-NaCl ($\pm$ CH₄), H₂O-CH₄, CO₂-CH₄, and H₂O-NaCl. H₂O-CO₂-NaCl ($\pm$ CH₄) compositions are observed in primary fluid inclusions in the primary quartz vein growth as well as secondary assemblages formed prior to regional deformation/metamorphism. Compositions of these earliest assemblages can be identified by microthermometry and laser Raman spectroscopy, however no pressure or temperature information can be obtained due to post entrapment re-equilibration (Diamond et al., 2010). H₂O-CH₄ and CO₂-CH₄ compositions are observed in secondary fluid inclusion assemblages which post-date regional metamorphism. The presence and density of CH₄ is verified and measured using laser Raman spectroscopy. Assemblages of H₂O-CH₄ inclusions are observed to have coincident inclusions that homogenize to the liquid and inclusions that homogenize to the vapor. CH₄ densities lack significant variability between liquid and vapor homogenizers, suggesting these were not formed during fluid immiscibility, and instead, formed along the critical isochore at elevated temperatures. We attribute the CH₄ fluid bearing assemblages to magmatic fluids exsolved from the nearby Wolf River Batholith, which has been shown to have reducing conditions during earliest batholith development (Anderson, 1980). H₂O-NaCl compositions are observed in primary and secondary inclusion assemblages with variable ranges in homogenization temperatures and salinities. Secondary higher temperature (205-312 °C) homogenization and high salinity (14-21 wt. % NaCl equiv.) H₂O-NaCl inclusion assemblages are enigmatic, but could also be related to Wolf River Batholith magmatism. Lower temperature (<50-158 °C) assemblages are observed in secondary trails in quartz and primary assemblages in calcite. When observed in quartz they have homogenization temperatures of 78-158 °C, lower salinity of 2.96-13.9 wt. % NaCl equiv. and are observed to cross-cut CH₄ bearing assemblages. Assemblages in calcite are observed either with no vapor bubbles (likely formed at temp. <50 °C), or assemblages with fluid only and relatively equant low vapor/fluid ratio inclusions (likely formed at temp. <150 °C). Calcite assemblage salinities (23.6-24.6 wt. % NaCl

equiv.) are measured using the metastable freezing of water temperature (Wilkinson, 2017). Lower temperature H₂O-NaCl inclusions are most likely related to Permian MVT fluid overprint.

Laser fluorination oxygen isotope measurements of quartz veins range in $\delta^{18}\text{O}$ from 6.8 to 10.8 ‰ (all results refer to VSMOW) and quartz from felsic intrusives spatially associated with the deposit veins range from $\delta^{18}\text{O}$ of 7.7 to 8.1 ‰. There is a trend of increasing $\delta^{18}\text{O}$ values of vein zones from west to east likely from a temperature gradient during formation with the highest temperatures found in the westernmost mineralized zone. This suggests the initial vein mineralization formed from a magmatic sourced fluid, with a possible starting fluid composition of 7.7 ‰ representing temperatures of ~500-850 °C.

Secondary Ion Mass Spectrometer (SIMS) in-situ oxygen isotope measurement of quartz and carbonate veinlets cross-cutting the primary quartz veins range in $\delta^{18}\text{O}$ from 8.5 to 28.4 ‰ for quartz, 25.3 to 28.1 ‰ for dolomite, and 9.61 to 29.3 ‰ for calcite. Isotopically heavy $\delta^{18}\text{O}$ (values in the 19+ ‰ range) are found in multiple cross-cutting features, at times, in direct contact with relatively lighter $\delta^{18}\text{O}$ values (8 to 11 ‰ range). Heavy $\delta^{18}\text{O}$ values are measured in a ~200 µm wide crustiform textured quartz stockwork veinlet, with lighter $\delta^{18}\text{O}$ values measured directly adjacent to the veinlet in the primary vein quartz. Heavy $\delta^{18}\text{O}$ values are found in dolomite observed in late cross-cutting veinlets, up to 10 cm in width, commonly with euhedral, open space growth dolomite. Void space in both quartz and dolomite open space growth features is later in-filled (with some dolomite dissolution) with heavy $\delta^{18}\text{O}$ calcite. Separate late calcite veinlets, ~100 µm wide, have two phases of growth with an earlier light $\delta^{18}\text{O}$ calcite that is later infiltrated by heavy $\delta^{18}\text{O}$ calcite along the veinlet selvage.

The lighter $\delta^{18}\text{O}$ measured by SIMS verifies the laser fluorination values for the primary quartz veins as being related to a high temperature portion of a VMS system, whereas the heavier $\delta^{18}\text{O}$ is verified in late cross-cutting calcite to be from a low temperature fluid related to MVT brine fluids. The system related to heavy $\delta^{18}\text{O}$ values measured in open space growth quartz and dolomite veinlets is less clear, with no fluid inclusions observed to measure temperatures or salinities. The quartz and dolomite veins could be related to low-temperature MVT mineralization as with the calcite, or it is also possible that a post-deformation, lower temperature (100-275 °C) distal magmatic fluid was responsible. Pyrite and chalcopyrite mineralization found in the brittle fracture quartz and dolomite veinlets offers some clues.

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Geochemical relationships between the Black Sturgeon sill and other Midcontinent Rift igneous units

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In this study, we investigate the relationships between the composition of the Black Sturgeon sill, a diabase sill near Nipigon, Ontario, and published compositions of other igneous formations from the Midcontinent Rift. Hollings et al (2007b) classified the diabase sills north of Lake Superior in the Midcontinent Rift Intrusive Supersuite under the heading of the Logan Igneous Suite. They further distinguished the sills to the north and south of Thunder Bay, Ontario, with the informal terms Nipigon sills and Logan sills, respectively. TiO_2 vs Mg# and Gd/Yb vs La/Sm were the primary signatures used to characterize the Nipigon and Logan Sills, and to clarify their relationship to other intrusions and volcanic formations in the region.

In order to simplify the problem of distinguishing between the various igneous formations, we performed a principal components analysis (Davis, 2002) using the ten major element oxides: SiO_2 , TiO_2 , Al_2O_3 , FeO^T , MnO, MgO, CaO, Na_2O , K_2O , and P_2O_5 , as well as ten commonly analyzed trace elements: Ni, Rb, Sr, Sc, V, Nb, Zr, Y, La, and Ce. The first three major element components (M1, M2, M3) and the first three trace element components (T1, T2, T3) each account for >90% of the geochemical variability.

Using these components, we were able to clearly differentiate between the Nipigon and Logan sills (Hollings et al, 2010, 2007b, 2007c). We are also able to distinguish the Osler basalts (Hollings et al, 2007a), the Misquah Hills/Pine Mountain granophyres and rhyolites (Vervoort et al, 2007), and the McIntyre and Jackfish sills (Hollings et al, 2007b, 2007c).

The Black Sturgeon sill substantially overlaps previous reported analyses from Nipigon sills, clearly demonstrating its “Nipigon” affinity. But compared to the other published Nipigon results, the compositions from this sill extend farther from, and do not as closely approach, the Logan compositions. This suggests that the Black Sturgeon sill may have a more characteristic “Nipigon” composition than some sills that have previously been studied.

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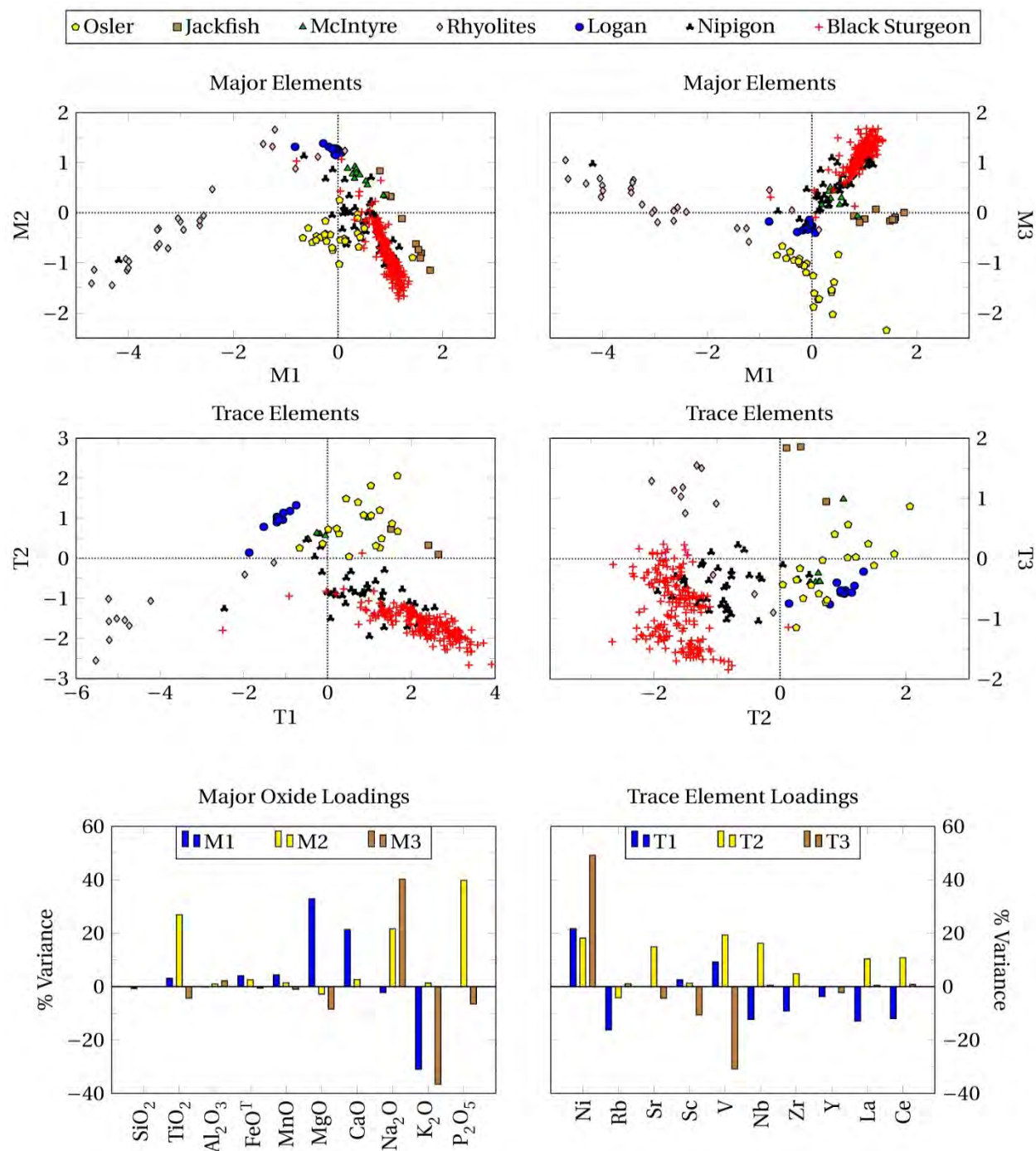


Figure 1. Principal components analysis of Midcontinent Rift magmas. Top panels: distinctions based on first, second, and third principal components using major oxides (top) and trace elements (middle). Nipigon sills, Logan sills, Osler Group, and Misquah Hills/Pine Mt felsics can be easily distinguished. Bottom panels: loadings of major oxides (left) and trace elements (right) on the first three principal components. For instance, M2 is primarily controlled by total (TiO₂+Na₂O+P₂O₅), consistent with previously identified contrasts between the Nipigon and Logan sills (Hollings et al., 2007b, 2010).

Field and petrographic evidence of migmatite formation near Lake Kabetogama, Voyageurs National Park, northern Minnesota

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Lake Kabetogama, in Voyageurs National Park, lies within the Quetico metasedimentary belt of the Superior Province in northern Minnesota. This area was geologically active between 2,668 Ma to 2,550 Ma, when high-temperature metamorphism and plutonic events produced multiple granitic and leucogranitic bodies (Day & Weiblen, 1986). As a result, the Lake Kabetogama area hosts widespread leucocratic injections and a variety of migmatites, including schollen/raft-structured diatexites, schlieric diatexites, and localized patch and stromatic metatexites. A field and petrographic study of the leucocratic migmatites was completed to determine the processes of migmatite development.

Based on field relationships and microtextures, the formation of migmatites at Lake Kabetogama is interpreted to be the product of high-grade metamorphism and melt injection combined with limited local anatexis. Leucocratic injection was the dominant process that formed the migmatites, as seen at most of the melt-bearing sites (Figure 1a), with formation of minor local *in situ* and in-source migmatites. Evidence for *in situ* and in-source anatexis

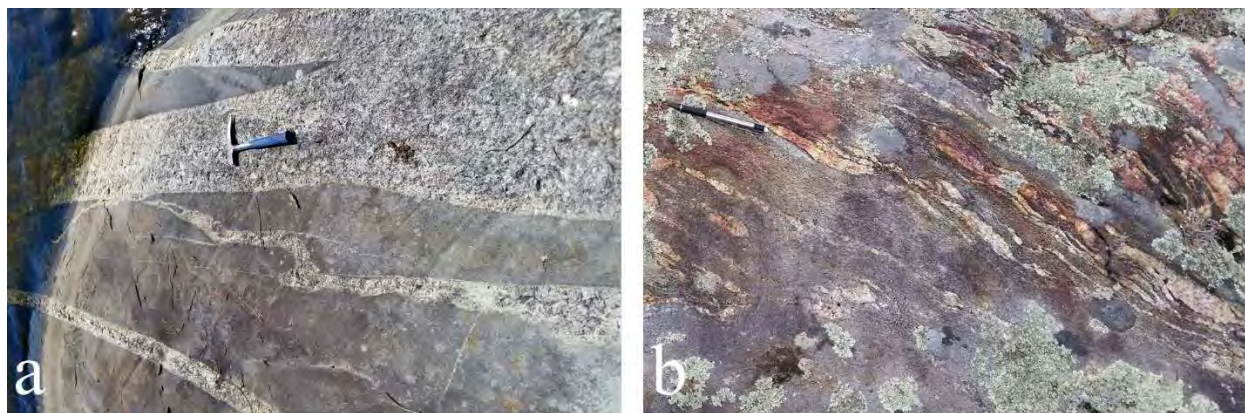


Figure 1: a) Representative leucocratic injection occurrence of planar, coarse-grained, muscovite-bearing leucocratic dikes. b) Representative local anatexis shown by stromatic metatexite migmatites displaying irregular strings of quartz- and feldspar-rich leucosome, and biotite-rich melanosome around boundaries.

includes patch and stromatic metatexite migmatites that contain felsic patches, pods, and strings with biotite-rich melanosome borders (Figure 1b). Microtextural observations of melt pseudomorphs (Figure 2), myrmekite textures (Figure 2b), and equilibrium grain boundaries demonstrate mineral crystallization from a melt, yet these migmatites lack a melt network that would have allowed the melt to leave the system (Holness & Sawyer, 2008; Sawyer, 2008). Conversely, evidence for leucocratic injection is supported by sharp boundaries on a variety of veins, sills, dikes, and leucocratic bodies. The absence of sufficient residual material indicates that most of these melt features were not locally produced.

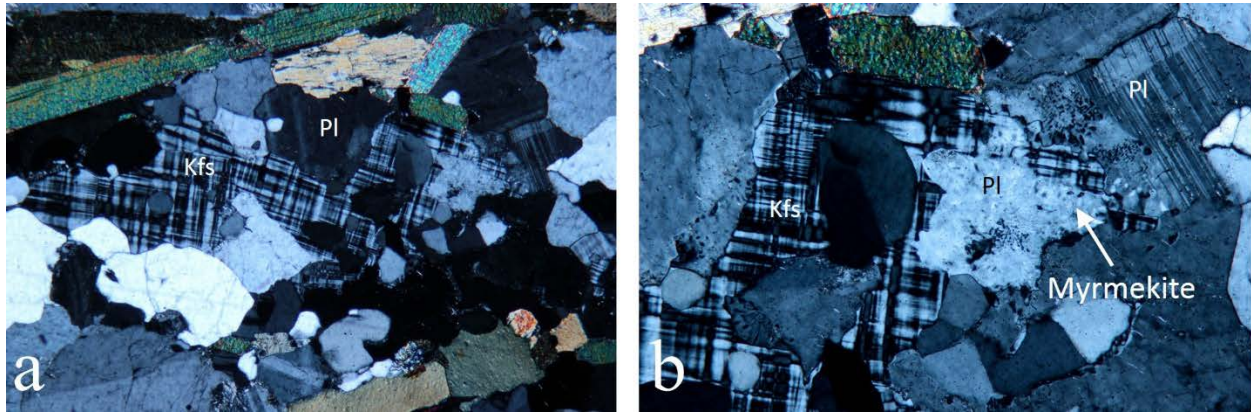


Figure 2: Melt pseudomorphs in a biotite-hornblende patch metatexite migmatite. a) Cross-polarized image of irregular microcline-twinned K-feldspar (Kfs) melt pseudomorphs, adjacent to rounded reactant minerals plagioclase and quartz. Long edge is 3 mm. b) Cross-polarized image of similar K-feldspar melt pseudomorphs and myrmekite rims along plagioclase (Pl) crystals, with rounded reactant minerals plagioclase and quartz. Long edge is 1 mm.

Overall, migmatite formation is interpreted to be largely due to melt injection with only localized anatexis. This conclusion supports the findings of Day & Weiblen (1986) regarding the Vermillion Granitic Complex, in which migmatites formed by the intrusion of leucogranite prior to emplacement of the Lac La Croix Granite. Although the origin of injected leucocratic material is not known, it was likely from a source external to the area; however, evidence from melt pseudomorphs indicates that the migmatites at Lake Kabetogama were still within the region affected by anatexis. Following the terminology of Sawyer (2008), rocks in the Lake Kabetogama area are further regarded as a leucocratic injection rather than a leucogranitic injection. Similar findings are reported from the Quetico metasedimentary belt and other migmatite occurrences in the Opinaca and Ashuanipi subprovince of the Superior Province (Guernina & Sawyer, 2003; Morfin et al., 2013; Sawyer & Barnes, 1988).

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Geologic mapping in the Central Arrowhead Area, northeastern Minnesota

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This presentation describes recently published products of bedrock, bedrock topographic, and surficial mapping in what we refer to as the Central Arrowhead Area of northeastern Minnesota. The area is one of three bedrock and four surficial map areas that over several years will collectively provide data and interpretations for county geologic atlases covering two of the largest counties in Minnesota—St. Louis and Lake. It encompasses mineral deposits that are currently in various stages of exploration, development, mine permitting, and production. It also lies within parts of the Boundary Waters Canoe Area Wilderness, Superior National Forest, and several state forests. The geology consists of Archean and Proterozoic bedrock, and Quaternary sediments derived from multiple advances of the Rainy, Superior, and Koochiching ice lobes (Figs. 1A, B). The preliminary maps and associated files that include details of bedrock topographic, geochronologic, and geophysical data are published as MGS **Open-File Report OFR2016-04**; some highlights follow.

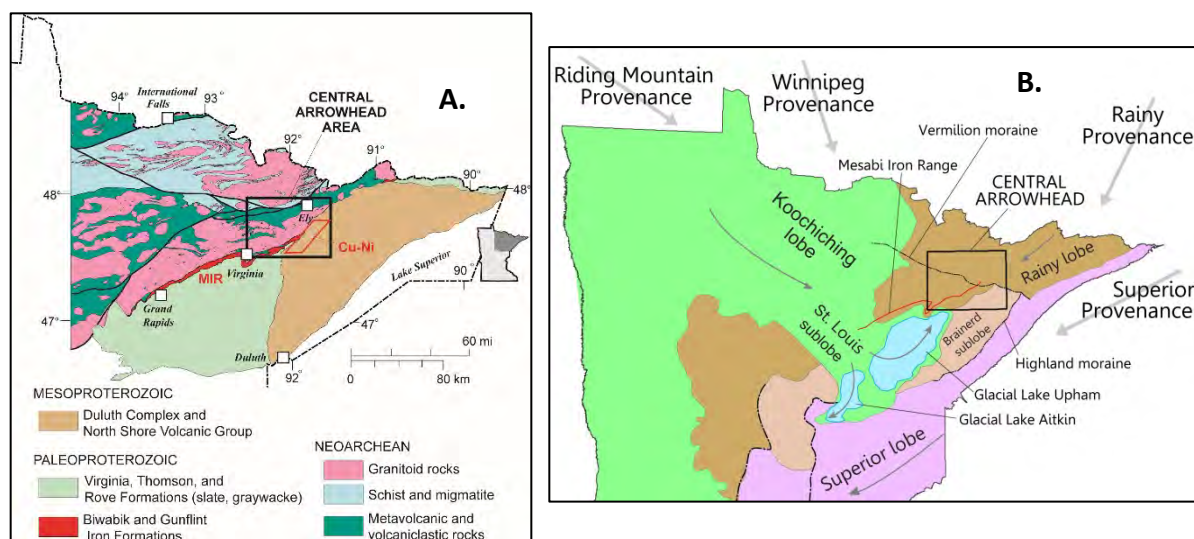


Figure 1. Maps showing geologic setting of Precambrian bedrock and Quaternary sediments in the Central Arrowhead Area (black outlines). **A.** Generalized bedrock geologic map of northeastern Minnesota. Red letters highlight Mesabi Iron Range (MIR) and the primary copper-nickel exploration district (Cu-Ni). **B.** Map of northern Minnesota showing trajectories of ice lobes (arrows), glacial sediment provenance, moraines (dashed), and former glacial lakes (blue).

The bedrock geology includes parts of the Wawa and Quetico subprovinces of the Archean Superior Province, Paleoproterozoic iron-formation and associated rocks of the Mesabi Iron Range, and portions of the Mesoproterozoic Duluth Complex (Fig. 1A). Bedrock mapping modified existing geologic interpretations using new field data guided in part by LiDAR imagery, drill core logging, and petrographic analysis; and reinterpreted them in the context of reprocessed geophysical data and models. The project also included a significant component of high-precision geochronologic analysis conducted by coauthor Schmitz. In this area of relatively few analytical ages for Archean bedrock, the intent was to establish temporal constraints on major events in the geologic evolution of this complex terrane. The

locations, geologic setting, descriptions, and analytical methods and results of 6 samples are published in the Open-File Report. Perhaps the most significant discovery arising from these data and other recently published ages is that the Lake Vermilion Formation—a major component of the Archean bedrock—is one of three successor-basin deposits in the map area that reflect an apparent 30 million year hiatus between earlier volcanism (~2722 Ma Ely Greenstone), and more recent volcanic and clastic deposition (~2690 Ma Lake Vermilion Formation). Deposits of the latter are typically bounded from the older rocks by unconformities and faults. Field work by the authors revealed several such boundaries, and identified an isolated sequence of felsic volcanic rocks on the order of 2690 Ma that shed sediment to the superjacent Lake Vermilion Formation. A surprising result is the ~2688 Ma age acquired from the gneissic Embarrass Tonalite. The tonalite was formerly considered to be one of the oldest intrusions in the region on the basis of its gneissic fabric and an imprecise published age (~2718±67 Ma). The more accurate age of ~2688 Ma places it within a younger suite of intrusions that typically exhibit considerably less metamorphic fabric. This implies residence of the tonalite at significant crustal depth during what is referred to as “D₂ deformation,” the major metamorphic and tectonic fabric-forming event at ~2680 Ma. From recently published data and the ages reported here, it now appears that there were five discrete Archean magmatic episodes in the region at approximately 2720, 2690, 2685, 2675, and 2661 Ma.

Surficial mapping of Quaternary sediments (Fig. 1B) built on existing interpretations using air photographs, LiDAR datasets, National Wetlands Inventory maps, data from the County Well Index (CWI), and two seasons of field work. Sediment cover is thin in much of the map area, though locally as thick as 347 ft. in channel and basin structures on the bedrock surface. The deepest and most prominent of these is a southwest-trending valley system that cuts through the Giants Range Batholith and Biwabik Iron Formation to form the “Embarrass Gap” near Biwabik—one of the few buried channels that cross the Mesabi Iron Range. The map depicts the distribution of sediments derived primarily from the Rainy lobe of the Laurentide Ice Sheet, with lesser contributions from the Superior and Koochiching lobes. Sediments deposited by each lobe derive from four unique bedrock source regions; however, migrating icesheds, coalescent margins, and polyphase depositional histories contribute to the development of units with mixed provenance. Tills (diamicton) are typically sandy and clast-rich, which locally obfuscates distinction between these and other coarse-grained sediments deposited by glacial meltwater. Fine-grained lacustrine sediments occur pervasively at the surface in the map area. The current temporal interpretation invokes coincidence of the Rainy lobe, Brainerd sublobe of the Rainy lobe, and Superior lobe during the St. Croix phase of late Wisconsinan glaciation. Asymmetric retreat of these lobes subsequently exposed the Toimi drumlin field. The Superior lobe readvanced during the Automba phase, extending to and forming the Highland moraine. Brainerd ice had not fully melted from the area north of the Highland moraine by this time, but was retreating rapidly. At this stage, the Rainy lobe stagnated at the Embarrass Gap, which was dammed by ice-cored sediment. Glacial Lake Norwood formed along the Rainy lobe margin north of the range—split by the continental divide west of the Dunka River Outlet—and followed retreat of the Rainy lobe to the Vermilion moraine. During this time, meltwater from both Rainy and Superior lobes flowed via the ancestral St. Louis and lower Cloquet rivers into a large basin south of the iron range, forming Glacial Lake Upham I. Upon readvance of Rainy and Brainerd ice to the Vermilion and Inner Isabella moraines, meltwater issuing from the Superior lobe at the Highland moraine was barred from northern drainage and diverted west along successively contracted ice margins, eventually depositing a series of deltas into Glacial Lake Dunka. Rainy, Brainerd, and Superior ice then retreated concurrently, and the St. Louis sublobe of the Koochiching lobe advanced, overriding sediments of Glacial Lake Upham I. Drainage of Glacial Lake Norwood succeeded collapse of the St. Louis sublobe.

Mapping was supported by the U.S. Geological Survey STATEMAP program Award #G15AC00239, the Minnesota Environment and Natural Resources Trust Fund, and commissioners of St. Louis and Lake Counties.

Probing the composition of the Lithospheric Mantle during the Initiation of the Mid-Continent Rift

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During the rifting of a continent, the existing lithosphere exerts a controlling influence on the processes of extension and lithospheric thinning. The continental lithosphere, which exhibits considerable yield strength, will require conditions that focus the strain in order to produce a continental rift (Buck et al. 2006). Metasomatic modification of the continental lithospheric mantle may provide this strain-focusing by facilitating melt generation and weakening the lithosphere. The Mid-Continent Rift contains within it an excellent stratigraphic record of rift development that is preserved due to the subsequent failure of the rift. While much work has been done studying the main phases of volcanism, little is known about the inception of the rift. Lamprophyre dikes are potassic, mafic or ultramafic melts thought to be derived from either an upwelling plume, or melting of enriched metasomes within the continental lithospheric mantle. Within the region surrounding the Mid-Continent Rift are a suite of lamprophyre dikes that may contain fragments that probe the composition of the Laurentian lithospheric mantle during the initial stages of rifting. These dikes lack evidence of deformation that is typical for pre-Keweenaw intrusions in the Superior Province. We therefore hypothesize that these dikes are related to magmatic activity associated with the younger Keweenaw large igneous province.

The dikes contain glomerocrysts and phenocrysts composed of forsterite, which is either derived during the earliest stages of fractional crystallization, or a refractory residuum during partial melting. Forsterite within the lamprophyres occur in two distinct groups containing crystals with Fo₇₄₋₇₈ and Fo₈₈₋₉₂ compositions. We suggest that the crystals with the higher Fo value could be fragments of the mantle remaining after the most fusible existing minerals, in what was likely a peridotite composition, were replaced by forsterite in a process described as metasomatic defertilization (Arndt et al., 2010). We infer that the metasomatic agent that interacted with the continental lithospheric mantle beneath the Mid-Continent Rift is a CO₂-rich fluid, supported by enrichment of TiO₂ and CaO in addition to depletion of Ni in olivine within the dunites. The geochemical characteristics of these olivines are consistent with other studies that showed similar dunite compositions were generated by pervasive melt-lithosphere interaction involving a CO₂-rich fluid (Arndt et al., 2010; Trestrail et al., 2016). This interaction is capable of facilitating dike generation, which effectively localizes the melt and decreases the yield strength of the continental lithosphere.

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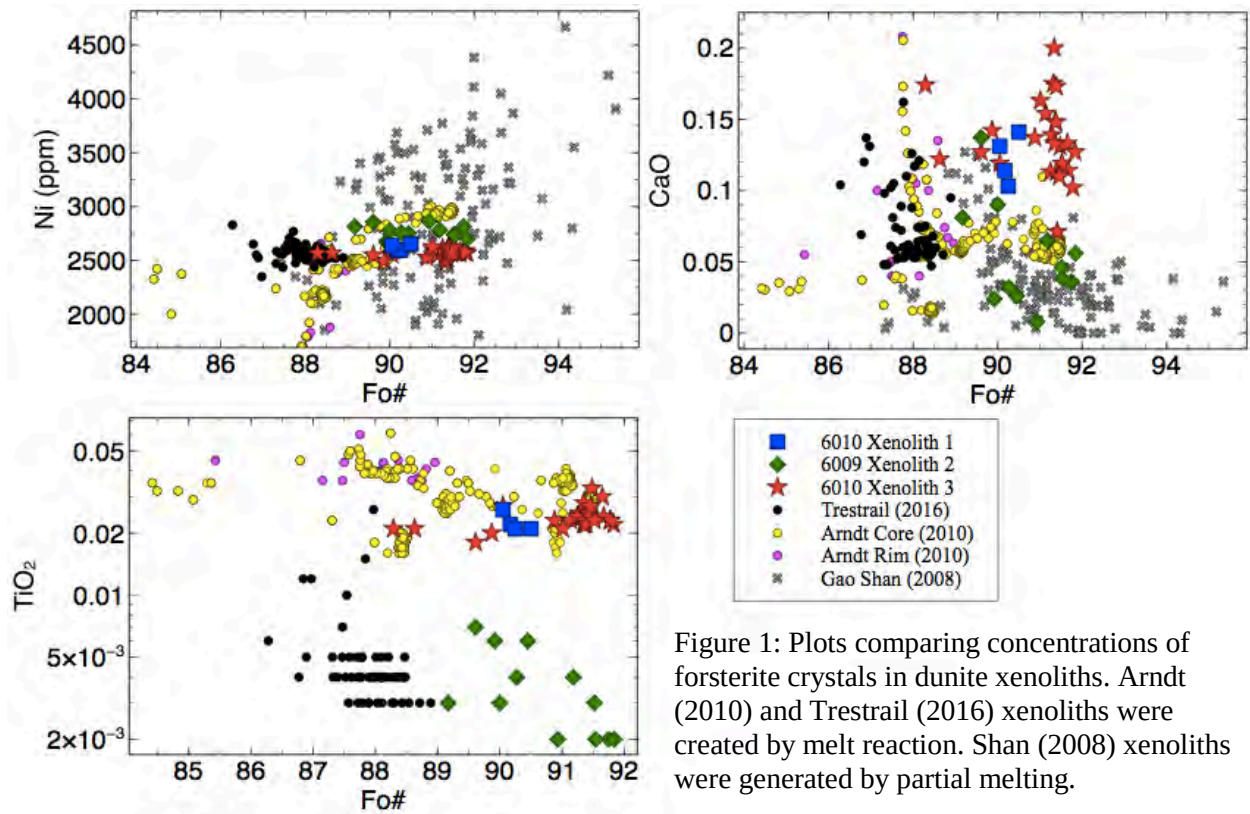


Figure 1: Plots comparing concentrations of forsterite crystals in dunite xenoliths. Arndt (2010) and Trestrail (2016) xenoliths were created by melt reaction. Shan (2008) xenoliths were generated by partial melting.

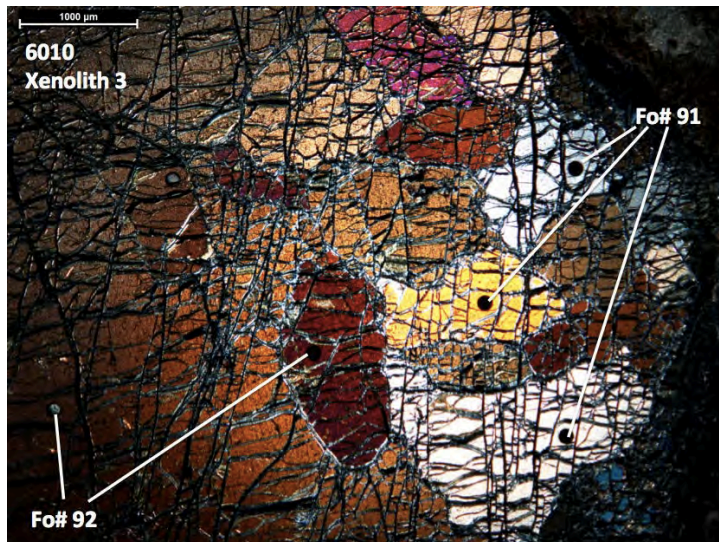


Figure 2: An XPL 2x thin section photograph of part of 6010 xenolith 3 displaying consistent Fo values for olivine crystals within dunite.

New Precambrian geologic mapping of the Baraboo Hills, southern Wisconsin constrains Baraboo-interval sedimentation and deformation

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The Baraboo Quartzite (<1710 Ma, Medaris et al., 2003) is present in the Baraboo Hills of south-central Wisconsin. It is one of eight quartzites included in the Baraboo interval (1750 – 1450 Ma, Dott 1983) that are expressed as isolated outcrops across the southern Lake Superior Region. These have been the focus of studies on the history of continental growth and stabilization of Laurentia (e.g. Holm et al., 1998) and Proterozoic climate (Medaris et al., 2003). Furthermore, studies of the Baraboo Quartzite were significant to the development of the field of structural geology (e.g. Van Hise, 1893), and the Baraboo Quartzite remains an important field trip destination for geology students in the upper Midwest (Medaris et al., 2011). However, the stratigraphy of the Baraboo interval strata that overlie the Baraboo Quartzite in the Baraboo Hills is debated, which limits understanding of the style and history of basin formation, sedimentation, and deformation, as well as correlation between the various regional quartzite bodies.

We present new bedrock geologic mapping of the Baraboo Hills area. Mapping is based on integration of traditional surface mapping, the US Geological Survey aeromagnetic anomaly map of southern Wisconsin (Snyder and Daniels, 2002), 34 drill cores, 226 historic drill hole records, 10 drill cuttings sets, and 89 well construction reports. Drill core and drill hole records were collected in the early 1900s for iron exploration and targeted the Freedom Formation. For the past 70 years historic drill hole records from the eastern Baraboo Hills were thought to have been lost; 47 of these were recently rediscovered in the basement of the Wisconsin Geological and Natural History Survey.

Our mapping confirms early interpretations of the stratigraphy of the Baraboo Quartzite and overlying Precambrian metasediments (Leith, 1935) and identifies a reverse fault in the western Baraboo Hills. The Baraboo interval includes two upward-fining sequences separated by an angular unconformity. The lower sequence comprises the Baraboo Quartzite, Seeley Slate, and Freedom Formation. The upper sequence comprises the Dake Quartzite and Rowley Creek Slate. Cores and core logs show that relief on the Precambrian surface prior to deposition of the Cambrian Elk Mound Group exceeded 1,000 feet (305 meters), more than double what it is today.

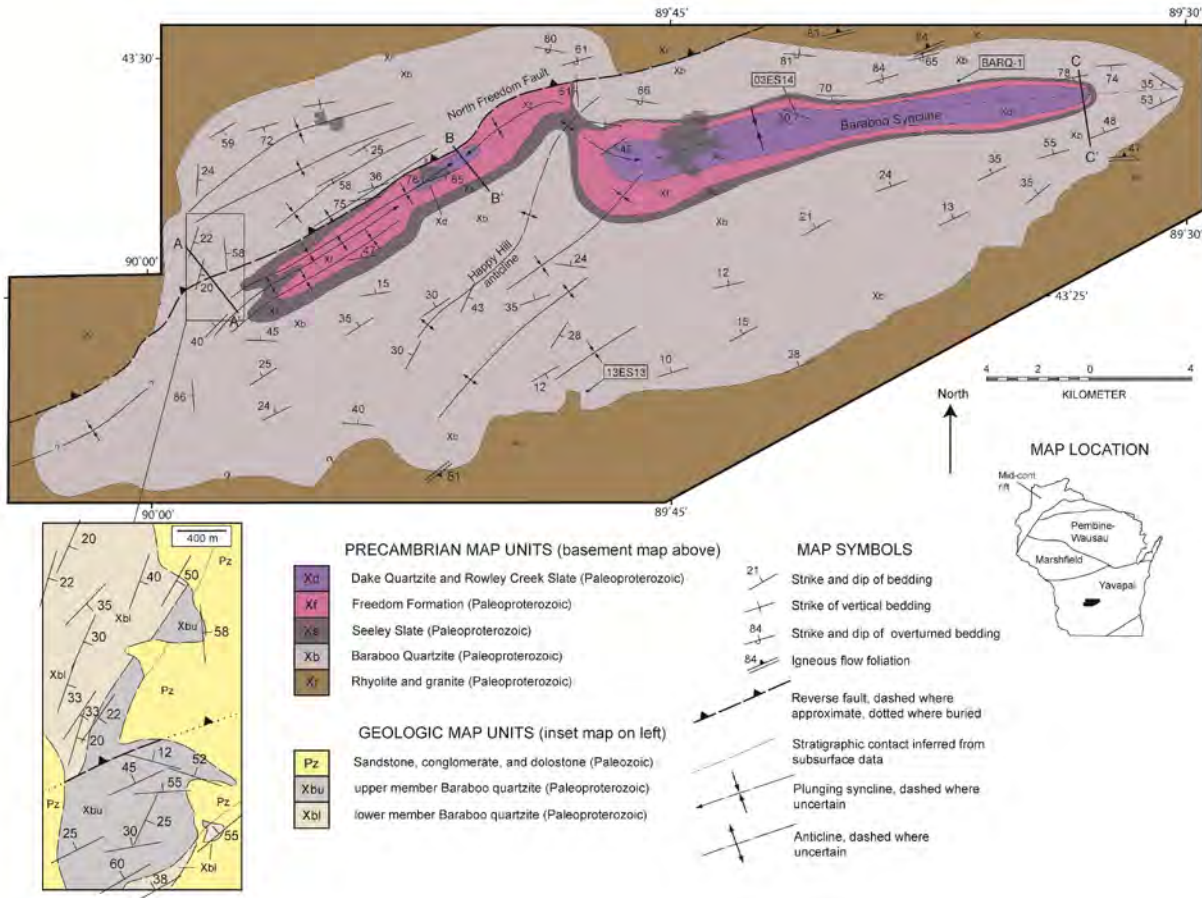


Figure 1. Preliminary bedrock geologic map of the Baraboo Hills, Sauk and western Columbia Counties, Wisconsin

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Locally subaerial evaporitic minerals (quartz pseudomorphs after gypsum) in the Gunflint Limestone Member and its relationship to the deposition of Sudbury impact ejecta-bearing debrisites

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Evidence of the presence of subaerial exposures of the Gunflint Formation was first noted by Addison et al. (2010) and described more recently by Karman and Fralick (2014). Subaerial exposure was seen both above and below the 1850 ma Sudbury ejecta-bearing debrisites. Our study was undertaken in order to characterize the occurrence of evaporitic minerals in relation to the Sudbury debrisites by detailed mapping of the Highway 11/17 site. Our findings are the result of the location of new exposures of the rocks concerned and reinterpretation of previous studies.

Figure 1 is a schematic stratigraphic column of the composite section capped by the Sudbury debrisite and lying on cherty iron formation. Maximum thickness is approximately 20 cm.

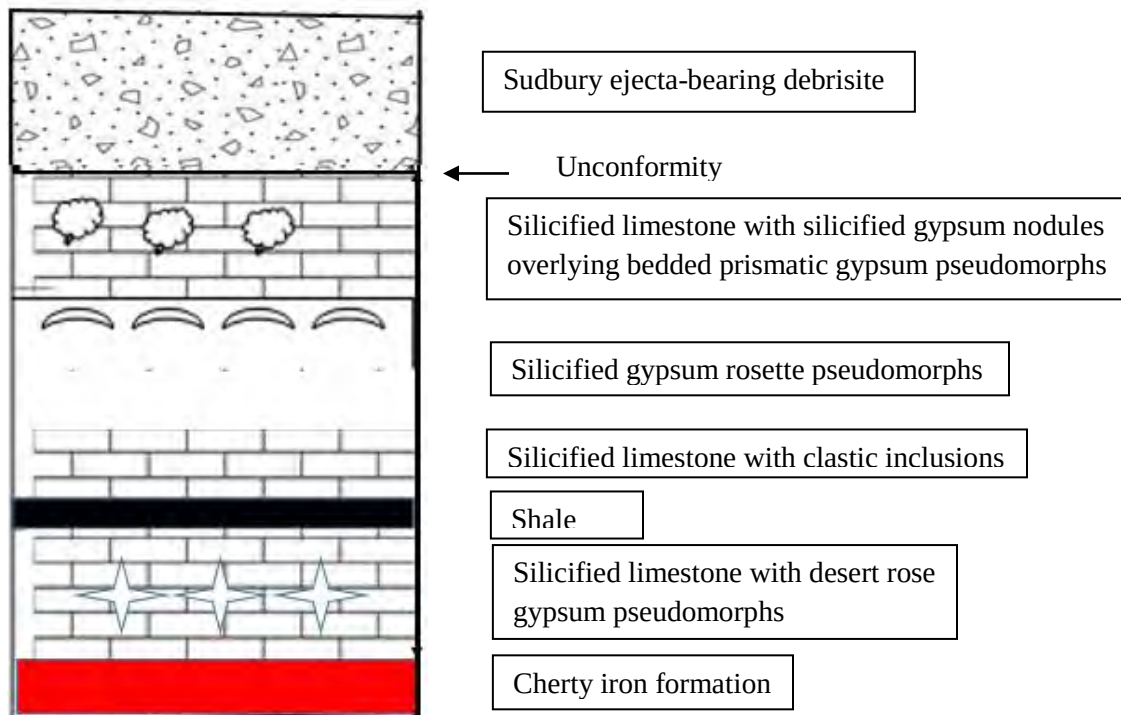


Figure 1. Stratigraphic column

The rocks in the section in Figure 1 have been extensively silicified such that gypsum and most of the limestone have been replaced by quartz, although the former presence of gypsum is evidenced by pseudomorphs.

The top unit in Figure 1 is silicified limestone containing silicified gypsum nodules (Fig. 2 and b). Below this layer is a layer of silicified gypsum in the form of pseudomorphs of rosettes (Fig. 3). This

layer is underlain by a layer of limestone overlying bedded gypsum. The evaporitic sequence overlies a thin layer of shale which in turn overlies a layer of silicified limestone containing pseudomorphs of gypsum desert roses (Fig.4).

The evaporitic section occurs sporadically at the top of the Gunflint Formation and in other locations maybe present as the Limestone Member. The evaporitic section may have been removed in other locations by the emplacement of the Sudbury impact layer.

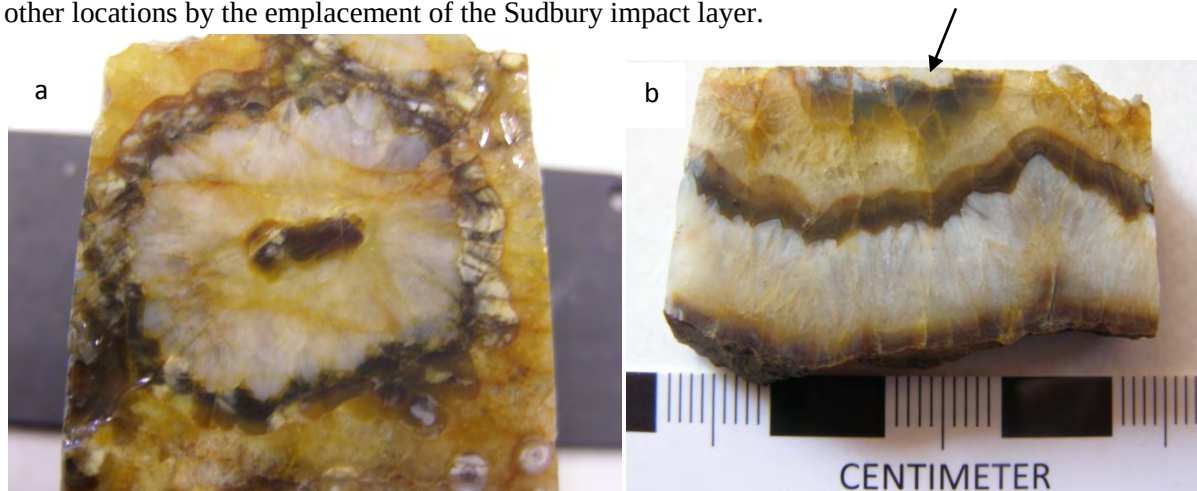


Figure 2. a) Section through silicified gypsum nodule. b) Side view of a) with arrow indicating the lower portion of the gypsum nodule.



Figure 3. Silicified gypsum rosettes. Photo from Karman and Fralick (2014)

Figure 4. Polished slab with gypsum desert rose pseudomorph, overlying cherty iron formation

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The Espanola Formation: A Huronian Paleoproterozoic Cap Carbonate

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During the change from the Archean to the Paleoproterozoic, the Earth's atmosphere underwent a significant increase in the concentration of free oxygen (Bekker et al., 2004). This introduction of previously unprecedented amounts of atmospheric O₂ had significant effects on global temperature as a result of the breaking down of atmospheric CH₄, and is believed to have led to a drop in global temperatures and subsequent glacial events (e.g., Lyons et al., 2014). An increase in concentrations of CO₂ as a result of volcanic activity, coupled with decreased rates of continental weathering, is believed to be the primary cause that ended snowball earth events, and resulted in the formation of cap carbonates. These are deposits which typically overlie Proterozoic snowball earth glacial diamictites and may provide valuable information about the dynamic oceanic and atmospheric changes that were occurring during these transitional periods (Kirschvink et al., 2000). This theory is supported by the low $\delta^{13}\text{C}$ signature of Proterozoic cap carbonates, which has been argued to be an indicator of increasing amounts of CO₂ in the oceans during the time of their deposition (e.g., Hoffman and Schrag, 2002). One example of these Paleoproterozoic diamictite and cap carbonate stratigraphic sequences is preserved in the ~2.4 Ga Quirke Lake Group of the Huronian Supergroup, in which glacial diamictites of the Bruce Formation are overlain by the Espanola Formation, a limestone- and dolostone-bearing unit (Robertson, 1968).

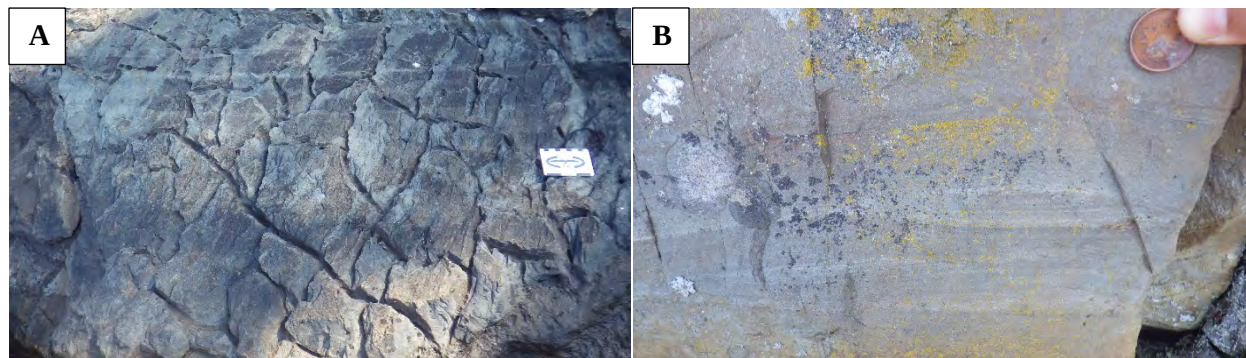


Figure 1: A) A desiccated surface within the Espanola Formation at Quirke Lake, indicating that the environment was subaerially exposed at times. B) Close-up of hummocky cross-stratification in the Espanola Formation at Panache Lake.

The Espanola Formation displays a staggering array of sedimentary structures including, but not limited to: a variety of ripple marks, possible stromatolites, soft sediment deformation, and brecciation and desiccation features. These structures, while mentioned in the literature, have hitherto not been investigated in their full stratigraphic context and the work that is currently being completed for this study indicates a geographical variation of water depth in which the Espanola Formation was deposited. To the north, near Quirke Lake, features such as desiccation cracks and symmetrical wave ripples suggest an environment that was shallow, and

at times, subaerially exposed. In contrast, outcrops observed further southwest, in the vicinity of Panache Lake, show evidence of a deeper nearshore environment, as is observed in the presence of well-preserved hummocky cross-stratification. Furthermore, slump deposits also outcrop along the Lake and suggest a possibly unstable substrate. These features are consistent with the current interpretation that the Huronian sediments were being deposited on the south-facing margin of the Superior Province.

Geochemical and stable isotopic analysis of the dolomitic and calcitic units within the Formation also vary with geographic location, but REE patterns do have some common trends. One of the more consistent features observed within the Espanola Formation is a general depletion in light rare earth elements (LREE), an enrichment in medium rare earth elements (MREE), and a slight to pronounced heavy rare earth depletion (HREE). MREE enrichment can be attributed to hematite particles, and as such, in order to determine whether hematite contamination was the cause of this trend, MREE enrichment was plotted against Fe values. No positive correlation was derived, and thus indicates that the enrichment must be the result of another factor. One possible explanation for this MREE enrichment is that it is sourced from continental runoff, rather than seawater, in this coastal setting.

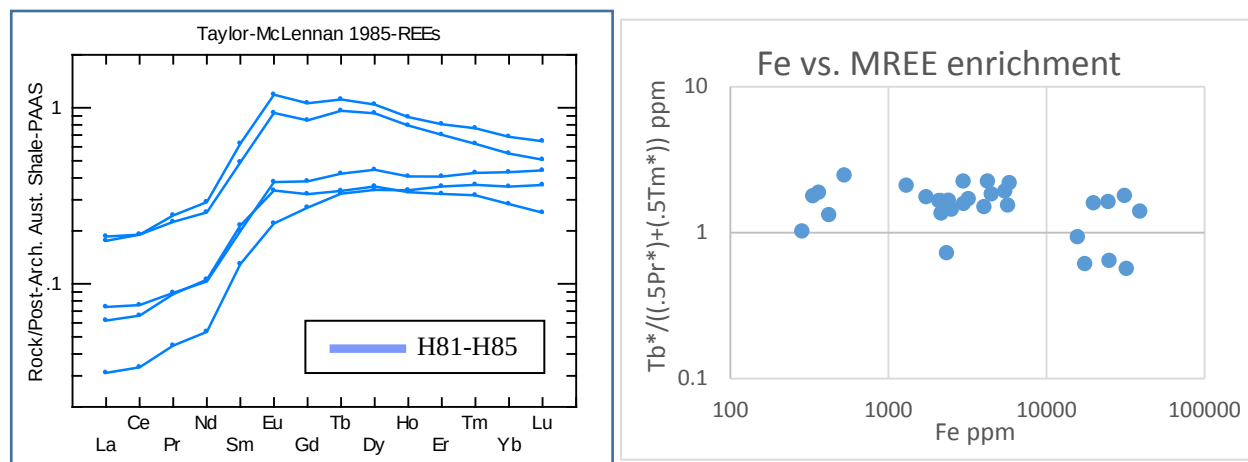


Figure 2: The plot on the left shows samples taken from carbonates of the Espanola Formation with typical LREE depletion and MREE enrichment. The diagram on the right shows that there is no positive correlation between MREE enrichment and Fe.

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Seismic slip, mylonitization and fluid flow along the Penokean Twelve-Foot Falls Shear Zone, Marinette County, Northeastern Wisconsin

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The Penokean-age Twelve-Foot Falls Shear Zone cuts through intrusive and extrusive units in the northeastern-most part of the Pembine-Wausau terrane, about 20 km south of and parallel to the Niagara Fault zone, the inferred suture between the Superior Craton and the 'Wisconsin Magmatic Terranes' arc complex (Schulz & Cannon, 2006). The Shear Zone can be traced for at least 20 km along strike in NW Marinette County, Wisconsin, from Twelve Foot Falls County Park on the north branch of the Pike River to just south of Kidd Lake. The timing of displacement on the shear zone is only broadly constrained; the zone transects the Twelve Foot Falls Quartz Diorite, which has a U-Pb zircon crystallization age of 1889 $\pm$ 6 Ma (Schulz & Schneider, 2005) as well as the older, metavolcanic Quinnesec Formation, and it lies immediately south of the 1862 $\pm$ 5 Ma Dunbar Gneiss Dome, a post-collisional intrusive complex (Sims et al., 1985; Sims, 1990). The vertical to steeply northeast-dipping foliation and mylonite bands in the Twelve-Foot Falls Quartz Diorite are broadly parallel to the foliation in the southern part of the Dunbar Gneiss Dome, but the Twelve-Foot Falls Shear Zone does not cut through the Dome. The sense of slip is also poorly constrained; a weak down-dip lineation points to dip-slip motion, but it is not clear whether the slip sense was reverse – which would suggest activity synchronous and sympathetic with convergence on the Niagara Fault – or normal, which would indicate slip related to late-orogenic relaxation.

The foliation and mylonitic fabric in the Twelve-Foot Falls Quartz Diorite are defined by bands of quartz and plagioclase alternating with aligned hornblende crystals (partly regressed to chlorite), indicating that both the overall schistosity and localized zones of high strain formed at peak metamorphic (amphibolite facies) conditions. At several locations on the southeastern end of the shear zone, dark discordant veins cut across both the foliation and the mylonitic fabric. These consist of a mesh of very fine needle-like hornblende crystals (altered to clinocllore) and are interpreted as devitrified pseudotachylyte, or frictional melt glass formed by slip at seismic rates (>1 m/s; Nadziejka and Bjørnerud, 2014). In some cases, the pseudotachylyte material is itself drawn into the mylonite zones, indicating that long-term ductile deformation alternated with sudden slip events. This type of behavior could occur in the middle crust if large earthquake ruptures propagating downward from shallow depths episodically intersected the brittle-plastic transition zone at ca. 15-20 km.

Additional field work on the Twelve Foot Falls Shear Zone now reveals that the occurrence of pseudotachylyte is even more extensive, and the rheological behavior of the zone more complex, than previously thought. Quartz veins that show evidence of plastic deformation both cut and are cut by the pseudotachylyte veins. This indicates that brittle tensile fracture and fluid flow occurred in alternation with seismic failure and ductile deformation. Some of the quartz veins contain significant amounts of pyrite. In addition, the foliation is in places transected by discontinuous (2-3 cm long) veins in which hornblende and quartz occur as fibrous crystals perpendicular to the walls. The crystals have growth bands and fluid inclusion planes oriented parallel to the vein walls.

These features suggest that the veins formed by the ‘crack-seal’ mechanism, in which cyclic fluid pressure variations cause hydrofracturing and incremental mineral growth. Crack-seal veins are most commonly found in the shallow upper crust; the fact that hornblende is one of the vein-filling minerals indicates that in this case, the process occurred at metamorphic temperatures.

In combination, these observations provide an exceptional glimpse into the complex interplay of deformation mechanisms and fluid flow in the middle crust during an orogenic event. Large earthquake ruptures apparently penetrated downward into rocks that were otherwise at temperatures high enough for full crystal plasticity. Strain incompatibilities related to these ruptures may have caused dilatancy and large fluid pressure gradients that led to the formation of quartz-pyrite and quartz-hornblende veins. Intriguingly, the gold prospect on the Menomonee River to the southeast lies directly along strike from the Twelve-Foot Falls Shear Zone.

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The Magenta Zone in the Northmet Deposit, Minnesota

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The Northmet Cu-Ni-PGE deposit contains about 970 Mt of unconstrained modelled resources mainly within a 250-meter thick zone in the lowermost layers (Units 1 and 2) of the dominantly troctolitic Partridge River Intrusion above its contact with Virginia Formation. However, about 5% (~50 Mt) of the deposit's tonnage lies in the so-called Magenta Zone, which comprises a tabular volume ~100 ft thick that crosscuts intrusive layering at a low angle in the main deposit's hangingwall. Its geometry precludes association with a high-angle structure. This study focuses on the nature and origin of this enigmatic zone.

Like the main mineralized zone, the Magenta Zone comprises troctolite and related anorthositic and gabbroic rocks. Most of the sulfide grains in drillhole core samples from the Magenta Zone show magmatic textures: they lie along albite twin planes in unaltered plagioclase grains, form symplectite with pyroxene, and comprise coarse polymineralic chalcopyrite-cubanite-pyrrhotite +/- pentlandite grains that have grown interstitially to plagioclase +/- olivine in unaltered troctolite. However, hydrothermal alteration of troctolite and related anorthositic and gabbroic rocks is common in the Magenta Zone: olivine is replaced by various kinds of serpentine as well as talc, while plagioclase (typically An40-60) shows variable alteration to amphiboles (actinolite and hornblende), chlorite, calcite, and plagioclase that is either more calcic or more sodic than its precursor. Similar hydrothermal alteration is observed in Unit 1. Very fine-grained sulfide, mainly chalcopyrite/cubanite but also rarely pyrrhotite, is locally intergrown with alteration minerals and is evidently hydrothermal. Larger sulfide grains in hydrothermally-altered rock are highly embayed, indicative of disequilibrium in the hydrothermal environment: these grains are likely relict magmatic sulfides.

While metal concentrations in the Magenta Zone are lower than in Unit 1, the ratios of important metals such as Cu, Ni, Pd, and Pt to one another are similar in the two zones, and they generally co-vary with rock type. At the same time, average sulfur content in Unit 1 is significantly higher than in the Magenta Zone, likely due to footwall contamination. Although the Magenta Zone sulfide mineralization grossly crosscuts intrusive layering, its mineralization appears to be magmatic, with relatively minor hydrothermal remobilization. Models for its formation will be presented.

Hydrothermal “natural ore” in the Fayal Reserve Mine, Mesabi Range, Minnesota

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The Fayal Reserve Mine exploited high-grade oxidized iron ore (“natural ore”) from a trough-style orebody localized along a high-angle fault in the Biwabik Iron Formation near Eveleth MN: initial reserves were 44 Mt within formerly “cherty” and “slaty” rocks of the LS2/LUC1 members. Samples of ore remaining in place contain up to 89 wt% Fe₂O₃tot (average 74%), with the mineralogy being dominated by goethite and martite/magnetite typical of highly-oxidized iron formation. This oxidation accompanied wholesale removal of carbonates and silica that had been present as chert and iron silicates. For over a century, the oxidation in the Mesabi Range has been interpreted by most as supergene in origin.

However, examination of a suite of samples from the Fayal Reserve Mine documented the presence of abundant minerals that are not typical of supergene environments but rather are hypogene. Two main alteration types have been observed. 1) In “cherty” rocks (Granular Iron Formation, or GIF), leaching of iron formation during oxidation produced abundant pores that contain later-precipitated euhedral pyrite, growth-zoned siderite, gypsum, and apatite. Pyrite (figure 1) comprises up to 6 modal % of the rock and is completely unoxidized: it usually directly overgrows goethite commonly as cubic grains typically 40-150 microns across. Siderite comprises up to 33 modal % of the rock, and typically overgrows pyrite. In these rocks, it occurs mainly as euhedral, equidimensional growth-zoned (variable Fe-Mn-Mg-Ca ratios) grains (figure 2) around 25-100 microns in diameter and as elongated grains intimately intergrown with fibrous goethite. Gypsum locally fills pores in place of siderite. Fluorapatite (identified by EDS) is relatively scarce (<1 modal % but P₂O₅ in whole-rock samples ranges up to 0.86%) and typically occurs as 10-20 micron euhedral grains bordering pore spaces (figure 3). None of these minerals shows evidence of any later dissolution, hence supergene alteration, even though they commonly line pores. 2) In “slaty” rocks (formerly Banded Iron Formation, or BIF) near the fault, magnetite has been partly altered to martite but has also been substantially replaced by siderite. Void spaces in the rock, presumably formerly occupied by chert or carbonate, are now filled with kaolinite that contains variable amounts of iron. Veins within the high-angle fault at the Fayal Reserve Mine contain carbonate ranging in composition from siderite to rhodochrosite, as well as stilpnomelane(?), blocky and comb-textured pyrite, and brecciated quartz.

A high-angle fault in the Thunderbird South Mine about 1 km from the Fayal Reserve Mine, and thought to been active at the same time as the Fayal Reserve Mine fault, contains colloform goethite intergrown in equilibrium textures with fine-grained quartz that cements brecciated vein quartz clasts. Previous work has shown this cement quartz contains fluid inclusions that contain saline fluids (7.3 +/- 2.3 wt% NaCl equiv) trapped at temperatures of about 175° C. This fluid was present during mobilization of oxidized iron and likely was involved in iron oxidation and attendant leaching in iron formation. It is very likely that the fault in the nearby Fayal deposit was infiltrated with fluids having similar properties, consistent with the epithermal character of the mineralization there.

The presence of hypogene, likely epithermal, mineralization that postdates oxidation and leaching in Fayal ores places significant constraints on the timing and nature of alteration. From regional evidence, we know that the now-exposed rocks were near (within 1 km or so) the surface during the Phanerozoic. As there is no evidence of hot springs (sinter, hydrothermal breccias, etc) in the region, the only time that the rocks could have been at the requisite

temperatures for the hypogene mineralization was when they were buried more deeply, likely several km, during the Precambrian. Fluid flow may have been driven by Paleoproterozoic orogenesis, as proposed by Morey (1999 Econ. Geol.), or less likely (given the paucity of appropriate-age rocks in the area) by rift-related deformation and heating.

As noted, the hypogene mineralization postdates oxidation and leaching of iron formation. This constrains the oxidation and leaching in the Fayal ores to be Precambrian in age. While it could conceivably be of supergene origin (that is, the rocks might have been exposed during the Precambrian, then buried and mineralized), the oxidation is more likely hypogene as well, as indicated by the elevated temperatures of quartz intergrown with goethite in a nearby fault. As with the oxidation, so with the leaching: Precambrian hydrothermal fluids are probably responsible for producing the abundant pores much like in similar deposits in Australia and Brazil. Late red earthy hematite, ubiquitous near the surface where it coats fractures, bedding planes, and voids throughout the Mesabi Range, is unequivocally supergene in origin. However, early, hydrothermal oxidation in the Mesabi Range may be widespread and locally important.

Figure 1. Pyrite (py) and siderite (sid) in oxidized GIF (gth = goethite). Reflected light.



Figure 2. Equidimensional siderite in pore-filling site, oxidized GIF. X nicols

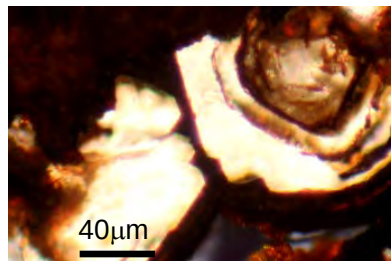
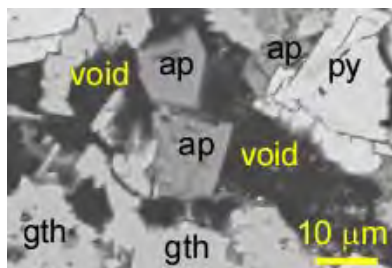


Figure 3. Apatite (ap), pyrite (py) in oxidized GIF. BSE image



Comparison of Whole Rock and Groundwater Geochemistry of the Gunflint, Rove, and other Geologic Formations of Thunder Bay, Ontario

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The purpose of this study was to use leaching test experiments to help explain the lithological controls on the groundwater geochemistry of different geologic formations in the Thunder Bay area, with a focus on the sedimentary rocks of the Gunflint and Rove formations. A secondary goal of this project was to test the effectiveness of the 15 minute USGS Field Leach Test for this purpose relative to more conventional 30 day deionized water and acetic acid tests.

A total of 31 samples were collected from outcrops in the City of Thunder Bay, and drill core from a hole drilled through the Rove and Gunflint formations in Blake Township. Samples were obtained from the Rove Formation (12), Gunflint Formation (12), diabase intrusions (3), granitoid intrusions (2), the Sudbury impact layer (1), and a quartz-carbonate vein (1). The Rove and Gunflint Formation sampling involved the collection of representative samples of the various lithologies that occur within these formations. Prior to analysis, the samples were milled into a powder through hand crushing by chrome-steel mallet and base, followed by agate-puck milling. The samples were bottled and labelled, with half being sent to Geoscience Labs in Sudbury, Ontario for whole rock geochemistry analysis, and half remaining in Thunder Bay to be used for leach tests.

Three types of leach tests were performed for this study. These included the USGS Field Leach Test, a 30 day double deionized water leach test, and a 30 day leach test using a 5% acetic acid solution. All three tests used a 20:1 leachate to sample ratio (2.5 grams of sample were used with 50 mL of leachate). The USGS Field Leach Test is a relatively new method used to quickly assess water reactivity and leaching potential of mine wastes, soils, and other geologic and environmental materials (Hageman, 2007). The test requires that samples collected in the field be shaken with double deionized water for a period of five minutes and then allowed to settle for ten minutes before being subjected to alkalinity and pH measurements, as well as geochemical analysis. The double deionized water and acetic acid solution tests involved the agitation of samples for five minutes every five days for the first 20 days of the testing period, followed by 10 days of settling, before being filtered and submitted for geochemical analysis. The analysis of the leach test solutions was completed in the Lakehead University Environmental Lab.

In order to display and compare the data received from the whole rock and leach test geochemical analyses, the samples were grouped based on the rock type they were obtained from. The sample groupings were as follows; Rove siltstone, Rove sandstone, Rove shale, contact metamorphosed Rove, Rove vein, Rove volcanic ash, Gunflint grainstone, Gunflint siltstone, Gunflint shale, diabase, granite, and Gunflint-derived hematite precipitate. Data obtained from the analyses of the sample groupings were used to create two different types of graphs. The first graph type showed the averaged whole rock, short-term water, long-term water, and long-term acid concentrations of the different elements analyzed to compare the four values. The second graph type showed the percentage of whole rock elemental concentrations that went into solution for the three different leach tests. These graphs were created for each element analyzed, and then compared to determine which elements behaved similarly in solution.

It was determined that the elements that most readily went into solution were calcium, magnesium, sodium, and potassium. These elements were present at the greatest concentrations in the ejecta layer, Rove ash, diabase, and Rove shale samples. These elements also yielded some of the highest percentages of whole rock concentration in solution, indicating that they were most readily leached into solution. The results are consistent with what was expected, as these are the four major cations that are found in most natural groundwater's.

The second method used to analyze the data obtained in this study was the construction of Piper plots for the short-term and long-term water leach tests. Piper plots are used to characterize the major ion (i.e. calcium, magnesium, sodium, potassium, bicarbonate, sulphate and chloride) geochemistry of groundwater and can provide valuable information about water-rock interactions. The Piper plots constructed for this study used averaged values for each of the sample groupings previously mentioned, and were compared to a standardized piper plot to determine the groundwater types produced. It was found that the short-term and long-term water trials for the Gunflint siltstone, Rove shale, Gunflint shale, and the long-term water trial for the Rove sandstone produced calcium-magnesium-sulfate-chloride type water. The short-term and long-term water trials for the Rove ash, contact metamorphosed Rove, and short-term water trial for the Rove siltstone produced sodium-bicarbonate type water. The short-term and long-term water trials for the ejecta layer, Gunflint grainstone, diabase, granite, and the long-term water trials for the Rove siltstone produced calcium-magnesium-bicarbonate type water. Lastly, the short-term and long-term water trials for the hematite precipitate produced sodium-chloride-sulphate type water. The Rove Formation results appear to confirm the hypotheses put forward by Puumala (2013) regarding the origins of sodium bicarbonate-type groundwater in that formation, while the significant geochemical variability in the Gunflint Formation samples indicates a complex relationship between lithology and groundwater geochemistry.

The USGS Field Leach Test was found to be less effective and less accurate than both the long-term water and long-term acetic acid leach tests. The field test period of ten minutes was not long enough to allow the suspended sample particles to settle to the bottom of the container, as they did in both the long-term leach tests. This made filtration of the short-term samples very difficult to impossible. As a result, the data for these samples were less accurate. The short-term water test also produced the lowest concentration values (often below detection limits) compared to the long-term leach trials. Therefore, this method is only suitable for the identification of highly reactive phases, and is not recommended for studies that are designed to evaluate the overall leaching characteristics of rock samples.

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Microanalysis of rock and mineral textures and its relationship to mineralization

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The processes involved in the formation of most ore deposits is well understood and research has typically focused on macro-scale processes, such as fluid migration, chemical and metal transfer, as well as physical and chemical changes (e.g. Cathles, 1981; Zientek, 2012). Results have typically been applied to large-scale features based on field observations, laboratory experiments, and theoretical assumptions to create models for the formation of ore deposits. However, our understanding of how small-scale properties (mineral grain size/shape, fracture characteristics, pore space interconnectivity) and their spatial distribution may influence mineralization and alteration processes is insufficient. Because various mineralization styles (e.g. disseminated, net-texture, vein-style) may be dictated by these features it is important to understand their role in larger-scale magmatic and hydrothermal mineralization processes (Prince et al. 1995; Wennberg et al. 2009; Liu, et al. 2014).

To obtain small-scale rock property information, multiple analytical methods (x-ray computed tomography - xCT, Electro Pulse Disaggregation - EPD, Mineral Liberation Analysis - MLA) were used to examine selected ore samples (porphyry, Mississippi valley type, volcanic massive sulfide, liquid magmatic sulfides from the Duluth Complex). Samples cores were scanned using xCT and spatial reconstructions were produced using 3D image processing software. This technique yields in-situ information such as grain size parameters, porosity distribution, or spatial orientation of mineral aggregates. Hand samples were disaggregated into individual mineral grains using EPD by sending repeated electric pulses through the material, causing mineral separation preferentially along mineral grain boundaries. This technology allows material separation while preserving mineral grain morphology (Cabri et al., 2008). This is a new and novel disaggregation method that may provide a true alternative to traditional methods of ore comminution. The resulting aggregate material was analyzed with scanning electron microscopy using MLA software. This software yields mineral liberation data from the EPD technology, in addition to grain shape, size, mineral associations, and mineral abundances.

Initial results show that xCT data can locate small-scale melt migration pathways (braid-like structure; fig. 1a) in addition to mineral grain morphology and size distribution. Size distribution of in-situ sulfide particles may also provide further information about the mineralization and cooling history of the sample, i.e. when did sulfur saturation occur relative to crystallization progress, was there significant sulfide melt movement in the crystal mush at the time of segregation, or do data indicate proximity to a specific region within the crystal mush? Results also indicate very good mineral separation of silicates from sulfides using EPD compared to traditional mechanical processing (fig. 1b). This strongly supports the conclusion that EPD has the potential to make otherwise uneconomical ores profitable to process, given reported energy savings of this technology of up to 15 % over traditional methods. This was confirmed on disseminated Cu-Ni-sulfide ore from Eagle Mine, which is currently treated as waste rock (fig. 1b). MLA information indicates a liberation yield of ~80 % of copper sulfides from silicates, with the remainder mostly associated with Ti-oxides present the sample (fig 1c).

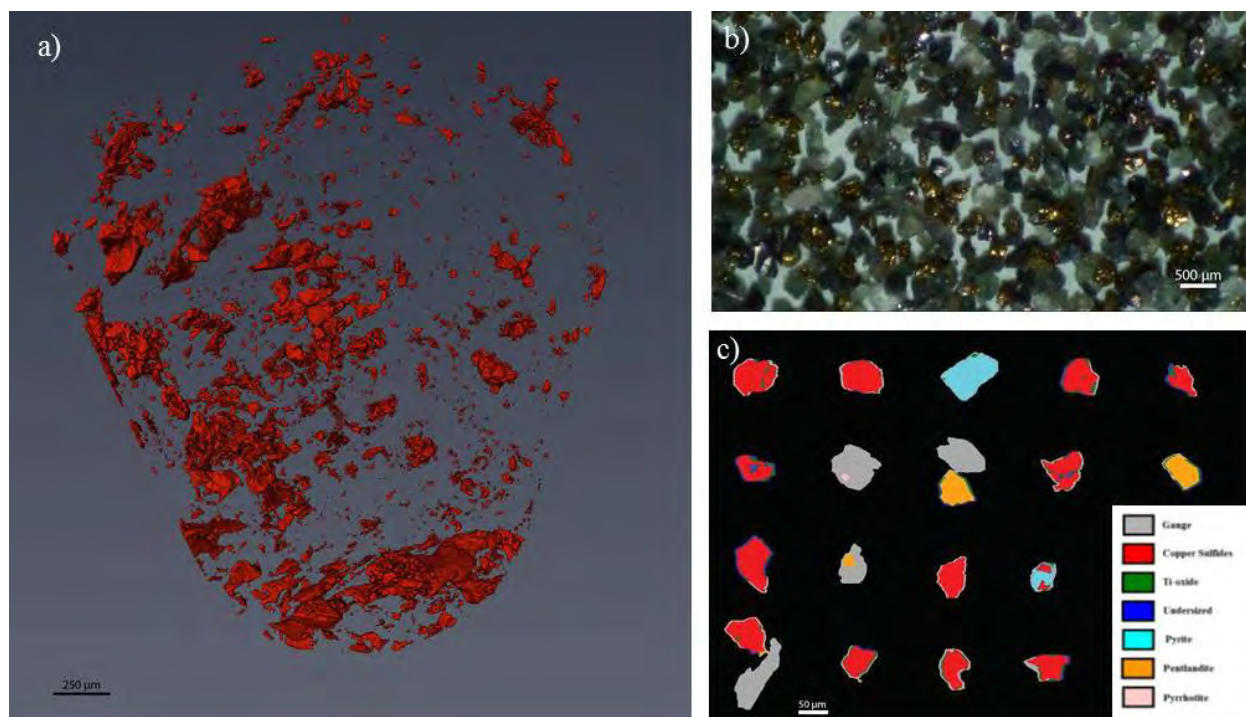


Figure 1 3 D representation of in-situ Cu-Ni sulfide distribution of Duluth Complex material (a -note braid-like structure in the bottom right). A sample of disseminated Cu-Ni sulfide ore from Eagle Mine disaggregated using EPD technology (b). A composite image showing a representative sample of sulfide mineralization from disaggregated Eagle Mine material using MLA software. It highlights the high degree of Cu-sulfide liberation from silicates while also showing minor Cu-sulfides association with Ti-oxides (c).

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Sedimentological features in the strata in and Adjacent to the Sudbury Impact layer in the Northern Paleoproterozoic Animikie

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The Sudbury Impact occurred at about 1850±1 Ma (Krogh et al., 1984). The impact itself created earthquakes of 10 on the Richter scale in the vicinity and fractured bedrock hundreds of kilometres away from point of impact (Addison et al., 2010). The Sudbury Impact Layer (S.I.L.) is used as a proxy marker and a reference point with other lithologies being placed below or above it, because of its relatively narrow date of deposition. The depositional environments prior to, during, and after the sedimentation of the S.I.L. in the Animikie Basin have been segregated into five units of different lithologies to create a new understanding of the paleogeography of this area in the Animikie Basin.

Starting at the bottom of the lithostratigraphic column, the first unit is the rocks logged in the Gunflint Formation greater than 3 metres below the S.I.L. This area is a baseline for the rocks further removed from the exposure surface associated with the top of the formation. This unit contains lenticular bedded grainstones alternating with fine-grained chemical sediments, alongside mudstone. This lithofacies association is assigned to the foreshore and upper shoreface environments (Pufahl, 1996; Pufahl and Fralick, 2000). Sections that consist of thicker grainstone lenses with only minor fine-grained sediment were most likely deposited in a more shore-proximal location (Pufahl and Fralick, 2000).

The second unit is of the upper Gunflint Formation that lies directly below the S.I.L. and consists of silicified grainstone facies, which were most likely due to the regression of the Animikie Sea that led to the subaerial exposures interpreted at most sites (Poulton et al., 2004; Addison et al., 2010). It is evident that this silicification of the uppermost Gunflint occurred prior to impact due to their shattered nature. Pre-impact silicification is also indicated by displaced silicified boulders, cobbles, and pebbles from the Gunflint Formation that are present in the S.I.L. itself, in addition to stalactite formations located directly underneath the S.I.L., denoting a subaerial vadose zone. This unit was once a nearshore environment which later underwent subaerial exposure.

The third unit is comprised of limestone below the S.I.L. This unit is less than 1 metre thick, and consists of fine-grained grainstone, coarse-grained grainstone, and stromatolites, all with blocky calcite cement. It represents a shallow-water environment assigned to the photic zones due to the presence of stromatolites and later the phreatic zone based on the cement. The fourth unit is the Sudbury Impact Layer. The northern area (Thunder Bay area) contains the calcite cement-bearing unit mentioned above, which separates the silicified regression surface from the overlying S.I.L. These cements formed from meteoric water that prior to the deposition of the S.I.L. (Fralick and Burton, 2008). In addition, mini-stalactites in vugs are located at the top of the S.I.L. indicative of a vadose zone conditions. It can be concluded that the area was above sea level (Addison et al., 2010), silicified and lithified with calcite cement at the time of deposition of the S.I.L. On the other hand, in the southern area (near Gunflint Lake), rocks indicate that brecciation and folding were the result of liquefaction produced by seismic waves that were generated by the Sudbury Impact, thus indicating that the impact occurred during a time when the Gunflint Lake area was at or slightly below sea level (Jirsa, et al., 2011). It can be deduced that in the north a regression surface was present, while the sea was present in the south.

The fifth unit is the rocks above the S.I.L. The area overlying the S.I.L. consist of 2-5 metres of carbonate facies iron formation. In some places immediately below the Rove Formation there are large calcite crystals surrounded by thin coatings of dark mud forming chicken-wire structures. These crystals contain banded growth lines interpreted to be caused by

fluctuation of dissolved constituents in the water from which the crystals precipitated, and are assigned to the middle-to-upper sabkha environment. In addition to banded crystals, gypsum desert roses are also present in this unit which are an indicator of an arid climate (Keyser, 1968). Also, mini-stalactites are found in vugs in this unit indicative of a subaerial vadose zone. This final and topmost unit indicates a fluctuation of relative sea level.

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The Sudbury Impact: Effects and outcomes

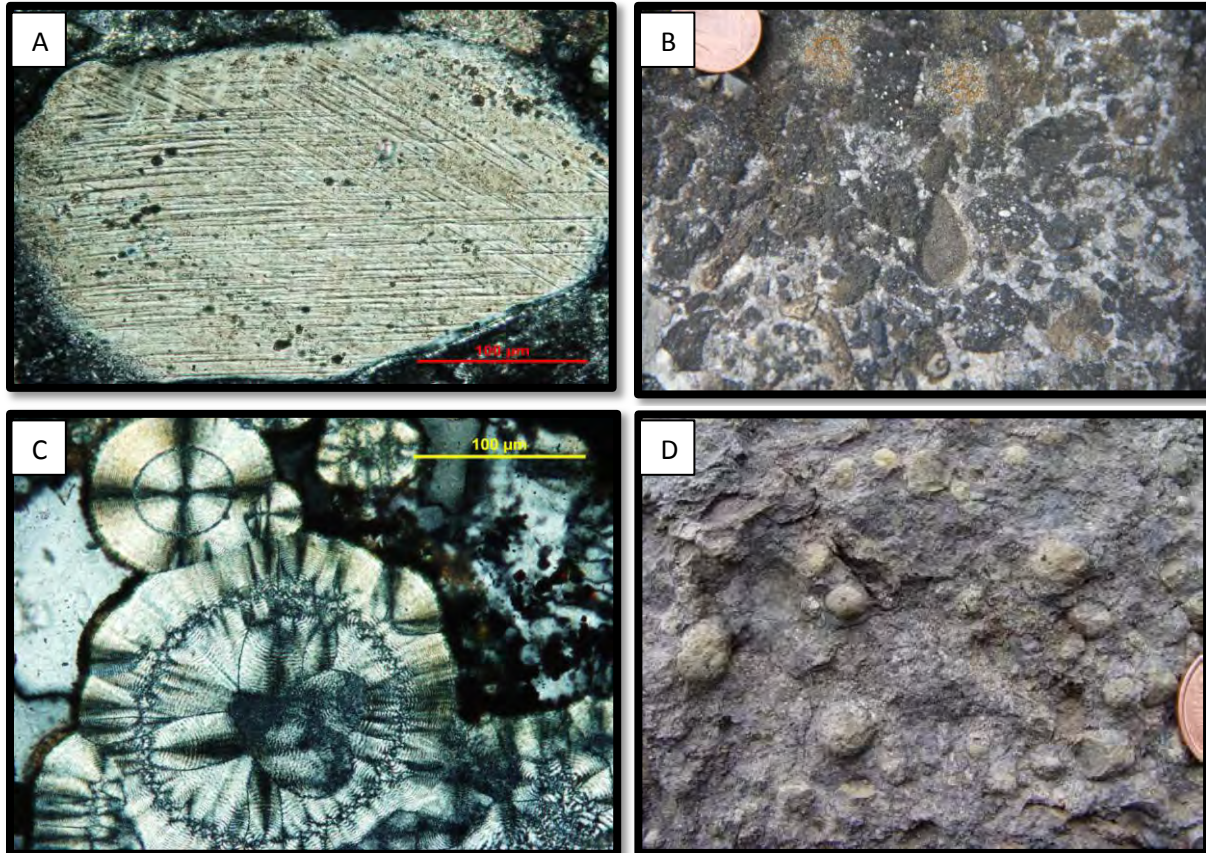
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Approximately 1850 million years ago, a bolide struck what is now Sudbury Ontario in Canada, creating a catastrophic chain of events. The bolide nearly 10 kilometres in diameter, formed a crater with a radius of ~130 km making the Sudbury Impact Event the third largest impact known in history to this date (Earth Impact Database, 2015). The collision created impact-induced earthquakes likely around magnitude 10 on the Richter scale in the vicinity, and managed to fracture bedrock hundreds of kilometres away.

Material ejected from the impact event has been discovered as far as 600-800 kilometres, or ~5-7 crater radii (Spray et al., 2004) from the Sudbury crater. This distal ejecta layer is found between the 1878.3 ± 1.3 Ma (Fralick et al., 2002) underlying Gunflint Formation, and the overlying 1832 ± 3 Ma (Addison et al., 2005) Rove Formation in the Lake Superior Basin.

The Sudbury Impact Layer is composed of two constituents: The first portion is a chaotic debrisite that was formed from the initial shock from impact which generated ground-hugging base surges that picked up and transported loose and fractured bedrock from the Gunflint. This chaotic constituent includes rip-ups and clasts of carbonate grainstone along with blocks of chert and pieces of stromatolite that have been torn and sheared from the underlying Gunflint Formation. The second portion consists of the ejected material from the impact event itself (Addison et al., 2010) and planar features in quartz grains (Figure A), includes devitrified glass (Figure B), spherules (Figure C), and lapilli (Figure D).



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Precipitation of Pedogenic Quartz and Concurrent Bulk Removal of Silica during Sub-Cambrian Weathering – a Paradox Resolved

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The first Phanerozoic continental-scale marine transgression is marked by the Cambrian Great Unconformity, the formation of which was preceded by extensive chemical weathering of continental crust, followed by widespread physical reworking of soil, regolith, and basement rock during advance of a transgressive shoreface system (Peters and Gaines 2012). Chemical weathering of silicate minerals exerted an important influence on Cambrian seawater geochemistry through the release of labile ions and chemical complexes, which was a significant factor in the diversification and appearance of multicellular organisms at that time.

Several North American Sub-Cambrian paleosols have been investigated to evaluate the characteristics of weathering during this important episode of Earth history. While doing so, it was discovered that a 285 cm-thick paleosol beneath the Upper Cambrian Mt. Simon sandstone in Trempealeau County, Wisconsin, contains pedogenic quartz, despite bulk removal of SiO₂ from the weathering profile. This paradox arises from the different weathering behaviors of hornblende and plagioclase, as explained below.

Pedogenic Quartz The Trempealeau paleosol protolith is a gabbro, consisting of subequal amounts of hornblende and plagioclase and containing $\leq 2\%$ quartz. Despite the paucity of quartz in the gabbro protolith, pedogenic quartz (q) is abundant in the paleosol, ranging from 11 to 23 wt.%; it occurs with pedogenic kaolinite (k), chlorite (c), goethite (g), and siderite (s) and metasomatic illite (i) and K-feldspar (f) (Fig. 1).

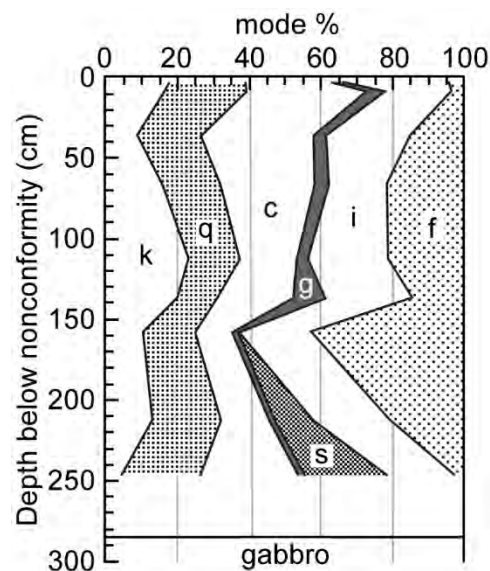


Figure 1. Depth variation in mineral modes

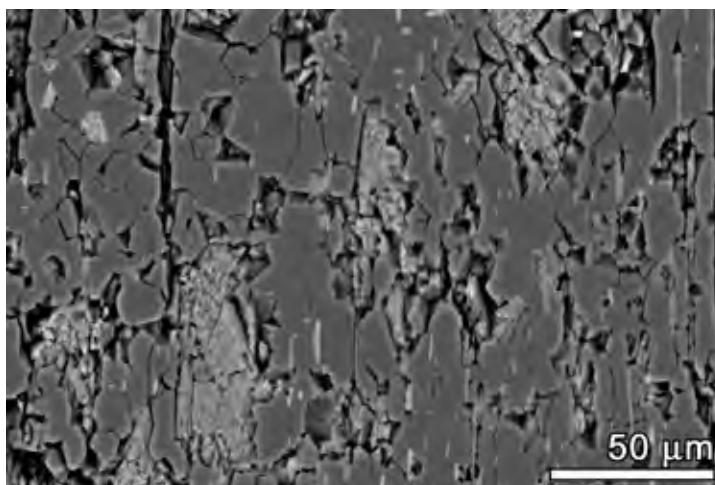
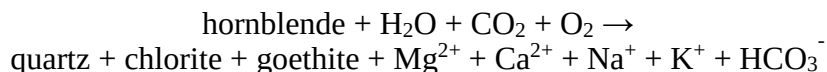


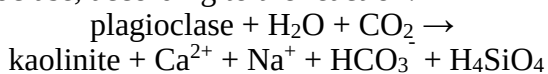
Figure 2. Back-Scattered Electron image of pedogenic quartz (dark gray) and pedogenic chlorite (medium gray) after hornblende

Hornblende was replaced by very fine-grained quartz and associated chlorite (Fig. 2) according to the reaction:



where SiO_2 was transferred from hornblende to quartz and chlorite, rather than being removed in solution, as in plagioclase hydrolysis. The labile elements in hornblende, Ca, Na, and K, were removed in solution, as was some Mg, with the remaining Mg being retained in chlorite.

Bulk Removal of Silica The percent changes in oxides with depth in the weathering profile have been calculated by taking Zr to be the immobile element as the basis for comparison (Fig. 3). The labile oxides, CaO and Na_2O (not shown), were completely removed from the upper part of the weathering profile. SiO_2 was substantially removed upward in the profile in the form of soluble silicic acid due to hydrolysis of plagioclase, according to the reaction:



The mass flux of SiO_2 is $-2.7 \text{ mols cm}^{-2}$, which corresponds to a total loss of 40% SiO_2 . Interestingly, 27% Al_2O_3 was also removed in solution, rather than being completely retained in kaolinite.

Paradox Resolved The paradox presented by the precipitation of pedogenic quartz accompanied by bulk removal of SiO_2 is resolved by recognizing that pedogenic quartz was produced by the weathering of hornblende, while SiO_2 was removed in solution in the form of silicic acid due to hydrolysis of plagioclase, resulting in a net negative mass flux of SiO_2 in the profile.

The Trempealeau paleosol represents an excellent example of the mature weathering that existed over much of the North American continent in Cambrian time. The total mass flux for the Trempealeau paleosol is $-6.0 \text{ mols cm}^{-2}$, corresponding to a total loss in mass of 50%. Such large quantities reveal the magnitude of Cambrian weathering, which played a critical role in promoting mass transfer from the continents to Cambrian oceans.

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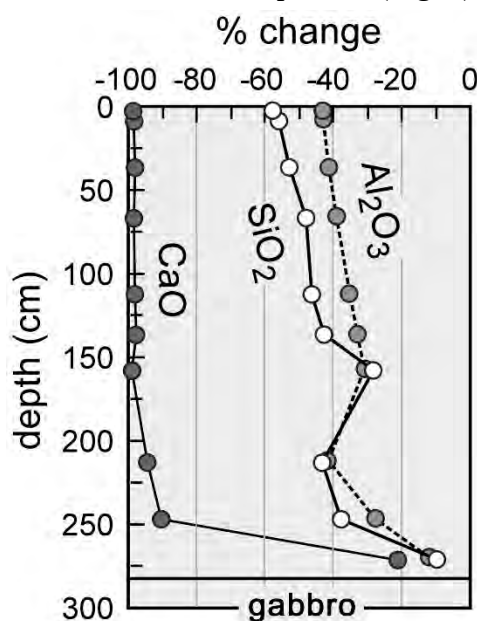


Figure 3. Percent changes with depth for selected oxides in the Trempealeau paleosol

The Mineralogy and Petrology of Layered Series Nepheline Syenite within Center II of the Coldwell Complex

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The Coldwell Alkaline Complex is the largest alkaline intrusion in North America, and was emplaced during initial magmatism of the Keweenaw Midcontinent Rift (MCR) at 1.1 Ga. Located on the north shore of Lake Superior, the Coldwell Complex was emplaced along the Thiel fault (the northern component of the Trans-Superior Tectonic Zone), and is host to rare earth elements (REE), Cu, Ni, PGE, and other high field element mineralization. Emplaced from east to west, the oldest – termed “Center I” is host to gabbro and Fe-rich augite syenite; “Center II” hosts biotite-gabbro and nepheline syenite; and “Center III” is host to a variety of syenite. This research evaluates the formation of layered nepheline syenite in Center II through field mapping, extensive sampling, and a detailed mineralogical study of the syenite, with an emphasis on identifying accessory minerals hosting incompatible elements, particularly REE minerals. This detailed assessment will help to understand the complex systematics of alkaline rocks in the Superior Province.

A layered texture within the nepheline syenite of Center II is an uncommon feature, and these layered sections are intimately associated with massive, hybrid, pegmatite, and heterogeneous zones of syenite. As well, biotite gabbro, lamprophyre dikes, and xenolith zones containing basalt and biotite gabbro xenoliths occur throughout the field area in Neys Provincial Park. The layered series nepheline syenite displays a cumulus texture feldspar, with post cumulus amphibole, biotite, apatite, and zeolites. Amphiboles plot within the ferro-pargasite range, with zoning compositions displaying a trend to Fe and Mn enrichment with Mg, Ca, Ti depletion. Biotite are classified as annite, an Fe-rich end member mica. Fluorapatite are enriched in LREE's (La, Ce, Pr, Nd) as well as varying Y abundance, with concentric zoning predominantly displaying increased REE concentrations from core to rim. Britholite is the main alteration product of fluorapatite, and is a primary host of REE's, with REE₂O₃ wt.% ranging from 44.19-69.75 (avg. 54.36). These apatite group minerals display significant variations in Ca, Si, LREE, and P contents that when plotted demonstrate the substitution scheme of: REE³⁺ + Si⁴⁺ ↔ Ca²⁺ + P⁵⁺. There is also an abundance of other accessory minerals present throughout the syenite, hosting significant concentrations of Nb, Zr, Ti, REE and Th, including: wohlerite, pyrochlore, titanite, allanite, and fergusonite.

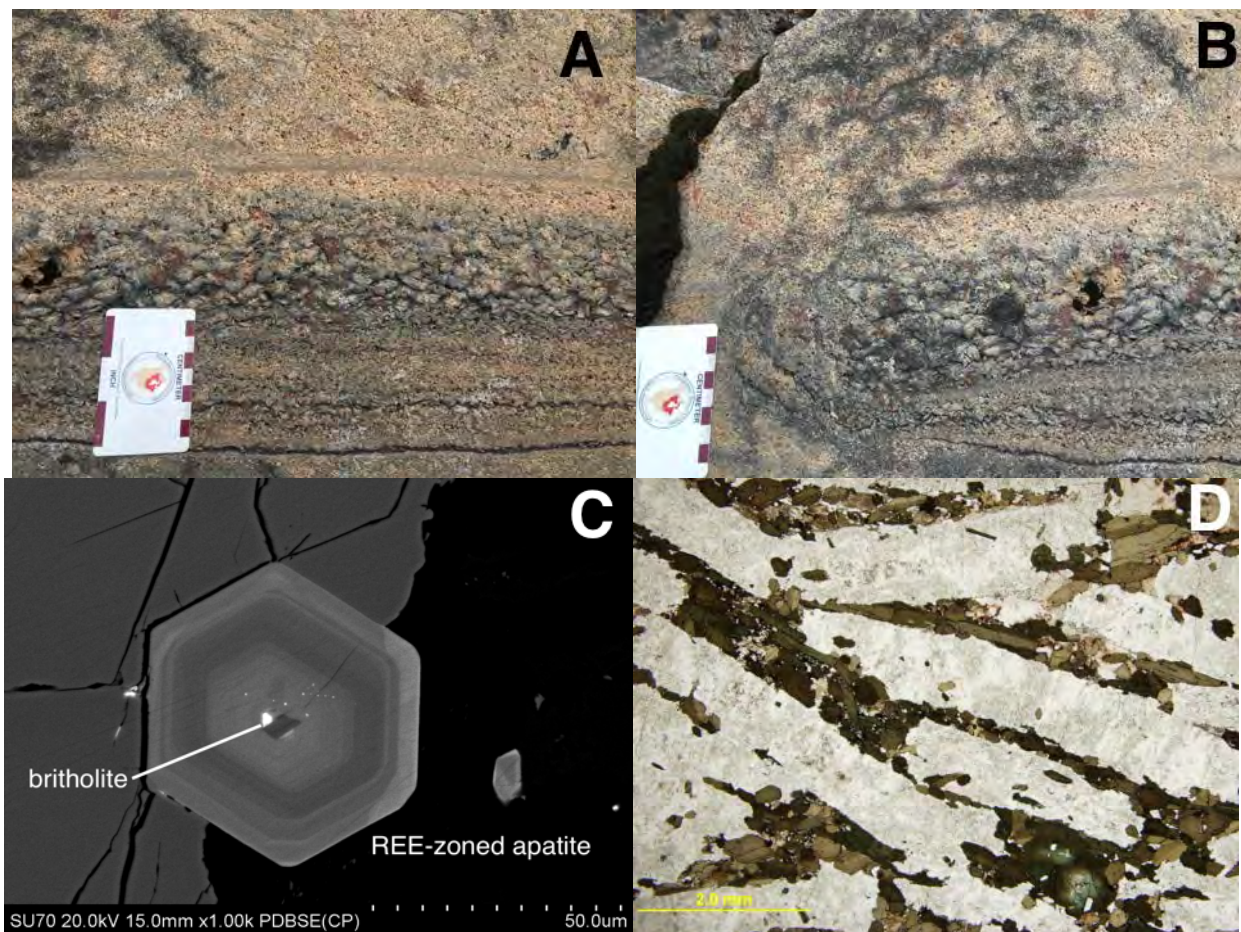


Figure 1: (A) Graded layered block; (B) Edge of slumped block with distorted layering; (C) concentrically zoned apatite with britholite alteration of DN9 (Layered; SEM image); (D) Cumulate feldspar with interstitial amphibole of CC7 (Layered; PPL image).

The origin of the layered series is favoured to be formed through hydrodynamic processes, which have produced an array of magmatic sedimentation features (graded layers, slumping, scour channels, flame structures and load casts). Surge-type density currents are proposed to have formed the modally graded cumulate layers. These processes are preferred in contrast to crystallization along a thermal boundary layer, which may produce layering without the associated sedimentary features, and commonly requires a stagnant magma. The layering of nepheline syenite, in conjunction with other features, indicates a strong convecting current operating during the formation of the rocks.

Sedimentology and Geochemistry of the 2310 Ma Kona Dolomite, Huronian Supergroup, northwestern Ontario and western Upper Peninsula of Michigan

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The 2310 Ma Kona Dolomite of Marquette, MI lies within the Chocoma Group of the Marquette Range Supergroup and has been correlated to the Cobalt Group of the Huronian Supergroup (Vallini et al., 2005; Rasmussen et al., 2013). The dolomitic units of the Gordon Lake Formation are equivalent to the Kona Dolomite in Marquette and this study refers to the two dolomite units as a whole. These formations, termed the Kona Dolomite (KD) were deposited on what was a passive continental margin, (Fralick & Miall, 1989) after the last Huronian glaciation and the Great Oxidation Event, making the KD an interesting suspect for analysis.

In order to better understand how free oxygen entered our atmosphere, sedimentological, geochemical, and isotopic techniques were utilized. It's important to have a good understanding of the sedimentology and lithofacies before looking at the geochemistry in order to see localized depositional trends with the ocean chemistry. Thus, nine lithofacies associations (LA) have been identified in the KD based on their morphological, and mineralogical differences. Each LA is indicative of its own depositional settings on a tidal flat.

The Ripples and Low Domes LA is composed of soft, centimetric, irregular, and wavy ripple laminations of varying pink and gray carbonates- representing climbing ripples, wave ripples, and low-domal stromatolites. Lenticular and wavy bedding show bi-directional cross stratification, a feature common in intertidal flat settings. Small domal to stratiform stromatolites (<4cm tall) are low pustular stromatolites that have laterally continuous lamination and tend to gradually change upwards into stratiform stromatolites. These likely formed in an intertidal flat setting as they are associated with the bi-directional ripples.

Smooth to crinkly, millimetric, and relatively isopachous laminations comprise the Parallel Laminated LA. Laminations are in places wispy and contain some low domes that are indicative of microbial activity that are likely situated within a pond on the intertidal flat.

Hummocky cross-stratified (HCS) gray carbonate sands have low-angle truncation surfaces and formed in a tidal channel environment that feed the tidal flat system. The stunning outcrop of, Large Columnar to Domal Stromatolites (LCDS) (Fig., 1) are located near Marquette, MI. They stand 5-6m tall and are composed of laterally continuous columnar lamination joined by cusped depressions that gradually shift into domal stromatolites. The LCDS grew on top of the sandy HCS within the tidal channels.



Figure. 1

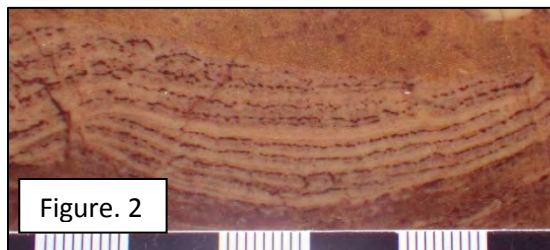


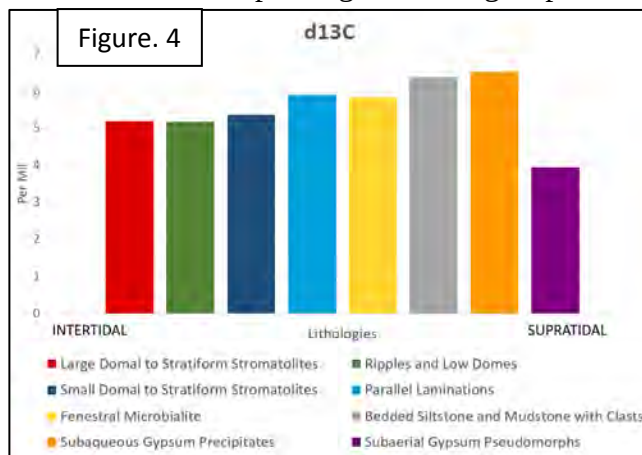
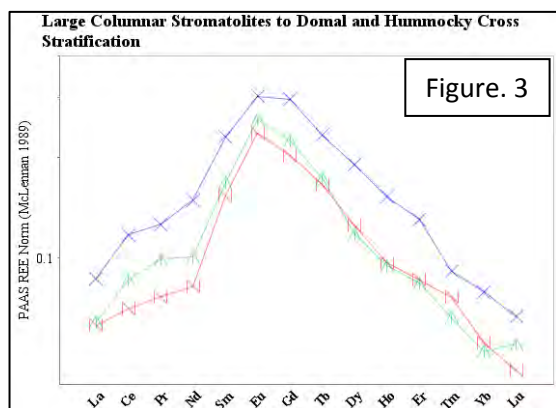
Figure. 2

Fenestral Microbialite LA show good fairly isopachous banding with dark reddish elongated fenestrae that are discontinuous on the microscale but show low domes on a macroscale (Fig., 2). The fenestral microbialite is similar in colour to the Bedded Siltstone and Mudstone with Clasts LA as they are both composed of similar reddish-brown siliciclastics and carbonate. The latter is composed of intercalated siliciclastics, iron-rich, and iron-poor carbonate mud, and contain sub-euhedral rectangular carbonate clasts. The clasts were deposited by storm events that ripped up the fenestral microbialite in the upper intertidal flat, flooded the supratidal flat and deposited them on a sabkha.

The Subaqueous Gypsum Pseudomorph LA is composed of laterally continuous chevron textured carbonates replacing vertical gypsum crystals, while the Subaerial Gypsum Pseudomorph LA is composed of euhedral, diamond shaped pseudomorphs that lie within a very fine-grained dark purplish siliciclastic- and carbonate-rich groundmass. The former would have formed in an open water supersaturated environment, such as a pond on the sabkha, whereas the latter would have formed within the sediment in the sabkha itself.

Geochemically, these LAs are enriched in middle rare earth elements (REEs), but do not have pronounced Eu anomalies. Prior to the 2310 Ma KD, ocean chemistry was controlled by hydrothermal activity that created Eu enrichment compared to the other REEs. This contrasts with today's oceans that are controlled by continental inflow. The absent Eu anomaly (Fig. 3) is illustrated in the REE concentrations of the LCDS and HCS LAs and represents what seems to be a turnover event from an ancient ocean system to a modern system.

Carbon isotopic ratios show an interesting trend when compared to their respective lithofacies (Fig. 4). The $\delta^{13}\text{C}$ increases from the lower tidal flat to the sabkha. This probably represents increasing evaporative loss of light CO_2 . This local trend is superimposed on the beginning of the Lomagundi Event which is known as the most prolonged and largest period of carbon 13 enrichment.



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The Lake Shore Traps – A terminal cycle of the Keweenaw Flood Basalt event

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The Keweenaw Flood Basalts, which represent the magmatic record of the best preserved example of a Precambrian Large Igneous Province (LIP), erupted contemporaneously with the development of the failed Mid-Continent Rift ca. 1.1 Ga. At $2 \times 10^6 \text{ km}^3$ in volume, the Keweenaw LIP is roughly equivalent in scale to the Parana-Etendeka LIP, but the origin and evolution of the magmatic source of the Keweenaw LIP remains poorly constrained. Specifically, while modern LIPs have a primary magmatic pulse lasting $<5\text{Ma}$, followed by a long phase of waning activity, the Keweenaw LIP underwent significant flood basalt eruptions for ca. 21 Myr.

Here we examine the geochemical characteristics of some of the final phases of mafic magmatic activity within the Keweenaw LIP – the Lake Shore Traps – which erupted $1085.57 \pm 0.25 \text{ Ma}$ (Fairchild et al., 2017). The Lake Shore Traps are a largely basaltic sequence which erupted within an alluvial fan sequence (Copper Harbor Conglomerate), and are temporally separated from the main phases of volcanic activity associated with the Keweenaw LIP. The Lake Shore Traps are best exposed at High Rock Bay, located at the tip of the Keweenaw Peninsula, where 62 flows (~ 1 to 30m thick) are observed intercalated with thin paleosols. The lavas in this area form a stack of flows that total $\sim 530\text{m}$ in thickness. Another exposure of the Lake Shore Traps is within the Porcupine Mountains region, where the total lava thickness is at least 77m. In this area, at least 13 flows are observed, though exposure is poor and this likely represents a minimum estimate. While this late-stage activity might represent a waning phase of magmatism, the thickness represents some half of the total average thickness of modern continental flood basalt provinces (Stein et al., 2016). The Lake Shore Traps is this an important episode of melt generation and represents a window in the late stage mantle processes operational beneath the Midcontinent Rift.

Our initial data from High Rock Bay suggests a dominantly tholeiitic magma series spanning an unexpectedly wide and continuous range of compositions from basalt to andesite. Distinctive geochemical stratigraphic patterns were observed suggesting crystal fractionation and recharge events dominated the magma system. Within the Lake Shore Traps sequence of the

Porcupine Mountains, less intraflow geochemical variation is observed and only two magma types can be clearly resolved. When comparing the Lake Shore Traps from High Rock Bay and the Porcupine Mountains, there are significant differences in the composition of magmas – the former having an overall more enriched incompatible trace element pattern in comparison to the latter. Our initial data do not show any unambiguous parallels between the geochemical characteristics of the Lake Shore Traps and prior phases of magmatic activity in the province. We therefore explore the potential source characteristics of these lavas to refine the source and conditions of melt generation during the terminal phase of activity in the region.

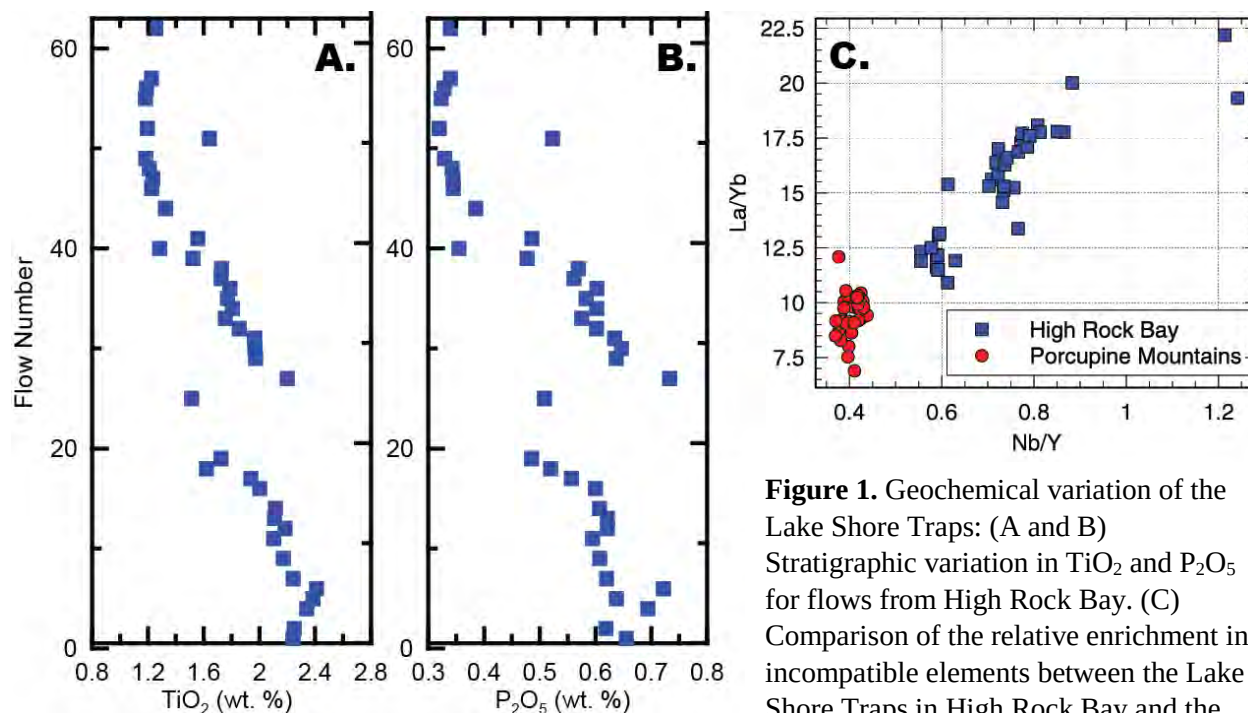


Figure 1. Geochemical variation of the Lake Shore Traps: (A and B) Stratigraphic variation in TiO_2 and P_2O_5 for flows from High Rock Bay. (C) Comparison of the relative enrichment in incompatible elements between the Lake Shore Traps in High Rock Bay and the Porcupine Mountains.

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Short-interval deposition, metamorphism, and intrusion in the Neoproterozoic Vermilion Granitic Complex, Superior province, Northern Minnesota

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Alternating belts of high-grade granite-gneiss and low-grade metavolcanosedimentary granite-greenstone are characteristic of Archean crust (4 – 2.5 Ga) (Condie, 1994). In the Superior province of northern Minnesota, these belts are represented as the Wabigoon, Quetico, and Wawa subprovinces (Williams, 1991). The formation of Archean metamorphic terrains is poorly understood, as estimates of Archean lithospheric thermal and mechanical conditions are debated, hindering consensus about petrogenetic models. Pressure-temperature-time (P-T-t) reconstructions are useful in exploring the evolution of metamorphic rocks present in such cases, and rely on aluminous minerals and accessory phases for (1) determining P-T paths, and (2) isotopic age dating. In many cases, the tempo and style of Archean crustal metamorphism are enigmatic as these terrains commonly lack the aluminous metamorphic assemblages useful for P-T-t reconstructions (Condie, 1988). Metamorphic rocks in the Quetico subprovince locally host a number of key aluminous phases, reactions, and accessory minerals that facilitate study of the formation and metamorphic evolution of this terrain.

The Vermilion Granitic Complex (VGC) defines the western region of the Quetico granite-migmatite subprovince in northern Minnesota. The VGC is bounded to the north by the Wabigoon greenstone belt, and to the south by the Wawa greenstone belt (Southwick and Sims, 1979). Country rocks of the VGC are comprised by biotite ± garnet ± sillimanite schist that are intruded by multiple phases of granitic injections. The mineralogy of the schist is variable, resulting from metamorphism of a compositionally-variable precursor consisting of interbedded greywacke and argillite, rather than by a metamorphic gradient. Compositions of protolith interbeds ranged from clay-rich semi-pelites to volcanosedimentary feldspathic arenites and greywackes, which were metamorphosed to assemblages of garnet-mica and biotite-amphibole, respectively. Metamorphic assemblages, reactions, and garnet-biotite thermometry indicate peak P-T conditions in the middle amphibolite-facies, at ~ 600 °C and 4-5 kbar. The core of the VGC is characterized by a large, kilometer-scale intrusion of the Lac La Croix Granite. Granitic intrusions of smaller volume occur locally throughout the complex, ranging in composition from granodioritic to leucogranitic. The relative timing of granitic injections is poorly constrained, as field relationships between these heterogeneous units are complex. Granitic injections and schistose country rock occur texturally together as migmatite. The VGC hosts a variety of structurally distinct migmatites, including stromatic, rafted, and veined types, mainly formed by injection. Migmatite and schistose country rock occur proximal to the margins of the VGC, while the core of the complex is largely granite and granite-rich migmatite.

New zircon and monazite U-Pb ages provide constraints on deposition, metamorphism, and the timing of granitic intrusion. Detrital zircon age populations in metamorphic country rock record mean igneous provenance ages of about 2.74 Ga and 2.72 Ga, establishing a maximum age of protolith deposition. Monazite ages document supracrustal metamorphism between about 2.69 Ga and 2.67 Ga. Zircon ages of

crystallization for granitic lithologies show complex behavior, but suggest intrusions were syn- to post-metamorphic (Figure 1).

These data demonstrate a temporally rapid evolution of the VGC, including consanguineous: (1) crystallization of plutonic source rocks; (2) exposure and erosion; (3) deposition of an interbedded greywacke-argillite protolith; (4) metamorphism of supracrustal rocks to the middle amphibolite facies; and (5) emplacement of syn- to post-metamorphic granitoid intrusions. The provenance, metamorphic, and granitic age constraints indicate that the sequential formation of an igneous sediment source, development of depositional basins, metamorphism, melt intrusion, and migmatite formation occurred over a short time interval of as little as ~10 my.

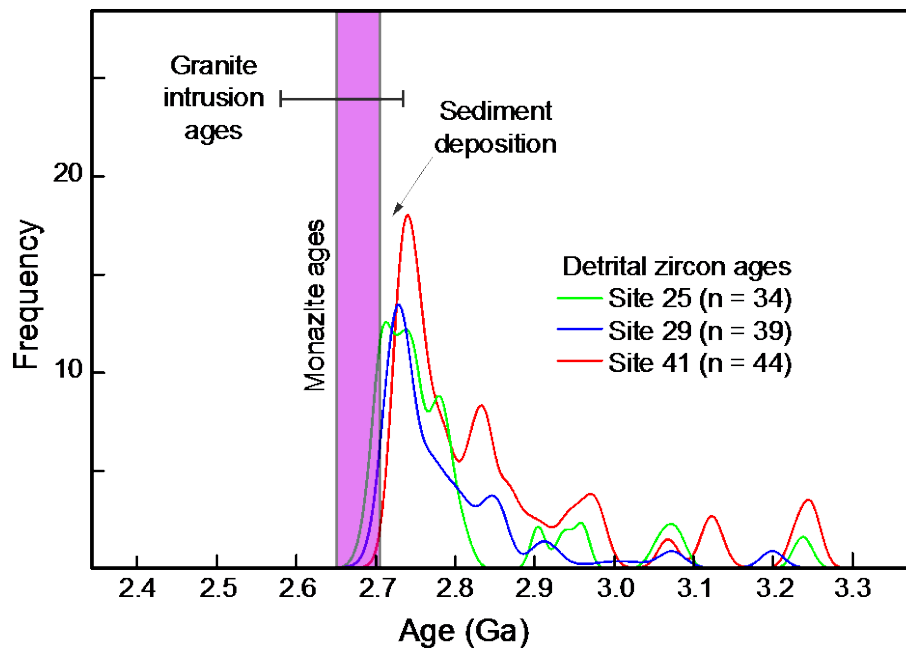


Figure 1. Probability frequency distribution of detrital zircon age populations in three schist samples. Monazite crystallization ages are represented by the purple bar. Granitic intrusive crystallization ages shown by the horizontal line.

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Seismic Interpretation of the 1.1 Ga Midcontinent Rift volcanic interval beneath Lake Superior

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The Mesoproterozoic (1.1 Ga) Midcontinent Rift is a major structure within the Precambrian basement of North America. Rift-related rocks include up to ~20 km of lower volcanic and intrusive rocks overlain by up to ~7 km of sedimentary rocks. Despite its significance as a crustal-scale structure that hosts economic mineral deposits, details of Midcontinent Rift structure and stratigraphy remain unresolved. We have interpreted 19 existing 2D seismic reflection profiles to define the geometry and extent of the volcanic rocks beneath Lake Superior in order to constrain the volcanic evolution of the rift. Our work is one piece of a larger geophysical reevaluation of the Midcontinent Rift in collaboration with the US Geological Survey. Fifteen industry profiles collected by Grant-Norpac, Inc. are available as image files from the Wisconsin Geological and Natural History Survey (McGinnis and Mudrey, 2003) and four collected through the Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE) are available as SEGY files from Natural Resources Canada (Behrendt et al, 1988).

We have identified distinct seismic facies, significant high or low impedance reflections, characteristic reflection geometries, and mapped key seismic reflections across all 2D lines. Similar to previous work, we recognize three main seismic packages: (1) pre-rift Archean and Paleoproterozoic basement; (2) rift-related layered volcanics and sills; and (3) sedimentary rocks. Specific high impedance reflections were selected to represent the top of the pre-rift basement and the base of the sedimentary package. We interpolated time surface maps for the base of the sedimentary units and the top of the basement package beneath Lake Superior and generated a time-thickness map of the Midcontinent Rift volcanic rocks (Fig. 1). Map accuracy is best where 2D lines are most closely spaced and is more limited where seismic lines are spaced far apart.

In detail, the interpreted volcanic package and seismic horizons within it display a variety of geometries that are repeated or can be followed over long distances within the lake. The laterally continuous reflections may represent boundaries between extrusive volcanic flows and possibly sills. We assigned descriptive names, including *waterfalls*, *smiles*, *rollovers*, *disruptions*, and antiforms and synforms to characteristic seismic reflection geometries in order to divorce observations from inferred genetic processes. Such an approach relies on careful mapping of the lateral and vertical distribution of seismic facies, reflections, and reflection geometries to clarify the role that processes such as faulting, subsidence, uplift, and intrusive and extrusive magmatism, and possibly others, had in the evolution of the Midcontinent Rift.

Our preliminary conclusions include the following: (1) Rift-related volcanic layers are tilted upward onto pre-rift basement structures that underlie western Lake Superior, consistent with Allen et al. (1997), who named the structures White's Ridge and Grand Marais Ridge (Fig. 1). (2) Volcanic layers commonly form antiforms and synforms throughout the lake. As noted by Allen et al. (1997), synforms in western Lake Superior thicken toward the synform axis, creating the geometry of *smiles*. In between White's and Grand Marais Ridges, the smiles appear

to create a bowl (Fig. 1). The bowl geometry suggests that White's and Grand Marais Ridges were actively uplifting during volcanism. (3) The interpreted volcanic interval is thickest in eastern Lake Superior (Fig. 1), although seismic control is not as good as in the western lake. (4) Shallowly dipping reflections that abruptly bend downward to steep dip are commonly observed (*waterfalls*). Previous workers have interpreted many of these as hinge zones or master faults in half-graben structures. We are considering alternative explanations. For example, they may be part of a larger, more complicated scenario of intrusive magmatism or early-rift volcanogenic processes that were later buried. (5) Smaller amplitude antiforms within the sedimentary section (*rollovers*) are prominent in the western lake, where they are associated with systems of small reverse faults. The reverse faults were recognized previously, but not mapped in detail. The reverse faults, especially in the GLIMPCE lines, appear to occur within the volcanic package, possibly between two flow layers, rather than extending to great depths in fault contact with the deeper volcanic layers. (6) Narrow interruptions of seismic reflections (*disruptions*), which are characterized by apparently vertical dips that become tightly folded near the surface, are typically associated with reverse faults in the Grant-Norpac lines, but are not imaged in the GLIMPCE lines.

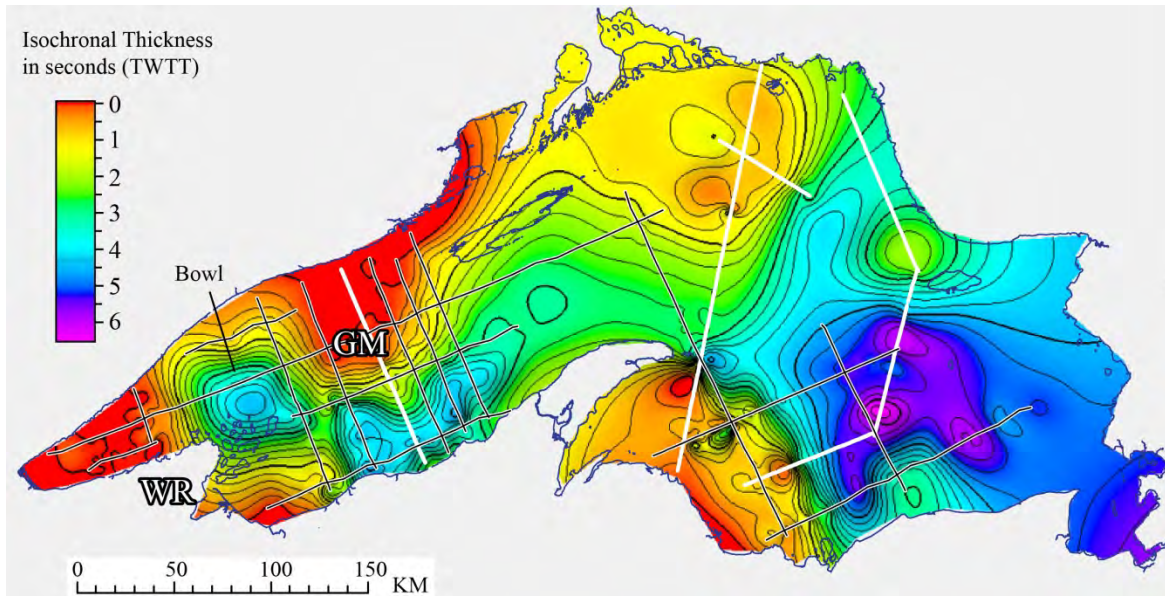


Figure 1. Preliminary isochronal thickness map in seconds of two-way travel time (TWTT) representing the thickness of the layered volcanic package beneath Lake Superior. Black and white lines are Grant-Norpac and GLIMPCE seismic lines, respectively. GM=Grand Marais ridge; WR=White's Ridge. Blue outline is the lake shore.

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High-technology metals in sulfide systems: In, Ge, Ga, and Tl content in the Vermilion District and Duluth Complex, northern Minnesota

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High-technology metals (HTMs) are increasingly used for a wide variety of technological applications from communications to transport to renewable energy generation. While the natural abundance of these metals in common rocks is well established (up to ~100 ppb; Terashima et al. 2001), their sourcing, transport, enrichment, or enrichment mechanisms in specific environments is not. As these metals do not form their own minerals or ore deposits, they are currently sourced as byproducts from mining volcanogenic massive sulfide deposits, Mississippi Valley Type deposits, and tin polymetallic/granite-hosted tin deposits (e.g. Ishihara and Endo, 2007; Pavlova et al. 2015). The reason why these metals are restricted to a few selected deposit types is unclear as is their general thermodynamic behavior; as a consequence, few data are available.

To better understand the behavior and distribution of these metals, and study their enrichment, existing geochemical data from the Vermilion District were collated using the database of Peterson (2001) as well as recent geochemical analysis of available drill core located within the known Zn anomaly of the volcanogenic Vermilion District. In particular, Zn-rich section and those showing visible chalcopyrite were chosen as these are the preferred minerals these metals substitute into. To compare different genetic environments, trace element data from the magmatic sulfide system of the Duluth Complex were included in the study.

Results show that, on average, HTM values in the Vermilion district are elevated relative to average crustal values by a factor of 2.5 to 3 except for Ga, which is depleted by a factor of 0.6 (figure 1). The reason for the divergent behavior of Ga is unclear by may be attributed to a) differing mobilization mechanism under hydrothermal conditions, b) hydrothermal fluids with Ga values lower than current average data suggest, or c) sample bias. Available data from hydrothermal fluids indicate that they would be capable of supplying measured In and Tl concentrations in the Vermilion district and potentially also for Ga but maybe not for Ge. As this does not explain the enrichment (2.5) of Ge in the Vermilion district another source of Ge would have to be invoked, provided the current data situation is a realistic reflection of the distribution of these HTM's.

Duluth Complex samples are generally depleted by a factor of 0.2 to 1 for all HTM's compared to average magmatic values. As these rocks are generally not known to concentrate these metals this discrepancy can be attributed to magmatic processes as well as the source of the Duluth Complex magmas as mantle values for In and Ge are very similar to Duluth Complex data but lower for Tl and Ga.

Overall, HTM data for the Vermilion district show several locations with elevated values, especially Ga (up to 60 ppm) and Tl (up to 40 ppm). A direct correlation between elevated Zn and In values is observed, a well-known substitution process in Zn-bearing sulfide minerals. Further data evaluation and sampling is needed to assess the significance of the HTM distribution and its connection to known elevated Zn values and its potential tie to a submarine hydrothermal system in the area.

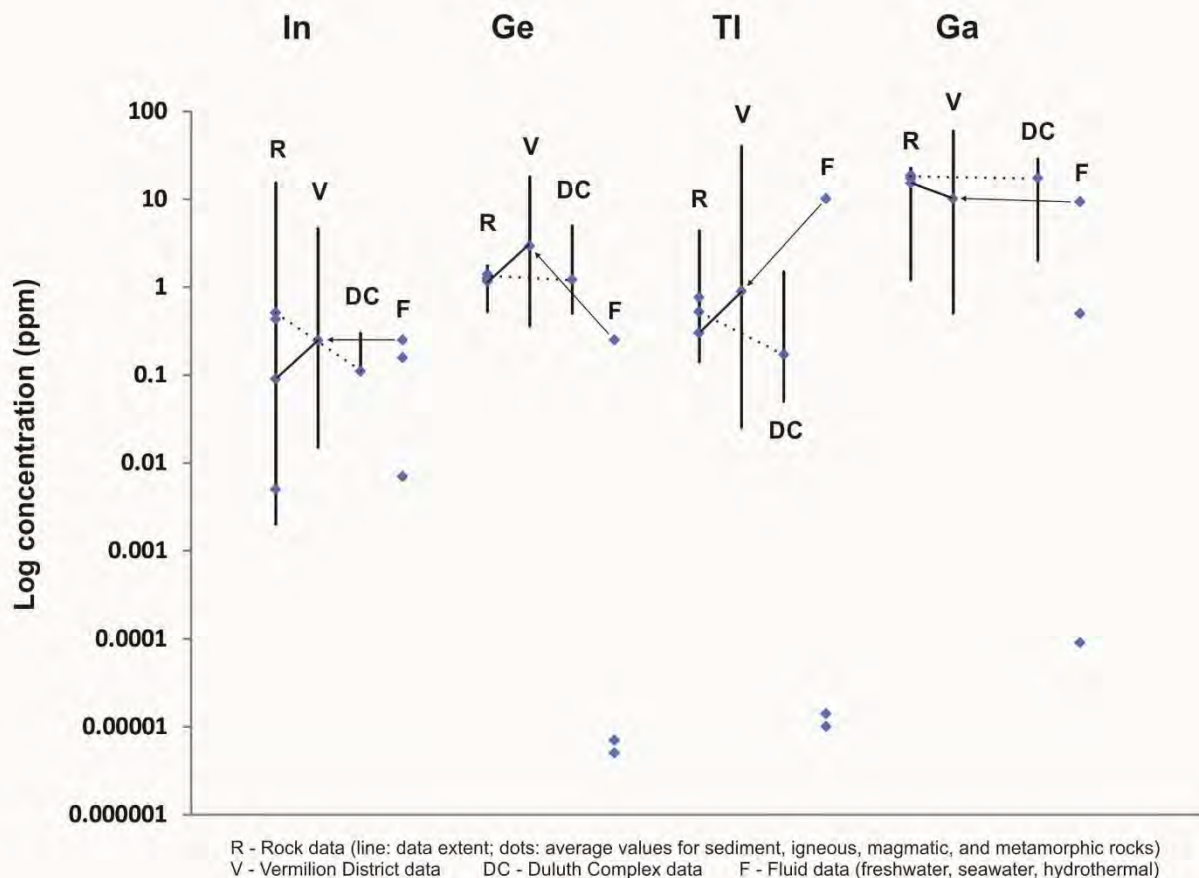


Figure 1 Concentration of In, Ge, Ga, and In in common rocks and fluids compared to samples from the Vermilion District and the Duluth Complex. Thin lines connect average values for similar rock types with positive slopes suggesting metal enrichment and negative slopes suggesting depletion or other processes; arrows connect potential fluid source to host rock.

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Stable oxygen isotopes, fluid inclusions, and microstructures in quartz cements and veins in the Baraboo Quartzite Breccia, north Baraboo Range, central Wisconsin

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Brecciated Baraboo Quartzite was first described in 1893 by Charles R. Van Hise¹ at Ableman's Gorge along the west side of the Baraboo River north of Rock Springs, Wisconsin. Since then, zones of breccia consisting of red, angular quartzite fragments ranging from 1-300mm across, which are cemented by massive (white) to euhedral (colorless) quartz crystals, kaolin, and hematite have been identified in four locations in the north limb of the Baraboo syncline. These four breccia locations are aligned parallel to the strike of relict, sedimentary bedding in the quartzite (Fig. 1). Though once believed to be sporadic features² disseminated throughout the Baraboo Quartzite in general, we suggest instead that breccia zones form a sub-continuous, strike-parallel feature in the north range.

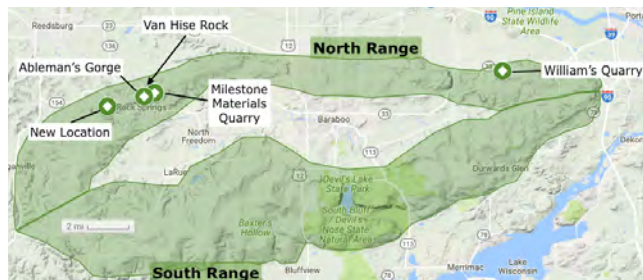


Figure 1: Outcrop locations of breccia.

Van Hise¹ hypothesized a formation mechanism of faulting, but clear evidence of faults has not been documented. The genesis of the breccia has remained enigmatic and some workers² have suggested that breccia zones are related to white quartz veins that cut the quartzite throughout both the north and south limbs of the syncline. ⁴⁰Ar/³⁹Ar ages of 1459 ± 3 Ma previously obtained from muscovite bearing veins in breccia in the south limb of the syncline along with fluid inclusion isochores and phase equilibrium constraints² suggest that at least some veins formed at 2 to 8 km depth from 200 to 280°C fluids and record 1465 Ma Wolf River magmatism³. The relationship between veins and breccia, however has been difficult to resolve. One hypothesis is that overpressured hydrothermal fluids explosively fractured the rock (natural hydrofracking) and then precipitated the quartz lining the vugs within the breccia and quartz veins⁴. It is clear that the events which brecciated the quartzite must be younger than the 1700 Ma quartzite itself and older than the ~500 Ma late Cambrian sandstones⁵ which lie unconformably on top of it.

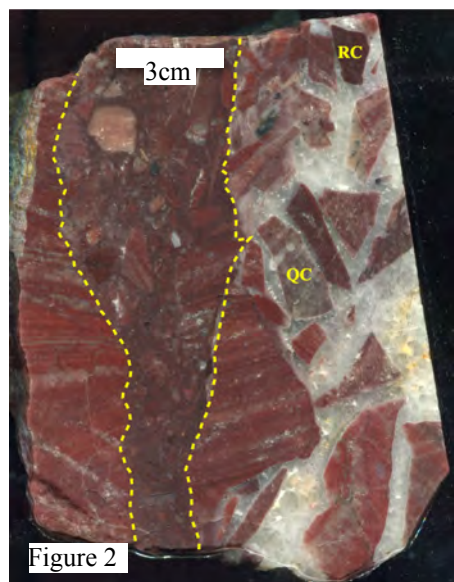


Figure 2

Clasts of Baraboo Quartzite (QC), surrounded by quartz and clay cement. Dashed lines outline earlier generation of breccia which is also present as clasts in younger breccia (RC).

Structural evolution of the breccia zone is difficult to evaluate because of multiple breccia generations (Fig 2.), and the highly variable morphology of the breccia even at the meter scale in outcrop. Breccia characteristics range from dispersed, rotated, and heavily cemented clasts (e.g. Fig. 2) to rectangular, evenly spaced clasts that appear to fit together, cemented by well oriented, rectangular stockwork veins. Massive, euhedral, white quartz crystals up to 10cm in width and 35cm in length are also associated with the breccia. Locally, colorless quartz crystals 1-7mm wide and 3-14mm long extend into vugs and veins which commonly include a central pocket of kaolinite.

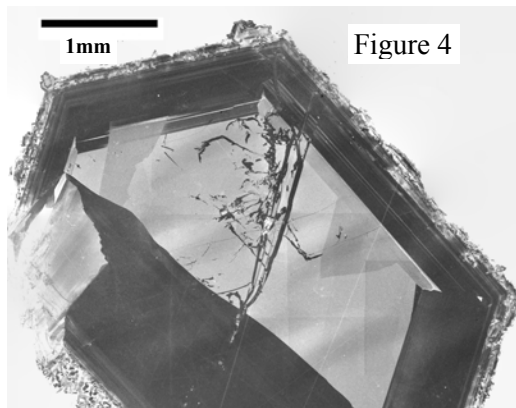
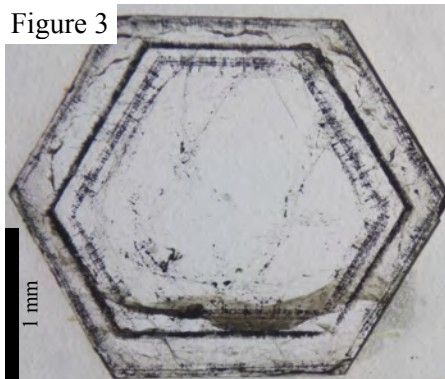
The colorless quartz crystals reveal concentric, tree ring-like growth zoning of hematite, clay, and fluid inclusions near their rims when cut perpendicular to the c-axis and viewed under transmitted light (Fig. 3). Fluid inclusion bearing healed fracture planes also cross cut the growth zoning. Cathodoluminescence (CL) images taken with a scanning electron microscope reveal more growth zoning and networks of micro-veins and healed fracture planes that are invisible with conventional light microscopes (Fig.4). Some of the fluid inclusion bearing, healed fracture planes in transmitted light are revealed to be micro-veins with CL. A

complex history of growth, fracturing, dissolution, and reprecipitation of quartz is indicated by the CL imaging.

Previous geochemical analysis⁶ of 1mm pieces of individual quartz crystal rims and cores by laser fluorination revealed $\delta^{18}\text{O}$ of 10‰ in the cores and 20‰ VSMOW in the rims. Recent, *in situ* analyses using the CAMECA 1280 SIMS with a 10 μm spot resolution revealed variations in $\delta^{18}\text{O}$ from 9‰ to 31‰ in the same crystals that were previously analyzed by laser fluorination. In addition, *in situ* SIMS analyses of many new samples revealed $\delta^{18}\text{O}$ values as low as -2‰ in a 30 μm growth band near the rim of crystals. Measured gradients in $\delta^{18}\text{O}$ within individual crystals are observed up to 22‰/20 μm and variations up to 32‰ are observed in crystals from the same hand sample. However, micro-veins and healed fractures were analyzed in crystals from multiple breccia locations and yielded consistent $\delta^{18}\text{O}$ values of 15 to 17‰. H_2O -rich fluid inclusions along the healed fractures (some of which were reclassified as micro-veins after CL imaging) resulted in homogenization temperatures of ~350°C and freezing points of -0.6 to 0.0°C.

Oxygen isotope values, fluid inclusion homogenization temperatures, and microstructures revealed by CL imaging record a complex history of brecciation in the Baraboo Quartzite. Cross cutting generations of breccia in outcrop and hand sample scale along with cross cutting micro-veins in the euhedral quartz crystals reveal multiple episodes of brecciation, while $\delta^{18}\text{O}$ and fluid inclusion values probably record mixing of the fluid sources that precipitated the quartz. Measured $\delta^{18}\text{O}$ values do not rule out the Wolf River magmatic event as a possible fluid source⁷, but do indicate either drastic temperature changes or mixing of fluid sources as the breccia zone formed.

Figure 3



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Directional drilling at Eagle, pros and cons, technical success, and Ni-Cu-PGE discovery in the Baraga Basin, Michigan.

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The Early Proterozoic Baraga Basin meta-sediments host a variety of mafic and ultra-mafic intrusions. This includes the economic Eagle peridotite intrusion at Eagle Mine (original reserves 5.18 Mt at 2.93% Ni and 2.49% Cu). And the recently discovered pipe-like chonolith extension of the Eagle East peridotite intrusion, known as the Eagle East Conduit (1.18 Mt inferred at 5.2% Ni and 4.3% Cu).

During the 2012 Eagle Deposit drilling campaign, Rio-Tinto geologists attempted to combat deviation with traditional wedges. This was met with mixed results. Eventually, geologists introduced Devico into the equation thus increased the success of hitting targets. Targets varied and were typically 300-400m down hole. However, Devico technicians tracked corrections and target coordinates.

Drilling through 2012 by Rio Tinto via conventional methods, had defined an upper, geologically mineralized, and relatively shallow keel-like chonolith at Eagle East. After the acquisition of Eagle by Lundin Mining, the Eagle exploration group developed a plan to test for a deep feeder/conduit extension of the Eagle East intrusion. Conventional methods would not suffice for the targets and depths. Eagle geologists turned to the use of directional drilling, multiple daughter branches, or kick-offs, from a single parent hole.

The original test was to drive a hole down the middle of the probable dyke from the last known intercept. To maintain the hole in or near a relatively small intrusion required the geologists to plot out the corrections/curves. Those curves would provide future kick off points for daughter branch holes. Early tests resulted in six kick offs from an open historical hole. This showed two things to the exploration team: 1) geologists could have more control over the drill hole by specifying target azimuth and inclination of corrections, and 2) the upper intrusion did extend deeper as a thin dyke that contained semi-massive sulfide mineralization.

Despite the steep learning curve through 2014, which included dealing with uncontrolled deviation and some hole abandonments, a third parent hole was successfully planned and executed. Curves were planned to allow kicking off for the subsequent holes (daughter branches). This resulted in 16 kick offs from a single parent drill hole. Those kick offs traced over 200 meters of strike length of mineralized conduit and the discovery of massive sulfide in what is now known as the Eagle East Conduit.

In 2015, the Eagle Exploration team needed to continue to trace the mineralization. The success was the design of 15EA334. This hole was collared 500m east from the collar of the discovery drill hole. The design of this drill hole was to trace the horizontal extent of the conduit.

Several intentional corrections/curves were planned to be future kick off points for upcoming daughter branches. Starting west and working east, zones could be drilled out, then pull up to the nearest curve, adjust the next zone of holes up, down, south, east, etc. and drill that zone. The adaptability of this coupled with the geologic knowledge of the system helped geologists determine where drill holes were in the conduit and where to go with the next set of holes.

In current exploration program at Eagle, geologists closely monitor drill progress and plan correction points and future branches on a daily basis using 3D modeling software Leapfrog.

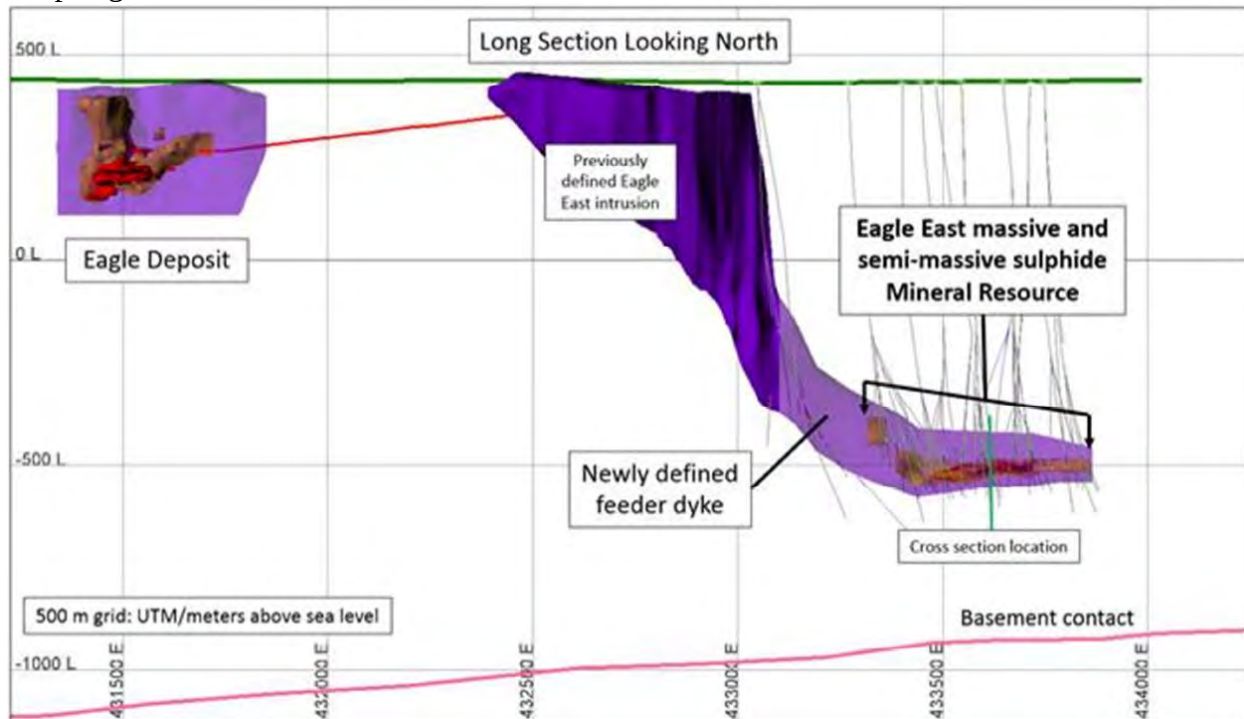


Figure 1: Eagle and Eagle East long sections showing exploration drill hole traces and an outline of Eagle East mineralization. Figure from Lundin Mining Press Release (June 29, 2016).

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Alteration Zonation and Geochemical Characteristics of the Back Forty Deposit, MI, a Replacement-style Volcanogenic Massive Sulfide Deposit

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The Aquila Resources Back Forty gold- and zinc-rich volcanogenic massive sulfide (VMS) deposit is located adjacent to the Menominee River near Stephenson in the Upper Peninsula of Michigan (Figure 1). VMS deposits are created in submarine environments when hydrothermal solutions circulate through the oceanic crust and precipitate base metals and Au as a result of mixing and cooling by ambient seawater. In the process, host rock mineralogy and geochemistry is modified by upwelling hydrothermal fluids, which produces distinct alteration mineral assemblages and metasomatic changes within the host rocks (Shanks and Thurston, 2012). Alteration mineral assemblages and their spatial distribution can be used to characterize individual deposits and help identify the location of sulfide mineralization. The relationship

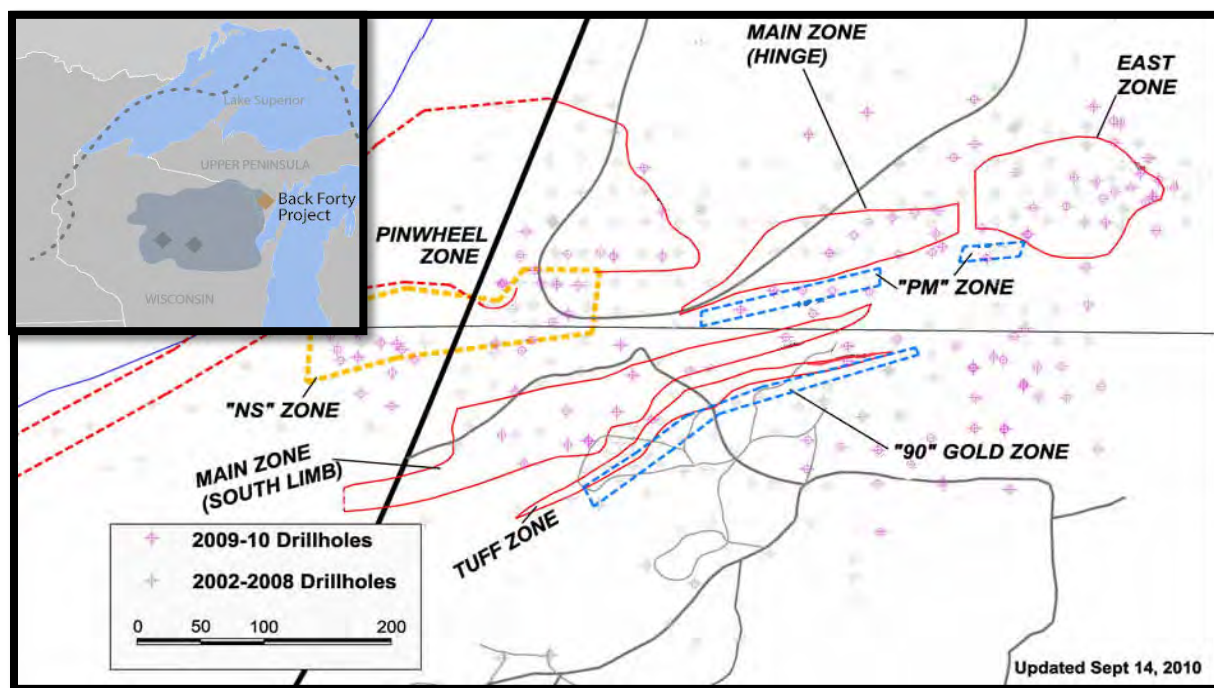


Figure 1: Geographical location of the Back 40 Deposit (inset), and the massive sulfide mineralized zones plus local drill hole locations. Modified from Aquila Resources Webpage (2017)

between host rock mineralogy and massive sulfide alteration is not well understood at the Back Forty deposit but vital for the understanding of its formation, mineralization history, and locating fluid sources responsible for the accumulation of base and precious metals.

The goals of this project are to: 1) Identify geochemical variations within the physical, mineralogical, and geochemical characteristics of the Back Forty deposit resulting from hydrothermal alteration, 2) use petrographic analysis and lithogeochemistry to define fluid flow pathways responsible for massive sulfide mineralization, 3) evaluate spatial relationships of the alteration distribution associated with mineralization, and 4) develop a geologic model of the Back Forty deposit alteration and identify potential hydrothermal fluid flow vectors.

Alteration mineral characterization will include geochemical and petrographic analyses, SEM and microprobe analyses, on-site geological mapping, and drill core logging specifically for alteration mineral assemblages and their distribution. Of the more than 500 drill holes in the Back Forty deposit, drill core samples will be selected according to their location relative to the main mineralization. Whole rock geochemistry as well as trace element data will be acquired. Results will be evaluated using the isocon method (Grant, 1986), alteration box plots (Large et al., 2001), as well as alteration mineral mass calculations. Findings will be essential to evaluate quantitative mass balance calculations of alteration mineral assemblages and their spatial distribution in order to identify potential fluid flow pathways and mineralization vectors within the deposit.

Using drill core analyses as well as structural and lithological data, a 3D subsurface map of identified alteration mineral zonation will be created to determine the relationship between massive sulfide mineralization and alteration assemblages, in order to denote existing mineralized sections and other potential ore zones. From these results, it may be possible to use alteration mineralogy to determine the source of hydrothermal fluids and identify the main source of metal accumulated in the Back Forty deposit. This work is relevant because most VMS deposits occur in clusters (Galley et al., 2007). Characterizing the alteration mineral assemblages and their distribution associated with mineralization at the Back Forty deposit will provide a better understanding of the Back Forty deposit and the geologic model may be a useful exploration tool to locate additional VMS mineralization on the Back Forty property.

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Sediment Provenance of Twin Ports Baymouth Bars

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Minnesota and Wisconsin Points (MWP) are perhaps the most iconic landmarks in western Lake Superior. Despite this, relatively little is known about how MWP or the neighboring Connor's and Rice's Points formed. Existing models (Kemp et al., 1978; Barlaz, 1983) call on a combination of longshore drift from the Wisconsin side of Lake Superior and sediment supply from the Nemadji and St. Louis Rivers, but none of these models can describe all observed features of the bars. Ongoing research by Mr. Swenson has led to a new conceptual model of bar formation. A fundamental component of this model involves determining the source, or provenance, of the sand that comprises these baymouth bars. To directly investigate the primary sources of sediment that comprise MWP, a sediment provenance study utilizing point-counting was conducted.

MWP has at least four major potential sediment sources—the St. Louis River, which drains a large area north and west of Duluth; the Nemadji River, whose watershed lies south of Duluth and crosses the Minnesota and Wisconsin borders; longshore transport of sediment derived from weathering of bedrock cliffs on the north shore of Lake Superior, and finally, longshore transport of sediment derived from wave attack of unconsolidated glacial-till bluffs on the south shore of Lake Superior. Sediment was sampled from 16 locations across the Duluth, MN and Superior, WI area, with 10 of these locations from MWP, and the other six from the sediment sources. The 1 mm portion of sediment from each location was analyzed under a binocular scope and grouped based on color and “coarseness”, an arbitrary term considering weathering, crystal size, how well crystal faces were formed, and roundedness. The sum of the grains in each group, in each locale, were summed and divided by the total number of grains at the location (Equation 1).

$$\frac{Qtz_{WPBW} + Qtz_{WPMB} + Qtz_{WPBY} + Qtz_{WPDC}}{Total_{WPBW} + Total_{WPMB} + Total_{WPBY} + Total_{WPDC}}$$

Equation 1: Calculation for deducing the quartz ratio for Wisconsin Point.

Out of all the valid potential sediment sources (the Nemadji's sediment is too fine for this study's methodology), the Amnicon River provides the best match when compared to MWP (Figure 1). The Amnicon's sediment flux, combined with south-shore longshore drift, are the most likely sources of sediment for Minnesota and Wisconsin Points. Future improvements on this work could utilize trace-element geochemical analysis for a grain size agnostic look at the sediments. This would not only allow for increased objectivity, but most importantly, would allow the sediment input from the Nemadji to be quantified.

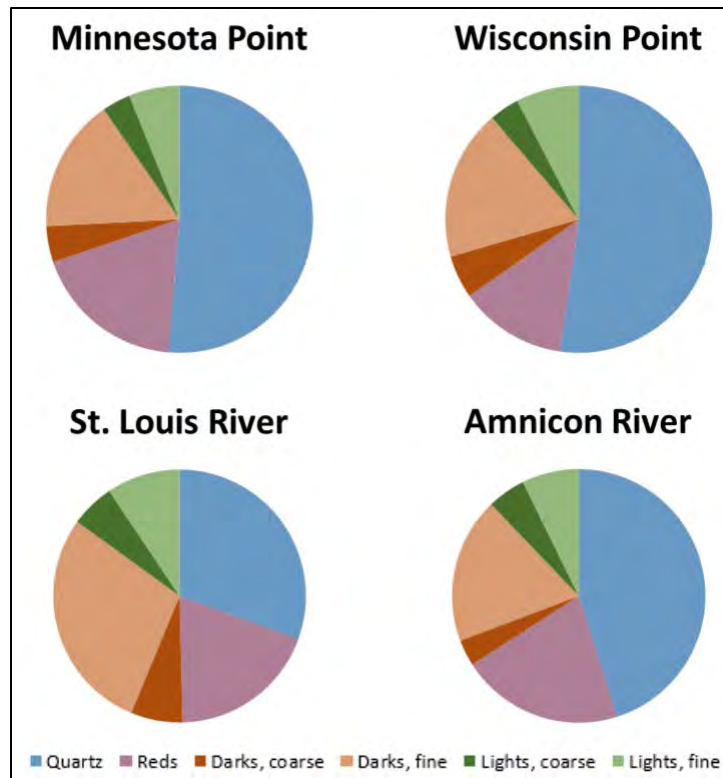


Figure 1: Cumulative ratio charts for MWP, St. Louis River, and Amnicon River.

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Trace Elements in Iron Oxides on the Marquette Range and Hemlock Volcanics

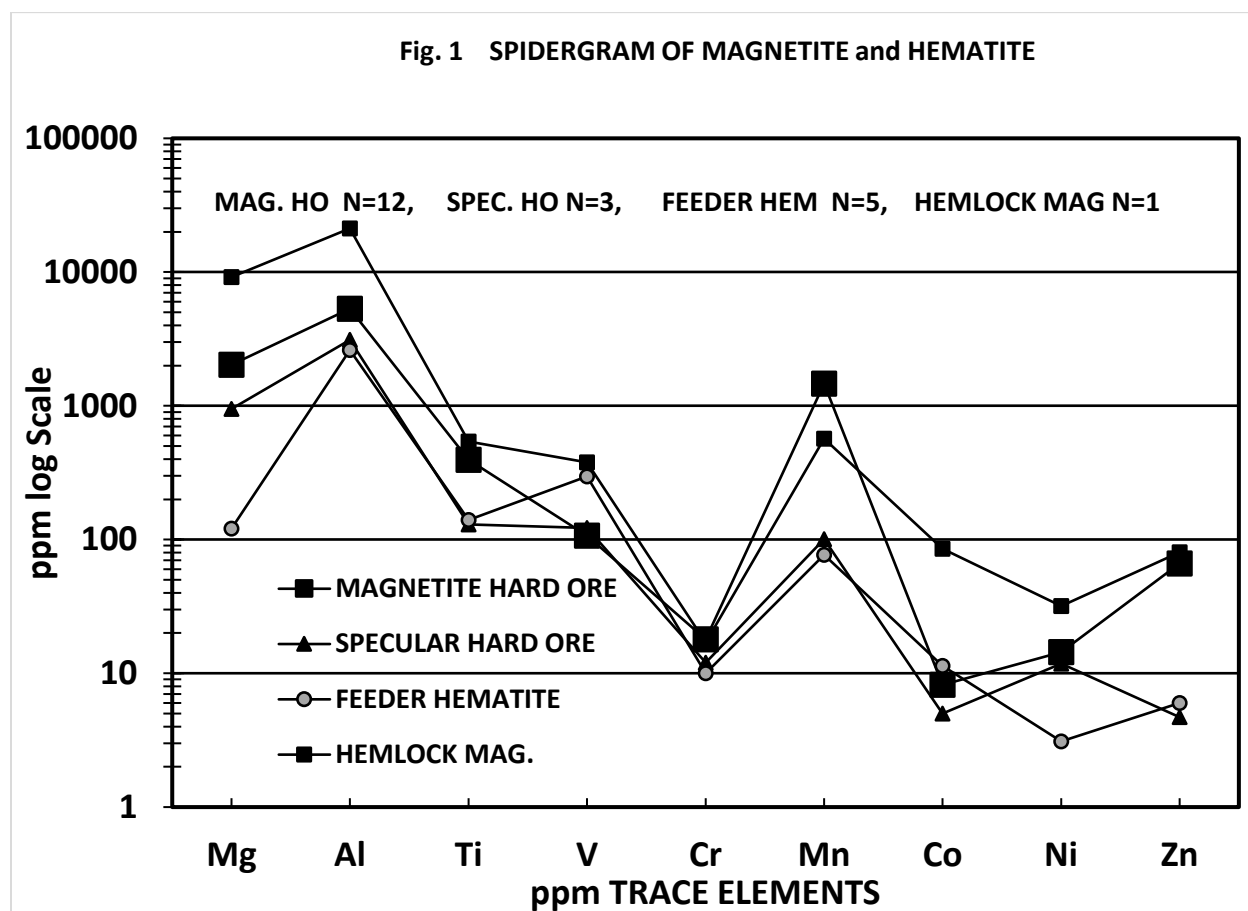
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The source of iron and silica in banded iron formations has remained elusive for many years. It has been postulated that the iron and silica originated from the ocean depths from vague unidentified igneous sources.

Trace elements in hard ore iron oxides from the Negaunee Iron Formation, located in Marquette and Baraga Counties, Michigan, and magnetite from the tholeiitic basalts of the Hemlock Volcanics, located in Iron County, Michigan, were determined by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). Discrimination diagrams, spidergrams (Fig. 1) and rare earth plots of the trace elements will be presented that illustrate the similarities and differences between iron oxides in the Negaunee Iron Formation and Hemlock Volcanics.

The overall similarity between the elemental abundance in the Negaunee Iron Formation and Hemlock Volcanics supports the hypothesis that a significant source of the iron of the Marquette Range is magmatic.



Textural and geochemical analysis of a continuous drill core from the Black Sturgeon sill, Ontario

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In this study, we examined stratigraphic variations in a 265 m continuous drill core through a Nipigon diabase sill from Black Sturgeon Lake, southwest of Lake Nipigon, Ontario. This sill is part of the 1.1 Ga Midcontinent Rift magmatic suite of ultramafic to mafic sills located in the Lake Superior region, Canada (Nicholson and Shirey, 1990). Previous research (Zieg, 2014) has identified several possible reinjection horizons where new magma has intruded older, partially solidified magma within a crystal mush zone. This investigation focused on creating a detailed stratigraphic column to aid in visualizing the textural, chemical, and mineralogical variations associated with reinjection and other petrogenetic processes.

The sill can be divided into zones, subzones, and divisions based on geochemistry (XRF), modal mineralogy (obtained by point count), texture (mean crystal size), and visual inspection of the core (see Table 1 below). In a companion piece (Zieg et al., this volume), we present evidence suggesting that the various zones reflect different magmatic histories.

The textural, mineralogical and visual observations, in conjunction with geochemical analysis, support the hypothesis that the Black Sturgeon sill was emplaced in a series of chemically and texturally distinct magma pulses. The results of this project will be used to guide future research into the evolution and emplacement mechanics of the Black Sturgeon sill and, by extension, other diabase sills.

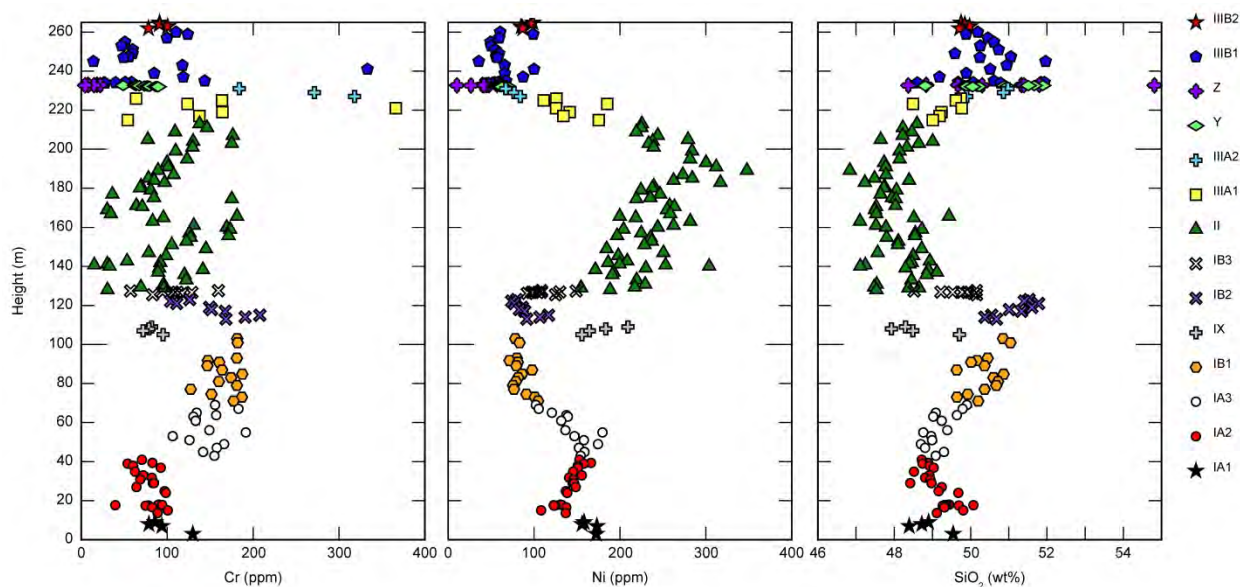


Figure 1. Major and trace element profiles show distinct chemical variations between zones in the sill.

Table 1. Zones, subzones and divisions within the Black Sturgeon sill

Zone	Subzone	Division	Description	Stratigraphic Interval [meters above base]
III	IIIB	IIIB2	Upper chilled margin. Glomeroporphyritic texture.	261.5 – 264.4
		IIIB1	Subophitic to ophitic diabase. Lenses of pegmatitic diabase.	233.5 - 261.5
	IIIA	Z	Discrete, transgressive granophyre lenses.	(e.g., 232.6 - 233.5)
		Y	Fine-grained granular diabase adjacent to granophyric horizon.	(e.g., 231.6 - 232.6)
		IIIA2	Intergranular diabase.	226.6 - 231.6
		IIIA1	Ophitic diabase divided by numerous thin (<1 m) sections of intergranular diabase and granophyre lenses.	214.5 – 226.6
II	II	X	Discrete olivine-rich horizons outside of Zone II.	(e.g., 103 – 109)
		II	Olivine-rich gabbro with moderate to well- developed plagioclase foliation.	127.6 – 214.5
I	IB	IB3	Texture transitional between IB2 and II anomalous/gradational compositions.	123 - 127.6
		IB2	Intergranular diabase. Compositionally distinct from IB1.	109 - 123
		IB1	Intergranular diabase.	69 - 103
	IA	IA3	Gradational change in textures from poikilitic to subophitic.	43 - 69
		IA2	Poikilitic olivine-bearing gabbro.	9 - 43
		IA1	Lower chilled margin. Glomeroporphyritic texture.	0 - 9

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Estimating volcanic SO₂ release from the 1.1 Ga Mid-Continent Rift through comparison with Phanerozoic flood basalt events

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The basalt-dominated volcanism related to the ca. 1.1 Ga Mid-Continent Rift ranks among the Earth's great flood basalt events in terms of both total volume of erupted lava and maximum effusion rates. The volume of surviving extrusive rock is estimated at 1.5 million km³, and the original pre-erosion volume may have exceeded 2 million km³ (Cannon, 1992). This is larger than the Miocene Columbia River Basalts (0.2 million km³; Reidel *et al.*, 2013); comparable to the end-Cretaceous Deccan Traps (Schoen *et al.*, 2015) and the end-Triassic Central Atlantic Magmatic Province (Blackburn *et al.*, 2015); and somewhat smaller than, but of the same order of magnitude as, the great Siberian Trap sequence of latest Permian time (>4 million km³; Ivanov, 2007).

The total period over which Mid-Continent Rift volcanic activity occurred was almost 30 million years, but eruption rates varied greatly over that interval. High-resolution geochronology has made it possible to recognize distinct stages in rift volcanism: an Early Stage from 1110-1106 Ma; the Main Stage from 1101-1094 Ma, and a Late Stage from 1094-1086. The Early and Main Stages account for by far the greatest volumes of erupted material, and during these times, effusion rates may have been on the order of 0.2 km³/yr, well within the range of more recent flood basalt events (Miller & Nicholson, 2013; Davis and Paces, 1990).

Given the association between flood basalt episodes and mass extinctions in Phanerozoic time, it is interesting to consider the possible biogeochemical impact of Mid-Continent Rift volcanism. Emissions of CO₂ and SO₂ from the Siberian Traps and Central Atlantic Magmatic Province are widely accepted as having destabilized climate and triggering the end-Permian and end-Triassic mass extinctions, respectively. There is also growing evidence that environmental perturbations related to Deccan Trap gas emissions may have compounded the devastation linked with the end-Cretaceous meteorite impact (Self *et al.*, 2008).

The climatic effects of volcanic CO₂ may have been less significant in Mesoproterozoic time, when oxygen levels were still only a fraction of the modern value and CO₂ levels were likely 7-10 times higher than today (Kah and Riding, 2007). Estimating CO₂ emissions from ancient volcanic rocks is also difficult due to the low solubility of CO₂ in mafic melts. SO₂ emissions can be estimated from young volcanic rocks by comparing sulfur content in glass inclusions and vent tephra, but inevitable alteration of glassy material makes this method inapplicable to older rocks. However, a strong observed correlation between the TiO₂:FeO ratio and sulfur concentrations in young volcanic rocks makes it possible to estimate SO₂ output in ancient eruptions (Self *et al.*, 2006).

Using this correlation, together with published geochemical analyses and the estimated 2 million km³ of lava from the MCR, we estimate that rift volcanism was accompanied by the release of 10.8 million Tg of SO₂ over a period of approximately 10 million yrs, for an average rate of almost 11 Tg /yr. This is comparable to the amount released by the 1991 eruption of Mt. Pinatubo, which cooled the Earth by 0.5° for 2 years. During Mid-

Continent rift volcanism, individual 1,000-10,000 km³ flows of the rift may have produced 5,900-59,000 Tg of SO₂ in as little as several hundred years.

The environmental effects of volcanic SO₂ depend strongly on the altitude to which it is injected in the atmosphere. If SO₂ reaches the stratosphere, as it did in the Plinian Pinatubo eruption, the effect is strong cooling related to the dispersal of fine, reflective sulfate aerosols. If it stays in the troposphere, as in the deadly 1783-84 fissure eruption in Iceland, it can form a toxic haze that finally dissipates as acid rain falls from the atmosphere (Thordarson and Self, 2003). While the Mesoproterozoic biosphere, still entirely microbial, may have been more resilient than Phanerozoic ecosystems, sustained emissions of SO₂ at such high levels almost certainly affected regional if not global biogeochemical cycles -- and may even have altered the course of evolution. We hope this preliminary study inspires further consideration of the environmental and biological effects of Mid-Continent Rift volcanism.

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Internal fractionation and phenocryst accumulation in the Black Sturgeon sill, Ontario

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The Black Sturgeon sill (BSS) is a ~250 m thick composite diabase intrusion belonging to the Nipigon sill complex (Hollings et al., 2007; Zieg, 2014; Hone et al., this volume). It consists of several discrete zones (Wallrich et al., this volume), which are distinguished on the basis of chemical and petrographic characteristics. We have analyzed compositional (major and trace element bulk rock geochemistry) and petrographic (modal mineralogy, crystal sizes, and plagioclase alignment) variations in the BSS, and in this report we document the complementary roles of internal fractionation and phenocryst accumulation in generating the observed zonation.

Rocks in the BSS display a broad range of compositions, particularly for a diabase sill without any apparent modal layering. MgO varies from 1.7-10.8%; SiO₂ varies from 47.3-56.3%; Ni varies from 10-350 ppm; Zr varies from 35-350 ppm. This corresponds to liquids ranging from basaltic to nearly andesitic. The bulk-rock Mg#, molar MgO/(MgO+FeO^T), increases consistently through much of the sill (Fig. 1d), suggesting that the differentiation process was more complex than simple crystal fractionation from a uniform liquid.

We simulated the fractionation trends for different potential parental liquid compositions using Rhyolite-MELTS (Gualda et al., 2012; Ghiorso and Gualda, 2015) and determined that the evolved compositions found in the sill are consistent with differentiation of all reasonable initial liquids. In fact, all liquid fractionation paths converge to join a single trajectory based on the chilled margin composition. Rocks with these evolved compositions are found as discrete lenses and patches in the upper part of the sill (zone III).

Based on the MELTS results, plus a principal components analysis (Davis, 2002) of rock compositions from the sill, we conclude that the compositions of the rocks in the central portion of the sill are strongly impacted by the accumulation of varying amounts of olivine, plagioclase, and pyroxene. Rocks in the lowermost part of the sill (IA) have compositions approximating the chilled margin and can be interpreted as solidified samples of the carrier liquid. In this model, rocks in zone IB have compositions consistent with accumulation of plagioclase ± pyroxene, and rocks in zone II have compositions consistent with accumulation of olivine + plagioclase.

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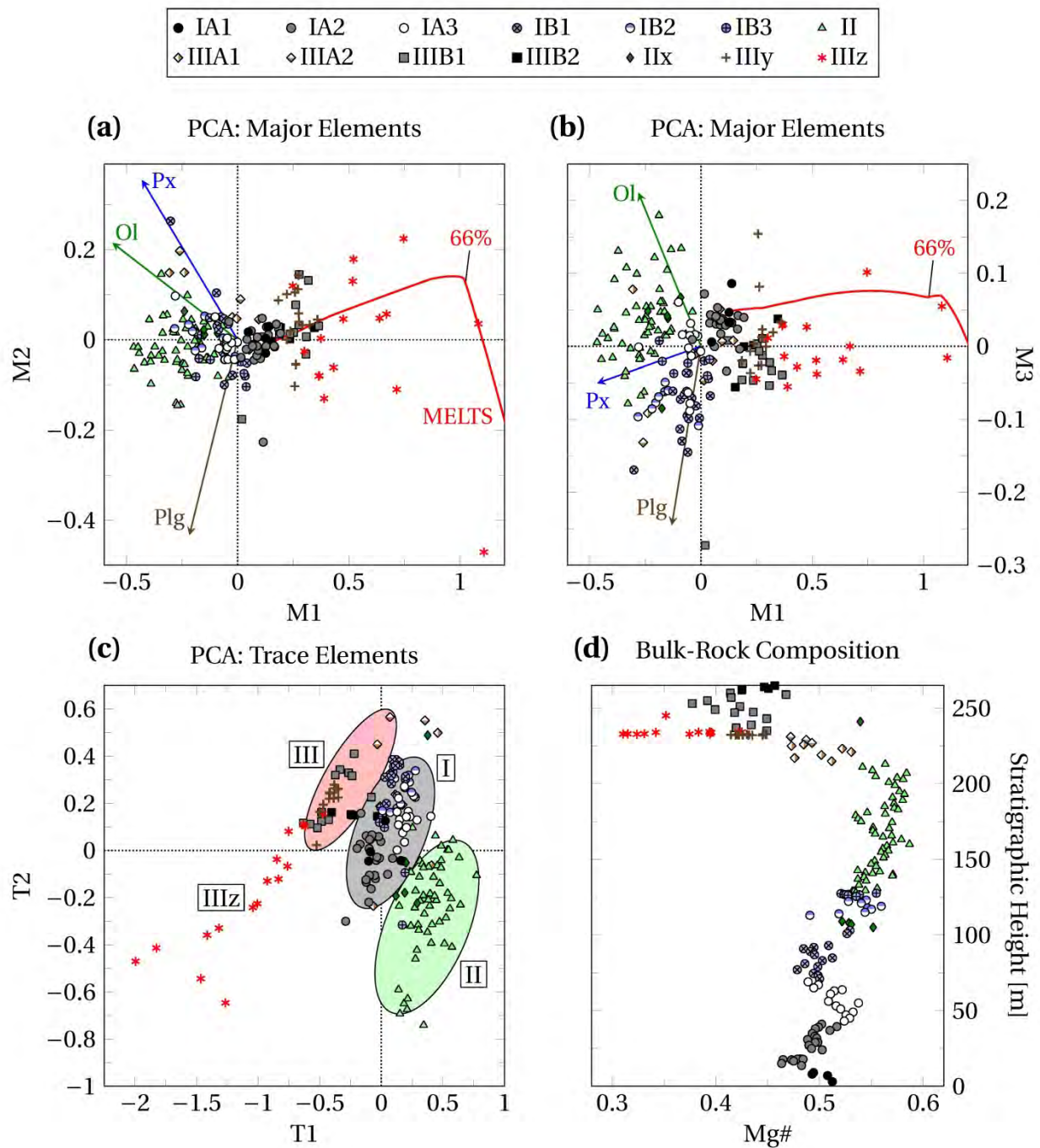


Figure 1. Compositional characteristics of the Black Sturgeon sill. a-b) Principal components analysis shows granophyres (stars) consistent with fractionation of liquid like the lower margin (IA1, IA2), and that rocks from the middle of the sill (IB, II) are consistent with accumulation of ol, plg, px. c) Zones I, II, III can be efficiently discriminated using trace element characteristics. d) Whole-rock Mg# increases upward from 10-15 m and from 75-200 m above base, and evolved rocks are found in discrete lenses.