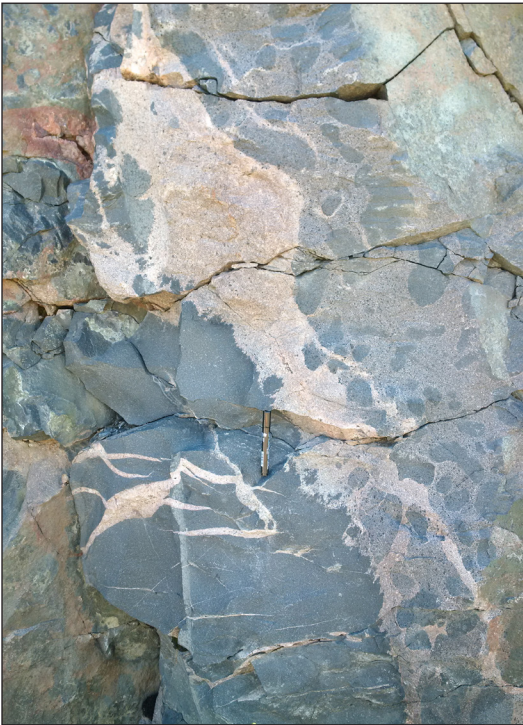


65th ANNUAL MEETING

Terrace Bay, Ontario - May 8-9, 2019

INSTITUTE ON LAKE SUPERIOR GEOLOGY

Part 1 – Program and Abstracts



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INDIVIDUAL CONTRIBUTORS TO STUDENT TRAVEL SCHOLARSHIP:

AL MacTAVISH, MARY KAY ARTHUR, L. GORDON MEDARIS,
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65th ANNUAL MEETING

INSTITUTE ON LAKE SUPERIOR GEOLOGY

May 8-9, 2019

Terrace Bay, Ontario

HOSTED BY:

Mark Smyk and Pete Hollings

Co-Chairs

Ontario Geological Survey and Lakehead University

Proceedings - Volume 65

Part 1 – Program and Abstracts

Compiled and edited by Mark Puumala

Cover Photos: Left - Little Pic River Breccia zone, Coldwell Complex, Middle - Toe of pahoehoe flow, Slate Islands. Right - Glacially polished syenite, Coldwell Complex.

65th INSTITUTE ON LAKE SUPERIOR GEOLOGY

VOLUME 65 CONSISTS OF:

PART 1: PROGRAM AND ABSTRACTS

PART 2: FIELD TRIP GUIDEBOOK

TRIP 1: THE SLATE ISLANDS

TRIP 2: MIDCONTINENT RIFT-RELATED CARBONATITES AND DIATREMES

TRIP 3: GEOLOGY OF THE WESTERN SCHREIBER-HEMLO GREENSTONE BELT

TRIP 4: GEOLOGY OF THE NIPIGON AREA

TRIP 5: A STRATIGRAPHIC TRANSECT ACROSS THE NORTHERN FLANK OF THE MIDCONTINENT RIFT
NEAR ROSSPORT

TRIP 6: GEOLOGY OF THE COLDWELL ALKALINE COMPLEX

TRIP 7: BUILDING AND ORNAMENTAL STONE SITES OF THE MARATHON AREA, ONTARIO

TRIP 8: GEOLOGY OF THE PAST-PRODUCING WINSTON LAKE CU-ZN MINE

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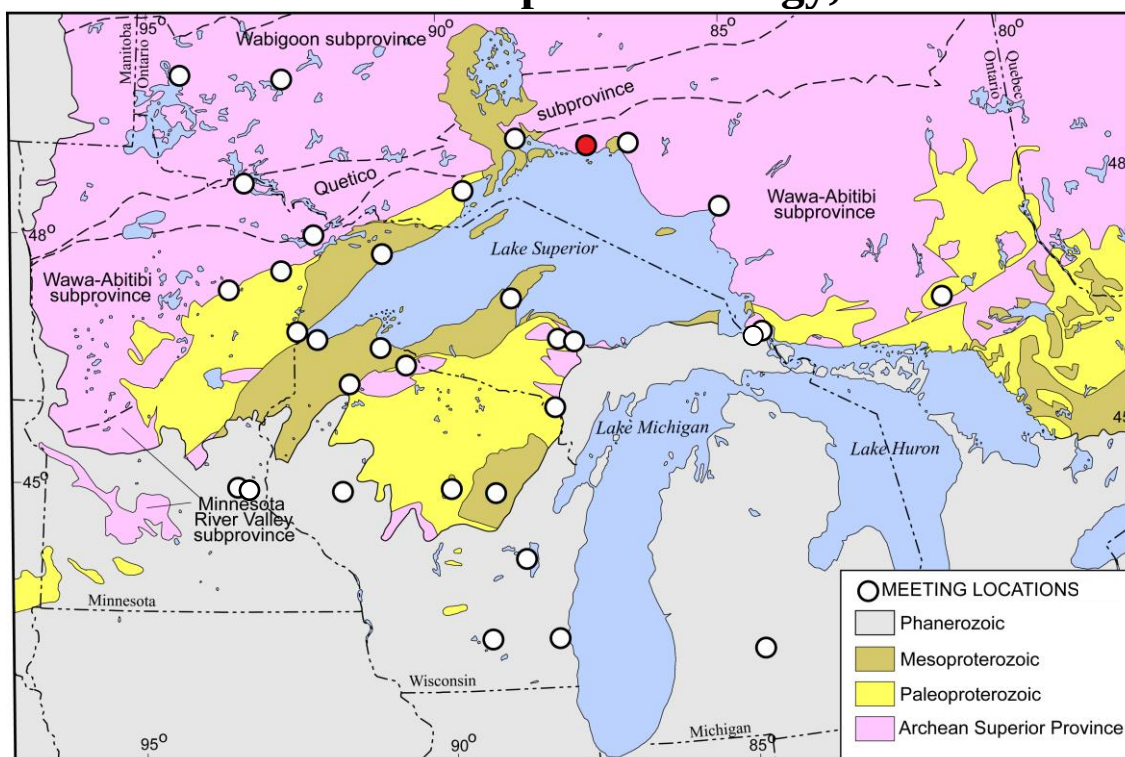
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Part 1: Program and Abstracts

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Institutes on Lake Superior Geology, 1955-2019



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

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

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	2016	Mark A. Jirsa
1980	<i>not awarded</i>	1999	Tsu-Ming Han	2017	Philip Fralick
1981	Carl E. Dutton, Jr	2000	John C. Green	2018	Val W. Chandler
1982	Ralph W. Marsden	2001	John S. Klasner		
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 &		
1992	William F. Cannon		Gregory R. Brumpton		
1993	Donald W. Davis	2011	Dean M. Rossell		
1994	Cedric Iverson	2012	James D. Miller		
1995	Gene La Berge	2013	Tom Waggoner		
1996	David L. Southwick	2014	Laurel Woodruff		
1997	Ronald P. Sage	2015	Rodney J. Ikola		

2019 GOLDICH MEDAL RECIPIENT

Mark Severson

Goldich Medal Committee

Serving through the meeting year shown in parentheses.

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

Dan England (2017-2020) Eveleth Fee Office

Steve Kissin (2018-2021) Lakehead University

Citation for the Goldich Medal Recipient to **Mark Severson**



ILSG Members, Goldich Medal recipients and guests, it is my honor to present the citation for this year's recipient of the Goldich Medal, Mark J. Severson.

Mark J. Severson has made significant contributions to understanding a vast number of topics associated with the geology of the Lake Superior region during his 30+ year career. Few can say they have contributed to the ILSG as a student, as an industry geologist, as an academic, as a thesis advisor, and as a teacher. In fact, Mark's contributions to understanding Lake Superior Geology fill at least 15 pages of a Google Scholar search! He exemplifies the essence of an "Institute on Lake Superior Geology" geologist, possessing both exceptional field skills and extraordinary lab skills which have enabled him to

conduct comprehensive, high quality scientific research. Mark also possesses the rare skills that allow him to communicate complicated geological features, models, and stories to professionals, students and the public in a way that teaches them (and even more importantly, gets them excited about) the amazing geology of the Lake Superior region and the countless geological wonders in their backyards.

Mark's research in the Lake Superior region began in the mid-1970s after obtaining his Bachelor of Sciences degree in Geology at Western Illinois University. In 1978, he was awarded his Master's Degree in Geology at the University of Minnesota Duluth, studying the "Petrology and Sedimentation of Early Precambrian Graywackes in the Eastern Vermilion District, Northeastern Minnesota" under the advisement of (at that time) future Goldich Medal awardee Dr. Richard Ojakangas. After stints as an exploration geologist searching for base metals, gold and uranium with US Steel and Santa Fe Pacific Mining, Mark started a distinguished 25-year long career with the Economic Geology Group at the Natural Resources Research Institute (NRRI) at the University of Minnesota Duluth (UMD). While at the NRRI, Mark established himself as one of the leading economic geologists in the Lake Superior region, producing nearly 40 NRRI technical reports, eight geologic maps, and numerous peer-reviewed journal and public poster presentations. The geologic topics covered in this work are diverse, and include:

- Performing a wide variety of research associated with the igneous stratigraphy, copper-nickel-platinum group element and titanium mineralization in the Duluth Complex (which included logging of over 1 million feet of Duluth Complex drill core and the production of 10 NRRI Technical Reports, 1 NRRI geologic map, and 11 peer reviewed journal publications);
- Completing substantial research evaluating sedimentary environments, mineralization, and the stratigraphy of the Biwabik Iron Formation, culminating in NRRI Technical Report NRRI/TR-2009/09, where he established the "Rosetta Stone" for interpreting the stratigraphy of the Biwabik Iron Formation;
- Writing numerous technical reports describing SEDEX-type mineralization in Carleton County and the Cuyuna District of eastern and east-central Minnesota, respectively;

- Producing an NRRI technical report describing the history of gold exploration in Minnesota;
- Completing an NRRI technical report explaining metallic exploration, mining, and processing permits in Minnesota;
- Co-authoring a significant NRRI technical report which describes rare earth element (REE) mineral potential across Minnesota;
- Developing technical reports describing clay deposits in the Minnesota River Valley;
- Producing the most detailed heat flow maps available for the State of Minnesota; and
- Co-authoring a federally-funded report describing possibilities for the development of pumped-hydro energy storage systems in legacy iron-mining landscapes in northeastern Minnesota;

During his time at the NRRI, Mark contributed to the education of undergraduate and graduate students, as well as teachers through his efforts as an Adjunct Professor in the Department of Geology at the University of Minnesota Duluth, as an instructor for the Precambrian Research Center geology field camp, and via the Minnesota Minerals Education Workshop.

Throughout his career, Mark collaborated on numerous projects with the Minnesota Geological Survey (MGS). This included co-authoring three Open File Reports (maps and reports) about Duluth Complex mineralization, as well as a significant Report of Investigation which describes the geology and mineral potential of the Duluth Complex and related rocks. It is important to note that these MGS publications were co-authored with Goldich Medal awardees John Green, Jim Miller, Mark Jirsa, and Val Chandler.

Since 2013, Mark has worked (and is now “semi-retired”) as a Senior Geologist for Teck American, where he continued to define Cu-Ni resources at the Mesaba Deposit in NE Minnesota. Despite his “semi-retired” status, Mark continues to make significant contributions to understanding Lake Superior geology in his role as Vice President for the Mesabi Range Geological Society.

Mark’s contributions to the ILSG since 1989 include authoring or co-authoring 22 abstracts and seven field trip guidebooks, serving as a session chair, and serving on student paper committees over the course of at least 20 ILSG meetings since 1989. It is worth noting that Mark served as the co-chair with Steve Hauck for the 50th Annual ILSG meeting that took place in Duluth in 2004. As well, Mark has undoubtedly increased the knowledge of those attending the many ILSG field trips that he participated in over the past 29 years.

All of us who have known and worked with Mark know of his passion for the geology. His significant contributions to understand and teach about the spectacular and diverse geology of the Lake Superior region, as well as his significant contributions to the Institute on Lake Superior Geology have all been accomplished with the highest level of professionalism and distinction. Please join me in congratulating Mark J. Severson as the 2019 recipient of the Goldich Medal from the Institute on Lake Superior Geology.

*Submitted by George J. Hudak
Director, Minerals-Metallurgy-Mining Initiative
Natural Resources Research Institute, UMD*

Honoring the Pioneers of Lake Superior Geology

(Adopted by the Board of Directors, 2016)

Preamble

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

Award Guidelines

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

The Board will review this award every five years.

Pioneers of Lake Superior Geology

2017 Douglass Houghton (1809-1845)

2018-19 *not presented*

In Memoriam

Gene L. LaBerge



This winter the Institute on Lake Superior Geology, its members, and countless others lost a dedicated geologist, and outstanding teacher, mentor, colleague, and friend-Gene LaBerge. Gene's contributions to the geology of the Lake Superior region and the study of iron-formation have been many and impactful. He will be greatly missed, not only for his scientific contributions, but also for his good humor, wise council, and generous nature.

Gene was a product of the Northwoods, born and raised in Ladysmith, Wisconsin, the eventual home of the Flambeau copper-gold mine in the mid-1990s. After serving a stint in the U.S. Marine Corp during the Korean War, he went on to study geology, obtaining his B.S., M.S., and Ph.D. degrees all at the University of Wisconsin-Madison. While a graduate student in 1957, he was hired by Ralph Marsden, head of exploration for U.S. Steel, to explore for iron-formation in northern Michigan. This, along with field trips around the region led by Ralph and Stan Tyler of UW-Madison, sparked his interest in iron-formation and the geology of the Lake Superior region. While he was working to finish his Ph.D. research, his advisor, Stan Tyler, suddenly died.

Fortunately, Ralph Marsden was able to step in, allowing Gene to finish and receive his Ph.D. His dissertation was on the origin of magnetite in iron-formation. After graduate school, he continued his study of iron-formation accepting a post-doctoral fellowship in Adelaide, Australia where his new bride, Sally, had received a Fulbright Scholarship. During this post-doc, he also spent several months in South Africa. After a year in Australia, Gene accepted a second post-doctoral fellowship, this time with the Geological Survey of Canada in Ottawa. Some of the samples of iron-formation he collected for his studies he subsequently used to build a beautiful fireplace in his house in Omro, Wisconsin.

In 1965, Gene joined the faculty at UW-Oshkosh as the third member of the then expanding Geology Department. It would remain his home for all his career. Early on, he and Sally would spend weekends driving the back roads of the Lake Superior region looking for outcrops and planning field trips. Gene's passion for geology was clearly expressed through the many (>100) overnight field trips he led during his 33-year teaching career. While still a graduate student, he had helped conduct a pebble survey in northern Wisconsin for U.S. Steel, identifying thousands and thousands of pebbles in gravel pits across the region. This experience led him to devise one of his classic (or infamous) student exams-*the pebble test*- where students had to identify the rock type and mineralogy of small pebbles using only a hand lens. Gene often said that "a rock or mineral was much easier to identify if you had seen it before". To reinforce that, students in his mineralogy and lithology classes learned to identify not only the most common minerals and rocks but also many less common ones, particularly those important in exploration for certain types of mineral deposits. His classes were always rigorous, comprehensive, and taught with infectious enthusiasm. Gene retired from teaching in 1998. Over his teaching career, Gene

received all the teaching and research awards offered by UW-Oshkosh, the only faculty member to have done so.

In the late 1960s, on the advice of Carl Dutton, Gene began mapping the geology around Wausau in Marathon County, Wisconsin for the Wisconsin Geological and Natural History Survey (WGNHS). The project eventually grew to include mapping all of Marathon County in collaboration with Paul Myers of UW-Eau Claire. In 1983, Gene began working part-time for the U.S. Geological Survey (USGS), an association he would maintain both formally and informally for the rest of his career. Much of the work he did for the USGS was done collaboratively with his good friend and colleague John Klasner of Western Illinois University. During his work for the WGNHS and USGS, Gene probably walked over more of Wisconsin and northern Michigan than anyone ever has. Along with authoring many technical journal articles, book chapters, and WGNHS and USGS publications, he used his in-depth knowledge of the geology of the Lake Superior region to write a book for non-specialists, *Geology of the Lake Superior Region*, first published in 1994.

Gene was an active and long-time member of the Institute on Lake Superior Geology (ILSG), giving his first presentation at the 1958 meeting in Duluth, only the fourth meeting of the Institute. He went on to give presentations at many more ILSG meetings, served as Chair for two meetings (1969 and 1984), and led field trips for several meetings. Gene received the Goldich Award in 1995 for his significant contributions to the geology of the Lake Superior region and the ILSG.

Gene also had other interests and pursuits. He was an avid mineral collector, building a world-class collection whose centerpiece was gem-quality tourmalines from locations around the world. The collection was effectively displayed in his house in cases he designed and built himself. The collection was eventually sold (a hard decision resulting from having to move and downsize), but not before he had his three daughters select their favorite specimens. In mid-life, when some go out and buy a new sports car or take up sky diving, Gene took up playing the guitar, a talent he found useful for all those nights sitting around a campfire on field trips. In 1999, he published a book with the help of his daughter Michelle, *Travels with Sophie*, chronicling the experiences of his mother, Louise, while she served as the first supervising teacher of Rusk County, Wisconsin in 1917-1918. Sophie was the name of the Model T Ford his mother used to travel between more than 100 one-room schools in the county at the time. Gene also recently completed a book with George Robinson, curator of the Seaman Mineral Museum at Michigan Technological University, on the minerals in iron ores, *Minerals in the Iron Ores of the Lake Superior Region*.

Gene led an active and productive life that touched and influenced many people through his research, teaching, writing, and public out-reach. He is survived by his wife, Sally, and daughters Michelle, Rene, and Laura and their families. Gene's passing leaves a hole in the fabric of the lives of all who knew him and called him a friend.

Klaus J. Schulz

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 2018, the ILSG Board of Directors selected two students to be granted research funding of \$750.00 each from the Joe Mancuso Student Research Fund. The awardees were:

Jacqueline L. Drazan

University of Minnesota-Duluth, MSc,
Department of Earth and Environmental
Sciences, draza004@d.umn.edu
TOPIC: *Morphological and Geochemical
Comparison between Archean Marine
Peperites (Fivemile Lake, MN) and
Pleistocene Freshwater Peperites
(Sveifluhals, Iceland)*

Thomas Bodden

Michigan Technological University, MSc,
Department of Geological and Mining
Engineering and Sciences, tjbodden@mtu.edu
TOPIC: *Stable isotopic composition of calcite
precipitated with native copper and other
minerals of the Keweenaw Peninsula,
Michigan*

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.

2019 Student Paper Awards Committee

Katarina Bjorkman – Bjorkman Prospecting

George Hudak – Natural Resources Research Institute–UMD

David Good – Western University

Board of Directors

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

Esther Stewart (2018-2021) – Wisconsin Geological & Natural History Survey

Anthony Pace (2017-2020) – Ontario Geological Survey

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

Pete Hollings - Secretary (2016-2019) – Lakehead University

Mark Jirsa – Treasurer (2017-2020) – Minnesota Geological Survey

Session Chairs

Ben Drenth- United States Geological Survey

Dan England – Eveleth Fee Office

Mary Louise Hill - Lakehead University

Amy Radakovich- Minnesota Geological Survey

Nicholas Swanson-Hysell – University of California, Berkeley

Laurel Woodruff – United States Geological Survey

Michael Zieg – Slippery Rock University

Shannon Zurevinski – Lakehead University

Field Trip Leaders and Guidebook Authors

Field trips have been the mainstay of the ILSG since its inception 65 years ago. We want to give a special thanks to the field trip leaders and guidebook authors who volunteered their time and talent in carrying that tradition forward.

1) The Slate Islands

Pete Hollings – Lakehead University
Mark Smyk – Ontario Geological Survey
Bill Addison and Philip Fralick – Lakehead University

2) Midcontinent Rift-related carbonatites and diatremes

Shannon Zurevinski – Lakehead University
Dorothy Campbell and Mark Puumala – Ontario Geological Survey

3) Geology of the western Schreiber-Hemlo greenstone belt

Seamus Magnus – Ontario Geological Survey

4) Geology of the Nipigon area

Philip Fralick – Lakehead University
Robert Cundari – Ontario Geological Survey

5) A stratigraphic transect across the northern flank of the Midcontinent Rift near Rossport

Pete Hollings and Philip Fralick – Lakehead University

6) Geology of the Coldwell alkaline complex

Allan MacTavish – Panoramic PGMs (Canada) Limited
Mark Smyk – Ontario Geological Survey
David Good – Western University
John McBride – Stillwater Canada Inc.

7) Building and ornamental stone sites of the Marathon area, Ontario

Peter Hinz – Ministry of Energy, Northern Development and Mines

8) Geology of the past-producing Winston Lake Cu-Zn Mine

Robert Lodge – University of Wisconsin-Eau Claire
Mark Smyk and Mark Puumala – Ontario Geological Survey

REPORT OF THE 64th ANNUAL MEETING OF THE INSTITUTE ON LAKE SUPERIOR GEOLOGY IRON MOUNTAIN, MICHIGAN

The U.S. Geological Survey with assistance from the Wisconsin Geological and Natural History Survey hosted the 64th Annual Institute on Lake Superior Geology on May 15 – 18, 2018 at the Pine Mountain Resort in Iron Mountain, Michigan. The meeting consisted of two days of technical sessions with pre- and post-technical session field trips. Laurel Woodruff (USGS), Bill Cannon (USGS), and Esther Stewart (WGNHS) were co-chairs for the 2018 meeting. Tom Mroz and Tom Waggoner helped with pre-meeting logistics. Darlene Comfort and Ted Bornhorst (A.E. Seaman Mineral Museum, Michigan Technological University) handled all pre-meeting registration and printing needs. Ted also supplied the poster boards and helped with many aspects of the meeting. Mary Kay Arthur and Dave Wilhelm (Geological Society of Minnesota) provided valuable logistical assistance on-site at Pine Mountain during the technical sessions. Connie Dicken (USGS) was the media czar for the technical sessions, keeping all presentations on track with fewer glitches than normal. Generous contributions to the ILSG general fund and in support of 2018 student travel scholarships came from Lundin Mining, the Geological Society of Minnesota, Ron Seavoy, Mary Kay Arthur, L. Gordon Medaris, Jr., and Steven Baumann. Total meeting registration was 189 (37 students), an excellent turn-out.

Proceedings Volume 64 was published in two parts: Part 1 – Program and Abstracts, edited by Esther Stewart, contains 62 published abstracts for 34 oral and 28 poster presentations; Part 2 – Field Trip Guidebooks, compiled by Bill Cannon, contains descriptions of four field trips, two pre-meeting and two post-meeting.

The 64th ILSG marked the second time in its long history that the annual meeting was held in Iron Mountain. The prior meeting was in 2003. Field trips visited two areas new to the ILSG and two trips that provided new stops in areas of prior trips. On Tuesday, May 15, Bill Cannon, Klaus Schulz, Robert Ayuso, and Tom Mroz led a field trip of 46 people to examine the stratigraphy, structure and economic geology of regional Precambrian rocks in the Felch District, Central Dickinson County, Michigan. Also, on Tuesday, Tom Waggoner was the leader of 37 people for a trip that looked at the Paleoproterozoic Hemlock Formation. Most stops of these two trips were to locations and geology new to ILSG attendees.

On Friday, May 18 Tom Mroz and Bill Cannon shepherded a large crowd of 56 somewhat wandering individuals on a field trip that looked at the geology of the Menominee Iron Range. This trip had little overlap with a trip of a similar title that was given in 2003 as it included a visit to the Archean Carney Lake Gneiss, newly recognized as containing zircons with cores as old as 3.8 Ga, and an underground tour of the Iron Mountain Iron Mine. Another Friday trip led by Klaus Schulz, with a contribution from Marcia Bjørnerud, examined the granitoid rocks of the Pembine-Wausau terrane in northern Wisconsin. In addition to examining granite, the 30 people on that trip had an additional task of keeping Klaus out of jail when he was caught looking at an outcrop along a railroad line.

One hundred and fifteen participants attended the annual ILSG banquet on Wednesday night, cheerfully bringing chairs from the technical session room into the banquet room. After an excellent dessert, everyone moved their chairs back to the technical session room. The 2018 Homer award was given to Pete Hollings for his confidence in the appropriate vehicles one needs to travel around Iceland. Al McTavish, fresh off the success of last year's Iceland trip, despite the Land

Rovers, gave a short promotional presentation for a proposed 2019 trip to another volcanic island, Hawaii.

As always, a highlight of the post-banquet activities was presentation of the 2018 Goldich Medal. This year's very deserving recipient was Val Chandler of the Minnesota Geological Survey (MGS). Val's wife and three adult children were all able to attend the banquet and award ceremony. The Goldich was presented to Val by David Southwick, Director Emeritus of the MGS and his colleague for many years. Dave's citation described Val's many professional contributions to the geophysical mapping and interpretation of Minnesota's mostly hidden geology. Val's long history with the ILSG started with a field trip when he was fresh out of Purdue, which serendipitously led to his distinguished career with the MGS.

This year's banquet speaker was Nancy Langston, a professor in the Department of Social Sciences at Michigan Technological University. Dr. Langston (or Nancy, as we all called her) gave a presentation that drew on her recent book titled *Sustaining Lake Superior: An extraordinary lake in a changing world*. The presentation described past, present, and future environmental challenges to Lake Superior, such as logging, Reserve Mining taconite disposal, and climate change. We all were encouraged by Nancy's final optimism that with responsible stewardship, the largest freshwater lake in the world will endure.

In 2018, the student paper committee had its usual difficult job of selecting the best among 7 excellent oral presentations and 16 excellent poster presentations for the Doug Duskin Student Paper Awards. This year's committee included Robert Cundari (Ontario Geological Survey), Esther Stewart (WGHNS), performing double duty along with her co-chair responsibilities, and Latisha Brengman (University of Minnesota – Duluth). In the end, there was a three-way tie for first place. Poster awards (\$300 each) were awarded to Samuel Hone (Slippery Rock University) for his poster titled: *Olivine crystal size distribution in the Black Sturgeon Sill, Nipigon, Ontario*, and William Fitzpatrick (University of Wisconsin-Eau Claire) for his poster titled: *Mineral chemistries of the Tower Mountain Intrusive Complex Au-deposit, Ontario*. Kira Arnold (Lakehead University) was recognized for her oral presentation titled: *Geology and geochemistry of the Terrace Bay Batholith, N. Ontario* (\$400).

Eisenbrey Student Travel Grants were given to 19 students: Daniel Wilkes, Emily Gerner, Kira Arnold, Vittoria Smith, and Simon Dolega – all from Lakehead University; Schuyler Borages, Erica Craddock, Ryan Leonard, Walter Johnson-Geis, Lily Atkinson, and Juliana Olsen-Valdez, all from Lawrence University; Jacqueline Drazan, Margaret Upton, and Matthew Matko, from the University of Minnesota-Duluth; Victoria Stinson, University of Saskatoon; Dustin Liikane, University of Toronto, Katharine Rose and Kevin Rupp, both from Western Michigan University, and Joseph Rasmussen, University of Wisconsin-Platteville.

The Institute's Board of Directors met on May 16, 2018 and a brief overview of the meeting is provided below:

1. Accepted the Report of the Chair for the 63rd ILSG from Ted Bornhorst and minutes of the last Board meeting from ILSG secretary, Pete Hollings.
2. Accepted the 2017-2018 ILSG Financial Summary from ILSG treasurer, Mark Jirsa.
3. Approved one co-chair from the 64th annual meeting, Esther Stewart, as the on-going board member.

4. Nominated Steve Kissin from Lakehead University to replace Shannon Zurevinski on the Goldich Committee.
5. Approved Terrace Bay, Ontario as the location for the 2019 ILSG annual meeting with co-chairs Pete Hollings and Mark Smyk.

The 64th ILSG meeting was a great success and we wish to thank all the people who contributed to that success. The staff of Pine Mountain was professional and responsive to the needs of a large group – plenty of excellent donuts. The weather was perfect, not too hot, not too cold, not rainy, not buggy. The field trips this year had many participants, and thanks are due to field trip leaders, intrepid bus drivers, those who drove support vehicles on field trips and handled each trip's logistics, as well as everyone else who stepped up when needed. As always, everyone who attended the 64th ILSG was willing to help as necessary and to adapt to any situation that developed. The meeting this year was well attended, and we are heartened by the excellent student participation and attendance, a trend we hope continues.

Your co-chairs are very pleased with the final outcomes of the 64th ILSG. Organizing a meeting and compiling the two Proceeding volumes requires a significant time commitment from the co-chairs and others, and we thank our respective organizations for their recognition of the importance of the ILSG. We also thank the ILSG community and members who make the experiences of the co-chairs almost fun, especially once the meeting is over, and we encourage others to take on the task.

Laurel Woodruff, Bill Cannon, and Esther Stewart
Co-Chairs, 64th Institute on Lake Superior Geology

TECHNICAL PROGRAM

TUESDAY MAY 7, 2019

All field trips begin and end at the Terrace Bay Cultural Centre

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

1) The Slate Islands

Pete Hollings – Lakehead University

2) Midcontinent Rift-related carbonatites and diatremes

Shannon Zurevinski – Lakehead University

3) Geology of the western Schreiber-Hemlo greenstone belt

Seamus Magnus – Ontario Geological Survey

4) Geology of the Nipigon area

Philip Fralick – Lakehead University

4:00 pm - 10:00 pm **Registration** (Terrace Bay Cultural Centre)

7:00 pm - 10:00 pm **Welcoming Reception and Poster Session** (Terrace Bay Cultural Centre)

WEDNESDAY MAY 8, 2019

8:00 am – 11:30 am **Registration** (Terrace Bay Cultural Centre)

8:30 **OPENING REMARKS** (Terrace Bay Cultural Centre)
Pete Hollings and Mark Smyk, Co-Chairs, 2019 ILSG

TECHNICAL SESSION I

Session Chairs:

Shannon Zurevinski – Lakehead University

Michael Zieg – Slippery Rock University

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

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

8:40 **Brigitte Gelinas, +Pete Hollings and Richard Friedman**
Geology and geochemistry of the Laird Lake property and associated gold mineralization, Red Lake greenstone belt, Ontario

9:00 ***Munira Afroz, Philip Fralick, Brian Killingsworth, Martin Homann, Pierre Sansjofre and Stefan Lalonde**
Sulfur, Carbon, and Oxygen Isotope Geochemistry of ~2.93 Ga Mesoarchean Chemical Sedimentary rocks in the Red Lake Area, Ontario

9:20 ***Brittany Ramsay, Philip Fralick, Paul Bielski, Martin Homann, Pierre Sansjofre and Stefan Lalonde**
Mesoarchean chemical sedimentary rocks of northwestern Ontario: Implications for hydrosphere composition in deep time

9:40 **Brad Gottschalk and Caroline Rose**
Recent efforts to curate and provide access to the historical documents of the E.K. Lehmann and Associates Exploration Company

10:00 **COFFEE BREAK**

10:20 **William F. Cannon, Klaus J. Schulz and Benjamin J. Drenth**
The Dickinson Group in the Central Upper Peninsula of Michigan: Part 1- Age and tectonic setting based on new geophysical, geochronological, and geochemical data

- 10:40 **Benjamin J. Drenth, William F. Cannon and Klaus J. Schulz**
*The Dickinson Group in the central Upper Peninsula of Michigan: Part 2-
 Geophysical expression and a preliminary interpretation of its eastward extent under
 Paleozoic cover*
- 11:00 **Ryan Clark, David Peate, Alison Kusick, Kenny Horkley and Raymond Anderson**
*Reexamining the Osborne core for new insights into the age and petrology of the
 Northeast Iowa Intrusive Complex (NEIIC)*
- 11:20 **Wouter Bleeker, Michael Hamilton, Sandra Kamo, Dustin Liikane, Jennifer Smith,
 Pete Hollings, Robert Cundari, Michael Easton and Don Davis**
*High-resolution dating of the magmatic plumbing system of the Midcontinent Rift
 System—Insights into rift evolution and mineralization processes*
- 11:40 **End of Technical Session I**
- 11:40 **LUNCH BREAK – BUFFET PROVIDED**
ILSG BOARD OF DIRECTORS MEETING

TECHNICAL SESSION II

Session Chairs:

Dan England – Eveleth Fee Office

Laurel Woodruff – United States Geological Survey

- 1:00 **Mark Puumala**
*Using graphitic sedimentary rock geochemistry as an indicator of gold potential in the
 Shebandowan greenstone belt, northwestern Ontario*
- 1:20 ***Chanelle Boucher and Pete Hollings**
Geology and geochemistry of ultramafic rocks in the Lake of the Woods area
- 1:40 ***Kira Arnold, Pete Hollings, Seamus Magnus, Shannon Zurevinski and Robert
 Creaser**
Geology and geochemistry of the Terrace Bay Batholith, N. Ontario
- 2:00 **David Holder, Francois Robert and John Hay**
*Geological characteristics and structural controls of Au mineralisation at the
 enigmatic Hemlo deposit*
- 2:20 **COFFEE BREAK**

- 2:40 **Paul A. Bedrosian**
Multi-scale AEM and MT mapping of the Precambrian in Upper Michigan, northern Wisconsin, and eastern Minnesota
- 3:00 **John McBride, David Good, D. Hollis and N. Arndt**
Pilot study: Using ambient noise passive seismic surveys for Ni-Cu-PGE mineral exploration at the Marathon PGM-Cu deposit, Marathon, Ontario
- 3:20 **Dave Good, Pete Hollings and Andrew Jedemann**
Recognizing MCR magmas generated by partial melting in the SCLM: Lessons from mafic magmas in the Coldwell Complex
- 3:40 **Ross Sherlock and Kate Rubingh**
Geologic architecture and precious metal mineralization in the southern Abitibi; new insights from the Larder Lake area
- 4:00 **POSTER VIEWING - AUTHORS WILL BE PRESENT AT THEIR POSTERS**
- 5:00 **END OF TECHNICAL SESSION II**
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- 6:00 **RECEPTION AND CASH BAR** (Terrace Bay Cultural Centre)
- 7:00 **ANNUAL BANQUET** (Terrace Bay Cultural Centre)
- Announcement of 66th Annual Meeting Location
 - **2019 Goldich Award Presentation to Mark Severson**

THURSDAY MAY 9, 2019

8:30 **INTRODUCTORY REMARKS AND UPDATES** (Terrace Bay Cultural Centre)
Pete Hollings and Mark Smyk, Co-Chairs, 2019 ILSG

TECHNICAL SESSION III

Session Chairs:

Mary Louise Hill – Lakehead University

Nicholas Swanson-Hysell – University of California-Berkeley

8:40 **Wouter Bleeker, +Sandra Kamo, Michael Hamilton and K. Chamberlain**
New age data and insights into the ca. 1887-1870 Ma Circum-Superior Belt, with startling implications for the Lake Superior area geology

9:00 **Robert Michael Easton**
*What do detrital zircon studies of the Huronian Supergroup tell us?
an analysis of all published data*

9:20 ***Sophie Kurucz, Philip Fralick, Stefan Lalonde and Martin Homann**
Paleoproterozoic snowball earth? Sedimentology and geochemistry of a Huronian glacial cycle

9:40 **L.G. Medaris Jr., D.H. Malone, G.C. Hill, B.S. Singer, B.R. Jicha, A. Van Lankvelt, M.L. Williams and P.W. Reiners**
The Wolf River Orogeny: Geon 14 magmatism, sedimentation, and deformation in the southern Lake Superior region

10:00 **COFFEE BREAK**

10:20 **Jim Miller**
The importance of “tablesetting” intrusions in creating economic Ni-Cu-PGE deposits in the Midcontinent Rift

10:40 **Robert Nowak, Espree Essig and Robert Mahin**
Geochemical vectoring towards a serpentinitized peridotite chonolith, Eagle East Ni-Cu-Co-PGE deposit, Upper Peninsula, Michigan

11:00 **Jennifer Smith, Wouter Bleeker, Mike Hamilton, and Duane Petts**
An investigation into the distribution of chalcophile elements and timing of mineralization within the Crystal Lake intrusion: A U-Pb geochronology and LA-ICP-MS study

11:20 **Jack Gibbons, Tamara Diedrich and Thomas Quigley**
Petrography of several cobalt-enriched samples from the Atikokan River Intrusions, Atikokan, Ontario

11:40 **End of Technical Session III**

11:40 **LUNCH BREAK – BUFFET PROVIDED**

TECHNICAL SESSION IV

Session Chairs:

Amy Radakovich – Minnesota Geological Survey

Ben Drenth – United States Geological Survey

1:00 **Thomas W. Buchholz, Alexander U. Falster and Wm. B. Simmons**

Updated mineralogy of a roadside pegmatite in the Stettin Complex, Wausau Syenite Complex, Marathon County, Wisconsin

1:20 ***Paul Bielski and Philip Fralick**

LA-ICP-MS micro-sampling of iron formation: what it can tell us

1:40 **Tamara Diedrich and Stephen Day**

Neutralization of proton acidity with sequestration of atmospheric CO₂ during experimental weathering of intrusive rocks from the Midcontinent Rift System

2:00 **Carson G. Prichard, +James J. Student, Jory L. Jonas, Nicole M. Watson and Kevin M. Pangle**

Catchment geology correlation with fish otolith microchemistry across disparate glacial till depths in the Lake Michigan basin

2:20 **COFFEE BREAK**

2:40 **J.M. DeGraff, C.W. Tyrell, G.E. Hubbell and B.T. Carter**

Keweenaw Fault system along Bête Grise Bay, Michigan: geometry, kinematics, and tectonic significance

3:00 **Esther K. Stewart, V.J.S. Grauch, Laurel G. Woodruff and Samuel Heller**

Seismic stratigraphy of the 1.1 Ga Midcontinent Rift beneath western Lake Superior shows evidence of differing subsidence histories for syn-magmatic sub-basins

3:20 **V.J.S Grauch, Esther K. Stewart, Laurel G. Woodruff and Samuel Heller**

Evaluating Alternate Geophysical Models along the Isle Royale-Superior Shoal Aeromagnetic Anomaly, Central Lake Superior

3:40 **Nicholas L. Swanson-Hysell**

Insights into Midcontinent Rift development resulting from a strengthened chronostratigraphic framework

4:20 **BEST STUDENT PAPER AWARDS**
STUDENT TRAVEL AWARDS
CLOSING REMARKS

4:40 **END OF TECHNICAL SESSIONS**

FRIDAY MAY 10, 2019

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

Field trips 5 to 8 begin and end at the Terrace Bay Cultural Centre

5) A stratigraphic transect across the northern flank of the Midcontinent Rift near Rossport

Pete Hollings – Lakehead University

6) Geology of the Coldwell alkaline complex

Allan MacTavish – Panoramic PGMs (Canada) Limited

David Good – Western University

7) Building and ornamental stone sites of the Marathon Area, Ontario

Peter Hinz – Ministry of Energy, Northern Development and Mines

8) Geology of the past-producing Winston Lake Cu-Zn Mine

Mark Puumala and Mark Smyk – Ontario Geological Survey

POSTER PRESENTATIONS

***Thomas J. Bodden, Theodore J. Bornhorst, Florence Begue and Chad Deering**

Stable isotopic composition of calcite precipitated with native copper and other minerals of the Keweenaw Peninsula, Michigan

Terrence J. Boerboom

Recognition of probable distal ejecta from the 1850 Ma Sudbury meteorite impact event along the southern edge of the Animikie basin in Minnesota

J.M. DeGraff and I.S. DeGraff

Southwest Margin of the Midcontinent Rift System in Eastern Lake Superior: Review and Preliminary Interpretation

***Jacqueline L. Drazan, George Hudak and Howard Mooers**

Morphology, mineralogy, texture, and genesis of peperite, Fivemile Lake, Vermilion District, Minnesota: Comparison with Pleistocene peperite, Iceland

Benjamin J. Drenth, William F. Cannon and Klaus J. Schulz

High-resolution aeromagnetic survey, central Upper Peninsula, Michigan

Don Elsenheimer, Cari Deyell-Wurst and Lionel C. Fonteneau

Hyperspectral Imaging of Bedrock Core from the Minnesota DNR Drill Core Library: A New Tool for Archival Preservation and Mineral Exploration

V.J.S. Grauch and K.J. Schulz

Superior Shoal revisited: Evidence for Keweenawan basalts with reversed- and normal-polarity remanent magnetization and early magma chemistry, central Lake Superior

Linnea L. Johnson, David H. Malone and John P. Craddock

Detrital Zircon Geochronology of Keweenaw Interflow Sediments within the North Shore Volcanic Group, Minnesota, U.S.A.

Seamus Magnus

Precambrian Geology of the Western Schreiber–Hemlo Greenstone Belt

Amy Radakovich, Val Chandler and Mark Jirsa

Wawa, undercover: Bedrock geologic and bedrock topographic mapping in north-central Minnesota

Laura Ratcliffe

Precambrian Geology of the Eastern Shebandowan Greenstone Belt - Insights into Stratigraphy and Structural History

Christian Schardt and Mady David

High-technology metals in ore-forming environments and their signature in volcanic-hosted sulfide mineralization in northern Minnesota and Wisconsin

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

Geochemistry of Archean Gneisses in Dickinson County, Northern Michigan

Clarence Surette and Jill Taylor-Hollings

Towards understanding geoarchaeological contexts in Northwestern Ontario: The newly formed lithic material comparative collection at Lakehead University

Nicholas L. Swanson-Hysell, Sonia M. Tikoo and L.M. Fairchild

New paleomagnetic constraints on the formation of the Slate Islands impact structure

Nicholas L. Swanson-Hysell, Sarah P. Slotznick and L.M. Fairchild

An oxygenated Paleolake Nonesuch and primary detrital hematite in the Freda river system

Shiwei Wang, Pete Hollings and Ben Kuzmich

Petrological and geochemical characteristics of the granitic rocks from the Dog Lake Granite Chain: Implications for the genesis of Quetico Basin

Laurel G. Woodruff, Suzanne W. Nicholson, Connie L. Dicken and Klaus J. Schulz

Mineral deposits of the Midcontinent Rift System - A new space/time classification

***Jackie Wrage, Adrian Fiege, Brian Konecke, Adam Simon, Philipp Ruprecht and Harald Behrens**

Sulfur mobility in arc magma systems: Implications for porphyry ore deposits

Michael J. Zieg

Multiscale Layering in the Black Sturgeon Sill, Nipigon, Ontario

* 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

Sulfur, Carbon, and Oxygen Isotope Geochemistry of ~2.93 Ga Mesoarchean Chemical Sedimentary rocks in the Red Lake Area, Ontario

AFROZ, Munira¹, FRALICK, Philip¹, KILLINGSWORTH, Bryan^{2,3}, HOMANN, Martin³
SANSJOFRE, Pierre³ and LALONDE, Stefan³

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

²Institut de Physique du Globe de Paris, 1 Rue Jussieu, Paris, France. ³European Institute for Marine Studies, CNRS-UMR6538 Laboratoire Géosciences Océan, Technopôle Brest-Iroise, Plouzané, France.

Isotope geochemistry provides important insight into ancient marine carbon and sulfur sources and their role in evolving biologic activity. This research studied ~2.93Ga Mesoarchean chemical sedimentary rocks and carbonaceous slate directly underlying the Red Lake carbonate platform to explore these interactions through the analysis of sulfur, carbon and oxygen isotopes.

Core samples of sulfidic iron formation, black slate, and carbonate rocks from 11 drill holes through the carbonate platform were analyzed using mass spectrometry. Multiple isotopes of sulfur (i.e. $\delta^{32}\text{S}$, $\delta^{33}\text{S}$, $\delta^{34}\text{S}$, and $\delta^{36}\text{S}$) were measured from sulfidic iron formation samples, while $\delta^{13}\text{C}$ was examined from carbonaceous slate and $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ from inorganic carbonates.

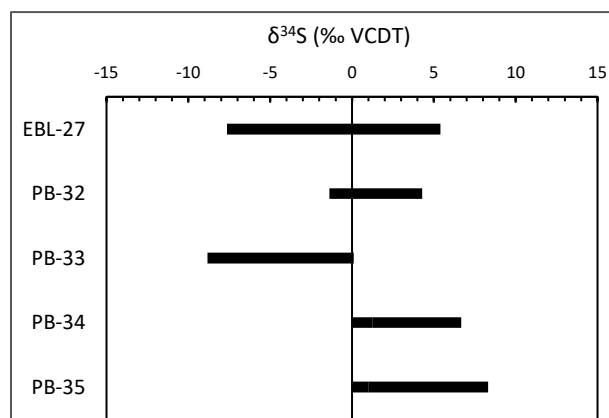


Figure 1: $\delta^{34}\text{S}$ plot of samples from different drill-holes.

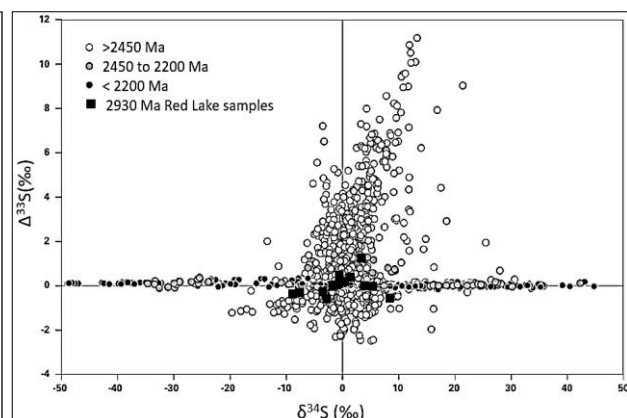


Figure 2: $\delta^{34}\text{S}$ vs. $\Delta^{33}\text{S}$ plot of Red Lake samples with additional literature data (After Johnston, 2011)

The analysis showed that sulfur in pyrite was derived from multiple sources as evident from the $\delta^{34}\text{S}$ values in Fig. 1. Near zero values of $\delta^{34}\text{S}$ indicate sulfur leached from primary sources due to high-temperature hydrothermal fluids (Thode et al., 1961), whereas $\delta^{34}\text{S}$ values of $>5\text{‰}$ indicate that some of the sulfur was derived from Archean seawater (Ono et al., 2003). Finally, the lower negative values are indicative of bacterial sulfate reduction in sediments (Seal, 2006). In addition, the $\delta^{34}\text{S}$ vs. $\Delta^{33}\text{S}$ plot (Fig. 2) reveals that mass-independent fractionation of sulfur (diagonal array of samples) as well as microbial processing of sulfur (horizontal trend of samples) was active in the Mesoarchean sulfidic iron formation (Ono et al., 2003). The organic $\delta^{13}\text{C}$ isotope plot (Fig. 3) has lighter $\delta^{13}\text{C}$ values ($\sim -30\text{‰}$) near the bottom of the stratigraphy while heavier $\delta^{13}\text{C}$ values ($\sim -17\text{‰}$) are exhibited towards the carbonate platform. This trend, especially less fractionated values of C, indicates that purple sulfur bacteria might be present in the shallow water carbonate platform along with cyanobacteria as these bacteria fractionate carbon isotopes differently (Posth et al., 2017). Furthermore, the dolostone samples have lighter $\delta^{18}\text{O}$ isotope values (Fig. 4) which suggests dolomitization was not confined to the marine

environment, instead, it was influenced by fresh water that produces lighter isotopic signatures (Wright and Tucker, 1990).

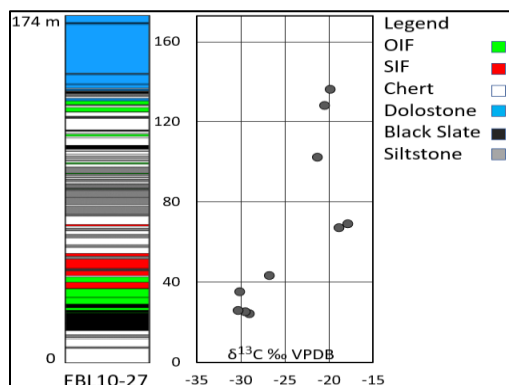


Figure 3: $\delta^{13}\text{C}$ plot with stratigraphy

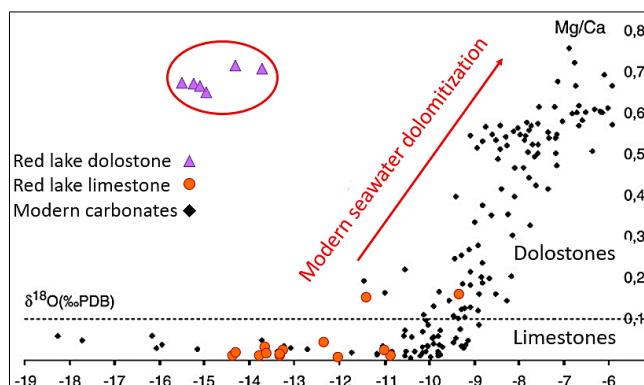


Figure 4: Mg/Ca vs. $\delta^{18}\text{O}$ plot of carbonates (After Jaffrés et al., 2007)

Based on the results, it is concluded that the source of sulfur was varied in the sediments below the Red Lake carbonate platform and was fractionated by both mass-dependent and mass-independent processes. The $\delta^{13}\text{C}$ trend of organic carbon hints that different bacterial communities were living on the carbonate platform. The $\delta^{18}\text{O}$ signature indicates that dolostones were precipitated from a mixed water environment.

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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, part of the larger Wawa-Abitibi terrane (Fig. 1). The pluton, emplaced at 2689 ± 1.1 Ma (Kamo 2016) intrudes *circa* 2720 Ma metavolcanic rocks, and a nearby pluton of equivalent age intrudes *circa* 2698-2693 Ma clastic metasedimentary rocks (Kamo 2016; Davis and Sutcliffe 2017). Younger plutonism in the region occurred between 2673 and 2667 Ma (Kamo 2016; Kamo and Hamilton 2017). The purpose of this study was to classify the Terrace Bay Batholith petrographically and geochemically in order to investigate the petrogenesis and tectonic setting in which the pluton formed, and to characterize the gold and base metal mineralization associated with the intrusion.

Detailed mapping showed that the pluton can be separated into three mineralogically distinct lithologies (Fig. 1): granodiorite (typically composed of medium to coarse quartz and feldspar phenocrysts in a groundmass of fine-grained amphibole, biotite, disseminated magnetite, and sulphide minerals), monzogranite (composed of medium-grained quartz and feldspar with increased amounts of potassium feldspar and amphibole relative to the granodiorite), and diorite (composed of medium-grained amphibole and plagioclase with little to no quartz or potassium feldspar present). Two types of hydrothermal alteration are present: chlorite-epidote alteration and a pervasive hematite alteration. The faults and shears in the pluton likely acted as pathways for the hydrothermal fluids.

Geochemically, the pluton is a homogenous calc-alkaline pluton, with minimal variation between lithologies. The pluton exhibits trace element signatures that are characteristic of supra-subduction zone magmas, including: fractionated heavy rare earth elements, negative high field strength element anomalies, enrichment of Th over light rare earth elements and enrichment of light rare earth elements. The fractionated heavy rare earth elements and the Th-Nb-La systematics are consistent with formation in a subduction zone at depths where garnet is stable. The Sr/Y and La/Yb signatures support formation within the garnet stability field and suggest small amounts of slab-derived melt were incorporated into the mantle wedge. The ϵ_{Nd} values ranging from +2.16 to +2.49 suggest that the pluton underwent minimal crustal contamination during melting and emplacement.

The emplacement of the pluton was determined to be through multiple injections derived from a single source. Prolonged fractional crystallization may have resulted in the formation of subtle mineralogical variation but no geochemical differences.

Molybdenum mineralization in the pluton is spatially associated with gold mineralization, which suggests it was deposited during the same hydrothermal event. Gold and molybdenum mineralization is generally disseminated throughout the pluton at low concentrations, with higher concentrations of the metals hosted in sulphide mineralized quartz veins. Rhenium-Osmium isotopes from samples of molybdenum from these sulphide-mineralized quartz veins yielded an age of 2671 ± 12 Ma, as well as postdating the emplacement of the pluton. Candela (1991) suggests that in plutons emplaced at greater depths, aqueous phases will remain dispersed

throughout the magma, resulting in disseminated mineralization such as that in the Terrace Bay pluton.

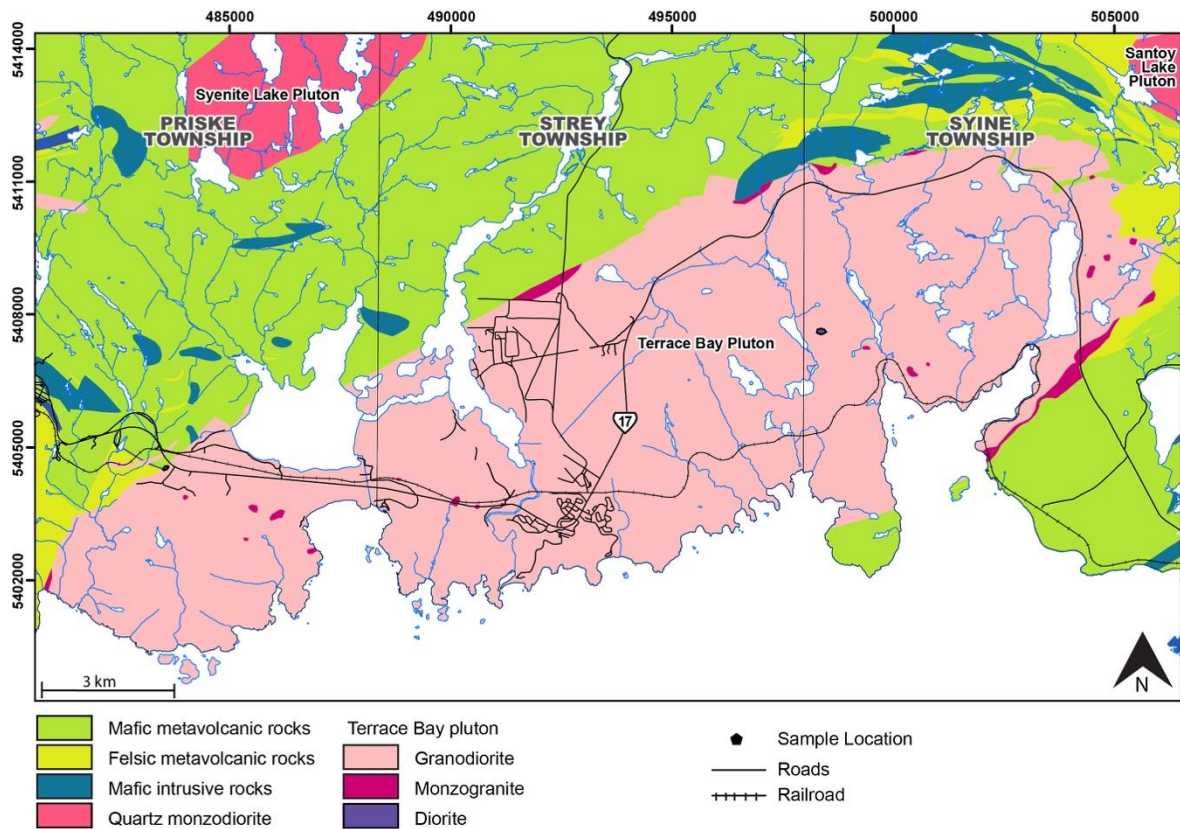


Figure 1. Simplified bedrock geology map of the Terrace Bay batholith and surrounding greenstone belt in Priske, Strey and Syine townships. Modified from Arnold et al. (2017).

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Multi-scale AEM and MT mapping of the Precambrian in Upper Michigan, Northern Wisconsin, and Eastern Minnesota

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The U.S. Geological Survey is conducting airborne electromagnetic (AEM) and magnetotelluric (MT) surveys over parts of Minnesota, Upper Michigan, and Wisconsin to map Precambrian geology and inform mineral resource assessments in this complex region. A total of 2,700 line-km of AEM data were collected along 16 regional transects over an area of 75,000 km². These transects range from 100 to 300 km in length and cross numerous structural boundaries and more than 2 billion years of geology. An additional 100+ MT stations have been collected along some of these transects to refine regional resistivity models (Bedrosian, 2016) based on broadly-spaced EarthScope MT stations (Fig. 1).

Pronounced contrasts in electrical resistivity exist between conductive sedimentary/metasedimentary rocks and resistive volcanic/intrusive rocks. Archean rocks of the Superior and Minnesota River Valley provinces are imaged as monolithic resistors (Figure 2), whereas strong conductors are linked to metamorphic graphite and metallic sulfides within Paleoproterozoic (PP) rocks of the Penokean orogen (most notably the Michigamme Formation). These conductors are evident in regional-scale resistivity models (Fig. 1b) and extend well into the lower-crust beneath the Penokean orogen (Bedrosian, 2016). Their upper-crustal geometry is being refined by ongoing MT investigations, while in the near-surface, AEM models image narrow (100s of meters wide) sub-vertical conductors (Fig. 2) extending for tens of kms along mapped or inferred faults and shear zones. Laboratory measurements on core samples confirm the presence of graphite in several of these conductive zones. Additional conductors mapped by the AEM data are preferentially located along the periphery of Archean gneiss domes in the region, suggesting that either the oldest PP units are anomalously conductive, and/or that locally-enhanced metamorphic grade is required to form conductive minerals. MT and AEM models of conductive PP rocks further constrain and refine structural details, such as a southern dip on the Niagara fault and a northward extension of PP rocks beneath younger rocks as far north as the Keweenaw fault.

Within rocks of the Mesoproterozoic Midcontinent Rift System (MRS), the primary electrical contrast is between resistive volcanic and intrusive rift rocks and the conductive sedimentary successions of the Oronto Group, the Bayfield Group, and the Jacobsville Sandstone. East of the Keweenaw Peninsula, a thick succession of the latter exhibits a similar resistivity signature to that of the Freda Formation on the other side of the peninsula. Relative to lab measurements on these rocks, conductivity in the AEM models for both Freda and Jacobsville is elevated, possibly indicating elevated salinity in the pore waters of these Precambrian aquifers. Together with well control, the AEM models refine structure in several locations, including recognition of the Bayfield Group as more spatially limited than previously recognized and models that suggest the concealed edge of the MRS crosses the central U.P. along a linear magnetic boundary (near 46°15'N, 86°30'W).

Imaged younger features include paleochannels cut into Precambrian sediments beneath Lake Superior (Fig. 2), an eastward-thickening wedge of Paleozoic cover in the Eastern survey area (the Northwestern edge of the Michigan basin), and a veneer of glacial sediments, the variable thickness of which can be mapped along each of the AEM profiles. The latter presents modeling

challenges, currently under investigation, due to strong induced-polarization effects in clay-rich glacial tills.

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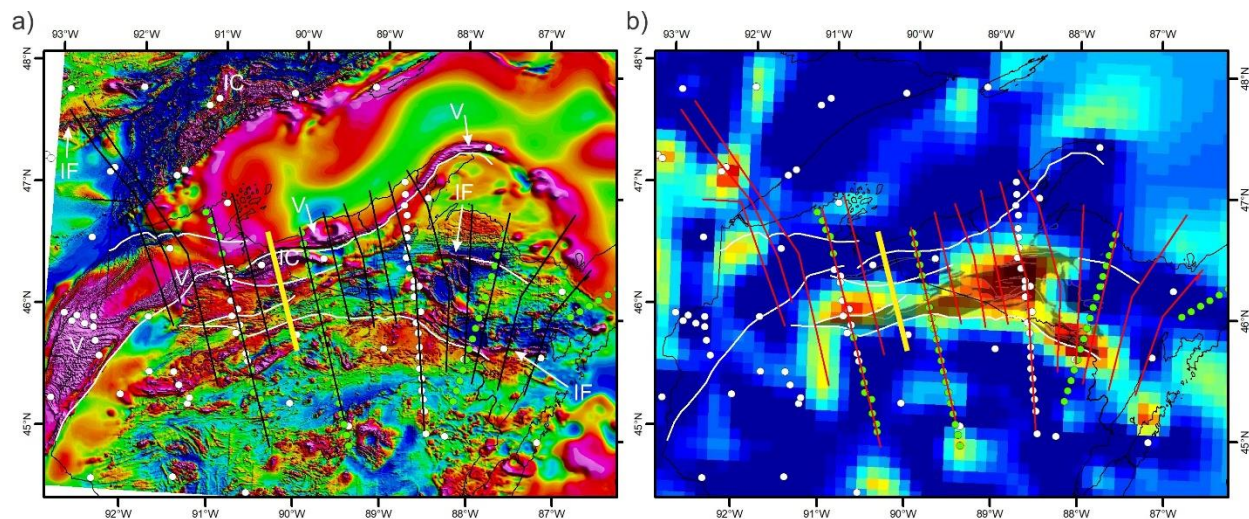


Figure 1: (a) AEM flight lines (black) and MT stations (white and green circles) atop magnetic anomaly map. Magnetic highs (red) are primarily due to thick volcanic successions (V), iron formations (IF) and intrusive complexes (IC). (b) Regional electrical resistivity model at 5 km depth. Conductors (red) correlate with PP metasedimentary rocks (shaded). White lines denote regional faults; yellow line indicates profile shown in Figure 2.

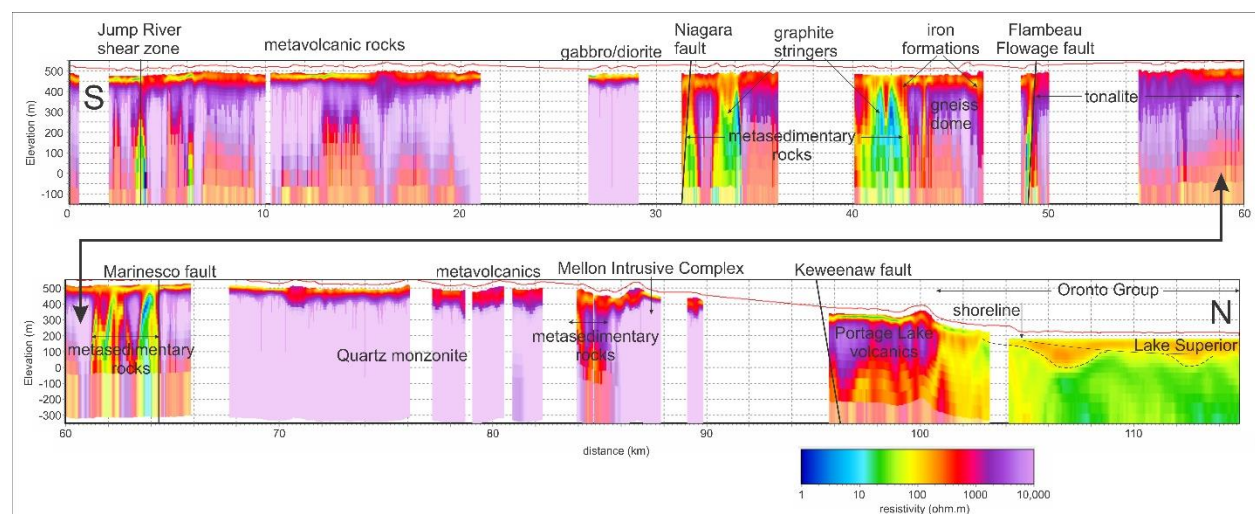


Figure 2: Interpreted resistivity cross-section derived from AEM data. Profile location highlighted in Figure 1. Vertical exaggeration 10:1.

LA-ICP-MS Micro-Sampling of Iron Formation: What it Can Tell Us

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The occurrence of iron formation during the Archean is well documented, however the mechanisms of their genesis are poorly understood within shallow waters and even less so within the deep-ocean. At the same time our understanding of Archean deep-ocean chemistry is also limited and poorly constrained. To address these issues, a new method for analysis of sulphide facies iron formation geochemistry is being conducted. This method involves a geochemical analysis of deep-ocean iron formation facies at a sub-lamination scale with attention to possible indicators of deposition rate and changes in water chemistry due to mixing of ambient seawater with a hydrothermal plume. Thus, changes in water chemistry during individual cycles of deposition can be measured. This method is conducted using Laser Ablation Inductively Coupled Mass Spectrometry (LA-ICP-MS) alongside Scanning X-Ray Fluorescence (XRF). To test this new application of small scale geochemical analysis, an investigation of the Morley Occurrence was conducted.

The Morley Occurrence is a deep-water Neoarchean (~2.7 Ga) sulphide-facies iron formation sitting upon intermediate flows and pyroclastic rocks and overlain by mafic flows and minor turbidites (Fralick et al., 1989). The occurrence itself is about 3 km south-east of Schrieber, Ontario. What makes this site interesting for this application is that oxides replace pyrite at the top of some thin colloform laminations (Fig. 1). These colloform structures are composed of sub-millimeter to millimeter thick pyrite laminations with increasing chert, carbon, and detrital minerals toward their tops. Applying LA-ICP-MS to these pyrite laminations at a sub-laminae level has provided information on geochemical changes of the depositional waters (Fig. 2) in addition to being proof of concept for this application to be used on other facies of iron formation. Laser ablation data (Fig. 2) shows a decrease in Ti upwards through pyrite laminations while Zr increases before resetting at each new lamination. Comparison with data on other hydrothermally sourced metals, such as Ni, Mn, Zn, and Pb, indicates that Ti is of hydrothermal origin while Zr is unrelated to venting fluids. This agrees with the pattern generated when plotting the series of laser ablation shots against Ti and Zr. The source of Zr could be thought to be from detrital origin, however the Zr concentrations are quite low for detrital sediments (Fig. 2). In addition, Zr has a positive relation to Y, Hf, U, and Th (high-field strength elements) along with samples having variable Zr/Hf ratios comfortably below and occasionally significantly above both chondrite and continental values which points to possible preferential scavenging of Hf from seawater by non-detrital sediment leading to fractionation between the two (Bau and Alexander, 2009). This explanation agrees with the data: a resetting Zr value at the beginning of each new pyrite lamination which increases with an assumed decrease in deposition rate with the general rate of deposition based off of chert and detrital sediments increasing upwards.

The LA-ICP-MS data from the Morley Occurrence indicates that hydrothermal influence decreased upwards through each laminae, while seawater influence increased upward. A decreasing deposition rate upward through a laminae resulted in increased scavenging time for elements such as Zr and possibly increased concentration of rainout detritus containing Zr.

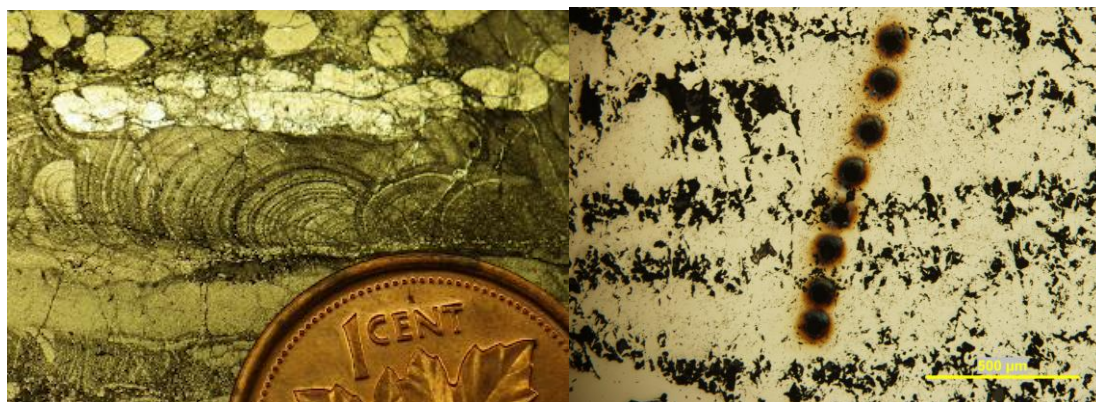


Figure 1. Left: A photomicrograph of colloform laminations. Right: An example of LA-ICP-MS shots through colloform laminations (Yellow scale bar is 500 um).

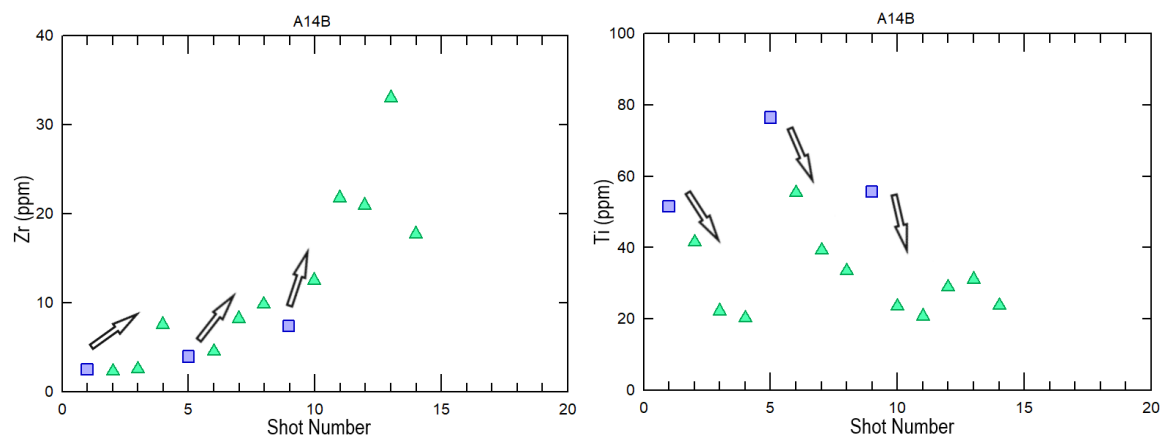


Figure 2. Plots of LA-ICP-MS Ti and Zr data taken through a set of colloform laminations. Square points represent where each of the three new pyrite laminations begin.

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High-resolution dating of the magmatic plumbing system of the Midcontinent Rift System—Insights into rift evolution and mineralization processes

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North America's Midcontinent Rift System is one of the best preserved and most accessible Proterozoic failed intra-cratonic rifts in the world, and therefore a pre-eminent natural laboratory for understanding the evolution of complex rift systems in cratonic settings, what generates them, what makes them fail, and the myriad of processes associated with their magmatic, sedimentary, and structural evolution.

A key dataset that is fundamental to any deeper understanding of this rift system, including its endowment of mineralization, consists of precise and accurate ages on all the different components that make up this rift system. Already, there is a rich literature on dating (mostly U-Pb) of the rift system (see Bleeker, 2018, for a recent summary). Much recent progress has focused on improving the age resolution of volcanic rocks that fill the rift, in conjunction with detailed paleomagnetic investigations, to resolve in more detail the rapidly evolving apparent polar wander path (e.g., Fairchild et al., 2017). Nevertheless, many key components of the rift system, including a wide variety of intrusions that are part of the complex plumbing system of the rift, remain undated or have ages that require refinement, or have dates that are clearly puzzling outliers in the evolving temporal framework of U-Pb ages. Some of the published ages were obtained on limited amounts of small baddeleyite crystals and suffer from associated complications (Pb loss and variable discordance, elevated common Pb and associated corrections, ambiguity in choice of regression line and upper intercept, subtly different systematics between baddeleyite and zircon, etc.). In some cases, there exists doubt on the exact provenance or sample location of dated samples.

Our aim is to revisit many, if not all, of the intrusions, and particularly those associated with mineralization, to improve and complete the U-Pb age framework, ideally at ~1 Myr resolution; and to link the intrusive record to the better resolved volcanic record as well as the overall tectono-magmatic evolution of the rift. Initially we have focused on some of the “outliers” such as the Inspiration Sill (Nipigon area, with a published age of 1159 ± 33 Ma), or the iconic Logan Sills overlooking Thunder Bay (Fig. 1), with an age interpretation of 1114.7 ± 1.1 Ma based on limited and discordant baddeleyites (Heaman et al., 2007). These problems can be tackled by searching for more optimum samples in the field, and applying ever improving U-Pb analytical techniques (lower blanks, new and better calibrated spike solutions, chemical abrasion of zircons, etc.). Searching for zircon-bearing samples is the key for ultra-high precision ages.

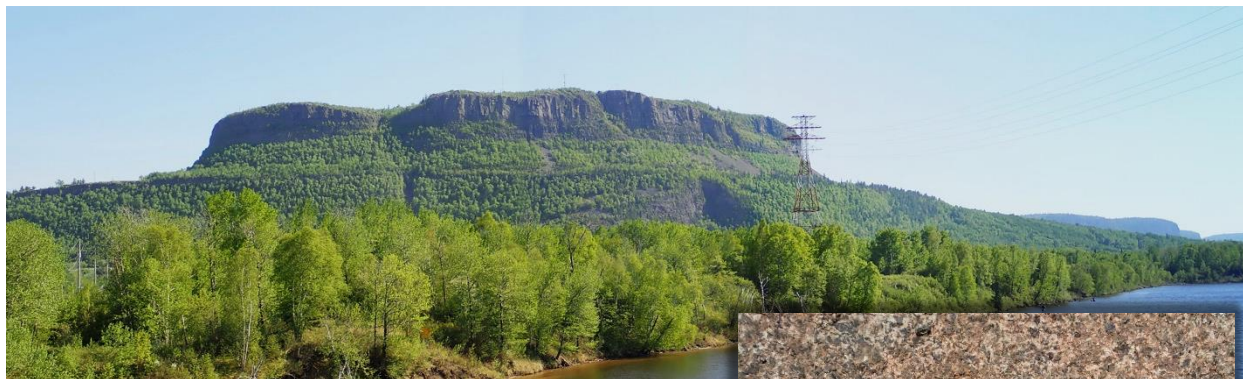


Figure 1: Above: the iconic Logan Sills (s.s.) overlooking the Kaministiquia River and the city of Thunder Bay. Two sills are visible, having intruded the mudstones and thinly bedded turbiditic sedimentary rocks of the ca. 1.85 Ga Rove Formation, Animikie Basin; an upper main sill capping the mesas, and a thin lower sill forming a minor ledge in the trees. Right: our optimum sample of evolved, late-stage, vari-textured and in part pegmatitic gabbro from near the top of the main upper sill, at Mount McKay.



Figure 2: Left: Cross-cutting relationship of younger NNE-trending Pigeon River dyke cutting across, and chilled against, older coarse-grained and sparsely porphyritic diabase of one of the main Cloud River dykes. New age data are available for both the Pigeon River and Cloud River dykes.

Together with searching for more optimum samples in the field, or in drill core, a key aspect of our study also involves resolving cross-cutting relationships in the field, where they exist, to help guide overall interpretation (Fig. 2).

Already we have new and more robust age data on ~10 key units, including previously undated mineralized intrusions, which will be discussed at the meeting. Among those are: the Inspiration Sill, the main Logan Sill (Fig. 1), Pigeon River dykes, Cloud River dyke, Sunday Lake and Current Lake intrusions, Crystal Lake intrusion, Mount. Mollie dyke, Bovine Igneous Complex, and several others.

Acknowledgements: we thank numerous industry partners and colleagues at the USGS for their keen interest in this study, their scientific input, and their generous cooperation.

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New age data and insights into the ca. 1887-1870 Ma Circum-Superior Belt, with startling implications for the Lake Superior area geology

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Introduction: The ca. 1887-1870 Ma Circum-Superior Belt (Baragar and Scoates, 1981) has long been recognized as one of Canada's major metallogenic belts, principally because of its world-class Ni-Cu-PGE deposits at Thompson and Raglan, as well as a number of other significant prospects elsewhere along the belt (e.g., Labrador Trough). Discontinuous outcrop along the margin of the Superior craton, remoteness, and the great extent of the belt has hampered detailed correlations between different segments. Although first-order correlations were suspected, and included volcanic rock in the Lake Superior area, U-Pb geochronology has only recently advanced to a point where we can demonstrate that peak mafic-ultramafic magmatism was coeval between localities such as Thompson and Raglan, with large volumes of Mg-rich ultramafic rocks being emplaced at 1882 Ma, both as flows, sills, and feeder dykes. Similar age mafic-ultramafic magmatism is now known from around the Superior craton, from northern Quebec to Minnesota, while ca. 1882 Ma dyke swarms intrude far into the cratonic hinterland. Carbonatites and kimberlites are coeval, within age uncertainty, with the mafic-ultramafic magmatism or precede peak magmatism by a few million years, an age pattern also seen in other large igneous provinces (e.g., Bushveld Complex and slightly earlier carbonatites, Phalaborwa). A model that best explains the present observations is that of a mantle plume impinging on the base of thick cratonic lithosphere of supercraton Superia (Bleeker, 2003), with hot, low-viscosity, plume mantle then flowing laterally into multiple thin spots and incipient rifts, localized along the present margins of the Superior cratonic fragment, where large-scale and nearly synchronous decompression melting ensued at 1882±1 Ma (Fig. 1; see Bleeker and Kamo, 2018; and references therein).

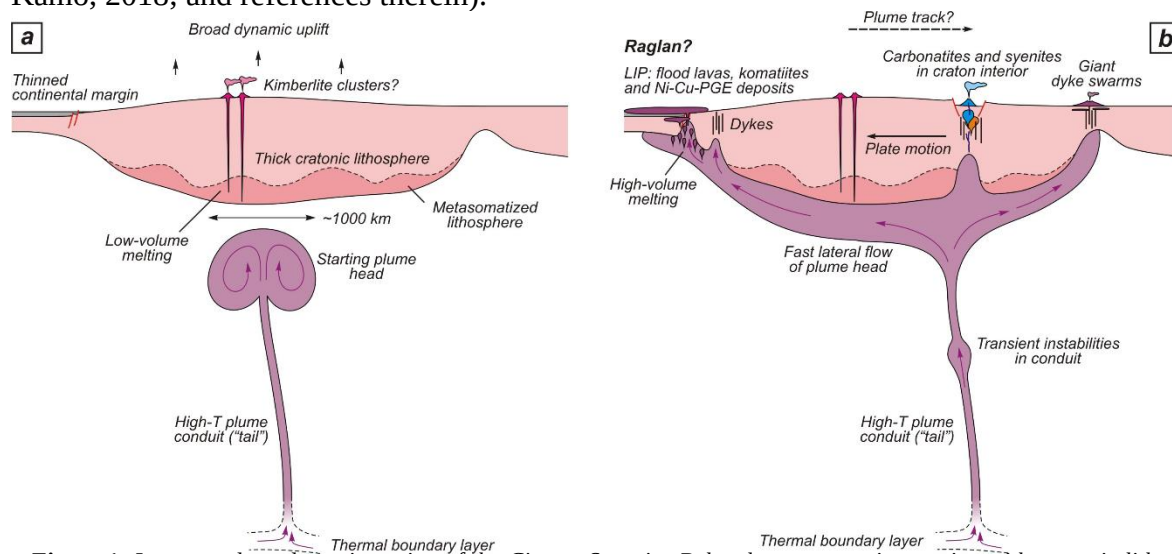


Figure 1: Interpreted geodynamic setting of the Circum-Superior Belt: plume ascent, interaction with cratonic lithosphere, and continental breakup. a) Ascending mantle plume impinging on thick lithosphere of the ancestral Superior craton, i.e. supercraton Superia. b) Flattening and rapid lateral flow of hot, buoyant plume mantle to thin spots, leading to nearly synchronous large-volume mafic-ultramafic magmatism (after Bleeker and Kamo, 2018).

Continental breakup: The emerging picture, with nearly synchronous mafic-ultramafic magmatism around what are now the margins of the Superior craton, clearly indicates a geological setting of continental breakup rather than that of accreting arcs at 1882 Ma. It is thus important to think about the Superior craton, and the geology of the Lake Superior area, in the context of progressive continental breakup. There is growing evidence that the Kaapvaal craton of South Africa, and thus also supercraton Vaalbara, was attached to the southwestern corner of the Superior craton (Bleeker et al., 2016; see also Gumsley et al., 2017), as part of an ancient terrane (also comprising much of Wyoming craton and Karelia) that collided with the growing Superia landmass at ca. 2650 Ma, and remained there until the ca. 1880 Ma breakup event introduced above. Indeed there are ca. 1880 Ma dykes in the eastern Kaapvaal craton. Furthermore, the proposed reconstruction is paleomagnetically viable. On final breakup, the Minnesota River Valley terrane, a piece of the ancient crust of the eastern Kaapvaal craton, was left stranded as an exotic terrane on the southern breakup margin of the Superior craton (Bleeker et al., 2016).

Predictions: The startling conclusion must be that Kaapvaal craton, indeed entire Vaalbara, Wyoming and Karelia, were contiguous with the southern Superior craton from ca. 2650 Ma until progressive breakup from ca. 2000 Ma to 1880 Ma, within the context of supercraton Superia. Indeed dykes of exact Bushveld age (2056 Ma) have been identified in the Western Superior craton (Bleeker et al., 2016), and 2167 Ma Biscotasing dykes have been identified in the eastern Kaapvaal craton (with matching trend!), two independent and exact age matches of short-lived mafic magmatic events that demonstrate, without any doubt, a “nearest neighbour” relationship (Bleeker and Ernst, 2006) of these cratonic fragments over this time interval. This leads to another startling prediction: a potential plume track that starts with the LIP-scale Marathon magmatic event in the eastern Lake Superior area, at ca. 2130 Ma, can be traced to the southwest, with pulsed 2125–2100 Ma mafic magmatism along the southern margin of the Superior craton; it then was responsible for the Fort Frances giant mafic dyke swarm at ca. 2070 Ma; it can then be traced into the easternmost Kaapvaal craton where it is first manifested by the 2060 Ma Phalaborwa and related carbonatites; and, finally, further west, it eroded the lithosphere and produced Earth’s largest layered mafic intrusion at 2056 Ma, the Bushveld Complex.

In conclusion: two of the best-known Archean cratons in the world, Superior and Kaapvaal, shared a common history from ca. 2650 Ma terrane collision until ca. 1880 Ma breakup. On breakup, a piece of ancient Kaapvaal crust, Minnesota River Valley terrane, was left behind. Kaapvaal and Superior were joined and contiguous all through the lead-up to the Bushveld Complex, and the magmatism that culminated with the Bushveld Complex started with the ca. 2130 Ma Marathon event, tracing a continuous plume track from the southern Superior craton into the Kaapvaal craton.

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Stable isotopic composition of calcite precipitated with native copper and other minerals of the Keweenaw Peninsula, Michigan

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Hydrothermal native copper deposits are hosted by Midcontinent Rift-filling volcanic and sedimentary rocks in Michigan's Keweenaw Peninsula. Butler and Burbank's (1929) classic U.S.G.S. Professional Paper documented the district-wide paragenesis of hydrothermal mineral precipitation and the relative age of minerals with respect to the precipitation of native copper, the principal ore mineral. Puschner (2002) subdivided hydrothermal mineral paragenesis into three Stages: Stage 1 (pre-native copper), Stage 2 (syn-native copper), and Stage 3 (post-native copper). Since Stage 1 and 2 minerals represent a single continuous episode of mineral deposition, they will be combined for data presentation below. Stage 3 is a distinct later episode (veins that cross-cut native copper deposits) and thus, will be considered separately. Stages 1-2 formed at a significantly higher temperature than Stage 3 based on mineral equilibria, stable isotope pairs, chlorite geothermometry, and fluid inclusions (Puschner, 2002; Livnat, 1983). In addition to temporal (paragenetic) variation of mineral precipitation within the native copper district, both within the district and the broader Keweenaw Peninsula, there is spatial variation in the suite of minerals in a particular locality (Stoiber and Davidson, 1959). The spatial mineral variation corresponds to a regular variation in the temperature of precipitation of minerals from the hydrothermal fluids.

This research is an extension of Bornhorst and Woodruff (1997) who proposed fluid-mixing was an important mechanism facilitating native copper precipitation on the basis of the variability of stable isotope data derived from Stage 1-2 calcite from the Kearsarge deposit; the largest basalt-hosted deposit in the district. Calcite is good to study the evolution of the hydrothermal fluids as it precipitates in all three stages and with native copper in Stage 2. The purpose of this study was to test the hypothesis of fluid-mixing proposed by Bornhorst and Woodruff (1997) using a geographically broader data set as well as using secondary ion mass spectrometry (SIMS) to obtain in-situ stable isotope values for calcite.

We have compiled 159 published oxygen-carbon stable isotope pairs for calcite from Livnat (1983; 88 pairs), Puschner (2002; 31 pairs), and Bornhorst and Woodruff (1997; 40 pairs) determined by traditional bulk mineral analysis. We have added an additional 101 pairs determined by SIMS on selected spots from three samples. Each of the pairs have been grouped according to paragenetic Stage when possible based on sample description, geographic location, and textural observation from cathodoluminescence imaging; those not able to be grouped are not included in the discussion below. Puschner's (2002) data was only obtained for Stage 1-2 calcite, as was the case for Bornhorst and Woodruff (1997) with the exception of one Stage 3 calcite. The new SIMS data are from: Stage 1-2 calcite from the Quincy deposit, Stage 2 calcite and Stage 3 calcite from the Kearsarge deposit. The variability of the SIMS spot data from only

three samples is similar to the entire range of the 159 bulk samples as a result of averaging by bulk sampling.

The oxygen and carbon isotopic composition of the hydrothermal fluids in equilibrium with the calcite has been calculated considering both temperature variation among paragenetic stages and differences in geographic location. For Stage 1-2 calcite a temperature of 250°C +/- 50°C was used and for Stage 3 calcite a temperature of 125°C +/- 25°C (Puschner, 2002; Livnat, 1983). The variation of Stage 1 and 2 water in equilibrium with calcite is widely scattered between $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ of about +22 to +4 ‰ and $\delta^{13}\text{C}_{\text{CO}_2}$ of about +3 to -8 ‰ (using midpoint temperatures). The total variability in Stage 1-2 water stable isotopic compositions can only partly be explained by considering paragenetic, spatial, and local temperature variation. Thus, the larger data set compiled for this study, representing Stage 1-2 water in equilibrium with calcite, is consistent with the observations of Bornhorst and Woodruff (1997). To explain the oxygen isotopic data in his limited data set, Puschner (2002) proposed that ore fluids were derived through metamorphism and mixed with a meteoric water at shallow depths during formation of the native copper deposits. The range in $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ and $\delta^{13}\text{C}_{\text{CO}_2}$ from our data supports this conclusion.

Stage 3 ranges in $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ from about +8 to -2 ‰ and in $\delta^{13}\text{C}_{\text{CO}_2}$ from about 0 to -10 ‰ using midpoint temperatures. In $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ and $\delta^{13}\text{C}_{\text{CO}_2}$ space Stage 3 calcite is generally different than Stage 1-2, but overlaps with Stage 1-2 at the higher values of $\delta^{18}\text{O}_{\text{H}_2\text{O}}$. Stage 3 calcite isotopic composition can only partly be explained by local temperature variation. The range of $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ for Stage 3 calcite overlaps the expected range of values for meteoric and metamorphic waters and is consistent with a tentative interpretation of fluid-mixing. Further interpretations are in progress.

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Recognition of probable distal ejecta from the 1850 Ma Sudbury meteorite impact event along the southern edge of the Animikie basin in Minnesota

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Petrographic examination of a drill core (LM-13-4) obtained in 2013 by Minerals Processing Corporation, located at the southeastern margin of the Animikie basin (Fig. 1), has revealed the presence of an approximately 5 m thick interval with features that can be attributed to distal Sudbury ejecta. These include sphere-in-sphere structures, vesiculated devitrified glass, zoned accretionary lapilli, anatase, and possible (albeit questionable) rare and poorly preserved decorated PDF lamellae in some quartz grains. These features are similar to those described from other locations, including Michigan (Cannon and others, 2010), and Ontario and Minnesota (Addison and others, 2005), among others. This location is approximately 950 km from Sudbury.

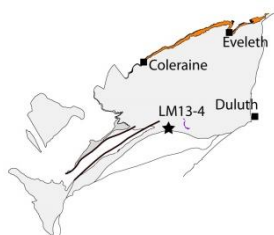


Figure 1. Cartoon map of the Animikie basin showing location of drill core LM13-4.

This core is from a belt that has historically been mapped as part of the southward-adjacent Mille Lacs Group which is thought to predate deposition in the main Animikie basin. However, a more recent reinterpretation (Boerboom, 2009) places this belt in the lower part of the Animikie basin, as part of the Thomson Formation, an interpretation supported by the presence of this ejecta layer. The vertical drill core intersects bedrock at 137'/42m depth (beneath glacial drift) and ends at 437'/133m depth. The ejecta horizon occurs in the 291-309' interval. Bedding is upright and (most likely) dips north an average of 60 degrees. Major folds appear to be lacking in this core, despite the presence of a weak, nearly vertical cleavage.

The approximately 5.5m thick interval attributed to the ejecta horizon lies within a thick, low-grade turbidite sequence. The core above the ejecta horizon is gray and orange-ochre banded 'ferruginous slate', likely a more weathered and oxidized version of the gray carbonaceous argillite and graywacke below the ejecta horizon which contains numerous thin beds of brownish carbonate beds and pyrite. The ejecta horizon can be divided into three distinct portions (Fig. 2) – a lower lapilli-rich layer (20cm, not all shown in Fig. 2), a middle fragmental and brecciated layer (10cm), and an upper sandy layer that



Figure 2. Lower portion of the eject interval. Top of core is to the left. Bottom 6 inches/13cm is not shown. Drill core is 3.5 cm in width.

continues upward for several meters and appears to grade into the overlying turbidites. The lower portion contains abundant dark gray vertically flattened, weakly and concentrically zoned accretionary lapilli that increase in size and abundance upward, in a matrix of small pale green and dark gray, angular shard – like clasts. The middle layer contains angular chert clasts at the base and larger elongate pale green shard-like clasts at the top. The upper layer is composed of a grayish-green sandy graywacke with 1-3mm lapilli in the lower part that are weakly concentrated along bedding planes. This interval may represent an influx of debris ultimately derived from the Sudbury impact crater, possibly a submarine debris flow slumped downslope from its original depositional source, within an otherwise unbroken turbidite sequence.

Despite thorough replacement by secondary phyllosilicate minerals, there are many well-preserved features (Fig. 3) that compare to those elsewhere attributed to ejecta fallout. To date positive identification of shocked quartz has been unsuccessful. However, some grains bear parallel arrays of linear bubble trains which may represent decorated quartz planar deformation features (Fig. 3c). Nonetheless there are many other features that can be attributed to ejecta fallout, and the location along the southern margin of the Animikie basin is where it logically would be expected.

Huber and others (2014) describe spherules (their term) from drill cores near Coleraine that contain microcrystalline rutile and anatase in the outer rims. They state that because the transition from rutile to anatase at low pressures is in the 500-600 C range, and because the rocks at Coleraine were only subject to low T metamorphism, that anatase formed in the spherulitic melt droplets as they cooled.

Thin sections from core LM13-4 contain abundant anatase as confirmed by SEM and by optical properties. However, the anatase does not occur as fine granular masses, but rather as prismatic crystals up to 0.8mm in length concentrated in microscopically dark-opaque zones interpreted to be deformed devitrified glass shards. The anatase laths are commonly rimmed by zones that are not opaque, implying they may have formed by some secondary mechanism such as diagenesis, hydrothermal alteration or low-grade metamorphism. In contrast, ilmenite is the dominant Ti-phase within the accretionary lapilli. The significance of this is currently unknown.

Ongoing petrographic work will attempt to more positively identify shocked quartz, and SEM and XRD work will be conducted to better characterize the secondary mineralogical assemblages. If further analytical and petrographic data conclude the material is ejecta-bearing, it will be the first such occurrence along the southern Animikie basin in Minnesota.

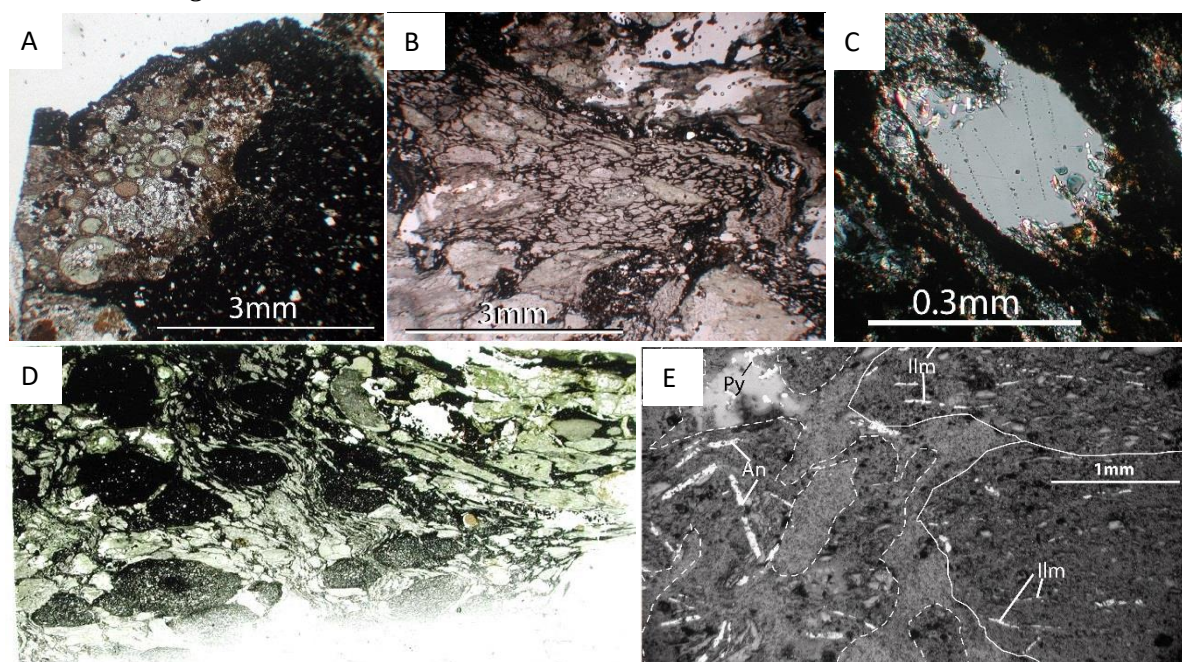


Figure 3. A. Sphere-in-sphere structures interpreted as melt droplets, with chloritic cores and sericitic rims. B. Clast of devitrified vesicular glass with internal spherical structures. C. Straight bubble trains in quartz – possible relict deformation lamellae? D. Zoned accretionary lapilli most visible at thin edge of thin section. E. Reflected light image of showing ilmenite (Ilm) in accretionary lapilli, and anatase (An) in dark semi-opaque zones (in transmitted light) that are interpreted as possible deformed pumice-like fragments.

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Geology and Geochemistry of Ultramafic rocks in the Lake of the Woods Area

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The Archean komatiites of the Lake of the Woods greenstone belt in Kenora, Ontario formed on the western extension of the Superior Province southern margin and have not been studied using modern methods. Although Archean plate tectonic processes have been the subject of decades of research, the nature of these processes remains the subject of considerable debate. Recent work has investigated the link between komatiites and Archean subduction zones. Komatiites are widespread in Archean terranes and together with spatially associated tholeiitic basalts form an important part of many Late Archean greenstone belts, therefore a better understanding of Archean geodynamic processes and comparison to modern day processes is required.

The Lake of the Woods greenstone belt (LWBG) is located in the Western Wabigoon Terrane which is composed dominantly by mafic volcanic rocks with large tonalite-granodiorite plutons. The LWBG is situated along the northwestern margin of the Western Wabigoon Terrane, bounded to the north by the Winnipeg River and English River terranes and to the south by the Quetico terrane (Ayer and Davis, 1997). It consists of a northeast trending metavolcanic plutonic belt that extends for 900km and is about 150km wide (Ayer and Davis, 1997). The LWBG is divided into three supracrustal assemblages: a lowermost mafic volcanic Lower Keewatin assemblage; a compositionally diverse, predominantly volcanic middle Upper Keewatin assemblage; and a predominantly sedimentary uppermost Electrum assemblage (Ayer and Davis, 1997). The Upper Keewatin assemblage consists of 1) mafic to felsic metavolcanic rocks of calc-alkalic affinity, 2) ultramafic to mafic metavolcanic rocks of komatiitic to tholeiitic affinity, and 3) turbiditic metasedimentary rocks (Ayer and Davis, 1997).

Detailed mapping in the Upper Keewatin Assemblage identified komatiites on the southern margin of the Long Bay Group. The komatiites are typically metamorphosed to upper greenschist facies and include a variety of schists that do not show any preserved primary textures or mineralogy. Polyhedrally jointed flow tops were observed in rare locations. Mineral assemblages include dominantly anthophyllite-tremolite-chlorite (Fig. 1A) and serpentine-tremolite-chlorite (Fig. 1B) schists, as well as lesser talc-tremolite-chlorite schists. These units are moderately to intensely foliated with chlorite and lesser amphibole defining the foliation and also include randomly oriented bladed amphibole grains that typically have tremolite cores and anthophyllite rims. The amphiboles show a chemical transition from core to rim with a loss in Ca as anthophyllite appears. Accessory phases include chromite, magnetite, ilmenite and apatite. Ultramafic rocks are very fine-grained, and mineralogy has been described using a compilation of petrography, XRD (x-ray diffraction) and SEM (scanning electron microscope) analysis.

Whole-rock geochemical analyses were conducted on 110 samples collected during field work in 2017 and 2018. The Upper Keewatin Assemblage is composed of dominantly mafic to intermediate volcanic rocks that are typically of tholeiitic affinity with rare calc-alkalic units. A total of 41 samples were determined to be ultramafic. The komatiite units are Al-undepleted rocks that display primitive mantle normalized patterns, as well as major and trace element concentrations consistent with melts derived from outside the garnet stability zone. They can be

subdivided into three suites with primitive mantle patterns that display strong Th and Nb depletions with flat HREEs (heavy rare earth elements), weak Th and Nb depletions with flat HREEs and enriched Th with moderate Nb depletions and flat HREEs. Neodymium isotope analyses, in conjunction with trace element geochemistry, suggests that some units have been weakly to moderately contaminated. Mafic tholeiitic units have low- and high-Ti varieties, in which most units are dark grey to black amphibolites and rare chlorite-tremolite schists. The geochemistry of the mafic units shows similar contamination trends to the ultramafic units.

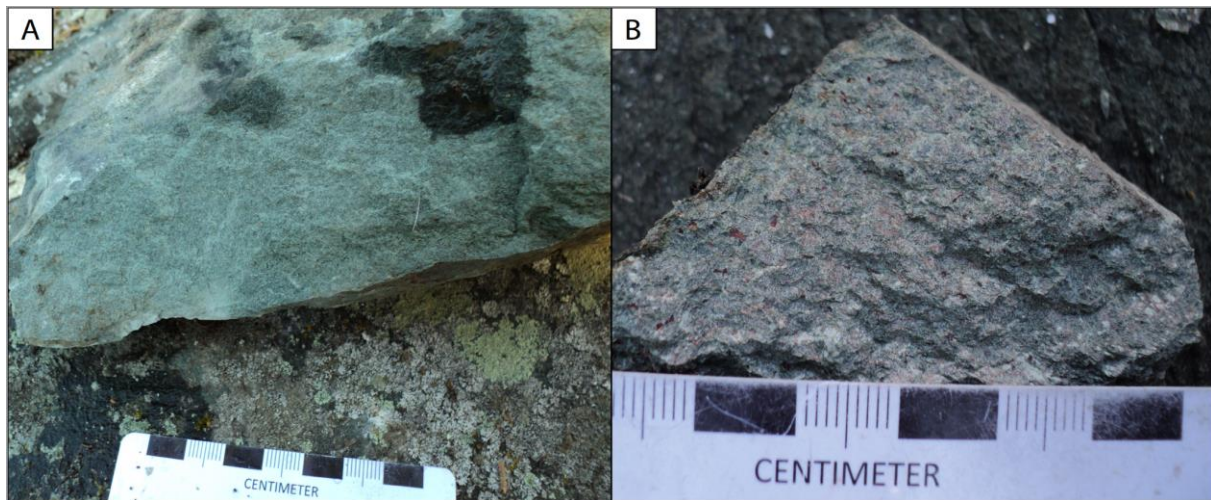


Figure 1. Field photographs of grey to dark green foliated ultramafic metavolcanic rocks.

A (LOW17CB19 15U 368614 5467778): Pervasive chlorite creates deep green color and moderate foliation. **B** (LOW17CB92 15U 368861 5465424): Talc alteration with red staining along strong foliation planes.

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Updated mineralogy of a roadside pegmatite in the Stettin Complex, Wausau Syenite Complex, Marathon County, Wisconsin.

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In 2017 we presented an initial report regarding a recently re-exposed pegmatite along 120th Avenue in the SW 1/4 NW 1/4 of Sec. 22, T.29, R. 6E near the western margin of the intrusion. It has become apparent that this aplite/pegmatite is the same roadside pegmatite described in Weidman (1907), having been obscured by slumped soil, rock and vegetation for the intervening 110 years. 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.

In 2017 we reported on the occurrence of albite, arfvedsonite, aegirine, microcline, pyrochlore, monazite-(Ce), bastnäsite-(Ce), cerianite, xenotime-(Y), zinnwaldite, zircon, goethite/hematite replacements after siderite, pyrite, a TiO₂ phase, columbite-(Fe), bismuthinite, astrophyllite and fluorite. Several other species were included in the poster presentation but not described in the abstract, hence these are included in the below descriptions.

Minor additional xenotime has been identified as sheaves of pale blue crystals in albite-rich aplite, associated with aegirine, while further analysis of pyrochlore indicates they are largely fluorcalciopyrochlore, although due to strong, ubiquitous zoning three or more pyrochlore species may be present in various zones in one crystal. Graphite is not uncommon as thin, black crystals in late quartz pods in and near pegmatitic portions of the dike but is easily missed, and several yellow-brown grains of thorbastnäsite have been found in microcline in core zone material. Euxenite-(Y) forms rare small, brown, elongated crystals in pegmatite, and probable thorite and grayite are sparse.

Careful visual examination of samples has revealed the first Be-bearing minerals in the Stettin complex in albite-rich aplite, located close to the transition to pegmatite. Phenakite is found as patches of clear, colorless phenakite poikilitically including albite crystals and as isolated grains in pegmatite, and true to its name (from Greek *phenas* for “deceiver”) is difficult to distinguish from similar quartz without the use of optical methods. Bertrandite was found as very pale blue platy crystals in patches in albite near phenakite, and feathery, pale yellow bavenite near bertrandite.

Heavy mineral separates have revealed a suite of unusual inconspicuous phases, some present in very small amounts. These include sparse grains of galena and sphalerite, native bismuth with small amounts of a Ca-Bi phase (perhaps kettnerite or beyerite) one small grain of akantite in native bismuth, and an Ag-Bi-S phase, also in bismuth. The Ag-Bi-S phase remains unidentified as the stoichiometry does not match benjaminite, dantopaite, matildite or pavonite (the known Ag-Bi-S minerals), and paucity of material precludes further investigation.

Cassiterite is not uncommon in some samples, but is difficult to visually distinguish from abundant zircon. Worldwide, cassiterite is very rare from alkalic complexes, as a review of applicable literature and Mindat listings revealed very few occurrences worldwide. Apparently, Sn is not commonly enriched in alkalic environments, although several additional occurrences of cassiterite have been noted in Stettin Complex pegmatites.

The occurrence of graphite in and near the core zone suggests a reducing environment during crystallization of those portions of the dike, while the late crystallization of cerianite (requiring oxidation of Ce^{3+} to Ce^{4+}), replacement of siderite by goethite and hematite, and common partial replacements of aegirine and arfvedsonite by Fe-oxide phases suggests a late transition to an oxidizing environment.

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The Dickinson Group in the Central Upper Peninsula of Michigan: Part 1- Age and tectonic setting based on new geophysical, geochronological, and geochemical data

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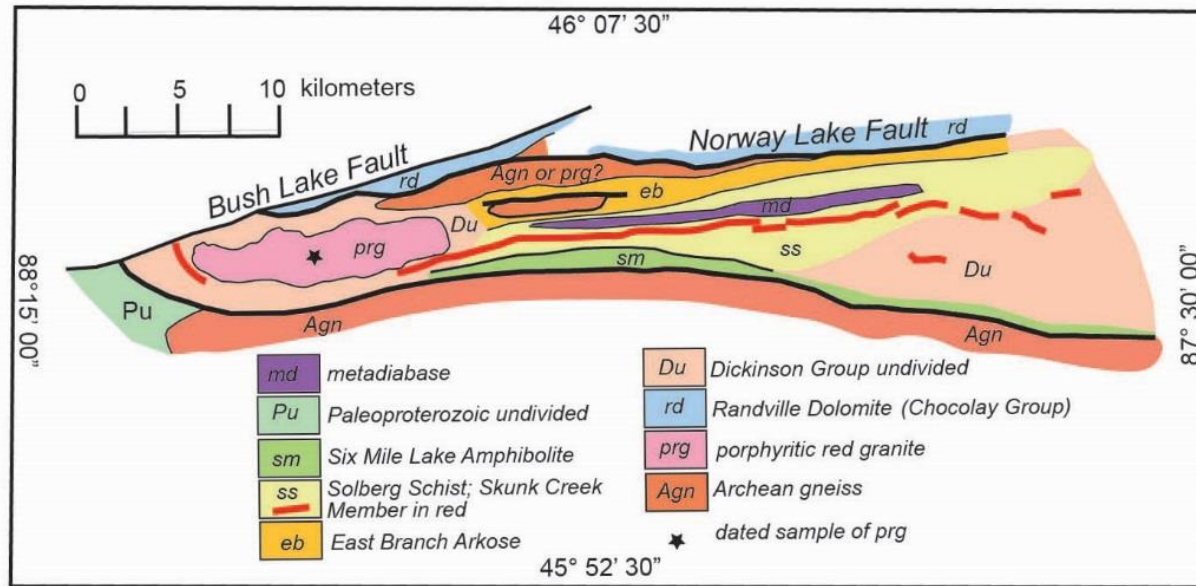
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A unique sequence of metasedimentary and metavolcanic rocks is exposed in a ~100 km² area of central Dickinson County, Michigan. James (1958) divided these rocks into three formations that comprise the Dickinson Group. James et al. (1961) provided additional details of structure and stratigraphy. Our recent geophysical, geochemical, and geochronological studies shed new light on this group and suggest substantial changes to previous interpretations. The basal East Branch Arkose (arkose, conglomerate, and minor basalt flows) grades upward to the Solberg Schist (finer grained-clastics with probable metavolcanic interbeds and a medial banded iron-formation, the Skunk Creek Member). The uppermost formation, the Six Mile Lake Amphibolite (massive to banded hornblende-plagioclase rock), is presumed to be mafic metavolcanics. James et al. (1961) concluded that the Six Mile Lake Amphibolite grades southward into Archean gneiss, so ascribed an Archean age to the entire Dickinson Group. The exposed Dickinson Group lies in a vertical, south-facing monocline about 5 km wide. James et al. (1961) considered this the approximate stratigraphic thickness of the group because they found no indication of internal folding or faulting across that distance. The lack of internal folding is especially well documented for the East Branch Arkose where abundant cross beds all indicate south-facing strata. In the Solberg Schist the Skunk Creek Member can be traced by its strong aeromagnetic anomaly (as much as 2000 nT) as a single horizon for 50 km without indication of structural repetition. This apparent structural simplicity is belied by a ubiquitous penetrative foliation that is steeply dipping and essentially bedding-parallel in the East Branch and Solberg as shown by oriented micas, stretched quartz grains, and, in the East Branch Arkose, flattened and elongated pebbles. In the Six Mile Lake Amphibolite oriented hornblende grains define a gently-plunging lineation (fold axes?). Development of these penetrative structures appears to have been synchronous with metamorphism that peaked at about 1.83 Ga (Holm et al., 2007) and thus records deformation during the Penokean orogeny. The exposed Dickinson Group may be the north limb of a large syncline whose southern limb is truncated by a fault against the Archean rocks to the south. East of the exposed area our new aeromagnetic data indicates that the belt of Dickinson Group rocks widens and is more structurally complex (Drenth et al., 2019).

The East Branch Arkose contains a significant population of detrital zircons with 2.1 Ga ages (Craddock, et al., 2013) and is clearly Paleoproterozoic rather than Archean. The most abundant clast type in the East Branch conglomerates is orthoquartzite likely derived from the older 2.2-2.3 Ga Sturgeon Quartzite. An age of 2.1 Ga has been determined for the “porphyritic red granite”(prg) (Ayuso et al., 2018), which is surrounded by Dickinson Group strata. The prg likely was an important source of detritus, including zircons, for the East Branch Arkose.

Correlation of the Dickinson Group with other Paleoproterozoic sequences of the region is not fully resolved. It is clearly younger than the 2.2-2.3 Ga Chocoma Group and its metamorphism at 1.83 Ga provides an upper age limit. Within current age constraints it could be equivalent to parts of the Menominee and/or Baraga Groups. But, another possibility is that the Dickinson Group is a vestige of a unique sequence deposited during the long hiatus between about 2.1 Ga (prg) and 1.9 Ga (Menominee Group). and provides a record of the final separation of the Superior and Wyoming cratons. The Six Mile Lake amphibolite and a metadiabase sill in the Solberg Schist have distinctive trace element chemistry consistent with a mantle plume source. Within the Lake Superior region that composition is known only in mafic dikes north of Lake Superior (Schulz et al., 2018) that were intruded between 2126 and 2067 Ma and mark a long-lived mantle plume event during separation of the two cratons (Halls et al., 2008). The coarse, locally derived fluvial sediments of the East Branch Arkose are consistent with extensional uplift during which much of the Chocoma Group was stripped from its basement and erosion unroofed 2.1 Ga granite plutons. The ensuing transition of fine-grained clastic sediments and banded iron-formation of the

Solberg Schist marks the transition to marine sedimentation culminating in plume-related mafic volcanism (Six Mile Lake Amphibolite) marking the final continental separation.



Geologic map of the Dickinson Group and surrounding units (modified from James et al., 1961).

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Reexamining the Osborne core for new insights into the age and petrology of the Northeast Iowa Intrusive Complex (NEIIC)

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The Keweenaw Midcontinent Rift System (MRS) has been the focus of decades of research for its enigmatic geologic history and its wealth of economic minerals. The latter has been concentrated in the Lake Superior region where the MRS is exposed at or near the land surface. Copper-nickel sulfide and platinum group element deposits have been identified along the north shore in Ontario (Coldwell Complex) and along the western shore in Minnesota (Duluth Complex). These magmatic deposits are related to the MRS and are geophysically distinct, with high amplitude magnetic anomalies and associated gravity highs (Drenth et al., 2015 and Drenth & Brown, 2016).

Since 2012, the U.S. Geological Survey (USGS) has conducted two major high-resolution geophysical surveys in northeastern Iowa and southeastern Minnesota in an attempt to better understand the nature of the Precambrian basement geology concealed beneath at least 1,000 feet (300 m) of Paleozoic sedimentary rocks. The surveys, both magnetic and gravity, have succeeded in refining the area previously identified as the Northeast Iowa Plutonic Complex (Anderson, 2006), now called the Northeast Iowa Intrusive Complex (NEIIC). The NEIIC has an aerial extent of over 6,000 mi² (15,500 km), including several large ring/horseshoe shaped anomalies and associated linear features. Some of these features have been characterized using geophysical techniques, yet with a limited number of boreholes that reach the NEIIC, accurate lithologic and geochronologic data has remained elusive.

One iron exploration core, the Osborne core, drilled in 1963 intersected a dike extending northeastward from the main part of the NEIIC and encountered more than 700 feet (213 m) of ultramafic olivine-plagioclase cumulate. The Iowa Geological Survey (IGS) and the University of Iowa Department of Earth and Environmental Sciences are reexamining the Osborne core to identify and characterize datable minerals. A systematic survey of compositional variations was done using a handheld portable X-Ray Fluorescence (pXRF) analyzer, with replicate analyses made on individual cores pieces, at an average sampling interval of 2 m along the core. These data show there are two distinct zones within the core that have elevated zirconium (Fig. 1), together with high K, P and Rb, indicative of trapped residual liquid. X-ray element mapping and backscatter images have identified baddeleyite and zirconolite minerals in these zones (Fig. 2). Samples have been selected and are being processed for geochronologic analyses. Obtaining a reliable age date from the Osborne core could provide a missing piece to the NEIIC puzzle and help answer the question of whether it is in fact related to the MRS and other economic mineral deposits in the Lake Superior region.

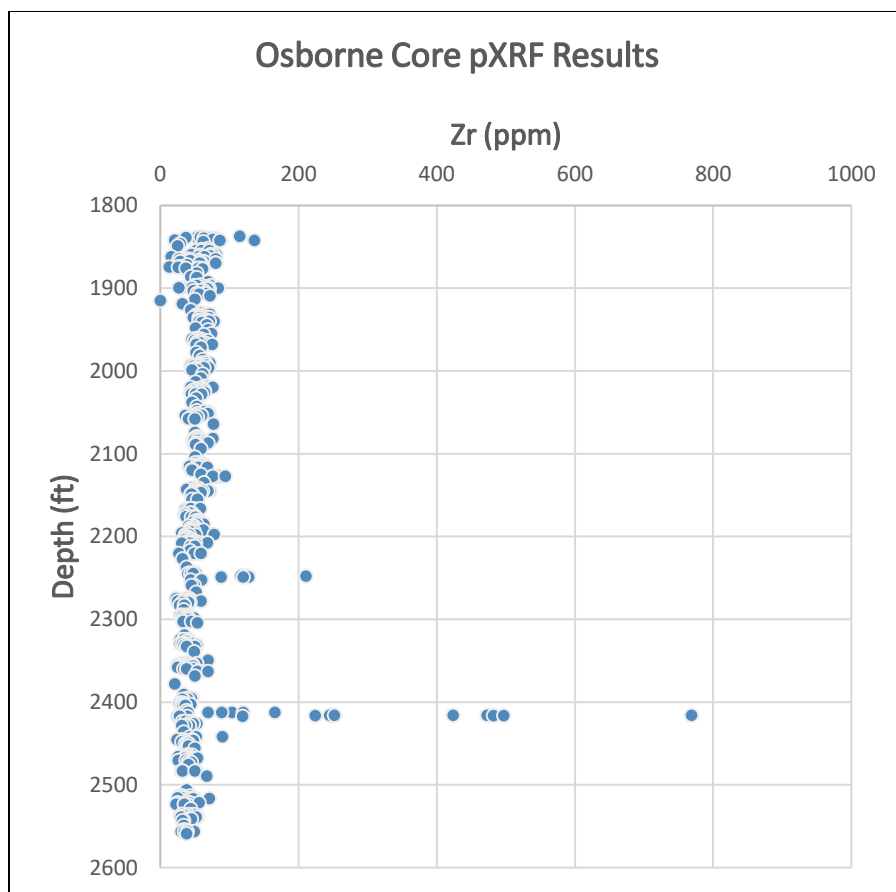


Figure 1: PXRF results for zirconium through the Precambrian sequence encountered in the Osborne core.

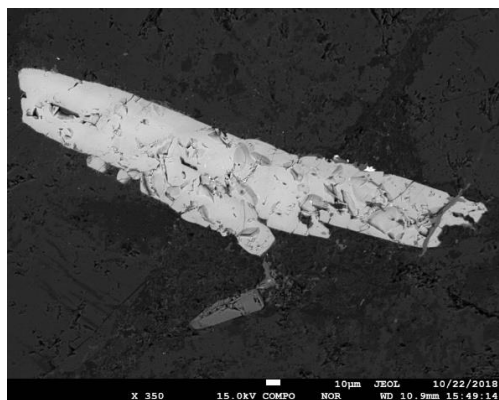


Figure 2: Backscatter image of a zirconolite crystal from the Osborne core at 2,416' depth.

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Keweenaw Fault System along Bête Grise Bay, Michigan: Geometry, Kinematics, and Tectonic Significance

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The Keweenaw Fault (KF) extends along the southern margin of the Midcontinent Rift System from northwest Wisconsin to near Keweenaw Point in Michigan. Reverse movement on the fault has thrust Portage Lake Volcanics (PLV, 1.1 Ga) over younger, mostly flat-lying Jacobsville Sandstone (JS) (Fig. 1), imparting a regional northerly tilt to PLV strata (1). The KF near Keweenaw Point is of interest because 1950s USGS maps (2-3) show five coastal areas with juxtaposed PLV and JS strata connected by an anomalously sinuous fault trace (Fig. 2a). Based on geophysical data, some have proposed that the KF continues offshore beyond Keweenaw Point in an arc curving over 90° to a southeasterly direction (4-5). These geometries seem incompatible with a simple thrust system. Furthermore, a lack of reported slip indicators prevents defining the ratio of dip to strike slip and estimating principal stress directions responsible for fault motion.

New mapping of the KF system along Bête Grise Bay reveals that the oddly sinuous fault trace of the 1950s oversimplifies important geologic relationships in the area (Fig. 2a-b). Three to perhaps four of seven PLV-JS contacts previously mapped as faulted instead have an unconformity between PLV lava flows and basal JS strata. Unconformable contacts to the west show fractured, locally saprolitic PLV basalt below moderately dipping JS strata of alternating muddy siltstone, lithic to quartzose sandstone, and pebble conglomerate with angular basalt fragments in a muddy matrix. An unconformable contact to the east shows slightly deformed JS strata overlying steeply dipping, intensely faulted and brecciated PLV strata, indicating major slip on this KF segment before local JS deposition. At other shoreline locations, deformed JS strata truncated on fault contacts with PLV lavas provide evidence of a second period of slip on the KF system after some or all JS deposition. Recognition of unconformable PLV-JS contacts, combined with mapping both onshore and offshore, breaks the sinuous single fault trace of the 1950s into at least six segments generally striking ESE and forming a left-stepping, en echelon pattern.

Well exposed fault surfaces near the shoreline have provided many opportunities to measure orientation of slip indicators and to infer slip sense. Analysis of such measurements at 36 sites indicates that the last period of activity on this part of the KF system was dominated by strike slip, with a 2:1 ratio of dextral strike slip to reverse dip slip (N side up). Geologic relationships across major fault segments are consistent with their north sides sliding to the right and upward relative to opposing sides. Inversion of fault-slip data further confirms a mostly strike-slip regime and indicates a maximum shortening direction of N80°W during the last period of fault motion.

South of the Bare Hill rhyolite, a major ENE-trending fault appears to link two ESE-trending, en echelon fault segments (Fig. 2b). The linking fault follows the core of a tight upright anticline in PLV strata with an interlimb angle of 30° or less. PLV strata on the SE flank of the anticline dip steeply to moderately SE (counter-regional) for at least 3.5 km along the shore. Poles to bedding on both flanks of the anticline define a fold axis plunging 21° at N82°E. The tightly folded nature of the faulted anticline in relatively rigid strata implies that the fold formed during dextral strike slip on the linking fault or was modified afterward by such shearing.

The trace of the KF system changes direction from NNE near Houghton to ESE at Bête Grise Bay (> 70°), which mimics the change in strike of PLV layers over the same distance (Fig. 1). Large crustal-scale faults often curve and split into segments near their terminations. The new mapping results thus imply that the KF system terminates near the end of the peninsula in a series of fault splays, possibly transferring slip to other faults farther southeast. Based on these results and regional information, we suggest that slip on the KF system changes from mostly reverse dip-slip along its NNE-trending portion

near Houghton to mostly dextral strike-slip near the tip of the Keweenaw Peninsula, and that total slip magnitude decreases over this same distance.

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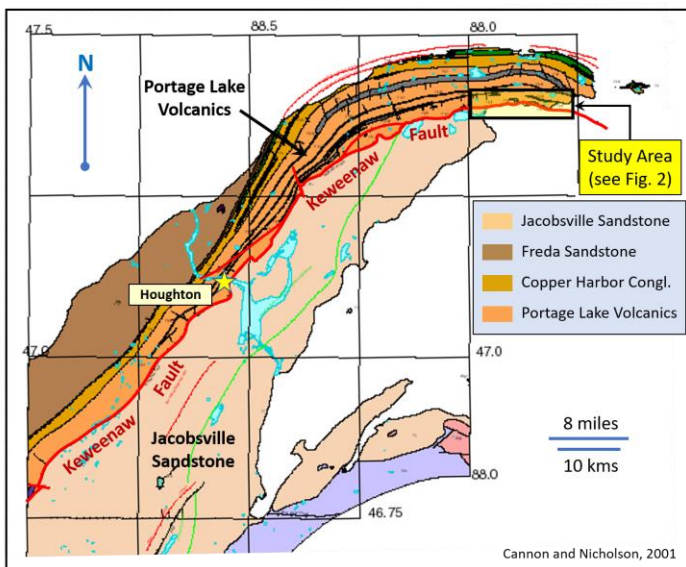
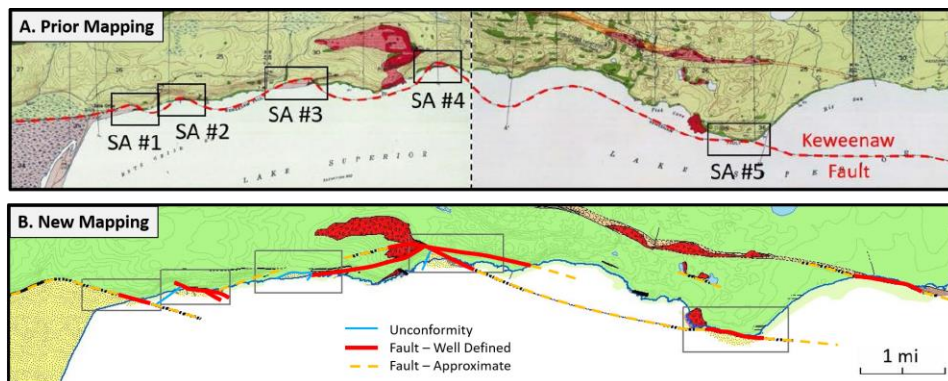


Figure 1 (left): Keweenaw Peninsula where Portage Lake Volcanics are thrust over Jacobsville Sandstone. Black rectangle near tip of the peninsula marks area of **Figure 2**. (adapted from 1).

Figure 2 (below): Study area along the Keweenaw Fault east from Bête Grise Bay. Main units: PLV mafic = greens; PLV felsic = reds; JS = pink-A / yellow-B. **A)** USGS maps from 1950s (2-3). **B)** New map highlighting fault pattern and PLV-JS unconformity.



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Southwest Margin of the Midcontinent Rift System in Eastern Lake Superior: Review and Preliminary Interpretation

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The relatively well-defined southwest branch of the Midcontinent Rift System (MRS) transitions to the less well-defined southeast branch near Keweenaw Point and the postulated Thiel Fault zone (1-3; Fig. 1). The southwest branch has abundant outcrops of rift-related rocks around Lake Superior and has been extended farther southwest beneath Paleozoic strata with geophysics and widely spaced deep drill holes. In contrast, rift-related rocks of the southeast branch mostly lie beneath lakes Superior and Michigan, post-rift Jacobsville Sandstone (JS), or Phanerozoic strata of the Michigan Basin. Current understanding of the southeast branch of the MRS mostly comes from geophysical data and rare deep boreholes that penetrate Precambrian basement. To better define the transition between the two branches of the MRS, we initiated research on the offshore geology between the Keweenaw Peninsula and the south shore of Lake Superior east of Marquette, Michigan (Fig. 2). Data to be obtained and used include new shoreline and underwater outcrop descriptions and existing seismic and potential field data. This poster provides some initial perceptions and thoughts in the context of prior investigations.

Outcrops of rift-related rocks in the area are mainly along the Keweenaw Peninsula and Manitou Island, but probably occur at Stannard Rock shoal and perhaps at other shallow areas along an arc from Keweenaw Point southeastward to Munising (Fig. 2). Information about Stannard Rock is limited to sketchy early reports and one rock sample described as “quartzless porphyry” or rhyolite (4-5). If Stannard Rock shoal proves to have rhyolitic rocks, this outcome together with the rhyolitic flows at the bottom of the Amoco St. Amour 1-29R borehole (6) could indicate a significant area of felsic volcanism along the southwest margin of the MRS in eastern Lake Superior. Other relevant outcrops in the area are Jacobsville strata that rim Keweenaw Bay and extend eastward along the south shore of Lake Superior to Sault Ste. Marie. Along the shore near Munising, aerial imagery available through Google Earth shows JS strata on the rift margin generally striking NS and dipping eastward toward the rift axis defined by geophysical data.

Qualitative review of available geophysical data provides additional insight into the nature of the rift margin north of Munising and structural trends in pre-rift basement between the two MRS branches. Five seismic reflection lines in eastern Lake Superior define: (1) an uplifted rift flank to the southwest with sub-horizontal strata, and (2) a rift margin-slope with strata dipping moderately northeast toward the rift basin. Some lines show evidence of a component of reverse faulting along the rift margin (7), but others may be interpreted as having only a flexure without obvious faulting. The NNW-trending rift margin has two jogs, a southern one near Munising and a northern one near Stannard Rock, implying that rift-margin faults are not continuous along the entire margin. The orientation of such faults is more than 90° off trend of the Keweenaw Fault, and so their slip direction must differ from that of the Keweenaw Fault. Therefore, faults along this rift margin are best regarded as distinct from the Keweenaw Fault and should have different names (e.g., Munising, Au Train).

Broad trends in potential field data are consistent with rift margin trends interpreted on seismic data, including the two jogs. In addition, aeromagnetic data define several circular to arcuate anomalies up to 16 km in diameter that cluster on the rift flank near the jogs in the rift margin (Fig. 2). Each cluster of circular anomalies appears to lie along ENE-trending zones that

may represent crustal-scale fracture zones. It is possible that these anomalies are caused by eruptive centers that sourced volcanic rocks in their immediate surroundings. Further work is required to test these ideas and to improve understanding of this less studied sector of the MRS.

Acknowledgements: We appreciate the helpful and encouraging comments by Bill Hinze (Purdue University) during a review of this abstract.

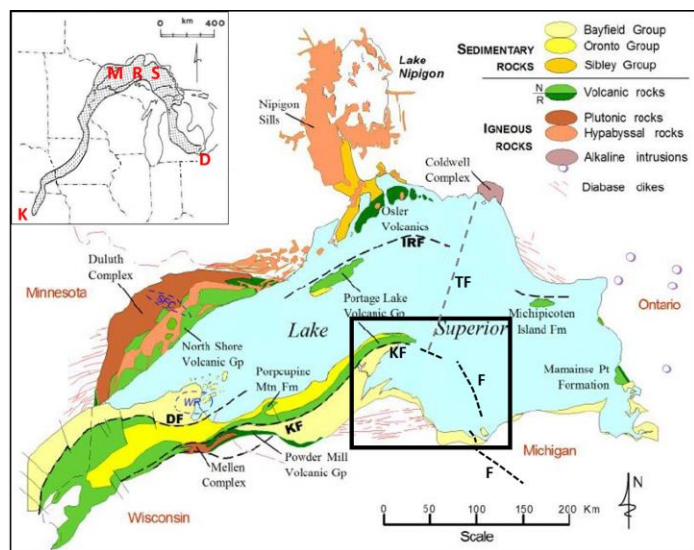
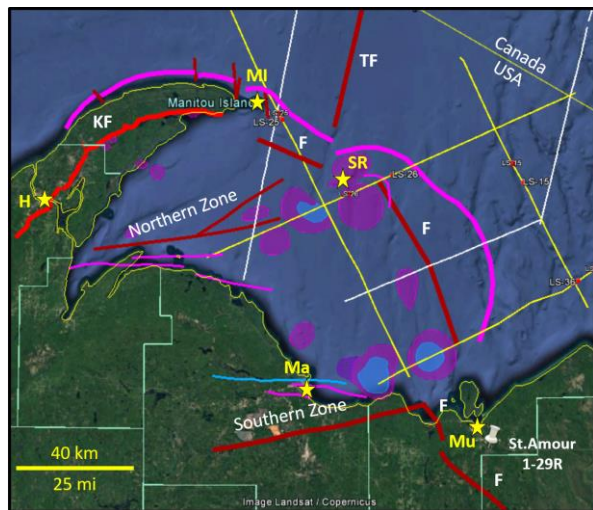


Figure 1 (left): Major rock units and faults in the Lake Superior area; KF-Keweenaw Fault, DF-Douglas Fault, IRF-Isle Royale Fault, TF-Thiel Fault (1). Inset map shows extent of Midcontinent Rift System (MRS) from Lake Superior southwest to Kansas (K) and southeast to Detroit (D). Black rectangle is area of Figure 2.

Figure 2 (below): Main structural elements between the Keweenaw Peninsula and Munising. H-Houghton, Ma-Marquette, Mu-Munising, MI-Manitou Island, SR-Stannard Rock; KF-Keweenaw Fault, TF-Thiel Fault, F-unnamed rift-margin faults. Dark red “faults” inferred from geophysical data. Purple and blue features interpreted from aeromagnetic data and explained in poster.



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Neutralization of proton acidity with sequestration of atmospheric CO₂ during experimental weathering of intrusive rocks from the Midcontinent Rift System

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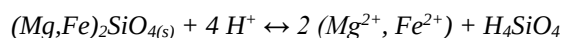
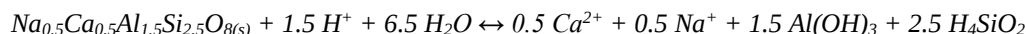
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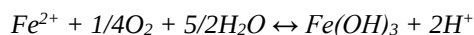
Intrusive rocks associated with the Mesaba Deposit¹, contained predominantly in the Bathtub Intrusion of the Duluth Complex², have been the subject of a comprehensive geochemical characterization program, initiated in 2010, to inform plans for managing water and waste rock on any potential future mining project. This program includes multiple experimental components to characterize subaerial weathering reactions, rates, and products; including, but not limited to, laboratory testwork using an ASTM standard method under the “humidity cell test” configuration, laboratory testing on columns of rock, and a field-based, larger scale barrel test program.

Duluth Complex rocks tend to contain abundant olivine and/or plagioclase, both of which are relatively reactive acid-neutralizing and, potentially, carbonate-forming silicate minerals. Experimental weathering outcomes confirm the effectiveness of silicate dissolution in neutralizing proton acidity through three distinct mechanisms: 1) consumption of protons as reactants in silicate mineral dissolution reactions; 2) reaction with dissolved alkalinity formed during dissolution of silicate minerals in the presence of atmospheric CO₂; and, 3) as reactants during dissolution of secondary carbonate minerals, which were precipitated as weathering products of primary silicate phases. Furthermore, as suggested by the latter two of the above enumerated mechanisms, silicate weathering reactions in the presence of atmospheric CO₂, represents a well-established net sink for atmospheric CO₂ in the form of carbonate mineral weathering products.

Weathering reactions for relatively reactive silicate minerals that are abundant in Duluth Complex rock include those shown below for An50 and olivine, respectively:



Subsequent oxidation and hydrolysis of iron from the olivine breakdown reaction releases hydrogen through the following reaction:



Every cationic charge unit³ added to solution corresponds to a proton being removed.

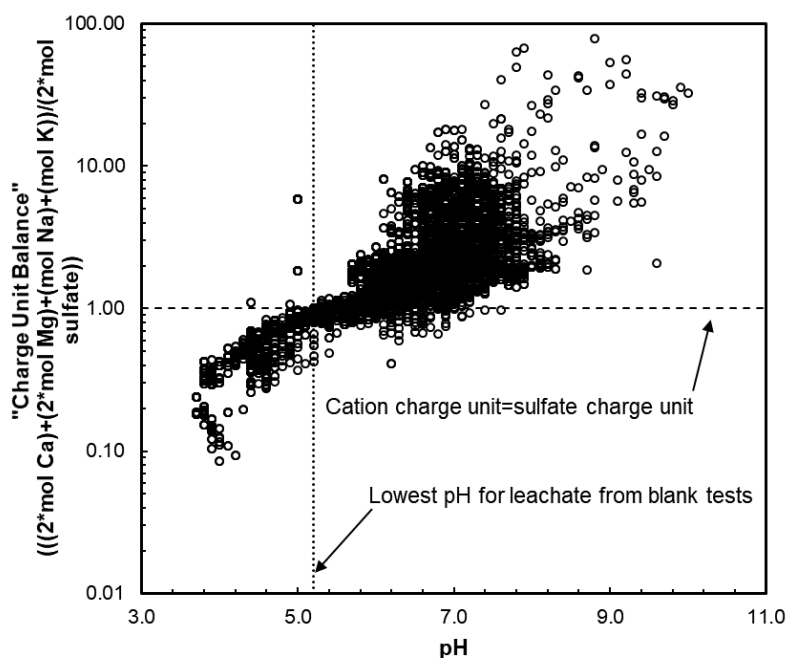
¹ The Mesaba Deposit is a magmatic copper-nickel-PGM deposit described by >800,000 feet of diamond drilling that is owned by Teck American Inc. a wholly owned subsidiary of Teck Resources Limited.

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³ Charge unit concentration is equal to molar concentration times charge. Release of Fe²⁺ during dissolution consumes protons, which are re-released upon oxidation and hydrolysis of iron. Therefore, release of iron is overall proton-neutral and not included.

The relationship between molar concentrations of cations and sulfate in weathering test leachate is a robust indicator of leachate pH across all experimental configurations. Figure 1 shows data from 3,053 individual leachate samples from over 40 different tests. The y-axis represents the relative rates of proton consumption and production during weathering, as indicated by the “charge unit balance” (defined in the figure) of the leachate sample. When the composition of the leachate indicates that protons are being consumed by silicate dissolution faster than they are being produced during sulfide mineral oxidation, the leachate pH is higher than the blank; i.e., there is a net decrease in proton concentration. Conversely, pH of the leachate becomes acidic when the composition of the leachate indicates that protons are being released faster than they are consumed. The clear relationship between rates of proton production and consumption, and drainage pH is an indication of the effectiveness of silicate mineral dissolution in neutralization of proton acidity in the weathering tests.

Figure 1. Leachate data from weathering tests ($n=3053$) showing relationship between charge unit balance and pH. “Charge unit balance”, defined as the molar ratio of cationic charge unit concentration to sulfate charge unit concentration (oxidation of one mol of sulfur in pyrrhotite to sulfate releases two protons). When charge unit balance is equal to one (shown as dashed line), the rate of consumption and production of protons during weathering is equal. Dotted line shows lowest pH observed in leachate from blank tests.



In addition to sulfide mineral oxidation, dissolution of atmospheric CO_2 into rainwater can provide protons for silicate dissolution, through equilibria between dissolved CO_2 and carbonic acid (H_2CO_3), and the subsequent dissociation of carbonic acid to bicarbonate alkalinity and protons. Therefore, in the presence of CO_2 , consumption of protons during silicate dissolution would continue to drive this reaction toward the reaction products, resulting in accumulation of bicarbonate alkalinity in associated waters. Under select conditions, this carbonate builds up and eventually reacts with the calcium and magnesium released during silicate dissolution to precipitate secondary carbonate minerals. While secondary carbonate minerals have not, yet, been directly detected as experimental products, leachate chemistry suggests that, as the ratio of the rock to water increases for different experimental configurations, the leachate becomes more concentrated in calcium, magnesium, and bicarbonate alkalinity, until, eventually, calcium/magnesium ratios decrease, as calcium carbonate is presumably being preferentially precipitated out of solution.

Morphology, mineralogy, texture, and genesis of peperite, Fivemile Lake, Vermilion District, Minnesota: Comparison with Pleistocene peperite, Iceland.

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Peperites are defined as a “rock formed essentially in situ by disintegration of magma intruding and mingling with unconsolidated or poorly consolidated, typically wet sediments” (White et al., 2000, p. 65). Pillowed dikes and associated peperite is well exposed at Fivemile Lake in the Vermilion District of northeastern Minnesota (Hudak et al., 2002; Hudak et al., 2003; Hudak et al., 2004). The rocks are Neoarchean in age (~2.7 billion years, Peterson et al., 2001), and contain well-preserved and well-studied volcanic facies (e.g. Hudak et al., 2002, 2003, 2004). The sequence at Fivemile Lake has been interpreted as recording a series of northeast-trending mafic dikes which have intruded wet volcanoclastic sediments to produce peperite deposits at different levels within the seafloor in a relatively shallow (<1500 m) submarine volcanic system (Hudak et al., 2004). In the current study, outcrops were mapped at a scale of 1:39 with field work focused on extremely detailed mapping to evaluate peperite deposit morphology, mineralogy, and textures.

The igneous component is pillowed to massive, dominated by amygdules, and grades into the host sediment (Fig. 1, right). Outside the margins of the pillowed dikes, both globular and blocky peperite comprising isolated igneous clasts floating in the host volcanoclastic sedimentary rock are present. The volcanoclastic sedimentary rocks are moderately- to highly-vesiculated, and locally contain 1cm wide highly vesiculated zones that are parallel- to sub-parallel to igneous component fragments within the peperite deposits. Although textures are well-preserved both at the outcrop and thin-section scales at Fivemile Lake, the original minerals/glass have been post-depositionally altered to quartz, epidote, and carbonate minerals.

As an analog for the Archean Fivemile Lake peperite, Pleistocene peperites from three locations in Iceland were described, sampled, and analyzed. Locations include three sites in móberg, two near Sveifluháls, Iceland, and a site at Reynisfjara Beach near Vik, Iceland. Kagy (2011) identified peperites along pillowed dyke margins in móberg near Sveifluháls, Reykjanes Peninsula, Iceland. Both blocky and fluidal types were described along with anomalous igneous clasts in a host rock of hydrothermally altered lapilli tuff (palagonite formation). The rocks are relatively unaltered and contain abundant glass with some alteration to palagonite. Host sediment is highly vesiculated and glassy, with broken, jagged hyaloclastite fragments making up the matrix (Fig. 1, left). Some fragments have phenocrysts, while other fragments are separated by a junky, opaque matrix, likely a result of surficial weathering at the outcrop.

Evaluation of the peperite at Fivemile Lake with comparison to Pleistocene peperites aids in identification of primary peperite textures and morphologies. Documentation and mapping of peperites is useful in determining and understanding magma-water interactions and hydrovolcanic processes like magma explosions in wet sediment. Formation of peperites at Fivemile Lake is spatially associated with synvolcanic faults and occurred near the paleo-

seafloor, which is a prospective geologic setting for volcanogenic massive sulfide deposits (Gibson et al., 1999; Rosa et al., 2016).



Figure 1: Field images on left from Iceland (Site 2L; Kagy, 2011) indicate pillowed dyke with peperite next to host sediment. On right, field image shows pillow lava intruding and budding off into host sediment on Peperite Point.

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The Dickinson Group in the Central Upper Peninsula of Michigan: Part 2 - Geophysical expression and a preliminary interpretation of its eastward extent under Paleozoic cover

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The Dickinson Group crops out in central Dickinson County, Michigan, and includes three formations (described in detail by James et al., 1961) that may contain a unique metasedimentary and volcanic record of the final breakup of the Superior and Wyoming cratons (Cannon et al., this volume). The basal East Branch Arkose is made up of arkose, conglomerate, and basalt flows. The overlying Solberg Schist consists of finer clastic rocks, metavolcanics rocks, and an iron-formation, the Skunk Creek Member. The uppermost member, the Six Mile Lake Amphibolite, consists of mafic metavolcanic rocks. The contact between the East Branch Arkose and Solberg Schist is gradational. The contact between the Solberg Schist and Six Mile Lake Amphibolite is not exposed, but was interpreted to be conformable (James et al., 1961). Where exposed west of the edge of Paleozoic cover, the Dickinson Group forms a nearly vertical, south-facing monocline extending more than 20 km with consistent east-west strike (Fig. 1). The Dickinson Group was originally interpreted as Archean, based on an apparent gradational contact between the Six Mile Lake Amphibolite and Archean granite to the south (James et al. 1961). However, various lines of evidence establish an apparent age range of ~2.1 to 1.83 Ga for the entire Dickinson Group (Holm et al., 2007; Craddock et al., 2013; Ayuso et al., 2018; Schulz et al., 2018; Cannon et al., 2018b; Cannon et al., this volume). Clearly, the nature of the Six Mile Lake Amphibolite-Archean contact (queried on Fig. 1) is critical to the interpretation of the Dickinson Group and merits further study.

Parts of the Dickinson Group have geophysically distinctive features compared to surrounding Precambrian rocks. The high-density Six Mile Lake Amphibolite is the dominant source of an east-west elongated, ~13 mGal gravity high that extends 10s of km over both the area of exposure and Paleozoic cover to the east (Drenth et al., 2018). The ~2.1 Ga (Ayuso et al., 2018) “porphyritic red granite” (prg, Fig. 1), a probable source of detritus for sedimentary parts of the Dickinson Group, produces a ~4 mGal gravity low and a zone of mostly quiet aeromagnetic anomalies. Geophysical data show that it is a larger body than shown by previous mapping. Numerous narrow, strike-parallel elongated aeromagnetic highs lie over all units of the Dickinson Group, including the following examples. Aeromagnetic highs with amplitudes up to 600 nT lie over the East Branch Arkose, interpreted to reflect interbedded basalt flows (James et al., 1961). The Skunk Creek Member iron-formation of the Solberg Schist produces an aeromagnetic high with a maximum amplitude of 2000 nT, distinguishing it from other anomaly sources in the area. Other aeromagnetic highs with amplitudes <500 nT do not have confirmed sources, but have been generally ascribed to diabase dikes, gabbroic intrusions, and other magnetic layers within the Dickinson Group (James et al. 1961).

A preliminary interpretation of the eastward subcrop extension (under Paleozoic cover) of the Dickinson Group (Fig. 1) is based on 3D inverse gravity modeling of the geometry of the Six Mile Lake Amphibolite, tracing the distinctive aeromagnetic signature of the Skunk Creek Member, and following the strikes of other aeromagnetic anomalies. The volume of the Six Mile Lake Amphibolite is interpreted to increase dramatically to the east of where it is exposed, and the Skunk Creek Member is interpreted to be complexly folded east of the Paleozoic contact, in

contrast to the monoclinical structure to the west. At least two, and perhaps three folds are indicated by aeromagnetic patterns. Collectively, these interpretive observations may be best reconciled by a model that involves complexly faulted and folded Solberg Schist and Six Mile Lake Amphibolite, including a possible thrust sheet (Fig. 1). The broader tectonic significance of this model hinges on the true nature of the Six Mile Lake Amphibolite-Archean contact.

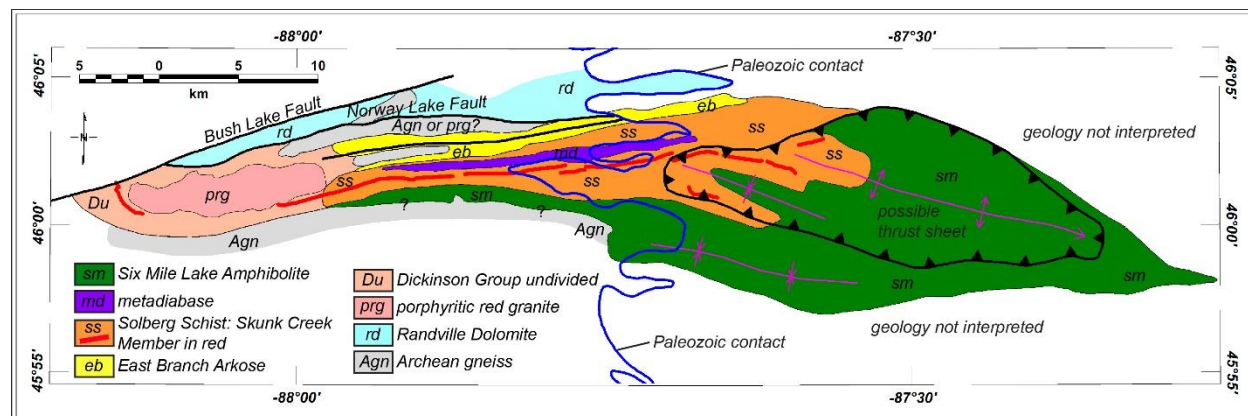


Figure 1: Preliminary interpretation of the full extent of the Dickinson Group, modified from James et al. (1961), Craddock et al. (2013), Cannon et al. (2018a,b), and Cannon et al. (this volume).

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High-resolution aeromagnetic survey, central Upper Peninsula, Michigan

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We present a new aeromagnetic dataset from a high-resolution (150 m line spacing, 80 m nominal terrain clearance) regional fixed-wing survey (~37,000 line km) flown over portions of the central Upper Peninsula of Michigan in 2018. The survey footprint includes areas with Precambrian bedrock between Marquette and Iron Mountain and extends eastward over a large area with weakly magnetized Paleozoic sedimentary cover (Fig. 1), which will allow interpretation of Precambrian subcrop.

Archean rocks of the gneiss terrane south of the Great Lakes Tectonic Zone (GLTZ), a Neoproterozoic suture, are generally weakly magnetized. A swarm of north-northeast trending magnetic dikes are imaged cutting the gneiss terrane between the Bush Lake fault and the GLTZ. These dikes are not detected north of the GLTZ, indicating the swarm predates the suture. Magnetic highs north of the GLTZ lie over exposures of the Archean greenstone-granite terrane and trend subparallel to the GLTZ trend.

Metasedimentary rocks of the Paleoproterozoic Chocoma and Baraga Groups are generally weakly magnetized. Iron formations within the Menominee Group (i.e., the Vulcan Iron-formation) produce very large amplitude positive anomalies. Anomaly amplitudes in the Felch and Calumet troughs reach ~15,000 nT. Several other very large amplitude anomalies (up to ~35,000 nT) lie over the Paleozoic sedimentary cover to the east and are produced by very strongly magnetized iron formations in the Precambrian subcrop that have been drilled by the private sector (Waggoner, 2007).

The Dickinson Group, once thought to be Archean (James et al. 1961) but now considered to be at least partly Paleoproterozoic (e.g., Cannon et al., 2018), is characterized by numerous east-west elongated, narrow magnetic highs. Some of these highs have been interpreted to reflect mafic volcanic rocks and an iron formation, but the sources of others are not explicitly known (James et al., 1961).

Multiple generations of likely Proterozoic dikes are expressed in the aeromagnetic data. Numerous reversely polarized dikes interpreted to be Keweenaw (i.e., related to the ~1.1 Ga Midcontinent Rift System) trend east-northeast. Normally polarized dikes that are also likely Keweenaw trend west-northwest. A swarm of northwest-trending dikes of unknown age trends subparallel to the GLTZ.

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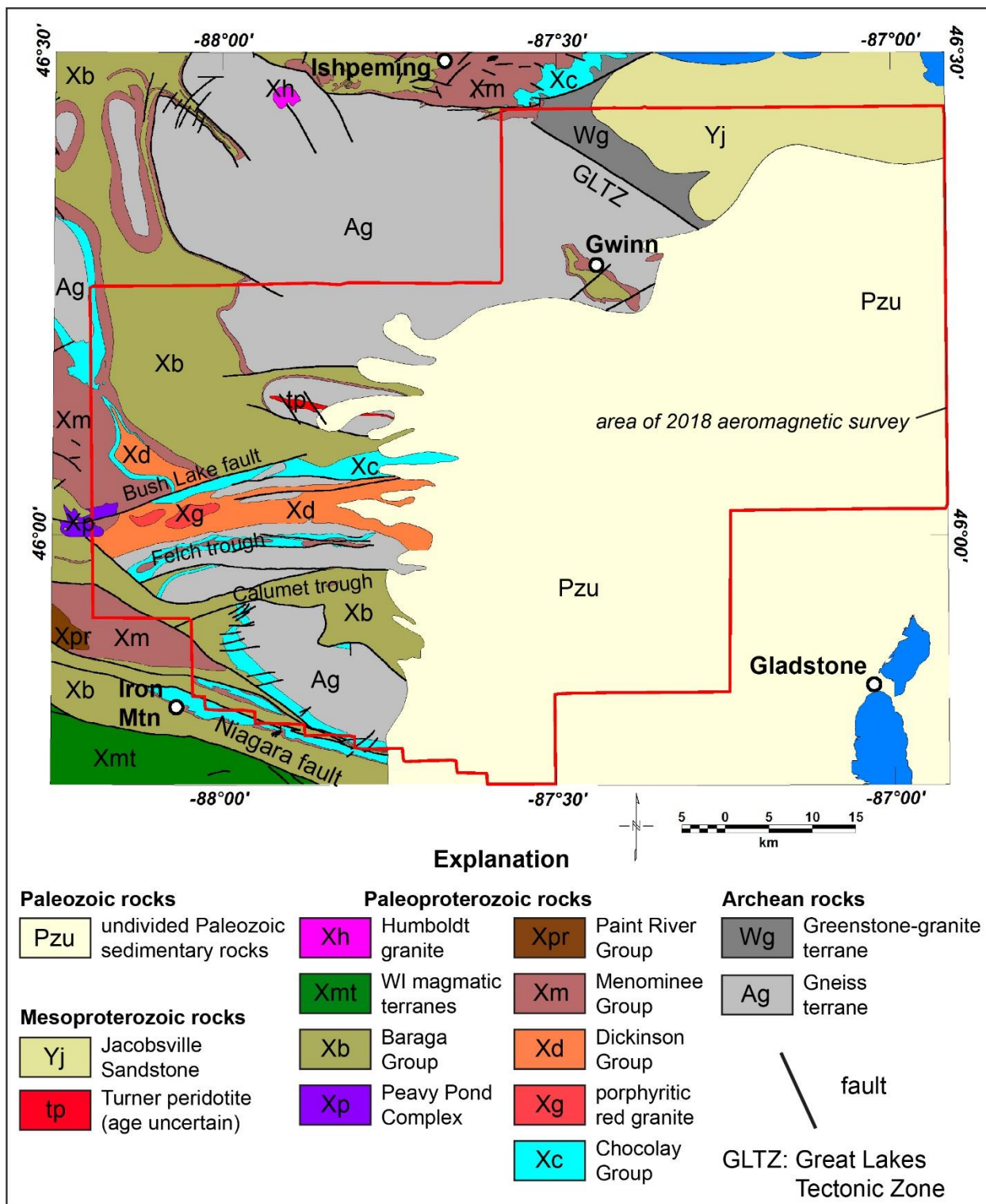


Figure 1: Simplified bedrock geology of the aeromagnetic survey region, modified from Cannon and Ottke (1999) and Cannon et al. (2018).

What do detrital zircon studies of the Huronian Supergroup tell us? an analysis of all published data

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Since the publication of the first detrital zircon analyses from the Huronian Supergroup in 2006 (Rainbird and Davis 2006), detrital zircon work has been completed on more than 25 samples of the supergroup, from almost every unit (except for the Pecors, Espanola and Bruce formations) (Craddock et al. 2013; Davis et al. 2018; Easton and Heaman 2008, 2011; Hill et al. 2018; Kenny et al. 2018; Long et al. 2011; Ménard 2017; Petrus et al. 2016; Rasmussen et al. 2013). Most of this work occurred in the area between Sudbury and Sault Ste. Marie, all north of the Murray fault, with only 2 samples studied so far from the Cobalt basin northwest of Sudbury. These data are summarized in Table 1, with age ranges and averages based on grains that are < 5% discordant, a lower cutoff than used in most studies. Key observations are:

- Zircons between *circa* 2450 and 2490 Ma, likely derived from either Huronian Supergroup volcanic rocks and/or related mafic and felsic intrusions, so far have been reported only from the Matinenda or the Mississagi formations, generally from sample sites near the base of the supergroup.
- Samples from the lower Huronian Sgp (Elliot Lk and Hough Lk groups) are dominated by Geon 26 detritus, consistent with provenance dominated by local sources characteristic of the Ramsay-Algoma granitoid complex. Where detailed stratigraphic sampling has occurred, the lowermost units have unimodal populations, becoming more diverse with increasing stratigraphic height (e.g., Easton and Heaman 2011). The only exceptions are the 2 samples from the Cobalt basin, which are dominated by Geon 27 populations, consistent with more >2.7Ga basement in that area.
- Above the Mississagi Formation, Geon 27 populations are dominant, but Geon 28, 29 and Geon 30 grains are also commonplace. This may reflect a change in sedimentation style, and/or increased erosion of the hinterland resulting in a wider range of source material becoming available.
- The uppermost Huronian Sgp units have ages of *circa* 2310 Ma (Hill et al. 2018; Rasmussen et al. 2013), meaning deposition of the entire supergroup took place between *circa* 2460 to 2310 Ma.
- Persistent throughout the sequence are occasional Geon 25 grains, typically with ages of 2550-2590; these grains become somewhat more abundant in the upper two groups. These grains have no known local source, and as suggested by Bleeker (pers. comm. 2019). may have a source region to the south, such as the Kaapvall craton, that was subsequently rifted away from North America.
- Currently it is not possible to determine if the detrital zircon populations differ between glaciogenic (e.g., Ramsay Lake, Gowganda) units and the non-glaciogenic sandstone units.
- Grains >3.0 Ga occur sporadically throughout the supergroup, mainly in the Matinenda and Mississagi formations, and could be sourced locally from Michigan (see Ayuso et al. 2017). More difficult to explain is the population of 29 ancient grains, 3.0-3.6 Ga, in the Gowganda Formation sample from Cobalt. Is this sourced locally in the Cobalt area, or have these grains been transported from sources currently exposed on the northeast shore of Hudson's Bay? It is unclear if the sampled unit is glaciogenic or not, as the sampled rock type was not specified by Kenny et al. (2017).

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Table 1. Summary of data for all Huronian Supergroup samples based on grains $\leq 5\%$ discordant, in most studies many more grains were analyzed. For samples with significant discordance, the lower numbers shown are for grains $\leq 10\%$ discordant. Also indicated are grains per Geon. All samples are sandstones unless otherwise noted. Samples from the Cobalt Basin are in italics. Abbreviations: cong, conglomerate; EL, Elliot Lake area; MCB, main conglomerate bed; S, Sudbury area; TH, Thessalon area.

Formation	Number	Range (Ma)	Main Peak (Ma)	24	25	26	27	28	29	>3.0
Bar River mudstone	n=16	2279-2745	2344		5	1	2			
Bar River EL	n=62	2523-3074	2706 (27>>26)		5	18	30	2	4	3
Gordon Lake EL	n=57	2284 -2840	2317 , 2702 (26 $\approx$ 27)	2	3	20	22	1		
Gordon Lake EL		3 sites	2308, 2308, 2311							
Lorrain EL	n=30	2684-2890	2713 (27>26)			6	18	6		
<i>Gowganda</i>	<i>n=172</i>	<i>2520-3614</i>	<i>2705, 2857, 2965, 3076, 3316 (27>26)</i>		2	34	51	38	18	29
Serpent EL	n=46	2549-3576	2719 (27>>26)		1	9	22	11		3
Serpent EL-S	n=10	2531-3317	2688 (5%)		1	4	4		1	1
	n=19	2531-3317	2688 (10%)		2	8	8			
Mississagi EL	n=63	2443-3617	2466 , 2692 (26>27)	4	5	24	13	4	7	9
Mississagi EL-S	n=22	2591-2832	2663 (26>>27)		2	18	1	1		
Mississagi (upper) S	n=130	2388-3286	2477 , 2697 (26 $\approx$ 27)	2	2	57	57	9		2
Mississagi S	n=117	2414-2978	2490 , 2560, 2689	3	10	47	39	11	7	
Mississagi S	n=72	2544-2949	2683 (26>>27)		4	44	22	2		
Ramsay Lake EL-S	n=65	2656-2887	2697 (26>27)			35	28	2		
Ramsay Lake S	n=25	2526-2719	2659 (26>>27)		3	19	3			
Ramsay Lake S cong	n=37	2607-2821	2677 (26>>27)			27	8	2		
McKim S	n=36	2533-2752	2670 (26>>27)		3	26	7			
<i>Mississagi cong</i>	<i>n=210</i>	<i>2366-2906</i>	<i>2459</i> , 2703, 2771	1	3	78	122	4	1	
Matinenda S	n=39	2505-3774	2557, 2661 (26>>27)		11	22	5			1
Matinenda EL-S	n=27	2451-2714	2457 , 2671 (26>>27)	3		20	4			
Matinenda EL	n=30	2650-2742	2680 (26>>>27)			25	5			
Matinenda (upper) EL	n=47	2620-2897	2664 (26>>>27)			47	3	1		
Matinenda EL	n=36	2617-2776	2649 (26>>>27)			33	3			
Matinenda above	n=5	2634-2651	2641 (5%)			5				
MCB EL	n=15	2621-2684	2643 (10%)			15				
Matinenda below	n=28	2546-2838	2641 (26>>>27)		3	24		1		
MCB EL										
Livingstone Creek TH	n=37	2507-2890	2698 (26 $\approx$ 27)		1	17	16	3		

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Hyperspectral Imaging of Bedrock Core from the Minnesota DNR Drill Core Library: A New Tool for Archival Preservation and Mineral Exploration

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The Minnesota Department of Natural Resources (DNR) hired Corescan Inc. to scan 4900m of bedrock core from the DNR Drill Core Library (DCL) using Corescan's hyperspectral core imaging system (Martini et al, 2017). The technique integrates both Visible Near InfraRed (VNIR) and Shortwave Infrared (SWIR) reflectance spectroscopy with high-resolution photography (50 µm) and 3-d laser profiling (200 µm) to identify minerals, estimate mineral abundances and create textural maps at 500 µm resolution. Hyperspectral imaging is a non-destructive analytical technique that supports the archival preservation of limited core material. Project results support DNR land management decisions on state mineral rights and promote mineral exploration and development. This project for the first time will provide public access to hyperspectral imaging data archived within the Coreshed® Virtual Core Library. DNR anticipates public release of project data and public access to Coreshed by summer, 2019.

The DNR selected project core from thirty-two (32) drill holes located in five areas in Northern and Central Minnesota with distinct mineral deposits and/or high mineral potential. Initial project results are from an Archean Wabigoon Subprovince greenstone terrane near International Falls (Seine Group) and Biwabik Iron Formation core from the Mesabi Range.

The Seine Group of greenschist-facies, metasedimentary and metavolcanic rocks sits at the contact between the Wabigoon and Quetico Subprovinces of the Archean Superior Province (Jirsa et al., 2014). Gold exploration in the region included an active period of drilling in the late 1980's. Frey (2012) re-logged and re-sampled several of the DCL-archived Seine Group cores, and identified alteration patterns and features favorable for gold mineralization, including greater abundances of porphyroblastic and vein tourmaline. Hyperspectral imaging of twelve archived DCL cores from the area extends Frey's tourmaline observations to drill cores that (due to active exploration) were not available at the time of his study. There is a positive correlation between gold concentrations and hyperspectral mineral identification of under-recognized tourmaline. Variations in the 2350nm feature position (Bierwirth, 2008) suggest tourmaline compositions within the dravite-schorl series (*Figure 1*).

Complete or near complete transects of the Biwabik Iron Formation (BIF) were imaged in six Mesabi Range drill cores (LWD99-1, LWD99-2, MDDP-2, -5, -7, and -8). Hyperspectral imaging of core from LWD99-2 is able to differentiate microplaty hematite banding from more martite-rich bands. Two chlorite types are also recognized within this same core based on absorption features; an Mg-Fe intermediate composition that occurs in the Virginia Formation and its contact with the underlying Upper Slaty Unit, and a more iron-rich chamosite found in the Lower Cherty Unit and its contact with the underlying Pokegama Quartzite.

Average albedo in the visible spectral range (448-740nm) highlights variation within the heavily sampled contact between the BIF and overlying Virginia Formation, where Addison et al. (2005) identified an ~25 to ~58cm thick ejecta layer associated with the 1850Ma Sudbury impact event. White mica is recognized based on absorption features within an ~ 2.6m interval of LWD99-2 core at the transition from BIF to Virginia Formation. Within this occurrence interval, a much smaller ~ 38cm interval with ammonium-rich white mica (feature around 2010nm, Canet et al. (2015)) is recognized in a thin layer of cherty carbonate. The discovery of relatively rare ammonium-rich white mica in association with an identified ejecta layer, if confirmed, would be significant.

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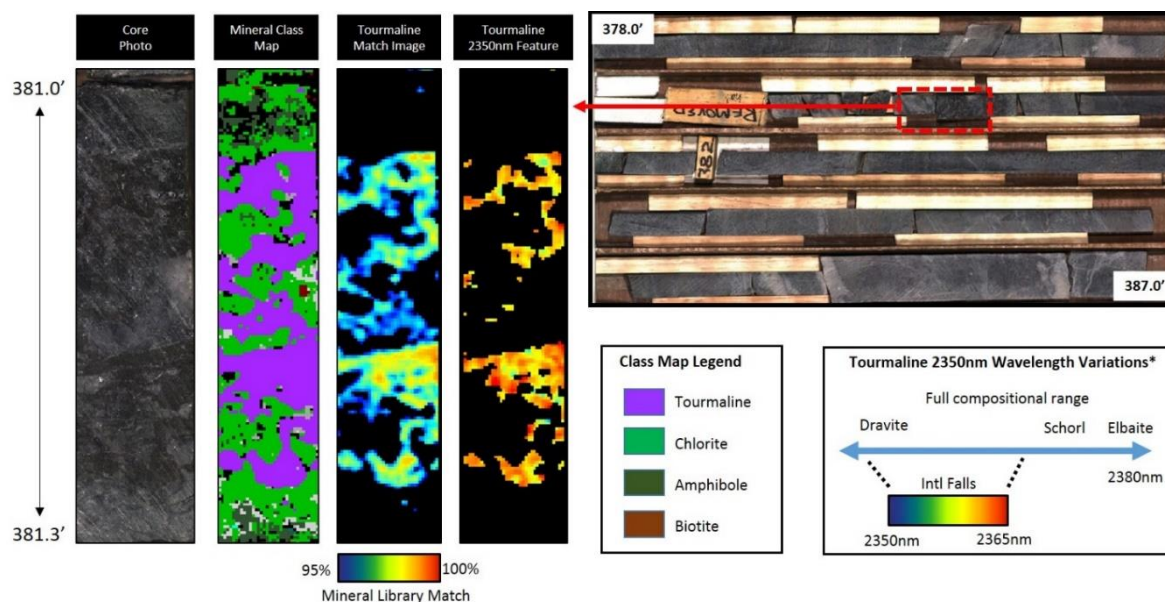


Figure 1: Hyperspectral imaging of tourmaline within an 8cm-long section of quarter-core from DDH TC35-1. This section is within a larger 4 foot (1.22m) core interval that assayed at 4020ppb Au. Variations in the 2350nm feature position (Bierwirth, 2008) suggest compositions within the dravite-schorl series.

Geology and Geochemistry of the Laird Lake Property and Associated Gold Mineralization, Red Lake Greenstone Belt, Ontario

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The Red Lake greenstone belt (RLGB) is one of world's best endowed gold districts and like many other gold-rich regions, the individual deposits are closely associated with regional contacts, in part unconformable (Robert et al., 2005). A regional break in Red Lake separates the Mesoarchean and Neoarchean assemblages and hosts 94% of all gold (production, reserves, and resources; Dubé et al., 2003) in the greenstone belt, yet, the relationship between the two Archean packages is still disputed in terms of tectonic history (Stott, 1996; Stott and Corfu, 1991; Hollings and Kerrich, 2000; Roger et al., 2000; Sanborn-Barrie et al., 2001; 2004; Hollings and Kerrich, 2006).

The Laird Lake property encompasses the regional break between the Balmer (2.99 to 2.96 Ga) and the Confederation (2.74 to 2.73 Ga) assemblages on the south-western end of the Red Lake greenstone belt, Northwestern Ontario. Multiple gold occurrences on the Laird Lake property generally occur within 200 m of the regional break and could represent the continuation of a similar gold system as seen at the Madsen Mine. The purpose of this study was to determine the tectonic setting in which the assemblages formed, and to characterize the controls on and nature of the gold mineralization associated with the tectonic contact between the Balmer and Confederation assemblages. Only 10 km east of the study area is the past-producing Madsen Mine, which lies on the north side of the regional break between the Balmer and Confederation assemblages. The ore is locally defined by the Austin and McVeigh ore zone, which displays a characteristic mineral banding (Dubé et al., 2000).

Detailed mapping of the Laird Lake area highlighted major differences between the two assemblages (Gélinas, 2018). The Balmer assemblage is typically composed of fine-grained, aphyric, locally pillowed mafic volcanic rocks, ultramafic intrusive and volcanic rocks with flow-breccia textures and local spinifex-bearing clasts, and banded-iron formations. In contrast, the Confederation assemblage consists of porphyritic (feldspar) or poikiloblastic (amphibole) mafic volcanic rocks intercalated with intermediate to felsic volcanic rocks that include crystal lapilli tuffs, crystal tuffs and tuffs. Syn-volcanic and syn- to post-D₂ intrusions commonly cross-cut the volcanic packages. A regional foliation (~E-trending) is present throughout the volcanic rocks and increases in intensity at the tectonic contact between the two assemblages where a deformation zone no thicker than 100 m is present within the Balmer assemblage.

Whole-rock geochemical analyses were undertaken on 161 samples from the Laird Lake area. The Balmer assemblage is composed of tholeiitic mafic volcanic rocks with minor Al-undepleted komatiites, whereas the Confederation assemblage is composed of transitional mafic and calc-alkalic intermediate to felsic volcanic rocks, which display FI, FII, and FIIIb rhyolite trends. Neodymium isotope analyses, in conjunction with trace element geochemistry, suggests that parts of the Balmer assemblage were weakly contaminated by an older intermediate basement. The data suggests both arc and back arc volcanism within the Confederation assemblage, with the arc rocks showing stronger a crustal component than the back-arc rocks. U-Pb geochronology of volcanic and intrusive Confederation units yielded ages of 2741 ± 19 Ma (FI quartz-feldspar porphyritic crystal tuff) and 2737.68 ± 0.79 Ma (diorite). The geochemistry and age of the tuff correlates within error to the Heyson sequence of the Confederation, whereas the diorite is likely a syn-volcanic intrusion.

The Balmer assemblage is interpreted to represent an oceanic plateau formed by plume magmatism on the margins of the North Caribou Terrane whereas the Confederation assemblage was likely built in an oceanic arc setting where both arc and back arc volcanism were occurring simultaneously. The presence of xenocrystic zircons within the 2741 Ma quartz-feldspar porphyritic crystal tuff suggest that melts within the main arc incorporated xenocrystic zircons during ascent through a thin Mesoarchean crustal fragment. Juxtaposition of the Confederation assemblage onto the Mesoarchean assemblages likely occurred between 2739-2733 Ma.

Gold mineralization at the Laird Lake property is controlled by a D₂ deformation zone within the Balmer assemblage at the tectonic contact between the Balmer and Confederation assemblages. The mineralization is commonly found associated with a mineral banded parallel to the main D₂ fabric, accompanied by disseminated arsenopyrite, pyrrhotite, pyrite ± chalcopyrite, similar to the features observed at the nearby Madsen Mine. The Laird Lake property likely represents the continuation of the same mineralized structure found at both the Madsen and Starrat-Olsen mines and was later displaced as far as 10 km west by the dextral Laird Lake fault post-2704 Ma.

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Petrography of several Co-enriched samples from the Atikokan River Intrusions, Atikokan, Ontario

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The Atikokan River Intrusions (ARIs) consist of five or more sulfide and oxide-rich mafic intrusive bodies that have been emplaced along a 28-km section of the Quetico Fault Zone (QFZ) east of Atikokan, ON. Sulfide and oxide mineralization within these intrusions was historically explored for iron ore, and locally developed into at least one small-scale, open pit and underground mine in the late 19th century. The intrusions and associated mineralization are also variably enriched in copper, nickel, and cobalt. Great Lakes Exploration, Inc. (GLE) currently controls an approximately 12-km long stretch of the ARIs, which includes a significant portion of the mineralized intrusions. GLE is currently evaluating the potential for these intrusions to contain cobalt, copper, and nickel at concentrations and in mineral phases that are economically recoverable. Optical petrography (reflected and transmitted light) observations, and bulk geochemical data, from seven ARI hand samples, constrain the nature of Co-mineralization and provide information on textural relationships between minerals, as described here.

Petrographic characterization indicates that sulfide mineral assemblages includes pyrrhotite, pyrite, and chalcopyrite. The presence of trace sphalerite was previously identified in other samples by QEMSCAN (conducted by XPS Consulting and Testwork Services). Pyrite occurs as 100- to 200- μm sized grains, while pyrrhotite and chalcopyrite occur as smaller 20- to 50- μm sized grains that compose larger aggregates that partially encompass pyrite grains. None of the observed sulfides display complex intergrowth or exsolution textures in the samples evaluated. Magnetite occurs with most sulfide assemblages, contains both chalcopyrite and pyrrhotite inclusions, appears to be roughly positively correlated with pyrrhotite abundance, and can locally replace pyrite. The abundance (15 to 20 volume percent) and textural relationship (e.g., contains sulfide inclusions and crosscuts/replaces igneous phenocrysts) suggest that at least a portion of the observed magnetite is secondary. Though no stoichiometric cobalt phase was definitively identified via optical petrography, cobalt assay results correlate well with pyrite abundance, consistent with the presence of cobaltiferous pyrite. Textural relationships suggest that the observed sulfide assemblage evolved from an early pyrite- to a late pyrrhotite-dominant assemblage, with chalcopyrite present in both early and late assemblages but likely increased in abundance in the latter assemblage. Examples of sulfide and oxide mineral occurrences are provided in Figure 1A-B.

Observations on silicate mineralogy help to establish potential peak metamorphic conditions, understand origin and composition of mineralizing hydrothermal fluids, and provide guidance in constraining timing of mineralization. Coarse-grained chlorite intergrowths with pyrrhotite appear to suggest that a portion of the observed mineralization possibly occurred during metamorphism. The lack of primary igneous minerals, in most samples, suggests that secondary alteration was intense, at least locally, and that peak metamorphic conditions reached upper

greenschist facies; historic reports (MacTavish, 1999) of rarely preserved garnet suggest that metamorphic conditions could have reached lower-most amphibolite facies at other locations within the ARIs. Examples of alteration products and textures are shown in Figure 2A-B.

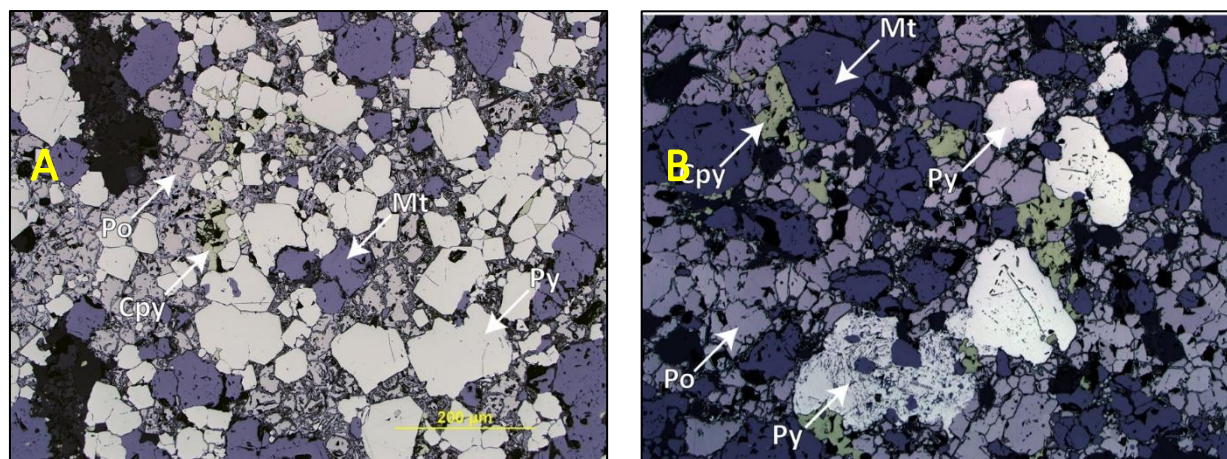


Figure 1. Examples of typical ARI sulfide assemblages. Both images taken in plane-polarized, reflected light. A) Coarse-grained pyrite and magnetite locally supported by a pyrrhotite-rich matrix. Trace chalcopyrite occurs between pyrite grains. Magnetite locally replaced several pyrite grains near the center portion of image. Pyrrhotite displays a slender reaction rind. B) Typical pyrite, pyrrhotite, and chalcopyrite assemblage. Several of the pyrite grains contain a distinct pitted core (partially outlined by dashed line) surrounded by a broad growth zone lacking inclusions, which might possibly indicate pyrite growth occurred in two stages. The scale of the image is the same as Fig. 1A.

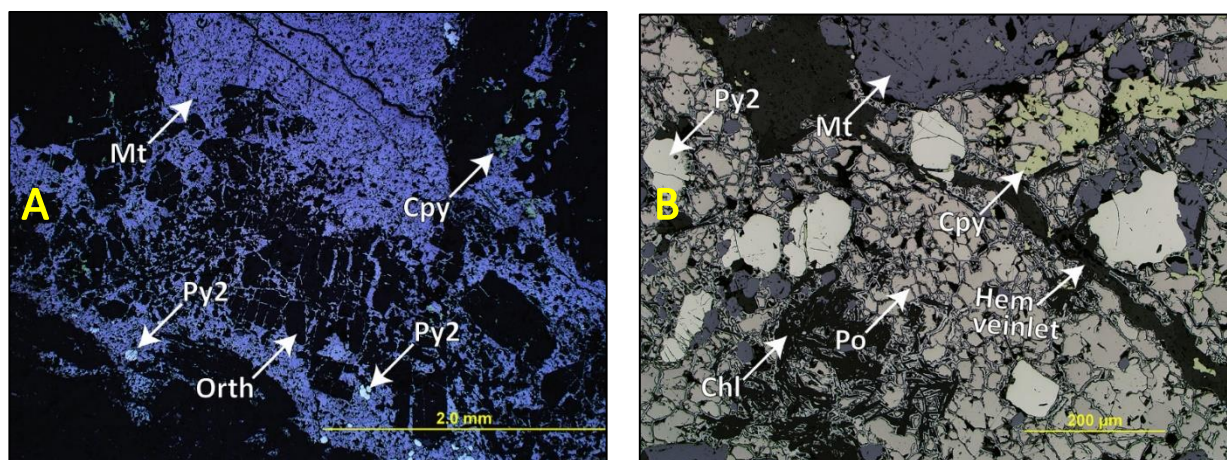


Figure 2. Mineral textures that help to constrain the timing and origin of observed sulfide assemblage. Both images taken in plane-polarized, reflected light. Images have been edited to highlight contrast between mineral phases. A) Large igneous orthoclase phenocryst replaced by magnetite. Trace amounts of pyrite and chalcopyrite occur within the magnetite. Pyrrhotite is absent from the sample. B) Coarse-grained, secondary chlorite is intimately intergrown with pyrrhotite in lower left portion of image. Alteration rind on pyrrhotite is very well developed in this sample. Pyrite locally replaced by magnetite. Chalcopyrite and pyrrhotite exhibit strong spatial association that is typical of this sulfide assemblage.

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Recognizing MCR magmas generated by partial melting in the SCLM: Lessons from mafic magmas in the Coldwell Complex

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We present new interpretations of a comprehensive data set for basalt and intrusive mafic rocks from the Midcontinent Rift. These data display well-defined trends for trace element abundances that demonstrate variable degrees of partial melting in a plume-like source and subsequent fractional crystallization. For instance, diagrams that compare highly incompatible elements Zr and La, La and Yb, or Nb and Th in MCR rocks show the majority of data plot in a field that spans compositions from E-MORB to OIB along approximately linear trends with constant inter-element ratios. Data that deviates from these MCR trends are explained by interaction of the magma with continental crust during ascent, consistent with elevated Th contents or Rb-Sr and Sm-Nd isotope values that confirm contamination. However, there are cases where evidence such as relative Th or major element abundances contradict isotopic evidence that may or may not agree with crustal contamination. Indeed, multiple isotope systems (Pb-Pb and Nd-Sm) are sometimes in disagreement with respect to the degree of contamination.

Another mechanism that might explain such irregularities is partial melting of a metasomatized SCLM source (Furman and Graham, 1999; Sgualdo et al., 2015). It has been well established that initial SCLM isotope values can be overprinted by metasomatism, and therefore isotope systematics, in particular Rb-Sr and Sm-Nd are ineffective for distinguishing between crustal contaminated plume magmas and SCLM-derived magmas. Establishing a set of geochemical criteria that could be used to distinguish between mafic rocks in the MCR that were generated by partial melting in the metasomatized SCLM from plume magmas that were contaminated in the crust is the subject of this presentation.

In wide-ranging studies of mantle xenoliths from Africa, New Zealand and Europe, secondary minerals found in veins include phlogopite, clinopyroxene and pargasitic amphibole (Frezzotti et al., 2010; Scott et al., 2014). The trace element signatures of each phase exhibit distinguishing features that, since they are among the first minerals to disappear during a partial melting event, will impart distinctive trace element signatures to the resulting magma composition. For instance, the different compatibilities of Rb, Ba and Sr in amphibole compared to phlogopite, or Nb and Th in amphibole compared to clinopyroxene will result in decoupling of LILE abundances due to the relative proportions of each mineral in the source rock. As these minerals contain very high concentrations of incompatible elements relative to the depleted protolith SCLM rock, a relatively small amount (<1-2%) of each mineral will have a very large impact on the resultant magma composition enabling recognition of trace element signature. Magmas generated from Areas of SCLM that have been less impacted by metasomatism, and thus might have a very low proportion of secondary minerals, will have a depleted HFSE signature marked by sub-chondritic Zr/Y, Zr/Hf and very low La/Yb values, and possibly anomalous Sr and Ba.

A key example of volcanic rocks that show contradictory isotopic and geochemical evidence for crustal contamination is Mamainse Point Volcanic Group 5b (Shirey et al., 1994), in

which the ϵ_{Nd} values of -3.5 and -6.3 indicate significant crustal contamination, but Pb-Pb data imply a maximum of 2% crustal material. The combination of sub-chondritic Zr/Y and Zr/Hf, low La/Yb, very low La, Th, and TiO₂ abundances, and corresponding positive Ba and Sr anomalies is strong evidence for derivation from a weakly metasomatized but initially depleted SCLM source. Examples of MCR magmatism from the Nipigon embayment that exhibit SCLM-like signatures are presented to test the usefulness of key features identified in mafic rocks of the Coldwell Complex that distinguish them as originating from the SCLM. The geochemical characteristics of the Nipigon intrusions are examined as test cases to establish whether or not they were derived from the SCLM.

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Recent Efforts to Curate and Provide Access to the Historical Documents of the E.K. Lehmann and Associates Exploration Company

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In October of 2015, the Wisconsin Geological and Natural History Survey (WGNHS) received a large donation of documents from Kate Lehmann, the daughter of renowned exploration geologist Ernest K. Lehmann. While Lehmann worked primarily in Minnesota, his company, E.K. Lehmann and Associates, also worked in northern Wisconsin from the late seventies into the mid-nineties and, during that time, donated a large amount of core from their drilling projects to WGNHS. After Ernest Lehmann passed away, his family donated the records related to his work in Wisconsin to WGNHS, and the paperwork related to his work in Minnesota to the Minnesota DNR.

With financial assistance from the Lehmann family, the Minnesota DNR scanned all of the documents donated to them and added them to their Drill Core Library and Mineral Exploration Collections' interactive map to provide online access. Staff at WGNHS have provided something similar to our users, but with a more narrowly focused scope. The donation to WGNHS was quite large—31 record boxes of reports and other documents, and two cardboard cases of rolled maps and figures. As WGNHS possesses limited resources, we knew we would have to find a way to focus our curation efforts. Consulting with Tom Evans, an emeritus Survey staff member and an authority on mining in Wisconsin, we decided to concentrate on documents that directly related to rock core in our possession. From December of 2015 to February of 2017, Tom Evans and Brad Gottschalk, the WGNHS archivist, searched for documents that provided data for drillholes. Once these were identified, they matched the Lehmann drillholes to records in our geological database, Geobase. 351 individual drillholes in 67 exploration targets were identified in the Lehmann documents. Of these 351 holes, we had physical core from 289.

Some of these Lehmann targets are still considered areas of interest for mineral development. The targets most extensively explored were Bend in Taylor County, Ritchie Creek in Price County, and Horse Shoe in Lincoln County. The documentation for drillholes in these and other targets include location maps, geological maps, logs, geological and geophysical cross-sections, chemical analyses of samples and assay reports.

In 2017, we received a grant from the USGS's National Geological and Geophysical Data Preservation Program (NGGDPP) to scan the Lehmann papers and put them online using an interactive map application. Selecting the documents for scanning was a complicated task. In the paperwork were monthly reports for many of the targets, as well as memos and final reports. The documentation for the drillholes was frequently duplicated in multiple monthly reports as well as in the final report. There were multiple cross-sections for the more widely explored targets, and, especially for the Bend target, which showed promise as a gold deposit, there was a great deal of assay data. Gottschalk and two student employees weeded out duplicates and scanned each unique document. In the end, some drillholes represented in the Lehmann papers were not included in the web application due to poor or incomplete data. After excluding these, we compiled data for 331 drillholes in 65 targets contained in 1153 individual documents. Of the 331 holes represented in the project, we have physical core samples from 288.

As the scanning portion of the project neared completion, Caroline Rose, GIS specialist, began to construct the ArcGIS application that would provide online access to the documents. Rose used ArcGIS Online's Storymaps templates and Web App Builder to present the Lehmann collection in two web maps: one organized by drillhole and one organized by exploration target. The first map features point locations and details of individual drillholes and links to all related documents. Document details can be followed to show all drillholes related to the document. Documents can be opened in PDF format from the map popup or from a table in the interface. The second web map shows exploration targets, which are collections of drillholes, as circular symbols sized according to the number of related documents. It is immediately apparent that three of the targets are related to more than fifty documents (Bend, Ritchie Creek, and Horse Shoe). Several other targets are related to more than ten documents. The targets are linked to their related documents. Again, documents in PDF format can be opened from the map or the table.

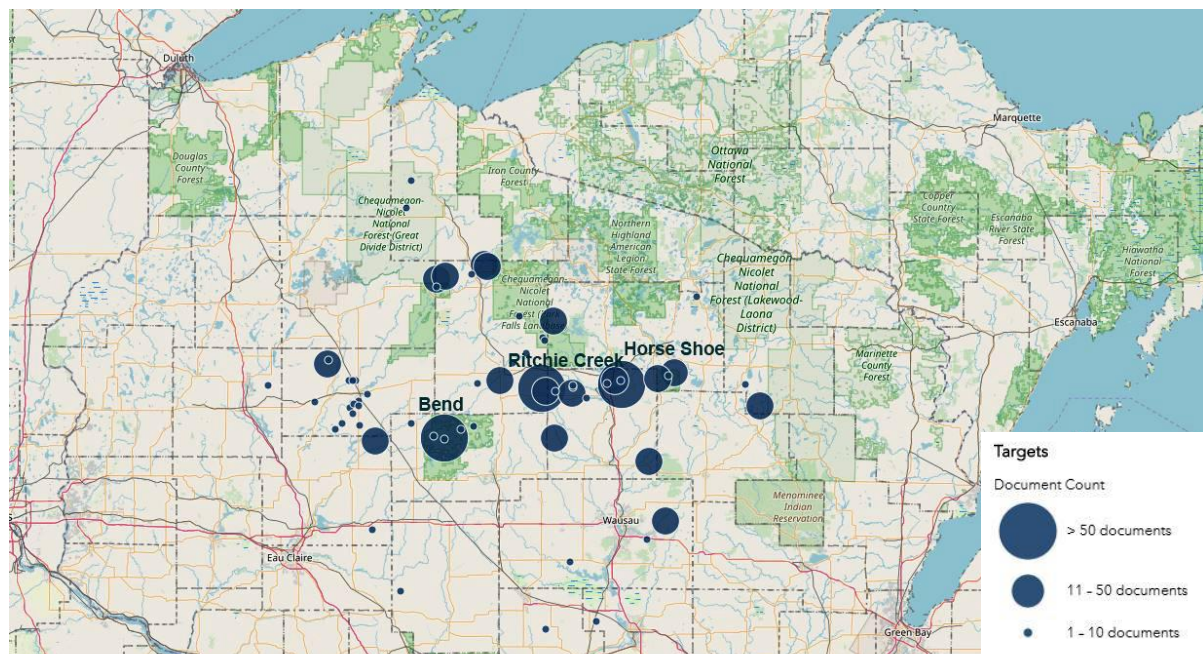


Figure 1: The interactive map showing the exploration targets represented in the Lehmann papers.

Rose configured the data using ArcGIS Pro to establish many-to-many relationships between the datasets, as one drillhole could be related to many documents, and one document could be related to many drillholes. She then used the ArcGIS Online WebApp Builder to create the interface, and a Storymaps template to create the tabbed layout.

At the end of the project, metadata records for the 1153 documents scanned and put online were uploaded to the USGS National Digital Catalog.

References

Minnesota DNR, 2016, Lehmann Family fund collection of Mineral Exploration Documents (including the Polaris Joint Venture (https://www.dnr.state.mn.us/lands_minerals/polaris/index.html))

Superior Shoal Revisited: Evidence for Keweenaw Basalts with Reversed- and Normal-polarity Remanent Magnetization and Early Magma Chemistry, Central Lake Superior

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Superior Shoal is an easterly trending, ~20-km-long bathymetric bedrock high below the water's surface near the center of Lake Superior. Being the only accessible bedrock within a radius of about 70 km, the Shoal can provide evidence critical to understanding the structure of the 1.1 Ga Midcontinent Rift in central Lake Superior, yet debates remain about its geology. Located at the intersection of two geophysically interpreted faults, the bathymetric high is composed of a series of ridges of Keweenaw basalts on the south and a broader ridge of sandstone on the north (Manson and Halls, 1991).

Previous studies of Superior Shoal give conflicting results on the age of the basalts based on the polarity of remanent magnetization. Magnetic polarities are commonly used to recognize early (>1100 Ma) Keweenaw lavas (reversed-polarity) from younger (<1100 Ma) lavas (normal-polarity), while acknowledging a separate normal-polarity event between ca. 1101-1103 Ma (Swanson-Hysell et al., 2019). Manson and Halls (1991) concluded from paleomagnetic measurements that the basalts have normal-polarity remanence, whereas Teskey et al. (1991) concluded from analysis of aeromagnetic data that the basalts have reversed-polarity remanence.

To resolve the apparent disagreement regarding magnetic polarity, we (1) reviewed the paleomagnetic results from the Manson and Halls study, (2) expanded on the aeromagnetic analysis of the Teskey et al. study, and (3) analyzed basalt samples collected during the paleomagnetic study of Manson and Halls to determine if they are chemically affiliated with typical early or late rift lavas (Nicholson et al., 1997).

Review of Paleomagnetic Study of Manson and Halls

A review of the methods, analyses, estimated errors, and results of the Manson and Halls (1991) study from their three basalt sites at Superior Shoal give confidence in their results. They found primary normal-polarity components, although orientations are somewhat dissimilar to those expected for typical normal-polarity Keweenaw basalts. They attributed the dissimilar directions to tectonic tilts that are nonuniform, but generally have northerly dip.

Expansion of Aeromagnetic Analysis by Teskey et al.

Teskey et al. (1991) analyzed the negative aeromagnetic anomaly at Superior Shoal using the principle that magnetic rocks forming rugged bathymetry should produce aeromagnetic anomalies that correspond to bathymetric shapes. In comparing the bathymetry of Superior Shoal to aeromagnetic anomalies along profiles, Teskey et al. noted an inverse correlation between bathymetric and aeromagnetic highs and lows, suggesting a reversed-polarity remanence. Expanding on this approach, a three-dimensional model of bathymetry was assigned magnetizations typical of normal versus reversed polarity for Keweenaw basalts. Comparisons of the magnetic fields computed from these models to the observed aeromagnetic anomaly show a good correspondence with the reversed-polarity model, supporting the conclusion that the bulk of the rock volume at Superior Shoal possesses very strong, reversed-polarity remanence.

Chemical Analysis of Paleomagnetic Samples

Recently, 10 samples from basalt sites 1 and 2 of Manson and Halls (1991) were analyzed for major and trace elements. The Superior Shoal basalt samples have similar geochemical characteristics with a limited range in MgO = 5.4 to 8.1 wt.%, TiO₂ = 1.6 to 2.4 wt.%, and La/Yb = 6.5 to 7.2. They are most similar in composition to Siemens Creek Type II basalts and are comparable to the Central suite of the Osler Group (Fig. 1), both of which are composed of early, reversed-polarity lavas that are mostly older than ca. 1105 Ma (Nicholson et al., 1997; Swanson-Hysell et al., 2019). The results of the basalt analyses combined with the paleomagnetic results suggest that basalts with early magma chemistry but with normal-polarity remanence are present at Superior Shoal.

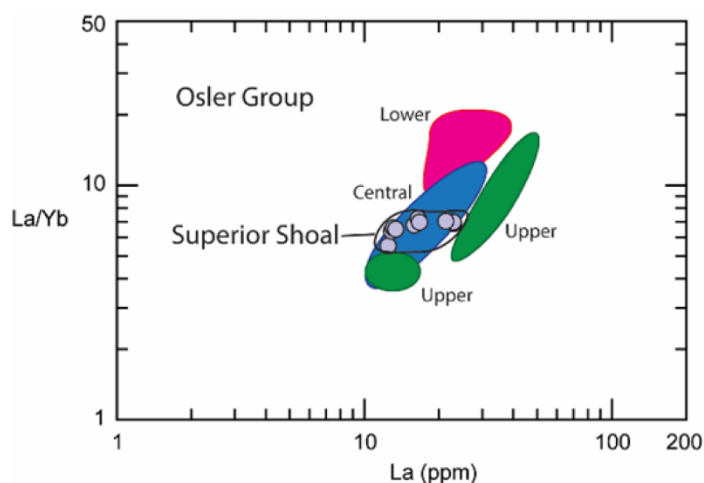


Figure 1. La vs La/Yb for Superior Shoal and Osler Group basalts (Osler Lower, Central, and Upper suites after Lightfoot et al., 1991).

Reconciliation of the Results

A more detailed analysis of flight-line aeromagnetic data allows that basalts of both polarities likely exist at Superior Shoal. Low-amplitude positive anomalies are superposed on the broader, high-amplitude negative anomalies, suggesting that a large volume of reversed-polarity early lavas underlie normal-polarity lavas of smaller volume (and/or lower magnetization). The apparent conflict of normal-polarity, early magma chemistry may be due to (1) magma typical of early rift magmatism that continued erupting into one of the later normal-polarity times, or (2) a previously unrecorded normal polarity event that occurred sometime between 1105 Ma and 1103 Ma. Further study at Superior Shoal appears warranted.

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Evaluating Alternate Geophysical Models along the Isle Royale-Superior Shoal Aeromagnetic Anomaly, Central Lake Superior

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As much as 3 km of Midcontinent rift basalts exposed on the NE-elongate island of Isle Royale (IR) in central Lake Superior dip SE and are commonly regarded as part of the upthrown block of a post-rift reverse fault just off the northern IR shore. A prominent, narrow, aeromagnetic high-low pair (IR-SS anomaly) emanates from the NE tip of IR, curving toward the SE to a strong negative anomaly at Superior Shoal (SS), a bathymetric high near the center of the lake (Fig. 1). The IR-SS anomaly is commonly interpreted as an extension of the IR reverse fault, involving younger (normal magnetic polarity) and possibly older (reversed magnetic polarity) rift basalts. Broad, linear to curvi-linear gravity highs parallel the IR-SS anomaly to the south (Fig. 1). A seismic-reflection line (GLIMPCE A) crosses the IR-SS anomaly at a complicated area of multiple linear magnetic anomalies (Fig. 1). The seismic section shows a 12-km-wide disrupted zone that extends vertically below the complicated area and divides packages of subhorizontal reflections that cannot be connected across the zone.

Previous geophysical models of the IR-SS anomaly satisfy some of the data sets, but none integrate all of them satisfactorily. For example, a vertical reverse fault with ~2.5 km of throw has been interpreted and modeled from the seismic-reflection and gravity data (Thomas and Teskey, 1994), but does not account for the shallow basalts observed near SS. Conversely, a magnetic model along flight-line L11260 east of GLIMPCE A (Fig. 1) fits the sharp IR-SS anomaly using a <5-km-wide zone of igneous rock extending from the lake bottom to ~4 km depth (Teskey and Thomas, 1994), but does not fit the broader gravity anomaly.

To develop models of the IR-SS anomaly that better integrate all the data and are constrained by new information that early lavas are preserved at SS (Grauch and Schulz, this volume), we tested a number of 2D gravity and magnetic models considering 3 conceptual models: (1) reverse fault with steeply dipping, south-facing basalt layers; (2) localized intrusions, such as volcanic feeder zones or dikes; and (3) remnants of an early-lava plateau extending northward from the IR-SS anomaly. We were unable to construct fully integrated models using the steeply dipping reverse-fault concept. Instead, models with moderately southward-dipping (<45°) basalt layers worked for profiles IRKP and IRKP2 (Fig. 1). The early-lava plateau remnant concept works well for profile L11070 across SS (Fig. 1). This model depicts strongly magnetic, reversed-polarity layers north of the IR-SS anomaly that abruptly terminate at the south side of the shoal (the linear positive anomaly there is the expression of this termination). Geologically, this model suggests that early lavas rest at shallow levels (~1 km depth) north of the IR-SS anomaly, possibly overlying a pre-rift sedimentary basin that has been pervasively intruded by a younger, rift-related mafic igneous complex. This is consistent with preliminary reinterpretations of GLIMPCE A, which suggest that a ~10-km thick, pre-rift sedimentary basin exists north of the IR-SS anomaly. Models that work best for profiles 8ext, 25ext, and 43ext include moderately dipping, south-facing basalts combined with concepts of both early-lava plateau remnants and localized intrusions.

The 2D model testing suggests that (1) the IR-SS aeromagnetic anomaly is likely the product of multiple geologic causes; (2) a steeply dipping reverse fault model is the least favored; and (3) models involving localized intrusions and shallow, early-lava and/or pre-rift rocks at or on the north side of the IR-SS anomaly need to be considered further.

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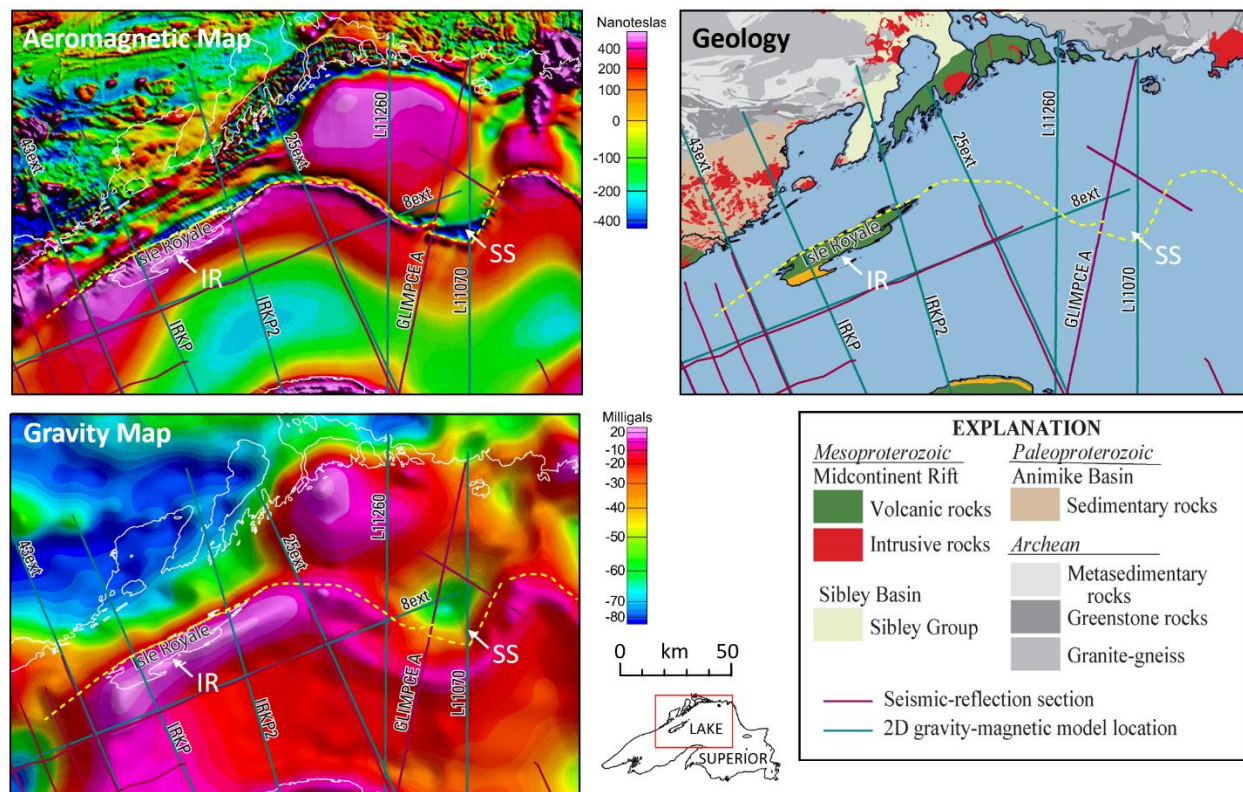


Fig. 1. Aeromagnetic, gravity, and geology maps for the study area showing locations of seismic-reflection lines and 2D model profiles. The IR-SS aeromagnetic anomaly is traced on all maps by the dashed yellow line. IR – Isle Royale; SS – Superior Shoal. Gravity and aeromagnetic compilations from Anderson and Grauch (2018). Geology generalized by E. Anderson from a USGS GIS compilation by C. Dicken (accessed January, 2015).

Geological characteristics and structural controls of Au mineralisation at the enigmatic Hemlo deposit.

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Hemlo is one of Canada's largest and most well-known mines, producing ~23 Moz Au since discovery in 1981. The deposit is located in the Hemlo-Schreiber greenstone belt within the Wawa sub-province of the Superior craton. The Wawa sub-province, with ~40 Moz Au endowment (past production + reserves + resources) represents the western continuation of the highly auriferous southern Abitibi sub-province (~281 Moz Au). The sub-provinces are separated by the Kapuskasing structural zone, which is thought to have facilitated uplift and erosion of the Wawa block, exposing deep, high-grade metamorphic rocks ranging westward from granulite to amphibolite (e.g. Thompson 2006).

Hemlo represents a rather unique deposit which is effectively isolated within the Hemlo-Schreiber greenstone belt. Located along the Hemlo shear zone, Hemlo is hosted within amphibolite grade tectonites of volcanic (predominately volcanoclastics and hypabyssal intrusion) and sedimentary origin (e.g. Muir 1997). The mineralisation is characterised by an unusual metal assemblage with significant enrichments of Mo-As-Sb-Hg-Tl-V-Ba, associated with K-metasomatism and pervasive feldspathisation (Poulsen et al., in press). The unusual characteristics of Hemlo mean it has been the focus of many scientific studies over the past ~35 years. However there is still no consensus regarding the deposit genesis and its origins remain enigmatic. This is in part due to the effects of high-grade metamorphism and intense deformation, which have modified the original character of mineralization and geometry of the ore body.

Historically, mining of the deposit has been carried out as 3 distinct operations; David Bell, Golden Giant (Main) and Williams (B- and C-zones) which has further hampered understanding of the system. Since unification of the mine by Barrick, a concerted effort has been made to determine the geological controls of mineralisation, focused primarily on the western-most C-zone, the main area of current operations.

The deposit can be split into two distinct zones (Fig. 1); [1] the Williams B-zone and eastern extensions; Golden Giant Main zone and David Bell (referred to as B-zone herein) and [2] the Williams C-zone. The B-zone, which accounts for most of the gold, is a moderate to steeply NE-dipping tabular ore body developed on the contact of a series of felsic volcanic rocks known as the Moose Lake Volcanic complex (MLVC) and a heterolithic volcanoclastic unit locally referred to as the "fragmental" unit (Poulsen et al., submitted). The B-zone represents the "classic" Hemlo ore, characterised by textually destructive K-feldspar alteration (microcline) with abundant pyrite, molybdenite, barite, and a variety of As- and Hg-bearing sulfides and sulfosalts. The grade-thickness distribution on a longitudinal section across the deposit (Fig. 1) highlights the overall NW-plunge of the mineralisation in this zone, with a main shoot plunging ~30° and a number of steeper internal shoots plunging ~60°. The geologic controls of these plunges are poorly understood at present and are the focus of on-going study.

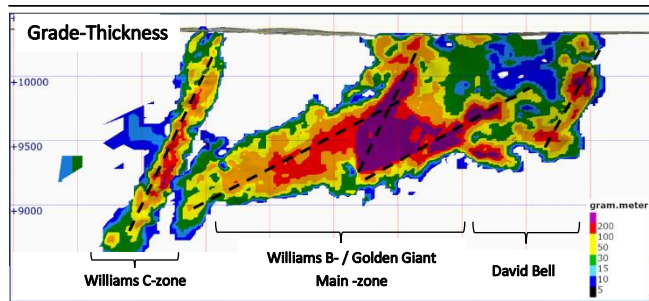


Figure 1: Interpolant gram.meter long sections (looking north) of the B-zone-David Bell (east) and Williams C-zone 100-series (west). The 300-series and B-zone footwall lodes not shown. Black-dashed lines highlight two apparent plunges to the mineralised system [60°-NW and 30°-NW]. Interpolant based on 0.5 g/t indicator grade shell.

The C-zone, located in the west part of the deposit comprises two sub-parallel W-striking moderately (~60°) plunging shoots (Fig. 1) known as the 100- and 300- series lodes. The 100-series mineralisation is developed within a tight NW plunging fold closure of the “fragmental” unit, whereas the 300-series is situated within the MLVC. The mineralisation is characterised by pervasive, textually destructive K-feldspar alteration with molybdenite and pyrite disseminations and stringers (Fig. 2a), cross-cut by high-grade recrystallized quartz veins and quartz-pyrite replacement zones (Fig. 2b). It is evident from

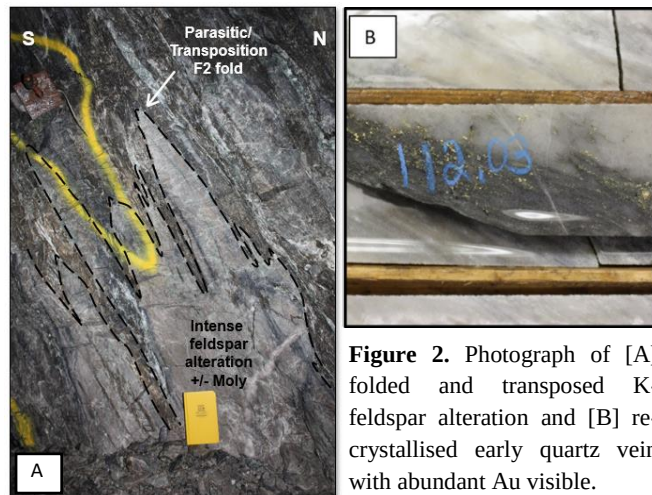


Figure 2. Photograph of [A] folded and transposed K-feldspar alteration and [B] recrystallised early quartz vein with abundant Au visible.

underground exposure and drill-core that the bulk of mineralisation pre-dates metamorphism and deformation: feldspar and quartz-pyrite alteration zones are folded and transposed by the penetrative S_2 foliation, which also transposes molybdenite and pyrite stringers (Fig. 2a). The early quartz veins and quartz-pyrite replacements display diffuse lobate contacts typical of recrystallised quartz, with sulfides and visible gold also transposed into the foliation planes (Fig. 2b). The current geometry of the C-zone mineralisation was evidently controlled by the development of F_2 folds. The overall moderate to steep NW-plunge of the mineralisation corresponds with plunge measurements of F_2 parasitic fold hinges and D_2 stretching lineations (e.g. Muir 2003). A late, post- D_2 mineralisation event is evident from a number of late crack-seal ribbon veins, oblique to and cross-cutting the S_2 fabric, and cutting the earlier quartz-pyrite mineralisation. These distinct and superimposed styles of mineralization indicate a complex and multi-stage history of the Hemlo deposit, a characteristic common to many giant gold deposits.

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Detrital Zircon Geochronology of Keweenaw Interflow Sediments within the North Shore Volcanic Group, Minnesota, U.S.A.

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During the early stages of the Mesoproterozoic Midcontinent Rift, the North Shore Volcanic Group was deposited around 1100 Ma. This group of volcanic rocks, composed of rhyolite, basalt, and andesitic basalt, are interlaid with detrital sediments whose source zircon ages do not coincide with the age of the rift system. These interflow sediments vary in composition, comprised of quartz arenite, lithic arenite, conglomerate, and conglomeratic sandstone. Collection of samples took place at two locations along the north shore of Lake Superior in Minnesota, USA. Samples were collected from ~10 m thick conglomeratic sandstone at Caribou Creek, a ~1 m thick overturned lithic arenite entrained in a xenolith of the Beaver Bay Complex at milepost 61 on Highway 61, and cross bedded sandstones at Leif Ericson Park in Duluth. Zircon analysis using LA-ICPMS at the University of Arizona Laserchron Center, determine the provenance of both these sandstones. Milepost 61 sample set (n=102) contains zircons with a maximum deposition age of 1081 Ma in addition to zircon ages ranging from 1073.0-1879.9 Ma. Using an age probability plot, four peak ages are identified to be 1116, 1440, 1688, 1778 Ma. The Caribou Creek sample set (n=61) contains zircon ages ranging from 1051.2-3184.1 Ma, with three peak ages of 1109, 1377, and 1730 Ma. A total of 101 zircons were analyzed for the Leif Erickson sample. Zircons from this sample ranged in age from 1074-2707 Ma and has a maximum depositional age of 1081 Ma. Age peaks for this sample are 1111, 1446, 1690 and 1778 Ma. Prior notions that interflow sediments were sourced only from within the rift system cannot be entirely true. New data we collected suggests that some of the interflow sediment was derived from an external source outside of the Midcontinent Rift basin. Zircon ages coincide with Archean terranes to the south, and may also include the Midcontinent Granite-Rhyolite, Mazatzal and Yavapai provinces. Fluxes in high lands from reactivation of faults bounding these provinces may have uplifted these potential source areas.

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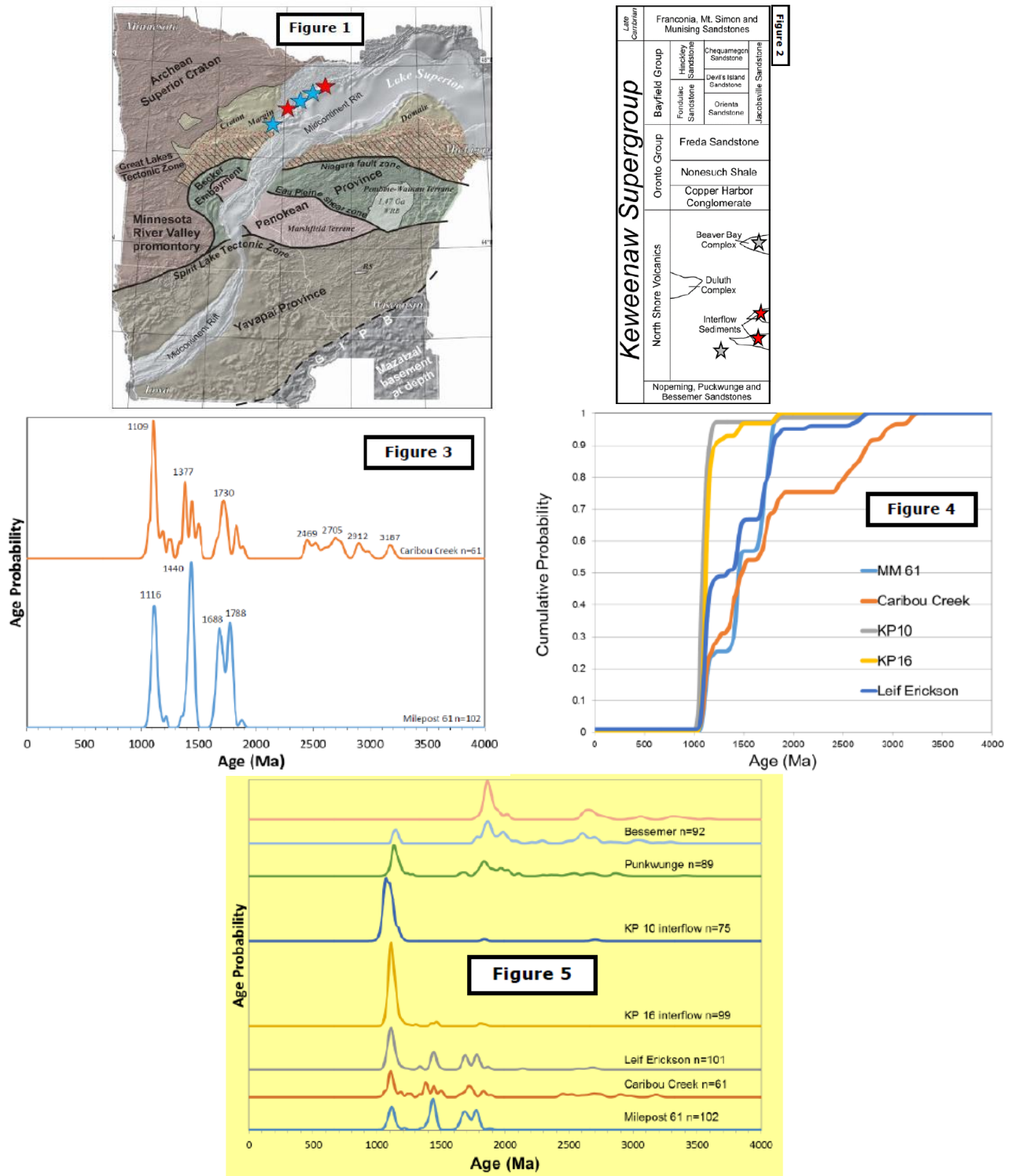


Figure1: A regional tectonic map with the Midcontinent Rift and major geologic contacts (Craddock et al., 2013). Milepost 61 and Caribou Creek sample locations are marked with red stars. The location for the KP samples (Craddock et al. 2013) are marked with blue stars.

Figure2: Stratigraphic column of the North Shore Volcanic Group strata in the Keweenaw Supergroup, showing the interflow sediments and sample localities (Craddock et al., 2013). Red indicates samples from the interflow sediments. Gray indicates samples from the Beaver Bay Complex and North Shore Volcanics.

Figure3: Stacked probability density plot comparing Caribou Creek zircon ages to mile post 61 zircon ages. Age peaks in Ma.

Figure 4: Cumulative probability plot comparison of current samples at Caribou Creek and Mile Post 61, with additional interflow sediment data set KP10 and KP 16 (acquired from Craddock et al., 2013).

Figure 5: Stacked age probability plots comparing interflow sediment with overlying sandstone units (acquired from Craddock et al., 2013) data set. Age probability plots are categorized with orogeny events.

Paleoproterozoic Snowball Earth? Sedimentology and Geochemistry of a Huronian Glacial Cycle

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The Paleoproterozoic Huronian Supergroup is a ~12km thick sequence of mostly sedimentary rocks that outcrops along the southern margin of the Superior craton and contains evidence for three complete glacial cycles within its stratigraphy. The second glacial event, represented in the Bruce Formation of the Quirke Lake Group is unique because of its overlying cap carbonate, the Espanola Formation, which is the only appreciable carbonate unit within the Huronian Supergroup. A cap carbonate overlying the glacial deposits of the Bruce Formation suggests that the Quirke Lake Group may record evidence for extreme climatic perturbations on the same scale as the later Neoproterozoic glacial cycles, where cap carbonates are ubiquitous overlying glacial deposits. The Neoproterozoic glaciations have been the source of much speculation regarding the cause of the formation of cap carbonates and the possibility of their representing the resulting effects of global ice cover during periods known as ‘Snowball Earth’ events (eg. Kirschvink, 1992). Thus, the presence of a cap carbonate overlying only the second of three glacial deposits in the Huronian Supergroup suggests that the conditions that led to its deposition were unique within the Paleoproterozoic and perhaps akin to those that prevailed during the Neoproterozoic glaciations. To assess the extent of the similarities between the Espanola Formation and the Neoproterozoic cap carbonates, the sedimentology, geochemistry, and isotopic composition of the Bruce glacial event was studied in its entirety.

Some of the most interesting and useful results were uncovered through systematic sampling of drill hole E150-2 (Figure 1). Firstly, the presence of a hitherto unmentioned laminated dropstone facies occurs in the uppermost Bruce Formation. This unit is unique because it records evidence of both carbonate precipitation and glacial activity at the same time; a feature that is not recorded elsewhere in the Quirke Lake Group sedimentology. In this facies, 1-10cm thick carbonate-rich laminae occur in a clast-poor diamictite unit with dropstones occasionally punctuating the laminae. The laminated dropstone facies is also exceptional for its extremely negative $\delta^{13}\text{C}_{\text{carb}}$ values of ~-10‰, which is on the same order of magnitude as the Shuram-Wonoka anomaly, the most extreme anomaly recorded from the Neoproterozoic cap carbonates (Halverson et al., 2005). Even more perplexing, are the unique REE patterns associated with this extreme $\delta^{13}\text{C}_{\text{carb}}$ anomaly. This unit is characterised by REE patterns with consistent negative Eu anomalies, flat light (L) REE and highly variable heavy (H) REE that range from negatively to positively sloped. These patterns stand in stark contrast to REE patterns of samples from the overlying interlaminated carbonate and siltstone facies of the Espanola Formation.

Carbonates from the overlying Espanola Formation have patterns with consistently depleted LREE and moderately enriched middle (M) REE, while HREE have a relatively flat pattern that transitions to a positive slope moving up stratigraphy. The relative depletion of LREE in these units that was not present in the underlying laminated dropstone facies indicates a stronger seawater signature, which may reflect a decrease in the influence of meltwater on the geochemical composition. Systematic sampling of the middle and upper Espanola Formation stratigraphy also produced a trend of upwards increasing $\delta^{13}\text{C}_{\text{carb}}$ values. Over approximately 110m of stratigraphy the $\delta^{13}\text{C}_{\text{carb}}$ values increase from ~-4.5‰ to -2‰. This is another feature that has been noted from some Neoproterozoic cap carbonates and has been interpreted to be related to a marine regressive sequence (eg. Giddings and Wallace, 2009).

Thus, the similarity between the Espanola Formation $\delta^{13}\text{C}_{\text{carb}}$ values and those of some Neoproterozoic cap carbonates supports the hypothesis that the Espanola Formation may have been formed under similar conditions as its Neoproterozoic counterparts.

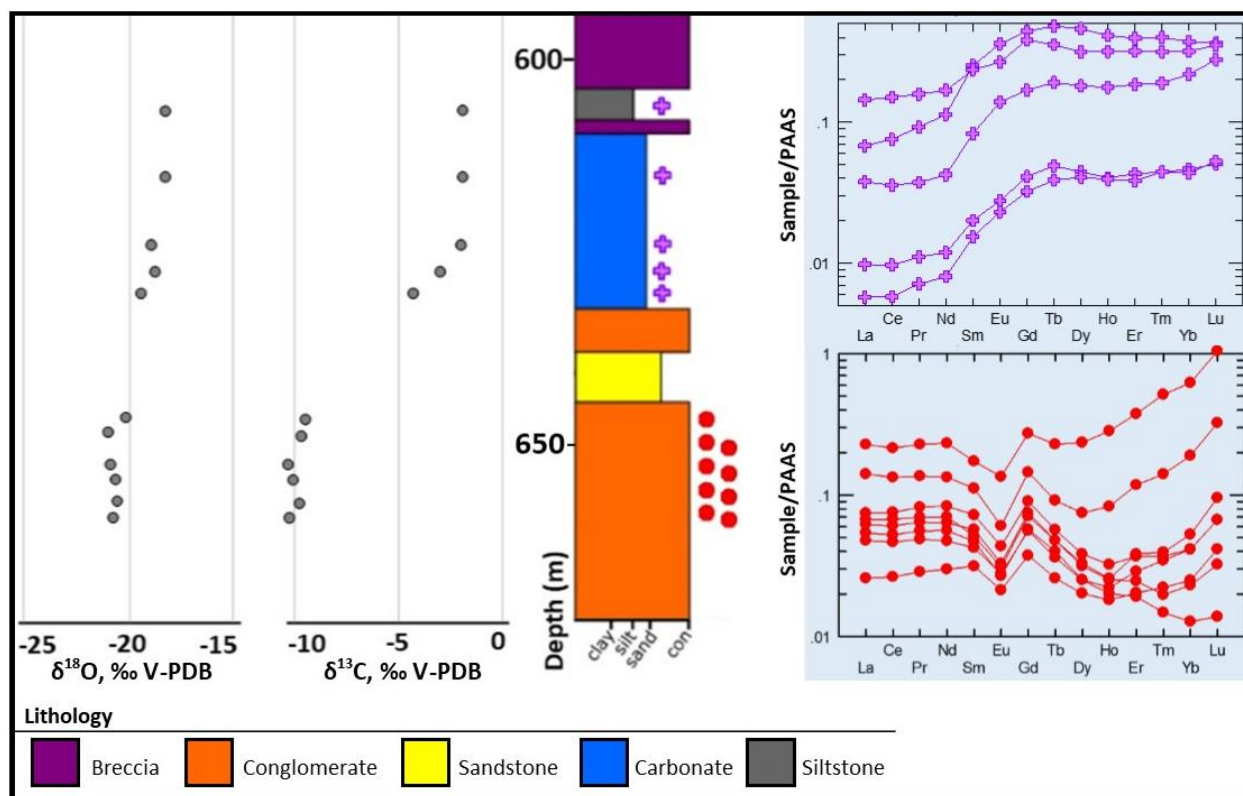


Figure 1: A ~75m section of stratigraphy sampled from drill hole E150-2 of the contact between the Bruce Formation and Espanola Formation. Red samples (lower REE plot) are from the laminated dropstone facies in the upper Bruce Formation. They have extreme negative $\delta^{13}\text{C}$ values of approximately -10‰ and consistent negative Eu anomalies. The $\delta^{18}\text{O}$ values do not show as anomalously low values but are noticeably lower than values further up stratigraphy and fall in the range of -21‰ to -20‰. The purple samples (upper REE plot) are from the interlaminated carbonate and siltstone facies of the lower Espanola Formation. These samples show a rapid trend upwards in $\delta^{13}\text{C}$ values from ~-4.5‰ to -2‰ and they have REE patterns with consistent LREE depletion and moderate MREE enrichment.

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Precambrian Geology of the Western Schreiber–Hemlo Greenstone Belt

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The Schreiber–Hemlo greenstone belt is located within the Wawa–Abitibi terrane of the Superior Province. The greenstone belt includes Neoarchean supracrustal and intrusive rocks that have been crosscut and unconformably overlain by Paleoproterozoic and Mesoproterozoic intrusive and supracrustal rocks of the Southern Province. Bedrock mapping in this area by the Ontario Geological Survey from 2015 to 2018 focussed on the Archean rocks of the western part of the Schreiber–Hemlo greenstone belt, with an emphasis on applying modern geochemical and geochronological techniques.

The supracrustal rocks in the western Schreiber–Hemlo greenstone belt are arranged in an upright stratigraphy consisting of four distinct depositional packages, with chemical and clastic metasedimentary rocks along disconformable contacts (Figure 1). The oldest rocks in the greenstone belt are felsic and mafic metavolcanic rocks of Package A, deposited *circa* 2720 Ma (Davis and Sutcliffe 2017) in a volcanic arc environment. These are overlain by Package B, which is composed mainly of mafic metavolcanic rocks deposited in a “back-arc” volcanic environment. In the western part of the project area, Package B is overlain by Package C, which is composed mainly of mafic metavolcanic rocks deposited in an “oceanic plateau” volcanic environment. In the eastern part of the project area, Package B is overlain by Package D, which is composed of turbiditic wacke and mudstone deposited between 2696 and 2690 Ma (Fralick, Purdon and Davis 2006; Davis and Sutcliffe 2017). The chronostratigraphic relationship between packages C and D is unknown, as contacts between these packages have not been observed.

The oldest felsic plutons that crosscut the supracrustal rocks are the *circa* 2690 Ma Terrace Bay and Steel River plutons (Kamo 2016). Regional ductile deformation likely started at this time, however, whether it began before or after emplacement of the plutons is uncertain. The *circa* 2667 Ma Santoy Lake pluton shows little evidence for ductile deformation along its margins, which suggests that regional ductile deformation ceased at approximately this time (Kamo 2016). Northwest ductile and brittle-ductile shear zones crosscut and displace all of the Archean rocks.

Dikes of the Paleoproterozoic Matachewan, Biscotasing and Marathon dike swarms crosscut Archean rocks in the project area, and outliers of the base of the Paleoproterozoic Gunflint Formation unconformably overlie the Archean rocks at the west end of the project area, southwest of Schreiber. The Coldwell Alkalic Intrusive Complex intrudes the Archean rocks at the east end of the Schreiber–Hemlo greenstone belt. Alkalic diabase dikes crosscut the Archean rocks and the intrusive rocks of the Coldwell Alkalic Intrusive Complex and are believed to be related to volcanism during rifting associated with formation of the Keweenaw Midcontinent Rift.

The Archean rocks host a variety of base metal and precious metal occurrences which have been the subject of exploration and limited mining activities for over a century. The *circa* 2720 Ma felsic metavolcanic rocks are correlative with rocks in the nearby Winston Lake and Manitouwadge areas that host past-producing Zn–Cu mines (Davis, Schandl and Wasteneys 1994; Zaleski, van Breemen and Peterson 1999). Gold mineralization is hosted in sheared and altered metavolcanic rocks and in veined and altered granitoid rocks. Proterozoic rocks in the north shore of Lake Superior region have potential to host magmatic sulphide and oxide mineralization including a variety of transitional metals and rare earth elements.

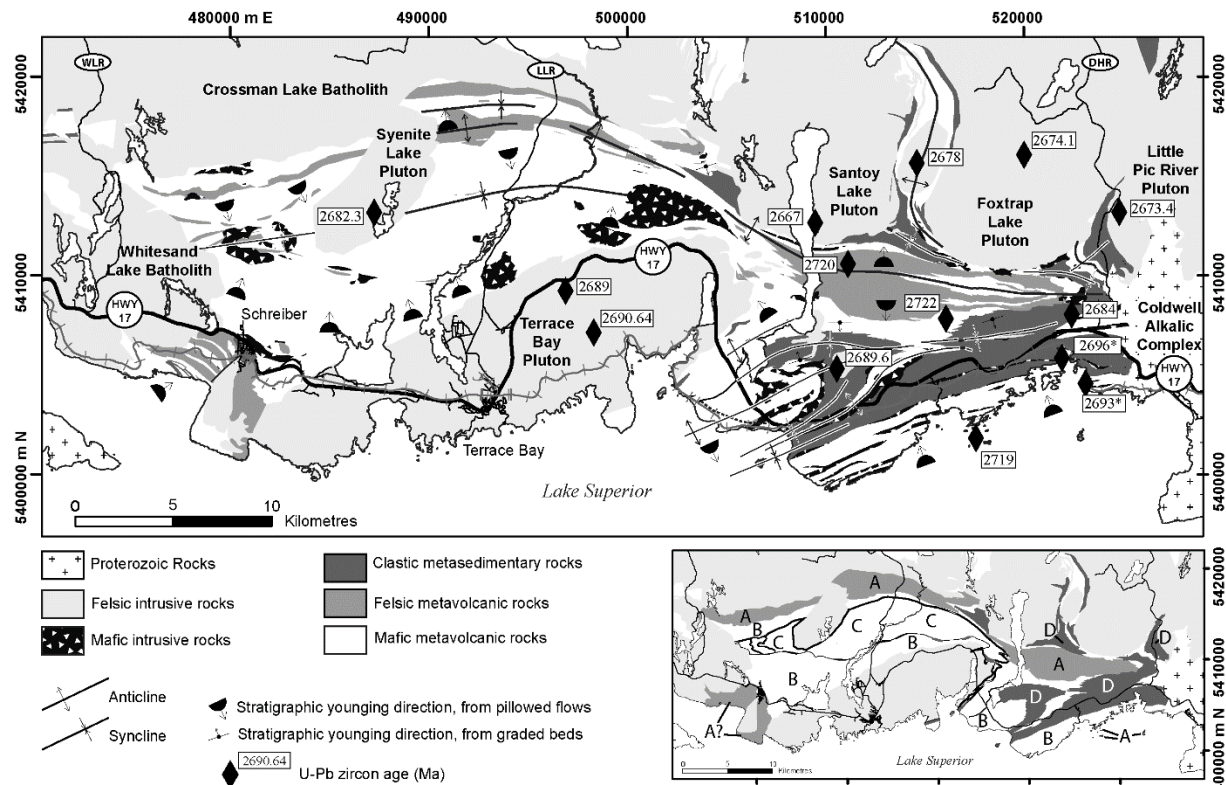


Figure 1: Simplified geological map of the western Schreiber–Hemlo greenstone belt, highlighting the major Archean rock types, some of the stratigraphic younging indicators observed during this study, all of the U-Pb zircon geochronological data in the area, and the inferred fold axial traces. An inset figure outlines the inferred depositional packages A, B, C and D. Note that Proterozoic diabase dikes, which are abundant in the map area, are not shown for clarity. Abbreviations: DHR = Dead Horse Road, HWY 17 = Trans-Canada Highway 17, LLR = Long Lake Road. See references for ages. All UTM co-ordinates provided using NAD83 in Zone 16.

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Pilot study: Using ambient noise passive seismic surveys for Ni-Cu-PGE mineral exploration at the Marathon PGM-Cu deposit, Marathon, Ontario

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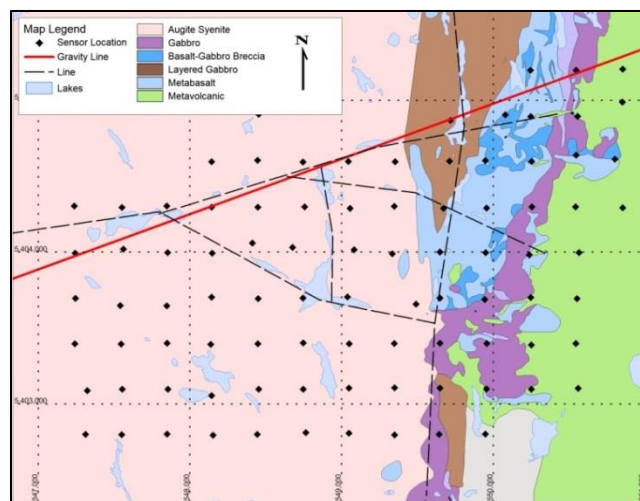
Active seismic surveys are a powerful geophysical tool for exploring to significant depth, and are commonly used in the oil and gas industry. However, because of the high cost and environmental impact associated with conducting a seismic survey, this method is rarely used for mineral exploration. Nevertheless, with the increased difficulty of finding economic mineral deposits, exploration companies continue to look deeper and there is a growing need to develop cheaper methods with less environmental impact to do so.

Passive seismic methods currently being tested by SISPROBE Inc. at the Marathon deposit have the advantage of being a low impact and low-cost method for examining velocity contrast in geologic units to depths below surface approaching 1 km. Passive seismic methods use ambient noise generated from the natural environment. At Marathon, the dominant noise source is wave action in Lake Superior with a minor contribution from waves in the North Atlantic Ocean. Additional noise is generated by traffic on the nearby highway and railway. The use of autonomous seismic data recorders allows for flexibility when designing sensor arrays, which is necessary in remote or environmentally sensitive areas that include challenging topography.

The Coldwell Complex is approximately 25 km in diameter and is composed of three centers of predominantly alkaline magmatism that intruded the Archean greenstone terrane (Mitchell and Platt, 1977) along the northern margin of the Midcontinent rift between 1108 and 1094 Ma (Heaman et al., 2007). Centre I is composed of augite syenite, quartz syenite and the Eastern Gabbro Suite. The Eastern Gabbro Suite outcrops along the eastern and northern margin of the complex and is composed of numerous gabbroic to ultramafic intrusions of the Layered and Marathon Series that cut a 1 km thick pile of metabasalt (Good et al., 2015; and Good and Lightfoot, 2019). Mineralization at the Marathon PGM-Cu deposit is hosted by Two Duck Lake gabbro and ultramafic rocks of the Marathon Series.

The Marathon PGM-Cu deposit is an ideal site to test the passive seismic technique because of the extensive geological database and the distinct petrophysical property contrast exhibited by the various syenites and gabbros of the complex, and the underlying Archean metavolcanic rocks of intermediate composition.

A preliminary noise survey was completed in 2017 to test ambient source signal-to-noise ratio. It was determined that wave action from Lake Superior generates sufficient ambient noise to proceed to a production scale survey. In 2018, a production scale survey was completed with 90 sensors deployed at 300 m spacing in an array that is elongated parallel to wave propagation in order to maximize signal pairs.



The geophones used were GSX-1 single channel units, which collected data in the vertical direction. They recorded data every 4 ms for a total of 26 days (Hollis, 2018).

The density and P-wave velocities for representative samples of each lithologic unit at the deposit were measured at Western University. These measurements were used to constrain interpretations of lithological boundaries determined from the 3D velocity inversion model for the survey data. Augite syenite (V_p of 5500 m/s and ρ 2650 kg/m³) overlies the Two Duck Lake gabbro (V_p 6200 m/s and ρ 3100 kg/m³) while the Archean metavolcanic footwall (V_p 5000 m/s and ρ 2800 kg/m³) lies below the gabbro. The ultramafic (V_p 6800 m/s and ρ 3500 kg/m³) units that host the mineralization occur as lenses and pods that are distinguishable from the gabbro units.

The geological boundary between the Two Duck Lake gabbro and the Archean metavolcanic footwall was successfully resolved by the survey. The survey also identified a high-velocity anomaly down dip from the Marathon PGM-Cu deposit at a depth of 600 m. The anomaly has a velocity value that is representative of an ultramafic unit. To validate the velocity anomaly, a 6 km gravity line was completed over the area which confirmed a high-density body at depth. By combining both passive seismic and gravity methods along with the structural association of the anomaly along feeder conduits, the anomaly is interpreted to be an accumulation of dense minerals such as magnetite, apatite, olivine and sulfide in a conduit setting.

The passive seismic technique therefore identified an exploration target at depth where previous electromagnetic and magnetic surveys had not. Passive seismic geophysics is an excellent technique for the mineral exploration industry as it brings considerable depth penetration with the advantages of 3D seismic imaging, at low cost while being sensitive to the environment.

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The Wolf River Orogeny: Geon 14 Magmatism, Sedimentation, and Deformation in the Southern Lake Superior Region

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The Proterozoic Wolf River Batholith (WRB), which is the most prominent Precambrian geological feature in northeastern Wisconsin, was first described in 1975 by Van Schmus et al. and initially interpreted to represent an episode of anorogenic igneous activity by analogy with the classic Proterozoic rapakivi granites in Finland (Anderson & Cullers, 1978). Subsequently, it was recognized that the WRB is the local expression of a transcontinental belt of Geon 14 granites that were again interpreted to be anorogenic (Anderson, 1983). More recent investigations reveal that emplacement of these transcontinental Geon 14 granites along the eastern and southern margins of Laurentia was associated with an orogenic event involving continental arc magmatism, sedimentation, and deformation (Whitmeyer & Karlstrom, 2007; Daniel et al., 2013), certain aspects of which are now recognized as being related to the Wolf River event in Wisconsin.

Magmatism The WRB underlies a minimum area of 1.45×10^4 km² and consists predominantly of alkaline biotite granite and biotite–hornblende adamellite and subordinate quartz syenite, monzonite, and anorthosite (Anderson & Cullers, 1978). U–Pb zircon ages for the different plutons range from 1468 ± 4 to 1484 ± 2 Ma, with the main part of the batholith yielding an average crystallization age of 1476 ± 2 Ma (DeWayne & Van Schmus, 2007). To the west of the WRB in Marathon county, the Wausau syenite and Nine Mile granite plutons yield older crystallization ages of 1522 and 1506 Ma, respectively. Oxygen, Sm–Nd, and Lu–Hf isotopic data indicate that the WRB was derived from partial melting of the late Paleoproterozoic crust in the region (Anderson & Morrison, 2005; DeWayne & Van Schmus, 2007; Goodge & Vervoort, 2006).

Sedimentation The Baldwin conglomerate occurs at the northeastern margin of the WRB, where it lies unconformably on the Geon 18 Macauley gneiss and Waupee metavolcanic and metasedimentary rocks and is intruded by the 1470 Ma Hager porphyry. The Baldwin conglomerate is polymict and chemically immature, containing clasts of the underlying lithologies set in a medium–grained arkosic matrix. A relative probability plot for detrital zircons in the Baldwin conglomerate displays a prominent Geon 14 (Wolf River) peak, subordinate Geon 16 (Mazatzal), Geon 17 (Yavapai), and Geon 18 (Penokean) peaks, and a single detrital zircon at 2690 Ma (Algoman) (Fig. 1). The maximum age of deposition (MAD) calculated from the youngest statistically homogenous population (MSWD ≤ 1.0) is 1458 ± 10 Ma. These results demonstrate that deposition of the Baldwin conglomerate was synchronous with crystallization of the WRB.

Deformation and recrystallization Evidence for Geon 14 deformation associated with the WRB is best revealed by metasedimentary rocks of the post–Mazatzal Baraboo Interval. In the Baraboo Range, muscovite parallel to slaty cleavage in four samples

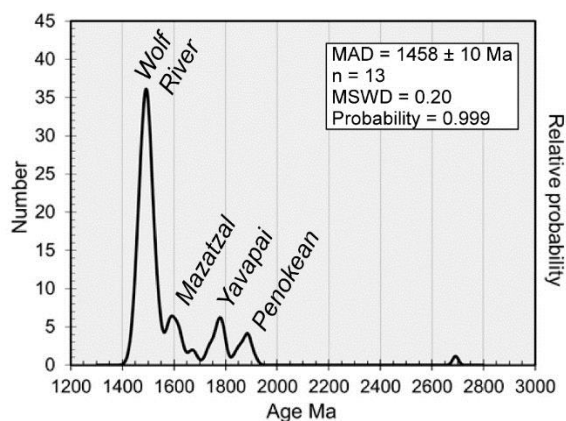


Figure 1. Relative probability plot for detrital zircons in the Baldwin conglomerate

of Seeley Slate yields $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages of 1473, 1483, 1493, and 1496 Ma (all with $\pm 3\text{Ma}$), and muscovite decorating crenulation cleavage in Waterloo metapelite yields $1465 \pm 7\text{ Ma}$. In addition, cooling ages of 1472 ± 3 , 1480 ± 11 , and $1469 \pm 11\text{ Ma}$ have been obtained for muscovite in breccia in the Baraboo Quartzite, in hydrothermal veins at the base of the quartzite, and in metamorphosed paleosol beneath the quartzite.

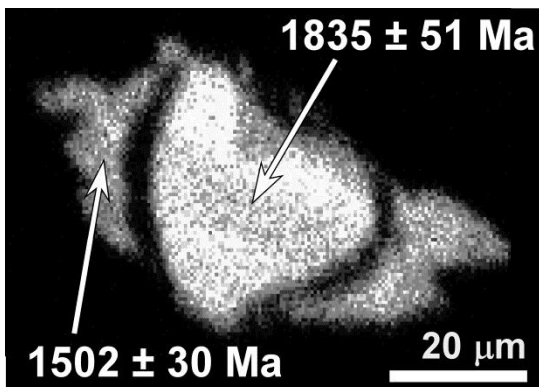


Figure 2. Th map and U-Pb ages for monazite in Seeley Slate

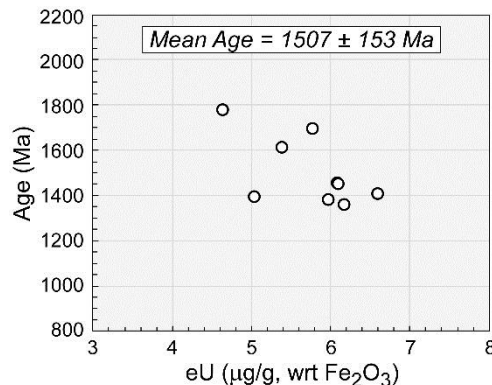


Figure 3. U/Th–He ages for hematite in Baraboo metapelite

Monazite occurs as a detrital mineral in the Seeley Slate, and some grains exhibit new monazite rims that extend parallel to cleavage (Fig. 2). Electron probe microanalysis and dating of monazite were done using the UMass Ultrachron probe. Detrital monazite cores yield Penokean and Archean ages; rims yield a date of $1502 \pm 30\text{ Ma}$, comparable to the age of the WRB.

In the Baraboo Quartzite, folded metapelite layers consisting largely of pyrophyllite contain tiny grains (50–100 μm in diameter) of recrystallized hematite. Such hematite yields a mean U/Th–He age of $1507 \pm 153\text{ Ma}$ (Fig. 3), which is consistent with the ages obtained for muscovite and monazite by other geochronologic methods.

Note that the Baraboo Interval sedimentary rocks containing evidence for Geon 14 folding and recrystallization, *e.g.* the Baraboo and Waterloo quartzites, are located within the trans-continental belt of Geon 14 granites, whereas those located outside the transcontinental belt, *e.g.* the Sioux and Barron quartzites, are neither folded nor recrystallized.

Despite the massive character of different Wolf River plutons and “anorogenic” appearance of the batholith itself, it is now clear that emplacement of the WRB was accompanied by Geon 14 sedimentation and deformation and can be viewed as an orogenic event. The Wolf River orogeny provides a link between the Pinwarian orogeny to the northeast and the Picuris orogeny to the southwest, thus completing the transcontinental extent of Geon 14 orogenesis in North America.

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The Importance of “Tablesetting” Intrusions in Creating Economic Ni-Cu-PGE Deposits in the Midcontinent Rift

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Some of the most promising targets for economic Ni- Cu-PGE sulfide deposits in the Lake Superior region are associated with small-scale ultramafic-mafic intrusions emplaced during early stages of the 1.1Ga Midcontinent Rift. While many of these intrusions share well documented attributes – small size, sub-horizontal conduit geometries, high grades and tenors of Ni-Cu-PGE sulfide ore, ultramafic host rock – one common attribute that is not so well known is the association of these mineralized intrusions with precursor intrusions. I refer to these earlier intrusions as “tablesetting” intrusions (TSI) as their emplacement appears to have played a major role in producing the well mineralized intrusions that followed. Before discussing what role TSI plays, the basic structural, lithologic and geochemical attributes of the TSI associated with four well-studied MCR ultramafic intrusions will be described. I am familiar with these intrusions through the MS thesis research of my UMD graduate students – Eagle (Mulcahy, 2018), Tamarack (Goldner, 2011), BIC (Foley, 2011), and Current Lake (Chaffee, 2015) - and through many years of discussions with exploration geologists such as Dean Rossell (Rio Tinto), Bob Mahin (Eagle/Lundin), Al MacTavish (MagmaMetal/Panoramic), and Geoff Heggie (Magma Metals/Panoramic).

The discovery of the Eagle deposit in 2002 by Dean Rossell and his Rio Tinto/Kennecott crew in the Baraga Basin area north of Marquette, Michigan set off a flurry of exploration activity in the Lake Superior region that continues to this day. Eagle is the only MCR-related Ni-Cu-PGE deposit that has progress to active mining, which began in 2014, soon after the property was acquired by Lundin Mining. In 2015, continued exploration in the area revealed additional economic mineralization in the subhorizontal conduit of the nearby Eagle East intrusion. With total minelife of the Eagle and Eagle East deposits projected to end in 2023, the company is aggressively exploring for additional deposits in the area. One of the main vectoring tools being employed is to seek out pyroxenite dikes. As observed at both Eagle and Eagle East, weakly mineralized pyroxenite to melagabbro (PYX unit) occurs at the margins of the main peridotite body that hosts the bulk of the Ni-Cu-PGE mineralization. Weakly mineralized pyroxenite also occurs as xenoliths in well-mineralized peridotite - the HTBX and IBRX units (Mulcahy, 2018). It is hoped that tracing the occurrences of the tablesetting PYX rock type will lead to discovery of another mineralized peridotite body in the vicinity of Eagle/Eagle East.

Concurrent with their exploration in Upper Michigan, RioTinto/Kennecott was seeking an Eagle-like occurrence in the Paleoproterozoic Animikie Basin in east-central Minnesota. This led to the discovery of significant Ni-Cu-PGE mineralization in 2008 in the Tamarack intrusion/deposit. The main zone of massive to semi-massive sulfide mineralization occurs in the “tail” section of the tadpole-shaped subhorizontal intrusion where two distinct peridotite bodies come into contact – 1) a deeper CGO unit, which is characterized by coarse cumulus olivine and significant intercumulus clinopyroxene and plagioclase, and 2) an overlying FGO unit, which is characterized by finer grained cumulus olivine and only a minor intercumulus component. Whereas Goldner (2011) concluded from petrographic and geochemical attributes that the CGO unit is the precursor intrusion, the local Rio Tinto/Kennecott crew has interpreted the FGO is the earlier intrusion. In either case, the mineralization is clearly focused where the two intrusive components come into contact.

The Thunder Bay North PGE-Cu-Ni deposit associated with the Current Lake Intrusion was discovered by Magma Metals in 2006 near the occurrence of glacial boulders of well mineralized peridotite on the shoreline of Current Lake. Like Tamarack and Eagle, the mineralization is hosted by peridotite, and like Tamarack, it has a subhorizontal tadpole shape (chonolithic). However, it is intrusive

into Archean granitoids and metasedimentary rocks rather than Paleoproterozoic black shales. Another significant difference is that the precursor rock is a strongly contaminated, commonly xenolith-rich lithology that Magma Metals termed the Hybrid Unit (with red and gray varieties). Petrographic studies by Chaffee (2015) determined this rock is a weakly mineralized quartz gabbro that is variably discolored by hematitic staining. Geochemical modelling also showed that the parental magma to the hybrid unit is a contaminated equivalent to the peridotitic magma that followed emplacement of the hybrid. The hybrid intrusions were emplaced in an orthogonal pattern of subhorizontal and subvertical dikes. The main mineralized peridotite tended to be emplaced at the intersections of the vertical and horizontal hybrid dikes to form chonolith-shaped bodies.

The Bovine Igneous Complex (BIC) is a funnel-shaped intrusion that, like Eagle, was emplaced into the Paleoproterozoic Baraga Basin of Upper Michigan. Because it is one of the few ultramafic intrusions with surface exposures, exploration activity on BIC by Dean Rossell and his Rio Tinto/Kennecott crew began in the mid-90's, though significant mineralization was not discovered until 2006. Detailed petrographic and geochemical studies by Foley (2011) on two drill core profiling the igneous stratigraphy of BIC showed it to be composed of two well differentiated intrusive cycles. The lower (early) sequence grades from an Ol cumulate upward to a Cpx+Ol cumulate. This is overlain by a cumulus reversal back to an Ol cumulate that grades upward to a Cpx+Ol cumulate, then an Ox+Cpx±Ol cumulate, and is capped by a Pl+Cpx+Ox cumulate. Both differentiated sequences show smooth cryptic layering of Mg/Fe ratio in olivine and augite, and Ca/Na ratio in plagioclase. Ni-Cu-PGE enriched sulfide mineralization occurs intermittently through the lower ultramafic sequence and at the basal contact between of the upper differentiated sequence. Although economic grades of mineralization appear to be lacking in these sequences, the possibility of finding more concentrated and higher tenor sulfide in the as yet undiscovered conduit to BIC seems high.

The main take-aways from the observation made of these four mineralized ultramafic intrusions in regard to the role of the precursor “tablesetting” intrusions (TSI) are:

- 1) TSI are important for establishing the plumbing system for subsequent intrusions.
- 2) TSI serve to pre-heat and begin devolatilization of sulfide-bearing country rock, but because of rapid heat loss to cold country rock, they tend to generate little sulfide of low tenor.
- 3) Subsequent intrusions of hot ultramafic magmas into a pre-heated and structurally compromised country rock created by the TSI are able to cool slowly and create cumulate lithologies. Larger, more closed intrusions may become well differentiated (BIC), whereas in narrow chonolithic intrusions that are perhaps open to surface, large volumes of ultramafic magma can pass through resulting in the crystallization of uniformly primitive cumulates (Eagle, Tamarack, Current Lake).
- 4) In open chonolithic systems, the dynamic passage of large volumes of metal-rich ultramafic magma that bore through and inflate the precursor TSI, can upgrade the tenor of any early-formed sulfide in the TSI and any additional sulfide devolatilized by the new heat pulse.
- 5) Wherever the intrusive plumbing network creates subhorizontal sheets, channels, or tube-shaped (chonolith) conduits, this allows for gravitational concentration of enriched sulfide liquid.

UMD MS Theses

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Foley, D., 2011, *Petrology and Cu-Ni-PGE Mineralization of the Bovine Igneous Complex, Baraga County, Northern Michigan*.

Goldner, B., 2011, *Petrology and Cu-Ni-PGE Mineralization of the Tamarack Intrusion, Aitkin and Carlton Counties, Minnesota*.

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Geochemical Vectoring Towards a Serpentinized Peridotite Chonolith, Eagle East Ni-Cu-Co-PGE Deposit, Upper Peninsula, Michigan

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Serpentinization is a low temperature ($\leq 500^{\circ}\text{C}$), surficial to hypabyssal metasomatic process in which pyroxene $[(\text{Ca},\text{Mg},\text{Fe})_2\text{Si}_2\text{O}_6]$ and olivine $[(\text{Mg},\text{Fe})_2\text{SiO}_4]$ react with H_2O +/- CO_2 to form hydrous silicates (serpentine) +/- hydroxides (brucite) +/- carbonates (dolomite, magnesite, calcite), and +/- Fe-oxides (magnetite) (Huang et al., 2017; Kelemen and Matter, 2008). These chemical reactions can result in the transfer of Mg^{2+} , Ca^{2+} , and Si^{4+} , the oxidation of Fe^{2+} (Kelemen and Matter, 2008), and, under very reducing conditions, the formation of nickel alloys (awaruite (Ni_3Fe); Preiner et al., 2018; Lawley, 2018). Pervasive serpentinization of peridotite can incorporate up to 13-15% H_2O by weight and result in an estimated volume increase up to 40% (Schroeder et al., 2002; Shervais et al., 2005). This process can significantly alter the properties of ultramafic to mafic rocks, resulting in decreased density, seismic velocity (Miller and Christensen, 1997), and rheological strength (Escartin et al., 2001), in addition to an increase in magnetic susceptibility (Toft et al., 1990).

The Eagle and Eagle East magmatic Ni-Cu-Co-PGE deposits, which formed during the Midcontinent Rift (MCR), are hosted within intensely serpentinized peridotite chonoliths. The aim of this study was to investigate whether a geochemical signature could be detected from drill core analyses outside the main serpentinized peridotite chonoliths and potentially utilized as an exploration vector toward mineralized peridotite. A pyroxenite sheet dike, which extends along strike and is crosscut by the Eagle East ore-hosting chonolith, was the focus of this study. Over fifty samples, collected from drill core intercepts of the pyroxenite sheet dike, were analyzed for major, minor, and trace elements (using ICP-MS and XRF methods) and utilized to generate 3-D models (using Leapfrog software).

Pyroxenite intercepts ~400 meters away from any secondary intrusion (i.e. peridotite chonolith or gabbroic stock) were used as a baseline comparison to pyroxenite intercepts above and below the Eagle East peridotite chonolith. Pyroxenite samples above the Eagle East peridotite conduit have relatively enriched (on the order of 1 to 5 wt %) SiO_2 and MgO values, and relatively depleted CaO contents (on the order of 1.5 to 2 wt%) relative to baseline pyroxenites. The enrichment and depletion trends become most pronounced ~50 meters above the flat-lying Eagle East conduit. Pyroxenite samples below the Eagle East chonolith contain relatively enriched SiO_2 , MgO , and CaO values, except for pronounced depletions within ~50 meters of the chonolith contact. Enrichment of nickel (on the order of 0.2 to 1 wt%) in the lower pyroxenites can extend up to 500 meters away from the lower chonolith keel contact (Fig. 1). The overall pattern of depletion proximal to the Eagle East chonolith is interpreted as resulting from near contact related serpentinization of the pyroxenites. The overall pattern of enrichment distal to intense serpentinization is interpreted as redistribution of these elements outside the zone of intense serpentinization into less-altered pyroxenites.

In summary, serpentinization is an important component to consider when modelling and interpreting the major and base metal element content of ultramafic and mafic rocks which can potentially host Ni-Cu-Co-PGE mineralization. The occurrence of proximal depletion, coupled with distal enrichment of MgO , CaO , and SiO_2 may provide exploration criteria that could be

used to vector towards serpentinized peridotite. The redistribution of Ni from serpentinized olivine, presumably into the mineral awaruite, displayed the most widespread detection halo (up to 500 meters outside the Eagle East system). The implications of this study could aid in determining the nickel prospectivity of a magmatic system and improve estimations on the potential size of a serpentinized system based on the scale of the geochemical halo observed.

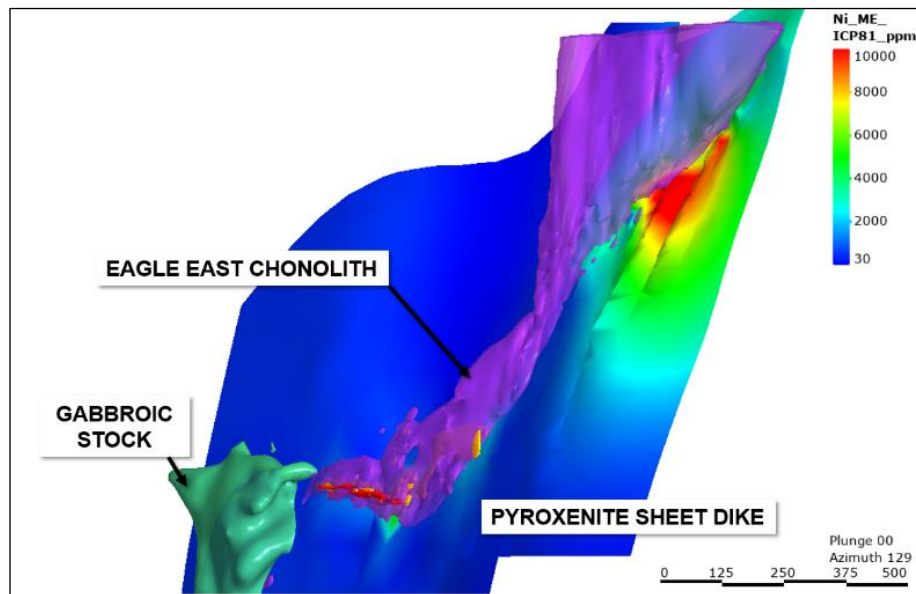


Figure 1: Long-section, looking southeast, showing nickel content (ppm) of pyroxenite samples projected onto the modelled pyroxenite plane. The modelled serpentinized Eagle East chonolith surface with massive- (red) and semi-massive sulfide ore-bodies (yellow) is also shown.

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Catchment Geology Correlation with Fish Otolith Microchemistry Across Disparate Glacial Till Depths in the Lake Michigan Basin

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Fish otoliths are calcium carbonate boney-like structures found in fish ears that grow concentrically, and as such they preserve a chemical record of select environmental changes during life. This study used laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) to record variations in signal intensities of magnesium (²⁵Mg), calcium (⁴³Ca), manganese (⁵⁵Mn), copper (⁶⁵Cu), zinc (⁶⁶Zn), strontium (⁸⁸Sr), barium (¹³⁷Ba), and lead (²⁰⁸Pb) isotopes in steelhead (*Oncorhynchus mykiss*) otoliths. These signals were then converted to trace element concentrations (in ppm) along transects that represent a timespan when each fish resided in a particular catchment. A portion of the otolith data used in this study was previously used to build models that discriminate Wild-and Hatchery-Origin steelhead across the Lake Michigan Basin (Watson et al., 2018). The current study incorporated results from 538 Wild-Origin steelhead otoliths that were collected in 2014 and 2015 (Prichard et al., 2019). A general introduction to otolith microchemistry applications, trace element uptake in otoliths, Michigan steelhead, and Michigan Geology and otolith microchemistry will be presented. Glacial deposits obfuscate much of the Michigan bedrock influence on stream chemistry, and this in turn influences the utility of Sr isotope systematics in lower peninsula Michigan streams as compared to bedrock dominated fluvial systems.

A primary application of otolith microchemistry is distinguishing natal origins of individual fish within a mixed-stock fishery. Stocks must be distinguishable according to stock-specific microchemistry patterns, with accurate stock assignment contingent upon microchemistry assessment of all sources contributing to the mixed-stock fishery. However, otolith microchemistry signatures of individual fish, upon which classification models are built, likely represent only a portion of the variability that exists for the stocks corresponding to each natal source. To statistically infer expected otolith microchemistry patterns among unsampled catchment areas proximal to sampled areas, we tested the hypothesis that variation in catchment geology among 35 stream sites across the Lake Michigan basin is correlated with the variation in otolith microchemistry signatures of age-0 steelhead collected at those sites. Matrices of Mahalanobis distances between all pairs of individual fish were calculated for each of the following: (1) assignment scores from discriminant function analysis of the variation among sites based on otolith microchemistry, and (2) the geology (bedrock age, bedrock lithology, and

surficial geology) underlying the catchments upstream of each of the sites where fish were sampled. Based on Mantel tests, these matrices were found to be significantly correlated, indicating that age-0 steelhead that exhibit greater differences in otolith microchemistry signatures tended to come from sites exhibiting greater differences in catchment geology. Surficial geology alone was more correlated with otolith microchemistry than bedrock age, bedrock lithology, or any combinations of the three geological datasets. The significant relationship between geology and otolith microchemistry, although weak, supports tenuous hydrologic and geologic bases for delineating natal source geographic boundaries.

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Using graphitic sedimentary rock geochemistry as an indicator of gold potential in the Shebandowan greenstone belt, northwestern Ontario

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Graphitic sedimentary rocks are a common feature of Archean greenstone belts. Due to their high carbon content, these rocks tend to be more metalliferous than non-carbonaceous sedimentary rocks. They also act as strong reducing agents to hydrothermal fluids and can sequester metals and other elements from those fluids (Barrie 2004). Springer (1985) noted that graphitic argillites in the Abitibi greenstone belt often contain anomalous concentrations of gold (up to 0.5 ppm Au), and that much higher concentrations (up to 15 ppm Au) can be found in graphitic argillites that show evidence of hydrothermal alteration (e.g., quartz veining and carbonate alteration). Given their relative abundance in Archean greenstone belts and their response to gold-bearing hydrothermal fluids, the geochemistry of graphitic sedimentary rocks should provide information to assist in the search for mesothermal gold deposits.

Detailed geochemical studies completed in the Abitibi greenstone belt by Barrie (2004) demonstrated that graphitic argillite proximal to the Owl Creek, Hoyle Pond, Holloway and Holt-McDermott mines typically contains elevated concentrations of gold (Au), arsenic (As), antimony (Sb) and mercury (Hg). Based on the results of this work, Barrie (2004) developed a method of calculating a hydrothermal alteration index that is based on concentrations of these elements and is normalized to graphitic and carbonaceous (non-carbonate) carbon (C*) and sulphur (S). Normalization of the data accounts for the likelihood that the degree of metal sequestration from hydrothermal fluids will be proportional to the graphitic/carbonaceous carbon and sulphur contents of the rock. The alteration index equation is as follows: $\log (Au \times Hg \times As \times Sb) / (C^* \times S)$; where concentrations of Au and Hg are in parts per billion, concentrations of As and Sb are in parts per million and concentrations of C* and S are in weight %. Alteration index (AI) values of >6.5 were deemed to be very significant and indicative of sample collection within 1 km of ore, while AI values <5.5 were considered insignificant.

During the 2017 and 2018 field seasons, staff of the Thunder Bay Resident Geologist Office collected 72 samples of graphitic sedimentary rock from various locations in the Shebandowan greenstone belt west of the City of Thunder Bay. The program included the collection of outcrop samples and drill core samples. Drill core was obtained from the Ontario Geological Survey's Thunder Bay and Conmee Township core repositories. The purpose of this sampling was to test the applicability of the graphitic argillite gold alteration index method of Barrie (2004) as an exploration targeting tool in the Shebandowan greenstone belt, and to establish a geochemical database for graphitic sedimentary rocks. Samples were analysed by the Ontario Geological Survey Geoscience Labs in Sudbury for the same comprehensive suite of major, minor and trace elements that were included in the Abitibi greenstone belt studies of Barrie (2004). This paper will focus on the work that was completed in 2017 (48 samples) near known gold and base metal occurrences, as results are still pending from the 2018 sampling program.

As shown on Figure 1, Alteration index (AI) values exceeding 6.5 were obtained from samples collected near three known gold prospects located in the Shabaqua area (West Zone, Bylund and South Zone). No highly significant AI values were obtained from samples collected proximal to volcanogenic massive sulphide (VMS) or ultramafic rock-hosted Ni-Cu occurrences located further to the south in Conmee, Adrian, Sackville and Aldina townships.

The highest AI value was obtained from an outcrop grab sample collected at the West Zone. Two more West Zone samples (1 outcrop and 1 drill core) also displayed elevated AI values. Gold at the West Zone is hosted in 2 brecciated, silicified and sulphide mineralized chert horizons. These horizons are both approximately 3 m wide and have assayed up to 6.87 g/t Au over 3.05 m. Anomalous AI values of 7.31 and 6.43 were obtained from two drill core samples collected proximal to the Bylund gold prospect. Gold mineralization on the Bylund property occurs in a 125 m wide zone of carbonate-altered rocks and stockwork quartz-carbonate veins. The anomalous AI value near the South Zone gold occurrence was obtained from a surface grab sample collected from a historic exploration trench. There are no known surface gold showings in proximity to this sample location. However, it is located approximately 20 m from the collar of the diamond drill hole that intersected the South Zone gold mineralization.

The results of this study are consistent with the findings of Barrie (2004) and demonstrate that graphitic mudstone geochemistry can be used as a gold exploration targeting tool in the Shebandowan greenstone belt. The Bylund-West Zone-South Zone corridor in the Dawson Road Lots area has been identified as a high priority gold exploration target.

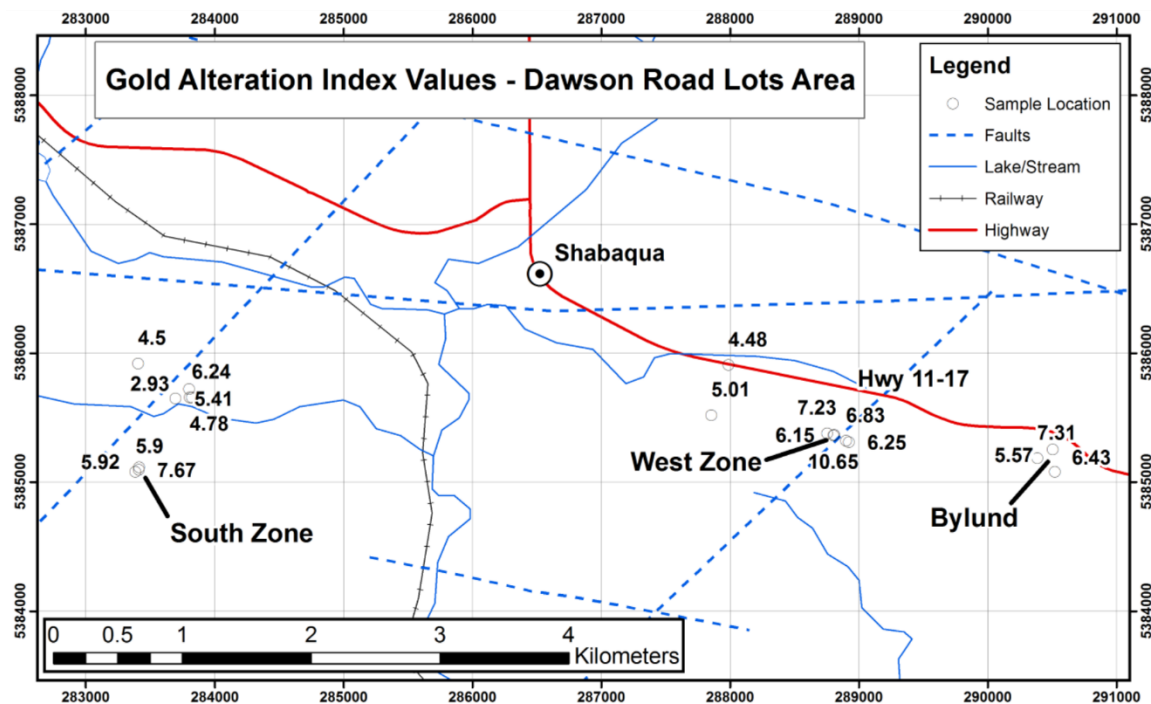


Figure 1. Map illustrating gold alteration index (AI) values for graphitic sedimentary rock samples collected in the vicinity of the South Zone, West Zone and Bylund gold showings near Shabaqua, Ontario. AI values of >6.5 suggest that the sample site may be located within 1 km of a significant gold mineralized structure. Map grid is provided in UTM NAD83, Zone 16 co-ordinates.

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Wawa, undercover: Bedrock geologic and bedrock topographic mapping in north-central Minnesota

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Recently published bedrock geology and bedrock topography maps for four counties in north-central Minnesota (Chandler and Radakovich, 2018; Jirsa and Chandler, 2016; Radakovich and Chandler, 2016a, b, c; Radakovich and Chandler 2018a, b, c) serve as a case study for mapping Precambrian geology in areas of almost complete cover by glaciogenic sediment. Production of the maps therefore relied heavily on data from geophysical investigation methods; successes and challenges are discussed herein.

Some exploration drill core and minimal outcrop data locally guided bedrock geology mapping; however, aeromagnetic and gravity data proved to be the most useful tools for deciphering bedrock composition in most of the four county area. Basement geology (Fig. 1A) consists chiefly of Archean metavolcanic, metasedimentary, and metaplutonic rocks of the Wawa subprovince, intruded by a suite of northwest-trending Paleoproterozoic mafic dikes. Geophysical modeling refined the characterization of the Archean Leech Lake Structural Discontinuity and several buried Archean iron formations across the study area. Younger sedimentary rocks of the Paleoproterozoic Animikie Group overlie the basement bedrock in several separate, formerly-continuous basins in eastern parts of the study area. Sparse drilling data indicate poorly consolidated sedimentary strata overlying bedrock of all ages, particularly in and along topographic lows in the Precambrian surface. Pollen analysis verified a Cretaceous age for these poorly consolidated sedimentary rocks.

Bedrock topographic surfaces (Fig. 1B) were hand-contoured based on limited bedrock elevation data from rare bedrock outcrops, exploration drill hole records, and drilling records of the small percentage of wells that reached the bedrock surface. As a result of the paucity of direct bedrock elevation information, a significant amount of data from passive seismic and conventional seismic soundings allowed bedrock elevation to be inferred over a large portion of the four-county area. Depth to bedrock calculations indicate that several hundred feet to as much as over 1000 feet of Quaternary glacial sediment covers the bedrock surface across most of the region. In some locations, bedrock composition and structure appear to have played a role in the development of paleo drainages on the bedrock surface; in others, drainage seems to have been less affected by apparent bedrock composition. One of the most difficult obstacles to depicting the bedrock topography was recognition of Cretaceous bedrock between the Precambrian weathering surface and the bottom of the Quaternary sediment. This poorly consolidated material is generally transparent to geophysical methods and rarely recognized by well drillers.

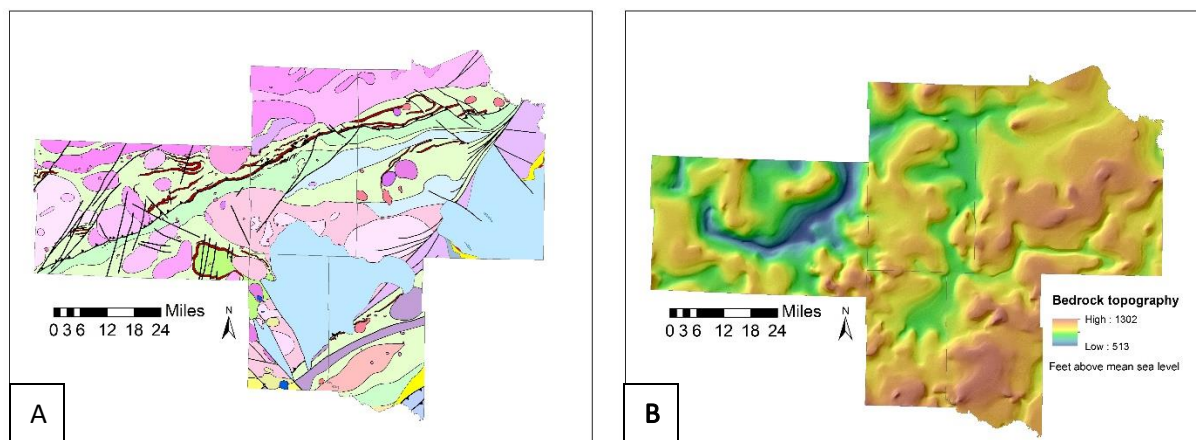


Figure 1. A) Bedrock geologic map of Wadena, Becker, Hubbard, and Cass (WaBeHuCa) Counties in Minnesota. Includes Archean, Paleoproterozoic, and Cretaceous strata. A full legend for bedrock units can be obtained in the referenced publications and will be discussed during the talk. B) Bedrock topographic map of WaBeHuCa counties. Sun illumination angle 315°, Sun elevation 45°. 5x vertical exaggeration.

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Mesoarchean Chemical Sedimentary Rocks of Northwestern Ontario: Implications for Hydrosphere Composition in Deep Time

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The 2.88 Ga carbonate sediments on Woman Lake, within the Uchi Subprovince of the Superior Province, preserve a chemical record of the Archean hydrosphere. Chemical sediments act as proxies for ancient waters by incorporating rare earth elements (REE) and isotopic signatures into their crystal lattice as they precipitate, thereby documenting the chemical composition of the waters from which they formed (Webb et al., 2009). Comparing the sedimentologic characteristics of Archean units to modern analogues enable us to determine the depositional environments of the past. Detailed stratigraphic columns linked with geochemical and isotopic data permit a more complete understanding of the depositional environment and evolutionary processes occurring at this early time in Earth's history.

At the base of the carbonate platform, lying atop rhyolitic Archean basement, is a massive carbonate grainstone unit, interbedded with minor crinkly-stratiform silicified microbial mats. A sharp contact separates them from a thrombolite unit (TB), composed of discontinuous and clotted laminations of dark, organic rich carbonate and white carbonate cement. Up section within the TB unit colloform stromatolites develop. This unit transitions into a stromatolitic unit that is comprised of 12-15cm thick carbonate grainstone (CG) alternating with 5-8cm thick pustular stromatolites (PS) for ~5m.

Geochemically interesting trends reminiscent of both Archean and modern oxygen-bearing signatures are evident in shale-normalized REE spectra (Fig. 1). REE concentrations were determined from weak acetic acid leaches by ICP MS and laser ablation-ICP-MS at the European Institute for Marine Studies (IUEM). The CG's display distinct negative Ce anomalies and slightly positive Eu anomalies while the PS show weaker negative Ce anomalies and no Eu anomaly (Fig. 1b). The TB unit displays consistent spectra with negligible Ce anomalies and positive Eu anomalies (Fig. 1a). Laser ablation-ICP-MS was used to obtain REE spectra exclusively from the TB's white calcite cements (Fig. 1c), which show a more pronounced Ce anomaly. Stable C and O isotopes were also analyzed at IUEM. The PS have slightly lower $\delta^{13}\text{C}$ values compared to the CG and TB (Fig. 2), however all samples fall within a relatively restricted range (-1.19 to 1.22‰).

Positive Eu and negative Ce anomalies are generally accepted as robust indicators of the influence of hydrothermal fluids and the presence of free oxygen, respectively (Derry and Jacobson, 1992). They are unique among REE in that they have two possible valence states ($\text{Eu}^{2+,3+}$, and $\text{Ce}^{3+,4+}$). In high temperature hydrothermal fluids, Eu^{3+} is reduced to Eu^{2+} , which renders it more soluble than its trivalent neighbors, a process that enriched Archean seawater with Eu and imparted a positive Eu anomaly on precipitating carbonates. Negative Ce anomalies result from the oxidation of Ce^{3+} to Ce^{4+} and the subsequent removal of the less soluble Ce^{4+} from solution. Once oxidized, Ce readily adsorbs onto particulate matter, removing it from solution and permitting Ce depleted chemical precipitation.

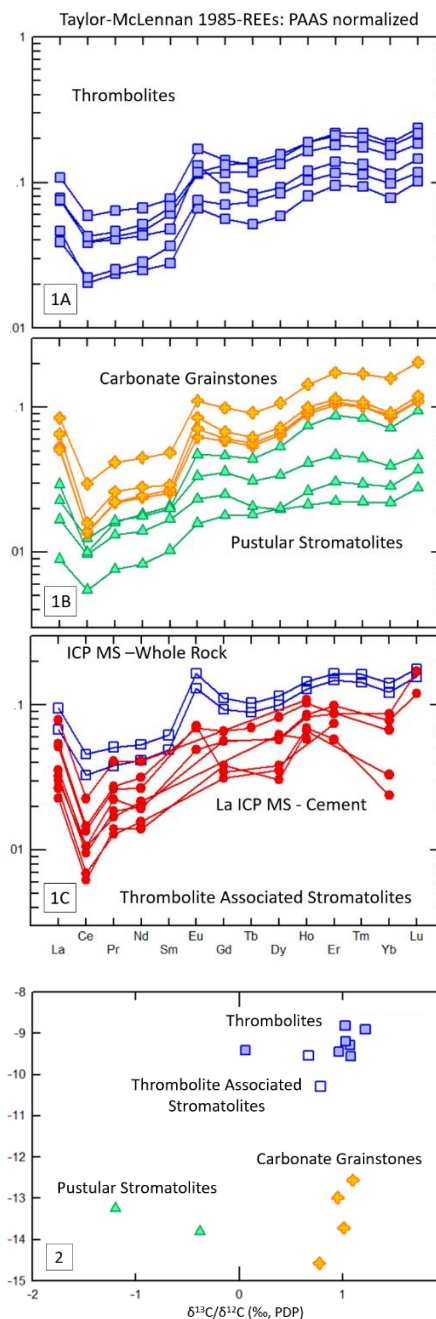
Stable carbon isotopes in marine carbonate rocks are widely used as proxies for carbon cycling through time and are commonly employed to track organic carbon burial, which

preferentially sequesters ^{12}C and leads to ^{13}C enrichment in residual dissolved inorganic carbon (Schidlowski, 2001). Throughout most of earth's history $\delta^{13}\text{C}$ varies only slightly from 0‰ (Veiser, 2001), and Woman Lake carbonates are no exception. The PS are slightly more negative compared to the CG and TB, likely due to the PS being more abundant in organic matter.

The geochemical anomalies and isotopic signatures present at Woman Lake seem to indicate that the carbonates precipitated from two different fluid sources. The positive Eu anomaly suggests a hydrothermal source which is characteristic of Archean seawater, while the Ce anomaly suggests fluids interacted with free oxygen. Stratigraphically, TB's precipitated first and contain a positive Eu anomaly (Fig. 1a), suggesting they precipitated within seawater. The overlying Stromatolitic Unit (PS and CG) contain negative Ce anomalies (Fig. 1b), which imply that they were deposited nearshore, where the PS could grow and interact with oxygen-bearing freshwater. The TB cements contain a more pronounced Ce anomaly compared to the whole rock composition (Fig. 1c). It is possible that the cements inherited the Ce anomaly from the overlying pustular stromatolites and grainstones. If they were subaerially exposed to rain, they may have partially dissolved and percolated through CG, reprecipitating with negative Ce anomalies in spaces within the TB producing the clotted fenestral appearance. It is also possible that the pustular stromatolites produced locally oxic conditions while the thrombolites were not as capable.

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Precambrian Geology of the Eastern Shebandowan Greenstone Belt - Insights into Stratigraphy and Structural History

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The Shebandowan greenstone belt (SGB), located in the Wawa-Abitibi terrane of the Superior Province, extends 150 km west from Thunder Bay to Quetico Provincial Park and has an arcuate shape. It is bordered by the Quetico Subprovince to the north and wraps around the Northern Light–Perching Gull Lakes batholithic complex to the south. Paleoproterozoic sedimentary rocks overlie the SGB's southeastern extent. This presentation reports on a multiyear project by the Ontario Geological Survey focused on updating the bedrock geology of the eastern part of the SGB, and new insights into the stratigraphy and structural history of the eastern SGB are explored. This work builds on previous work by Shegelski (1980), Williams et al. (1991), Berger (1993) and Corfu and Stott (1998).

The Shebandowan greenstone belt contains a succession of supracrustal rocks and their syn-eruptive intrusive equivalents. Geochronological data and previous geological studies have defined 3 main supracrustal assemblages: the Greenwater assemblage (*circa* 2720 Ma), the Kashabowie assemblage (*circa* 2695 Ma), which is not currently recognized in the eastern SGB, and the Shebandowan assemblage (*circa* 2690 to 2680 Ma) (Corfu and Stott 1998).

Based on the interpretation of Corfu and Stott (1998), the SGB has undergone 2 main stages of deformation (D₁ and D₂). D₁ deformation occurred at approximately 2695 Ma, and is thought to have tectonically imbricated rocks of the Greenwater and Kashabowie assemblages across the SGB, this event is poorly understood in the eastern SGB. D₂ deformation is constrained between 2685 and 2680 Ma and thought to record oblique northwest-directed compression. Regionally, the emplacement of sanukitoid plutons between 2685 and 2680 Ma is thought to have occurred during the waning of D₂.

In the eastern part of the SGB the Greenwater assemblage (*circa* 2720 Ma) comprises predominately massive, aphyric mafic volcanic flows with minor aphyric, pillowed and locally variolitic mafic flows. Among the mafic volcanic flows are thin layers of felsic and ultramafic volcanic rocks 100 to 750 m thick, as well as thin 100 m layers of terrigenous-clastic sedimentary rocks. Syn-eruptive intrusive mafic and ultramafic rocks occur throughout the Greenwater assemblage as sills and dikes. In the eastern part of the SGB the Shebandowan assemblage (*circa* 2690 Ma) is comprised of predominately intermediate volcanoclastic to epiclastic, heterolithic, amphibole- and plagioclase-phyric tuff, lapilli tuff, tuff breccia and coarse tuff breccia and/or terrigenous-clastic wacke, siltstone and conglomerate. The conglomerate commonly contains sedimentary fragments. The contact between the Greenwater and Shebandowan assemblages regionally has been interpreted to be an unconformity (Corfu and Stott 1998), however it is not been clearly demonstrated in outcrop.

Mapping as part of this project has identified a distinct lithostratigraphic unit separating rocks from the Greenwater and Shebandowan assemblages. The 1 to 1.5 km thick (in plan view) “boundary zone” comprises intermediate tuffs and flows and/or wacke to siltstone, interlayered with chemical sedimentary rocks and lenses of conglomerate (containing chemical sedimentary rocks ± mafic, ± ultramafic, ± felsic volcanic fragments). The “boundary zone” may be interpreted as the inferred lower stratigraphic unit of the Shebandowan assemblage or as the rocks deposited during a transitional period between the Greenwater and Shebandowan assemblages. Work is ongoing to evaluate the geologic context of this distinctive unit and its significance with respect to the stratigraphy of the SGB.

Some new constraints on the timing of deformation in the eastern SGB are provided by local outcrop observations and targeted geochronological analyses. An outcrop where structural relationships are well

exposed consists of a wacke deposited after 2694 ± 3 Ma (Davis, Ménard, and Sutcliffe 2018), that is assigned to the Shebandowan assemblage intruded by a set of tonalite dikes emplaced at 2682 ± 2 Ma (Davis, Ménard, and Sutcliffe 2018). Bedding and a layer parallel foliation in the wacke are folded and the folding is cross-cut by the tonalite dikes (Photo 1A). The tonalite dikes are also folded and boudinaged (Photo 1B), and finally a weakly penetrative cleavage overprints the previously described features. These observations indicate there were multiple phases of deformation affecting the Shebandowan assemblage rocks and that deformation continued past the emplacement of the dikes *circa* 2680 Ma.

Corfu and Stott (1998) considered the final phase of deformation in the SGB to be between 2685 Ma and 2680 Ma and that tectonic activity was quiescent after 2680 Ma in contrast to the adjacent Quetico Subprovince, and other greenstone belts farther east in the Wawa Subprovince, where deformation is recorded after 2680 Ma. However, the previously described outcrop observations show that there were multiple phases of deformation in the SGB after *circa* 2680 Ma. Thus, tectonic activity in the eastern SGB continued for longer than previously interpreted.

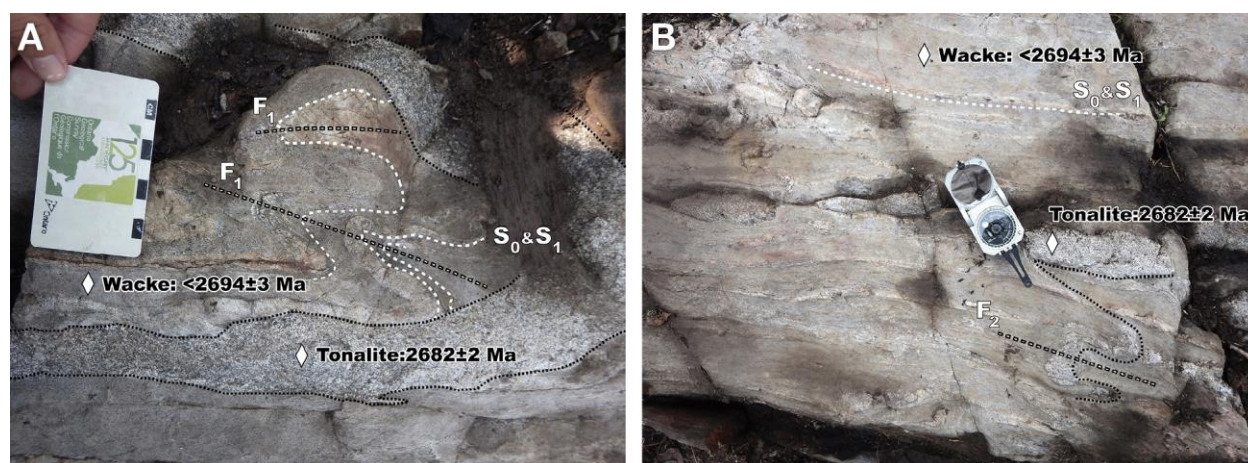


Photo 1: Photographs from a well exposed outcrop showing structural relationships. Two geochronology samples were analyzed from this location and ages are displayed (Davis, Ménard, and Sutcliffe 2018) (290782E 5363887N). **Photo A)** Folded primary layering and layer parallel schistosity (S_0 and S_1) cross cut by a tonalite dike. The dike is outlined by the black dashed line. The primary layering and layer parallel schistosity is indicated by the white dashed line. The folding event preceding dike emplacement is annotated in white and black (F_1). **Photo B)** Tonalite dike emplaced in a thinly bedded wacke and siltstone is folded and boudinaged. The dike is outlined by the black dashed line. The primary layering and layer parallel schistosity (S_0 and S_1) is indicated by the white dashed line. The folding event following dike emplacement is annotated in white and black (F_2). Compass is 22 cm long including sighting arm. The UTM co-ordinates are provided using NAD83 in Zone 16.

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High-technology metals in ore-forming environments and their signature in volcanic-hosted sulfide mineralization in northern Minnesota and Wisconsin.

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While the use of high-technology metals (HTMs), such as In, Ge, Ga, and Tl, is increasing in essential industrial applications and renewable energy technologies, our understanding of the sourcing and accumulation of these elements is insufficient. This applies to both their general distribution in various geological environments, their sourcing by ore-forming processes, and their deposition in selected ore deposits from which they are being mined.

Typical concentrations for these metals are very low in most rock types (0.1 - 2 ppm; e.g., Terashima, 2001) and may reach concentrations > 1 % in certain ore deposit types (Murao et al., 2008; Kampunzu et al., 2009) by substituting for common metals (Zn, Cu, Sn) in familiar ore mineral such as sphalerite, chalcopyrite, or stannite (Johan, 1988, Pavlova et al, 2015).

The formation of ore deposits showing elevated values of In, Ge, Ga, and Tl (volcanic-hosted massive sulfides, granitic tin deposits, MVT deposits) are relatively well understood but it is unclear why these metals do not accumulate in other ore-forming environments, i.e. SEDEX, SSC, or porphyry deposits, known to contain elevated concentrations of other HTMs. Little research has been conducted into the general thermodynamic behavior or potential enrichment mechanisms and there is no organized database of the concentration of these metals in various geological settings or their sourcing in ore-forming systems. Previous work (Schardt and David, 2018) initiated data collection and analysis of these metals in common rock types and an interpretation of potential sources. In this study, the database has been expanded to include most common ore-forming environments to better understand commonalities and differences with regards to selected HTMs and evaluate volcanic-hosted massive sulfide signatures from northern Minnesota (Vermilion district) and Wisconsin (Penokian Volcanic Belt).

Figure 1 plots all available data (whole rock, mineral, ore material, alteration) for the most common ore deposit types and compares them to available data from the Vermilion district as well as known volcanic-hosted massive sulfide deposits in the Penokean Volcanic Belt of Wisconsin. Except for Tl, both environments show low average concentrations compared to similar formation environments (V). Data would suggest that either a) hydrothermal processes unrelated to volcanogenic massive sulfide formation (e.g., lower- temperature SEDEX, epithermal, gen. hydrothermal, SSC, MVT) are more efficient at sourcing and concentration HTMs, or b) the difference in host/source rock has a significant influence on the ability of the ore-forming system to source and accumulate HTMs. Most rock types have very similar HTM concentrations, except for Ga, which is significantly more abundant in volcanic rocks (~ 1 ppm vs. ~ 20 ppm). Higher fluid temperatures, such as those found in granitic ore systems (G in figure 1) do not exhibit any specific HTM enrichment but their whole-rock data (stippled line in figure 1) indicate that In may be more mobile under these conditions.

This interpretation is speculative as available data are scattered and these elements are not routinely analyzed. While no systematic work has been conducted to assess the behavior of these metals a robust database is now available to study their distribution in hydrothermal systems and apply results to exploration efforts in Minnesota and Wisconsin.

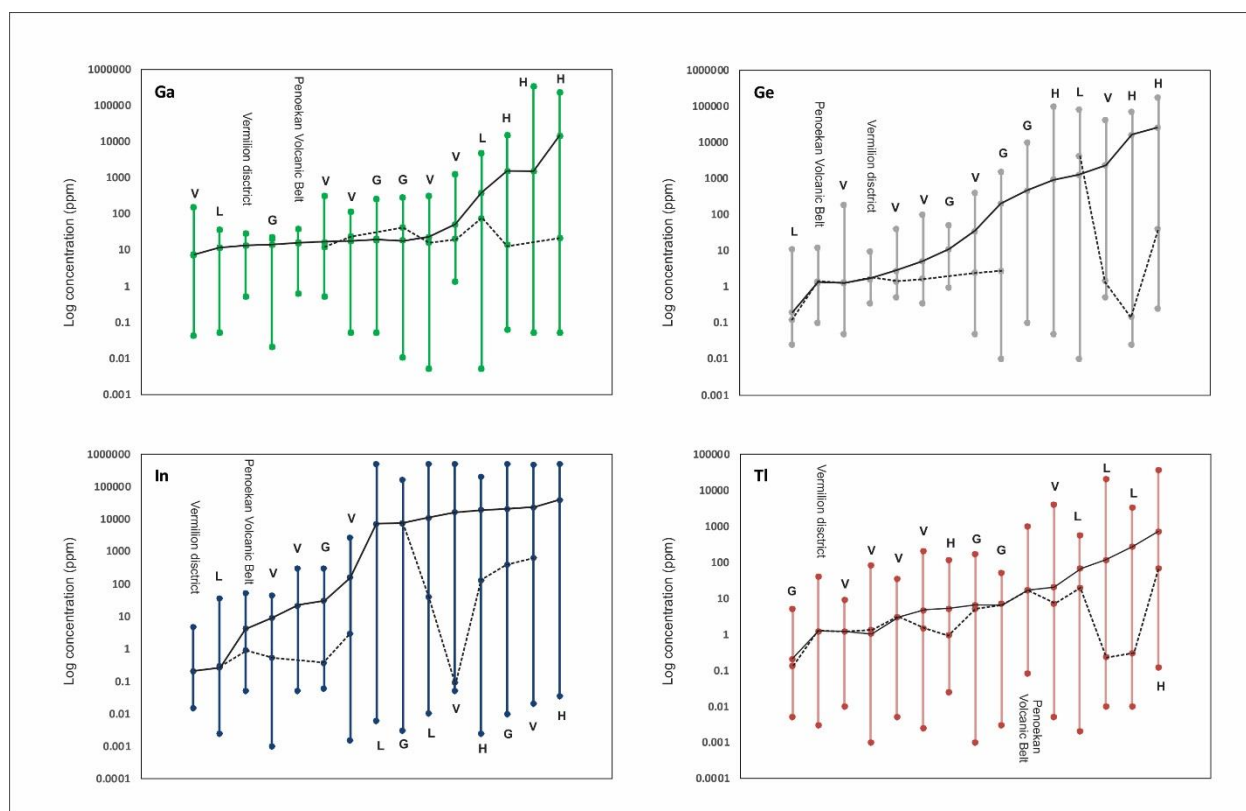


Figure 1. Plot of HTM concentrations as a function of ore-forming environment. Vertical bars represent minimum, average, and maximum values for each ore deposit type (see text). Solid lines denote trend in average concentrations (all data) while stippled line shows whole-rock concentrations only. L – low temperature (SSC, MVT); V – volcanogenic (all types of VHMS); H – hydrothermal (SEDEX, epithermal, hydrothermal), G – granite-related (skarn, tin, porphyry).

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Geochemistry of Archean Gneisses in Dickinson County, Northern Michigan

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A terrane composed largely of Meso- to Paleoproterozoic gneisses and granitic rocks occurs along the southern margin of the Neoarchean Superior Craton in the Lake Superior region. These rocks are best documented from exposures in the Minnesota River Valley (MRV) in southwestern Minnesota, but they also occur in basement uplifts in northern Michigan including the Watersmeet Dome in the Marenisco-Watersmeet area, the Carney Lake Gneiss north of the Menominee iron range, and the Southern Complex south of the Marquette Trough. Recent studies in the MRV have shown a range in ages primarily between ~2.6 Ga to ~3.5 Ga, representing both primary intrusive events and metamorphic/tectonic overprints (Bickford et al., 2007 and references therein). Similarly, dating of the gneisses in the Watersmeet Dome (Miska et al., 2018) and Carney Lake Gneiss (Ayuso et al., 2018) have a range of ages from ~1.8 Ga to ~3.6 Ga, but also several spot analyses of zircon cores and xenocrysts that date at ~3.8 Ga. Thus, the northern Michigan gneisses show evidence of an Eoarchean component and effects of the Penokean orogeny neither of which are seen in the MRV. Here we report on the geochemistry of Archean gneisses from Dickinson County in northern Michigan including the Carney Lake Gneiss.

The Archean rocks in Dickinson County are described in James et al., (1961) and Bayley et al., (1966). As is typical of Archean gneiss terranes, the rocks consist mostly of variably banded and deformed tonalite-trondhjemite-granodiorite (TTG) gneisses and granites.

Geochemistry

Major elements

Major element geochemistry of the gneisses in Dickinson County span the compositional range from tonalite to granite. Using the granite classification of Frost et al., (2001), the gneisses are magnesian and mostly calcic, although some of the more felsic gneisses are alkali calcic. A notable feature of the gneisses is that they are weakly to strongly peraluminous and corundum normative (Fig. 1A). The Na₂O content ranges from 3 to 5 wt.%, and the K₂O content ranges from ~1 to 5 wt.% (medium- to high-K range); Na₂O/ K₂O ratios are mostly <2. There is a positive correlation between Na₂O and Al₂O₃ contents, and a negative correlation between K₂O and Al₂O₃ contents.

Trace elements

Unlike many Archean TTG suites which are typically characterized by Sr contents >400 ppm, the Sr contents of the Dickinson County gneisses are variable but <400 ppm. Rubidium/Sr ratios are variable, ranging from <0.1 to ~1, and show a negative correlation with Al₂O₃.

Samples exhibit significant variation in chondrite normalized REE patterns, both in terms of pattern steepness and size of the Eu anomaly (Fig. 1B, C). The (La/Yb)_N for samples from the Carney Lake Gneiss varies from 29 to 183 with no to moderately negative Eu anomalies; the more felsic samples tend to have higher light REE abundances and larger negative Eu anomalies (Fig. 1B). In contrast, two biotite gneiss samples from near Felch have much flatter patterns ((La/Yb)_N of 14 and 24) and moderate to large negative Eu anomalies (Fig. 1C). Two samples of Norway Lake Gneiss from north of Felch have intermediate sloped REE patterns ((La/Yb)_N of 44 and 58), no Eu anomaly for the tonalite sample, and moderate negative anomaly for the more granitic sample (Fig. 1C). All samples have negative Nb and Ta anomalies on primitive mantle normalized trace element plots.

Comparison with Archean TTG suites

Archean TTG suites are commonly silica-rich (SiO₂ >64 wt.%, but commonly ≥70 wt.%), have high Na₂O (>3.0 wt.%) and Na₂O/K₂O (>2), and low ferromagnesian element contents (Moyen and Martin, 2012). They trend from metaluminous to slightly peraluminous (A/CNK ~1; normative corundum <1%), with A/CNK increasing in more granitic compositions. Two subgroups are recognized: most

Archean TTG suites have high Al_2O_3 (>15 wt.% at 70 wt.% SiO_2) with high Sr contents (>400 ppm) and strongly fractionated REE patterns ($(\text{La}/\text{Yb})_N$ up to 150); the second subgroup has lower Al_2O_3 (<15 wt.%) as well as lower Sr and less fractionated REE patterns.

The Archean gneisses and granitic rocks in Dickinson County have the geochemical characteristics of typical TTG suites with respect to Al_2O_3 and strongly fractionated REE patterns. However, most samples are more potassic and less sodic than typical TTG and have lower Sr contents (<400 ppm). In addition, the Dickinson County samples are all peraluminous.

Discussion

Most models for the genesis of typical TTG involve partial melting of garnet amphibolite or eclogite (Moyen and Martin, 2012). However, the geochemical characteristics of the Archean gneisses in Dickinson County suggest a more complex petrogenesis involving melting of preexisting evolved crustal sources. This is supported by the presence of ~3.8 Ga xenocrystic zircons in some samples (Ayuso et al., 2018).

It has been proposed that the Archean gneiss terrane in the Lake Superior region is a remnant of the Wyoming Craton, which was rifted from the Superior Craton in the Paleoproterozoic. In this regard, it may be significant that the quartzofeldspathic gneisses and granitoids in the Wyoming Craton have similar geochemical characteristics to the Archean gneisses in Dickinson County including relatively high K_2O , low Sr, variably steep REE patterns, and are also mostly peraluminous (Frost et al., 2006).

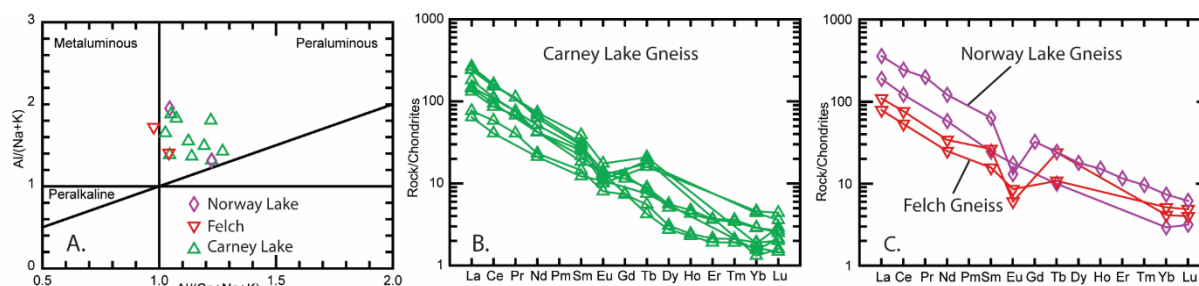


Figure 1. A. Aluminum index; B. Normalized REE patterns Carney Lake Gneiss; C. Normalized REE patterns Felch and Norway Lake gneisses

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Geologic Architecture and Precious Metal Mineralization in the Southern Abitibi; New Insights from the Larder Lake Area

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Metal Earth is one of the largest mineral exploration research project ever undertaken and is a fully funded \$104M / 7 year research project focused on the processes responsible for differential metal endowment and ore localization during the Archean. A major focus of Metal Earth is to use geological and geophysical data to define crust to mantle scale differences across ancestral fault systems and volcanic centres that have variable metal endowment.

As part of the Metal Earth project, research has focused on a ~40 km long north south geologic transect that is centered over the Cadillac-Larder Lake break and extends northward into the Ben Nevis volcanic complex and to the south over the Lincoln Nipissing shear zone. The Cadillac-Larder Lake break is a regionally extensive crustal break and hosts a number of gold deposits including the Kerr Addison mine which historically produced over 11Moz of gold. The Ben Nevis volcanic complex (2696.6 ± 1.3 Ma), part of the Blake River group ($2701 \pm 3 - 2698.5 \pm 2$ Ma), is correlative to the Noranda VMS camp but lacks significant metal endowment. The Lincoln Nipissing shear zone is similar to the Cadillac-Larder Lake break, in that it juxtaposes different geologic domains and is marked by ultramafic volcanic rocks, clastic sedimentary rocks and Timiskaming aged small volume intrusive rocks and associated gold prospects. At both the Cadillac-Larder Lake break and the Lincoln Nipissing shear zone, ultramafic rocks of the Larder Lake group (ca. 2710-2704 Ma) (Piché in Quebec) are unconformably overlain by clastic rocks of the Timiskaming (2677-2670 Ma) or Hearst assemblage (<ca. 2700 Ma). This suggests that the original geologic relationship was stratigraphic in nature and subsequently overprinted by deformation and alteration associated with the gold deposits, in contrast to the previous interpretations that only considered a structural emplacement.

Recent geological and geophysical surveys from the Metal Earth research project indicate that the Cadillac-Larder Lake break is well-resolved using seismic methods to depths of over 30 km and has a corresponding MT conductivity anomaly. In contrast, the Lincoln Nipissing shear zone, although sharing similar characteristics to the Cadillac-Larder Lake break, is poorly resolved by seismic and MT methods, perhaps correlating with the relative lack of metal endowment along the shear zone. This is MERC-Metal Earth publication number MERC-ME-2018-177.

An investigation into the distribution of chalcophile elements and timing of mineralization within the Crystal Lake intrusion: A U-Pb geochronology and LA-ICP-MS study

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A detailed geochemical and isotopic study is underway on the 1099.1 ± 1.2 Ma (Heaman et al. 2007) Crystal Lake intrusion, which has previously been compared to the proximal Duluth Complex (Thomas 2015). The aim of this study is to gain further insights into the controls on ore genesis within the ‘main-rift’ intrusions (Miller and Nicholson 2013). The Crystal Lake intrusion, located 47 km southwest of Thunder Bay, Ontario, Canada, outcrops as a prominent Y-shaped body within the Paleoproterozoic Animikie basin, intruding sulfur-bearing shale, argillite and greywacke of the Rove Formation. Although a number of dating studies have been undertaken on the MCR (see Heaman et al. 2007, for a relatively recent compilation), many of the intrusions either lack the precision that is now possible with routine chemical abrasion U-Pb geochronology or are yet to be dated. We are currently undertaking a comprehensive geochronology study throughout the MCR, this includes detailed dating of the Crystal Lake intrusion. In addition to refining Heaman’s et al. (2007) baddeleyite age of 1099.1 ± 1.2 Ma we aim to constrain the relationship of the northern and southern limbs of the intrusion. Furthermore, we plan to untangle the timing of the Crystal Lake intrusion relative to other MCR intrusive events including the NE-trending Pigeon River dykes, the NW-trending Cloud River dykes and the sulfide-bearing Mount Mollie intrusion developed to the east.

Ni-Cu-PGE sulfide mineralization is developed within the northern and southern limbs of the Crystal Lake intrusion in association with vari-textured gabbros and irregular Cr-spinel-bearing horizons. The association of sulfides and metal enrichment with pegmatitic/taxitic units is also observed within other Ni-Cu-PGE deposits such as the ca. 1108 Ma (Heaman and Machado 1992) Coldwell Complex, Merensky Reef, Norilsk and Voisey’s Bay. Sulfide mineralization is largely disseminated, with massive sulfides (<50 cm in thickness) developed locally within the northern limb. The disseminated ores are variable in texture with globular (capped and uncapped), blebby and interstitial sulfides identified. Silicate-capped sulfide globules have been recognized in other Ni-Cu sulfide deposits (e.g. Norilsk, Insizwa Complex; Barnes et al. 2017; Le Vaillant et al. 2017) and are interpreted as being the remnants of former segregation vesicles that attached to an immiscible sulfide melt (Mungall et al. 2015). Within the Crystal Lake intrusion, the morphology of the caps, which are comprised of amphiboles, clays, chlorite and calcite, is variable. Convex silicate caps, identical to those modelled by Mungall et al. (2015), are present along with very irregular silicate attachments. The implications of degassing, which appears to be a common process within the Ni-Cu ore systems, for sulfide transportation and deposition is yet to be constrained. Furthermore, the cause (e.g. contamination, pressure changes) and timing of degassing relative to crystallization is not well understood.

A detailed elemental deportment study is currently in progress, focused on characterizing the distribution and mineralogy of platinum-group minerals (PGMs). Element mapping of sulfides by LA-ICP-MS has been used to further investigate the control on the distribution of the chalcophile elements during sulfide fractionation. Preliminary observations indicate that Pd resides in solid solution within pentlandite (1 – 150 ppm) and as small As-Bi and Sb-bearing PGMs. Within the massive sulfides Pd-bearing minerals show a strong association with nickel arsenides resulting in lower concentrations of Pd (~1 ppm) in the pentlandite than typical of other sulfide assemblages (10–150 ppm). Platinum is not compatible in any of the sulfide phases, instead occurring as discrete As and Sb-bearing PGMs. The PGMs are found either enclosed or attached to sulfides or within secondary silicates around the altered margins of the sulfides. It is yet to be established whether the crystallization of Cr-spinel and/or low-temperature alteration of the sulfides has had any control on the mineralogy and distribution of PGEs.

Element mapping of the sulfides by LA-ICP-MS has revealed some interesting structural and or/mineralogical controls in the distribution of chalcophile elements. Although not observed throughout the primary sulfide assemblage, some unaltered sulfides are characterized by a strong microfabric (Fig. 1). This fabric is defined by several elements including As, Mo, Bi, Pb, Pd and Re which appear to be preferentially concentrated along thin, parallel linear features within the pyrrhotite-pentlandite-chalcopyrite assemblage. The molybdenum map also shows thicker banding and elevated concentrations within pyrrhotite (Fig. 1). Interestingly this fabric is not confined to a particular sulfide phase. This is best shown by As, Mo and Re which clearly cut across the grain boundaries of pyrrhotite, pentlandite and chalcopyrite, which suggests that this fabric was developed subsequent to crystallization of all three phases. For other elements such as Pd and Pb, the fabric is restricted to the pyrrhotite and pentlandite (Fig. 1). Silicate infilled fractures appear to cut the fabric as shown in the As map. Further work is in progress to determine the controls on selected element mobility (i.e. low temperature alteration or deformation) and to gain an understanding at what scale this remobilization is occurring. If various elements are remobilized over long distances, then it could have implications for vectoring of Ni-Cu ore systems. Element mapping by LA-ICP-MS is an extremely powerful tool, providing unparalleled detail at the micro scale. This technique provides insight into the behavior and mobility of chalcophile elements during sulfide fractionation, low temperature alteration and/or deformation and may provide a link to larger element haloes associated with some Ni-Cu-PGE deposits.

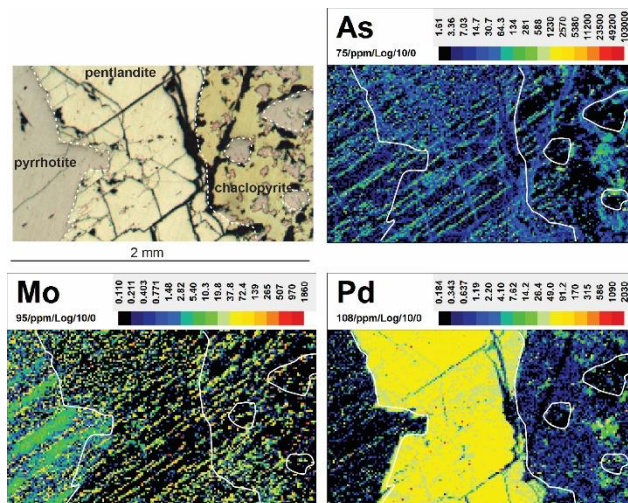


Figure 1. LA-ICP-MS element maps of primary sulfide assemblage

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Seismic stratigraphy of the 1.1 Ga Midcontinent Rift beneath western Lake Superior shows evidence of differing subsidence histories for syn-magmatic sub-basins

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The nature of the Midcontinent Rift where it is hidden beneath Lake Superior can only be understood from geophysical interpretation and inferences from geologic concepts onshore. Many decades of collecting geophysical data and improving the geologic framework for the Lake Superior region have led to evolving paradigms on its structure and geologic history. We are taking a new look at the existing geophysical data considering recent age dating and geologic mapping as part of an ongoing effort to characterize the 3D geometry of the rift through time. In particular, we are constructing a seismic stratigraphic framework from reflection data collected in the 1980s to characterize the basalt-filled sub-basins present beneath the western lake. Integration with gravity and aeromagnetic data and correlation of seismic stratigraphy to onshore geology provides insight into the geometry of the sub-basins and the timing and rates of subsidence and concurrent magma accumulation.

We interpret 3 reprocessed and 7 geolocated images of industry seismic sections and public seismic data (GLIMPCE Line C) using a 3D visualization software platform. Seismic sections were converted from time to depth using existing seismic refraction models as guides. Dips and thicknesses of onshore geology projected onto nearby seismic profiles tie seismic stratigraphy to mapped geologic units. Aeromagnetic modeling helps distinguish igneous rocks with strong, reversed- versus normal-polarity remanent magnetization, which constrains the cooling ages of syn-rift rocks to before or after about 1100 Ma, respectively.

Seismic facies and reflection geometry image volcanic flows, sills, intrusions, and pre-rift crust. We have identified three seismic stratigraphic units. The lowest unit has clinoform reflection geometry and may represent pre-rift sediments intruded by sills. The middle and upper units have synform reflection geometry, but aeromagnetic modeling and correlations to onshore geology suggest the middle unit represents older (>1100 Ma) basalts with reversed-polarity and the upper unit represents younger (<1100 Ma) basalts with normal magnetic polarity.

As pointed out by previous workers (e.g., Allen et al., 1997) we do not observe large normal faults bounding sub-basins. Except for a possible growth fault of limited extent at depth on GLIMPCE Line C (Fig. 1), we observe sub-basins that sag and thicken toward their centers, implying that syn-magmatic subsidence may have been the primary control on basin development in western Lake Superior. The sub-basins are flanked by two previously recognized seismic highs that are associated with gravity lows: Grand Marais Ridge (GMR) south of Grand

Marais, MN, and White's Ridge (WR), centered on the Bayfield Peninsula (Fig. 1; Allen et al. 1997).

An isopach map of the seismic stratigraphic unit interpreted as normal-polarity basalts shows differences in thickness and age of basin fill within sub-basins surrounding GMR (Fig. 1). We correlate most of the basin fill in a western, bowl-shaped basin to the Beaver Bay Complex and younger North Shore Volcanics that were deposited or emplaced on the present-day northern lake shore of Minnesota between ca 1096 – 1094 Ma. In contrast, only 4-9 km of normal-polarity basalt infills an adjacent, elongate basin that wraps around the southeast and eastern sides of GMR. We correlate this material with the ca 1094 – 1091 Ma Portage Lake Volcanics on Michigan's Keweenaw Peninsula. The difference in basin geometry and age indicates each basin developed independently. The western basin subsided and infilled at some 5mm per year. After the main subsidence and infilling of the western basin waned, the adjacent, shallower basin began to subside at some 3 to 1.3mm per year. Reflections interpreted as reversed- and normal-polarity basalts in the shallower basin truncate against the southern side of GMR. Truncation of these once laterally continuous basalt layers was likely caused in part by the basins' different subsidence histories and relative uplift of GMR. A mechanism for the syn-magmatic basin subsidence and dramatic difference in subsidence rates is unclear.

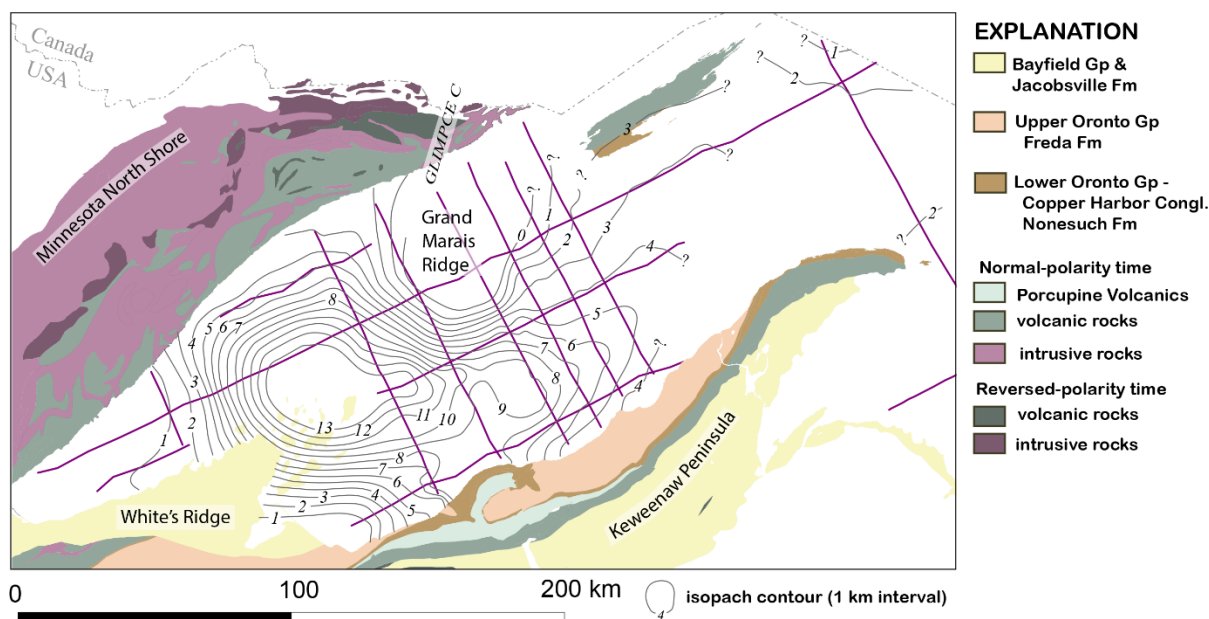


Fig 1: Isopach map of normal-polarity basalt. Onshore geology highlights the distribution of reversed- and normal-polarity basalt and overlying sedimentary units. Purple lines locate seismic profiles, with line GLIMPCE C labeled.

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Towards understanding geoarchaeological contexts in Northwestern Ontario: The newly formed lithic material comparative collection at Lakehead University

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Stone tools were created by flintknapping, which is the process of utilizing percussion and pressure flaking techniques on fine-grained siliceous raw materials that were carefully selected by ancient people. Excellent preservation of lithics in the boreal forest of Northwestern Ontario provides some of the best evidence in the archaeological record for reconstructing these past human activities. Professional archaeologists have been finding and interpreting stone tools from the earliest known Palaeo or Early Period (ca. 9,000-7,000 years before present) sites in the Thunder Bay region beginning in the 1950s (Dawson, 1984; MacNeish, 1952). However, little is still known about the variation and sources of them in Northwestern Ontario, despite lithics being the most commonly found artifact class.

For site descriptions, archaeologists must try to identify lithic artifacts to the best of their abilities, both describing the material and then attempting to find the source from which people had obtained it. Although geologists are not typically as concerned about the macroscopic nuances of each flakeable material (e.g., chert rather than brown banded Hudson Bay Lowland chert), archaeologists note variability in order to understand ancient miners' choices whether for better flaking, durability of formed edges, or sometimes even esthetic appeal. These descriptions often reflect superficial macroscopic observations and a misunderstanding of regional geological characterizations even in terms of major rock types (i.e., sedimentary, igneous, or metamorphic). During the cataloguing process, many archaeologically recovered lithic types are erroneously categorized, leaving many artifacts to fall into the category of "unknown material type". Perhaps one of the biggest challenges in Northwestern Ontario is the limited availability of comparative collections to try and identify lithic raw materials.

To counteract this issue, Surette, colleagues, and students in the Department of Anthropology at Lakehead University began collecting geoarchaeological samples of knappable materials in 2011, and at primary sources where possible. Secondary and tertiary source examples were also collected, even though their contexts are more complicated to understand from a geoarchaeological perspective. Geological maps were examined and geoarchaeological contexts were considered (ancient hydrology, stratigraphy, etc.) to determine where these silica rich materials might be located and which would have been accessible at different times. In addition, we have started sharing and trading for samples with archaeologists and geologists from other institutes in Canada and the U.S.A. to build a representative library. To date, there are nearly 5,000 samples from both countries, of which 1,300 are from various locations in Ontario. One of the better understood hosts of raw materials is the Gunflint Formation near Thunder Bay, which has been the recent focus of much sampling for the comparative collection (e.g., Vickruck, 2018).

Unfortunately, archaeologists in Canada rarely describe knappable rocks and minerals by attributes, in detail, or using correct geological terminology, even for quarry sites where there is typically one or limited sources found. This factor is problematic because it is then difficult for other researchers to determine if their samples are made of the same material - perhaps found at a different site due to trading or people obtaining quarry samples and utilizing them elsewhere. In Northwestern Ontario, there are also few basic descriptions of flakeable materials used by early Indigenous populations (Hamilton, 1981 for Lac Seul, Taylor-Hollings, 2017 regarding the Bloodvein River, and Vickruck, 2015 for the Thunder Bay region). Therefore, we aim to change that in our discipline through the study of samples in the Lakehead University lithic collection and make this information available to other researchers (eventually online).

The Lakehead University lithic material comparative collection in the Department of Anthropology will provide archaeologists and geoscientists with opportunities to examine the minutia of knappable rocks and minerals, with emphasis on the Gunflint Formation but also from many other regions. This new database provides raw material examples that can be studied in many different ways, either at a large scale or microscopic studies of individual rocks or minerals. Due to having a large collection, we now know that different sources can produce similar flakeable rocks, which emphasizes the need to chemically test them to clarify provenance. The next steps are to catalogue and properly describe these samples in the collection. We also plan to develop methods for analyzing these materials with non-destructive techniques, which may be also applied to artifact characterization. Combined, this will help us address both the problem of not knowing about sources in Northwestern Ontario and illustrating these materials properly through basic lithological descriptions and in some cases, further non-destructive geoarchaeological analytical techniques. Ultimately, that will help us address the selection processes of ancient Indigenous people in the area.

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Insights into Midcontinent Rift development resulting from a strengthened chronostratigraphic framework

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Correlation of volcanostratigraphic sequences across the Midcontinent Rift has been a long time focus of research efforts with major advances made on the basis of lithostratigraphy (e.g. Green, 1982), magnetostratigraphy (e.g. Books, 1972), chemostratigraphy (e.g. Nicholson et al., 1997), and U-Pb geochronology-based chronostratigraphy (e.g. Davis and Green, 1997). As the result of an effort to obtain high-resolution U-Pb geochronological constraints on paleomagnetic poles from the Midcontinent Rift and constrain rates of rapid plate motion, we have published 14 new chemical abrasion–isotope dilution–thermal ionization mass spectrometry (CA-ID-TIMS) $^{206}\text{Pb}/^{238}\text{U}$ dates (Swanson-Hysell et al., 2015; Fairchild et al., 2017; Swanson-Hysell et al., 2019). Single zircon analyses of chemically-abraded grains improves the geochronology of previously dated units in addition to resulting in high-precision dates developed for previously undated units. These dates can be used to construct a chronostratigraphic framework for Midcontinent Rift volcanic and sedimentary succession shown in Figure 1 that is further informed by magnetostratigraphic data and paleomagnetic pole position.

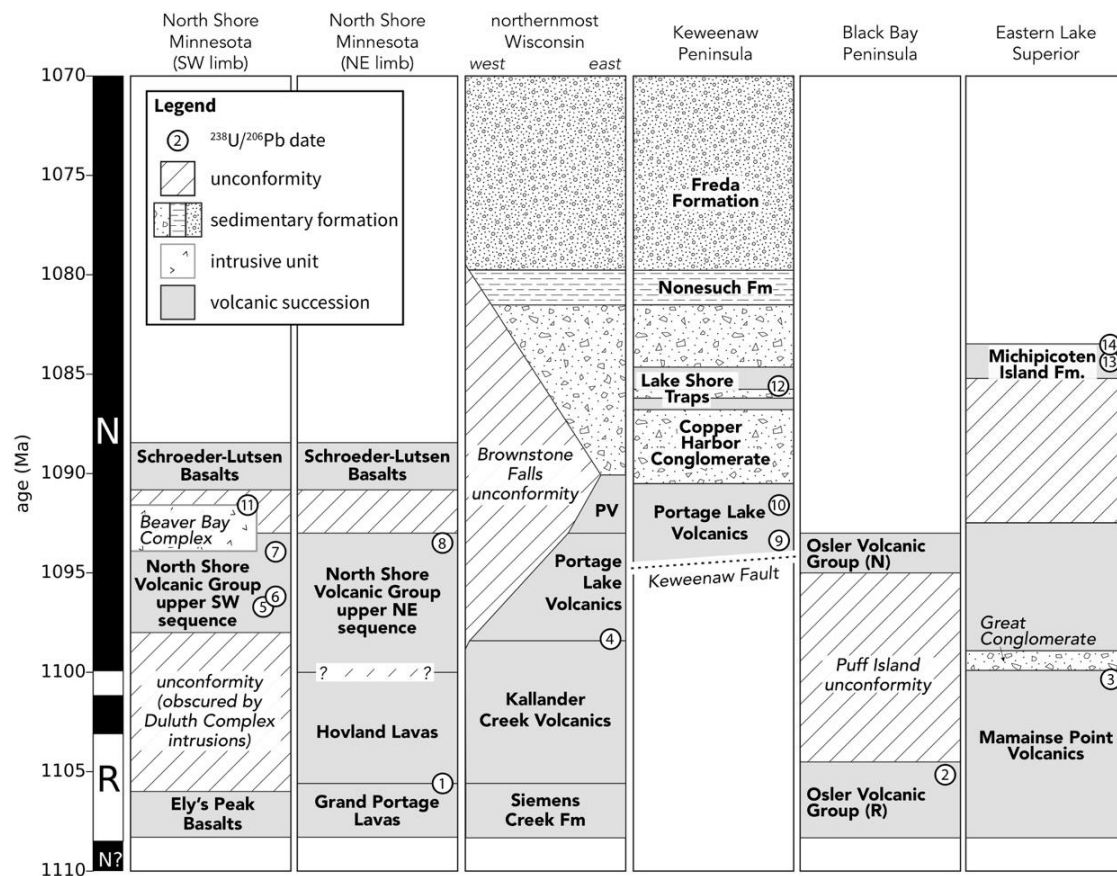


Figure 1: Chronostratigraphic correlation of Midcontinent Rift volcanic sequences across the Lake Superior Region of North America, informed by new U-Pb dates. The numbered circles correspond to CA-ID-TIMS $^{206}\text{Pb}/^{238}\text{U}$ dates. The analytical uncertainty, which can be used when comparing these dates to one another, is less than the time represented by the height of the circles. Extrapolated eruption rates, paleomagnetic data (both polarity and pole position) and $^{207}\text{Pb}/^{206}\text{Pb}$ dates (not shown) inform the chronostratigraphic interpretation, but the chronostratigraphy is most robust in the proximity of the $^{206}\text{Pb}/^{238}\text{U}$ dates. Figure from Swanson-Hysell et al., 2019.

To aid in the discussion of geomagnetic polarity zones, I propose naming them following the guidelines of the International Commission on Stratigraphy resulting in the Alona Bay reversed-polarity zone, the Flour Bay normal-polarity zone, the Flour Bay reversed-polarity zone and the Portage Lake normal-polarity zone with current evidence suggesting that the Portage Lake normal-polarity zone was particularly long-lived (Driscoll and Evans, 2016). The geomagnetic polarity timescale and the major inclination change recorded as the result of paleolatitude change throughout of the time period of active Midcontinent Rift magmatism continue to present opportunities to constrain the chronostratigraphy of volcanic, intrusive and sedimentary rocks of the rift. Future high-precision $^{206}\text{Pb}/^{238}\text{U}$ dates on intrusive units coupled with paleomagnetic data may offer further opportunities related to the polarity record in the earliest history of rift development. The mafic nature of the earliest Midcontinent Rift lavas (including picrites), and the associated lack of zircon, continues to present challenges to efforts to robustly constrain the chronostratigraphy of the early magmatic stage of rift development.

Age constraints on the angular unconformities within the Osler Volcanic Group, between the North Shore Volcanic Group & Schroeder-Lutsen Basalts and at the base of the Oronto Group in northern Wisconsin are insightful as relates to the timescale of active rifting and the transition to the thermal subsidence stage of rift development. Post-rift unconformities can be particularly useful for constraining the timing of the end of rifting as they juxtapose underlying syn-rift strata with post-rift strata. The Brownstone Falls unconformity at which Oronto Group sedimentary rocks overlie progressively lower stratigraphic levels of the Porcupine Volcanics, Portage Lake Volcanics, and Kallander Creek Volcanics (Fig. 1) is well-explained as a post-rift unconformity. The volcanics underlying the unconformity can be interpreted as syn-rift strata with the overlying Oronto Group having been deposited during widespread thermal subsidence. The syn-rift strata in this interpretation include the Portage Lake Volcanics which could constrain the post-rift phase to postdate $1091.59 \pm 0.27/0.52/1.3$ Ma (Swanson-Hysell et al., 2019). The youngest well-dated magmatic product from the Midcontinent Rift is the Davieaux Island rhyolite of the Michipicoten Island Formation ($1083.52 \pm 0.23/0.35/1.2$ Ma; Fairchild et al., 2017) although the Bear Lake volcanics are likely younger still (Kulakov et al., 2018).

When combined with paleomagnetic data, these chronostratigraphic constraints provided evidence for very rapid motion of Laurentia leading up to the collisional orogenesis associated with the Ottawa phase of the Grenvillian orogeny.

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An oxygenated Paleolake Nonesuch and primary detrital hematite in the Freda river system

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In addition to preserving an extended interval of volcanism, sediment deposited within the thermal subsidence phase (Cannon and Hinze, 1992) of the Midcontinent Rift provide an exceptional record of late Mesoproterozoic terrestrial environments. The Orono Group, deposited during this thermal subsidence phase commences with the Copper Harbor Conglomerate ca. 1086 Ma, which represents terrestrially-deposited alluvial fan and fluvial sediments (Elmore, 1984). The Nonesuch Formation overlies the Copper Harbor Conglomerate and is interpreted as a lacustrine facies association (Stewart and Mauk, 2017) that is exposed along a >250-km-long belt in northern Michigan and Wisconsin. The sediments of the Nonesuch Formation indicate that the lake in northern Wisconsin and Michigan (referred to here as Paleolake Nonesuch) was large and persistent. Lacustrine sedimentation continued until after the transition into the overlying Freda Formation — a transition typical based on color rather than lithofacies. The overlying Freda Formation is dominantly composed of channelized sandstone and overbank siltstone deposits that were deposited within a terrestrial fluvial environment (Ojakangas et al., 2001).

Five drill cores from northern Wisconsin were used by Stewart and Mauk (2017) to develop a sequence stratigraphic framework for the Nonesuch Formation. In work published in Slotznick et al. (2018) we focused on two of these cores (DO-8 and WC-9) and have now extended our analyses to outcrop sections as well as cores from the Presque Isle syncline. In this research, we have used experimentally determined estimates of magnetization and coercivity on samples that span sections of the Nonesuch Formation. These rock magnetic data can be used to interpret three distinct magnetic facies (Slotznick et al., 2018). These three facies and their juxtaposition can be explained as the result of an oxycline in Paleolake Nonesuch. The detrital input to the lake is preserved in facies 2 and included magnetite and hematite due to weathering and oxidation of the source igneous material during transport. Magnetic facies 1 is associated with sediments in the deepest part of the lake with a magnetic mineral assemblage that shows that delivered iron oxides underwent reductive dissolution through microbial metabolic processes. Much of this iron and iron within sheet silicates reacted with sulfide to form pyrite, but sulfide availability was restricted to pore waters and not sufficient to sulfidize all of the available reactive iron. These data indicate that the sediments in the deepest part of the lake were anoxic, possibly with anoxia extending into the water column. In contrast, intermediate oxygen levels in waters throughout much of the lake allowed for the preservation of detrital magnetite and hematite in facies 2. In the shallow waters of the lake recorded in facies 3, oxic conditions prevailed and most of the detrital magnetite, as well as iron in other phases, was oxidized to hematite. In Slotznick et al. (2019), we interpreted this vertical sequence of facies to reflect a stacking of laterally distributed environments such that the transition from the deepest-water low-iron-oxide facies into the intermediate-water magnetite-rich facies and the shallower-water hematite-rich facies is the result of an oxycline within the ancient lake. The depth dependence of the oxycline is similar to that found in modern eutrophic lakes wherein the aerobic respiration of descending organic matter leads to a decrease in dissolved oxygen with depth. Overall, these data indicate that this ca. 1.1 billion-year-old lake was more deeply oxygenated than has previously been interpreted (e.g. Cumming et al., 2013) providing a hospitable environment for the diverse biota that was present in the lake that included early eukaryotes (Wellman and Strother, 2015). This framework is strengthened by new data from a section along Potato River Falls that was near a paleo-highlands. In this section, the magnetic mineralogy is dominated by Facies 2 and 3 through repeated fluvial-lacustrine cycles without the anoxia seen in the deeper part of the lake.

The interpretation of a low-latitude paleolatitude of Laurentia at the time of Nonesuch and Freda deposition is reliant on magnetizations held by hematite (Henry et al., 1977). While detrital hematite in sediment can lead to a primary depositional remanent magnetization, alteration of minerals through interaction with oxygen can lead to the post-depositional formation of hematite. We have used the exceptionally-preserved fluvial sediments of the Freda Formation to gain insight into the timing of hematite remanence acquisition and its magnetic properties. This deposit contains siltstone intraclasts that were eroded from a coexisting lithofacies and redeposited within channel sandstone. Thermal demagnetization, petrography and rock magnetic experiments on these clasts reveal two generations of hematite. One population of hematite demagnetized at the highest unblocking temperatures and records paleomagnetic directions that rotated along with the clasts. This component is a primary detrital remanent magnetization. The other component is removed at lower unblocking temperatures and has a consistent direction throughout the intraclasts. This component is held by finer-grained hematite that grew and acquired a chemical remanent magnetization following deposition resulting in a population that includes superparamagnetic nanoparticles in addition to remanence-carrying grains. This primary magnetization can be successfully isolated from co-occurring authigenic hematite through high-resolution thermal demagnetization. These data lend credence to existing paleomagnetic data from the Freda Formation as well as future efforts to develop such data at higher resolution.

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New paleomagnetic constraints on the formation of the Slate Islands impact structure

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Pioneering paleomagnetic study by Halls (1975, 1979) was central to establishing an impact origin for the Slate Islands Impact structure. We have conducted further paleomagnetic study of both the injectite lithic breccia dikes throughout the structures as well as the target rocks which have an impact-related overprint. These data enable further conclusions about the timescale of cratering processes and the origin of the impact-related overprint discovered by Halls (1975, 1979).

In our work, we previously used lithic breccia dikes that were injected into the target rock during crater excavation to constrain the rate of crater modification within the central uplift of the Slate Islands Impact structure (Fairchild et al., 2019). We studied both the matrix as well as the clasts within the breccia dikes throughout the impact structure paleomagnetically. These data revealed uniform and linear paleomagnetic directions both in the matrix and in the clasts that are best interpreted as being due to frictionally heating above the magnetite Curie temperature (580 °C) during dike emplacement and subsequently cooling *in situ* through magnetic blocking temperatures. The work of Halls (1979) used data from the matrix of the breccia dikes to argue that the dikes acquired a thermal remanent magnetization during cratering and our data provide strong support for this hypothesis. The tight clustering of paleomagnetic directions from these breccia dikes indicates that the dikes cooled and locked in their magnetic remanence during a time interval in which the impact structure had reached a stable state with no major ongoing structural rotations. Applying a conductive cooling model to the thinnest sampled breccia dike demonstrates that magnetic remanence was being acquired six minutes after emplacement which indicates a stable crater structure at that time. This constraint of a stable crater structure only minutes after impact that results from breccia dike paleomagnetism is a rare case in which a geological process can be resolved on such a short time scale.

We have also pursued paleomagnetic study paired with hydrocode modeling of the Slate Islands impact structure host rocks. The goal of this study is to determine the relative contribution of the competing nature of shock and thermal effects on the magnetization of moderately to highly shocked rocks within the crater. Target rocks within the central peaks of complex craters are often exposed to pressures >10 GPa (such as the case in the Slate Islands; Dressler et al., 1998) and thus experience shock heating to >200 °C (Stewart et al., 2007) as well as baked contact heating to higher temperatures associated with the emplacement of impact breccias (Fairchild et al., 2016). Under such conditions, magnetization acquired during the passage of a shock wave (shock remanent magnetization; SRM) would be largely overprinted by a higher intensity thermal overprint during post-impact cooling (Tikoo et al., 2015). In our thermal demagnetization experiments, the impact-related magnetization component was predominantly removed from samples by laboratory unblocking temperatures of ~250-350°C consistent with heating to such temperatures. These data, combined with results from paleointensity experiments, support an interpretation that the Slate Islands overprint is primarily thermal in origin. This result is consistent with paleomagnetic studies of several other terrestrial impact craters, which report thermally-induced magnetizations in target rocks (Elbra et al., 2007; Jackson and Van der Voo, 1986). The potential for thermal and viscous remagnetization, as well as the acquisition of chemical remanence from hydrothermal activity (Pesonen et al., 1999; Quesnel et al., 2013), render it unlikely that SRM will be preserved in rocks as the dominant impact-related magnetization in the majority of settings.

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Petrological and geochemical characteristics of the granitic rocks from the Dog Lake Granite Chain: Implications for the genesis of Quetico Basin

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The Archean Quetico Basin is a metasedimentary terrane of the Superior Province between the Wawa-Abitibi Terrane to the south and the Western Wabigoon, Winnipeg River, and the Marmion terranes to the north. The majority of plutonic rocks within the Quetico Basin are granitoids (Williams, 1991), and are an important tool to investigate the evolution and genesis of the Quetico Basin and the nature of Archean tectonic processes (Sawyer et al., 2002). Percival (1989) studied the geology of granitic intrusions in the western Quetico basin and identified three main types: (i) an older, rare, white foliated hornblende-biotite tonalite, (ii) a pink, magnetic, medium- to coarse-grained, mostly massive, biotite leucogranite (e.g., the Lac La Croix Batholith), and (iii) a white-grey, medium-grained to pegmatitic, muscovite leucogranite (e.g., the Sturgeon Lake Batholith). He proposed that the muscovite leucogranites were S-type granites with a metasedimentary source, whereas the pink biotite granite had lower SiO₂, and higher Na₂O, K₂O, and Sr than the S-type granite and could have been derived from either an S-type or I-type source (Percival, 1989).

The Dog Lake Granite Chain, consisting of six ovoid magnetite-bearing intrusions (Shabaqua, Silver Falls, Trout Lake, Barnum Lake, White Lily and Penasen Lake), is characterized by a linear trend that parallels the tectonic boundary between the Wawa-Abitibi terrane to the south, and the Quetico Basin to the north. The intrusive rocks in the Dog Lake Granite Chain can be divided into three units: monzodiorite, microcline-phyric monzonite/quartz monzonite, and granite. The majority of monzodiorite and monzonites are metaluminous, whereas the granites are peraluminous. Whole rock data show that the Al₂O₃ and LREE (La, Ce, Pr and Nd) contents of the monzodiorite show a positive correlation with SiO₂, whereas the monzonite and granite units show a negative correlation. Similarly, the K₂O content of the monzodiorite unit correlates positively with SiO₂ content, whereas the monzonite and granite units show no strong correlation. The HREE (Er, Tm, Yb and Lu) contents of the monzodiorite and monzonite units decrease with SiO₂ content, whereas in the granites they increase. In combination this suggests that the three units were likely derived from different magmatic sources.

Mantle-like whole rock ϵ_{Nd} (+1.30 to +1.76) and zircon ϵ_{Hf} (+0.34 to +7.27) values, and arc-like geochemical signatures characterized by the enrichment of large ion lithophile elements (LILE) and low HSFE, suggesting that the monzodiorite unit was likely generated by partial melting of the mantle wedge above a subduction zone. The monzonite units show I-type granite

signatures with the positive whole rock ϵ_{Nd} (+0.81 to +1.23) and slightly enriched zircon ϵ_{Hf} (-0.21 to +3.81) values, consistent with them having formed from re-melting of metavolcanic rocks. The S-type granites exhibit positive Ce anomalies, negative Eu anomalies and a ranges of whole rock ϵ_{Nd} (-1.75 to +0.43) and zircon ϵ_{Hf} (-2.04 to +3.37) values, suggesting a mixed source comprised of arc-like orogenic sediments and minor metavolcanic rocks. Therefore, we conclude that the addition of voluminous melt generated by partial melting of arc-like orogenic sediments likely caused the transition from I-type to S-type magmas as the magmatic system evolved.

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Mineral deposits of the Midcontinent Rift System - A new space/time classification

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The Midcontinent Rift System (MRS) hosts a diverse suite of magmatic and hydrothermal mineral deposits, largely known from rift rocks exposed at or near the surface in the Lake Superior region (Nicholson et al., 1992). Most of these deposits, which are significant past, present, and likely future providers of critical minerals, can be placed into a new space/time metallogenic framework (Fig. 1). This framework was developed using 552 mineral deposits compiled from the U.S. Geological Survey Mineral Resources Data System (MRDS^a) and the Ontario Ministry of Energy, Northern Development and Mines Mineral Deposit Inventory (MDI^b). Deposits were classified by deposit type, host rock age and type, and estimated mineralization age. The deposits were then put into a tectonic evolutionary framework for the MRS, which showed that many deposits formed in unique spatial and temporal stages of rift evolution.

The distribution of 106 zircon/baddeleyite age dates, also compiled in this study, reflects three main magmatic MRS stages: 1) an early Plateau Stage from ~1113 to ~1105 Ma, characterized by widespread subaerial volcanism (e.g., magnetically reversed North Shore Volcanic Group, Osler Volcanics, Siemans Creek Volcanics) and related intrusive activity (e.g., Coldwell Complex, Early Gabbroic/ Felsic Series of the Duluth Complex); 2) a Rift Stage (~1102 to ~1091 Ma), characterized by eruption of thick sections of subaerial flood basalts largely confined to central, sagging basins (e.g., magnetically normal North Shore Volcanic Group, Portage Lake Volcanics) accompanied by voluminous intrusive events (e.g., Anorthosite/Troctolite Series of the Duluth Complex, Beaver Bay Complex, and Mellen Complex); and 3) a Late-Rift Stage (~1090 to ~1083 Ma) with diminished sporadic, mainly andesitic/felsic volcanism (e.g., Lakeshore Traps, Michipicoten Island Volcanics). A Post-Rift Stage is dominated by sediment deposition from the margins of the rift as subsidence within the central basins continued because of thermal collapse. This created thick sections of sedimentary rock (Copper Harbor Conglomerate, Nonesuch Formation, and Freda Sandstone that comprise the Oronto Group) that overlie stacked basalt flows within rift basins. The time frame for Oronto Group deposition and its relationship to clastic sediments of the Bayfield Group and Jacobsville Sandstone, the youngest rocks assigned to MRS history, are poorly constrained. The last event that put a close to the MRS was a Compressional Stage (~1060 and ~1040 Ma) that created reverse faults along some margins of the rift and carried older rocks over younger.

Mineralization in the MRS evolved within this broad tectonic context, beginning with intrusive magmatic deposits that formed contemporaneously with intrusion of MgO-rich mafic/ultramafic magmas during the Plateau Stage. Deposit types in this stage include: 1) small conduit-type sulfide deposits (e.g., the Ni-Cu-PGE Eagle, Tamarack, and Thunder Bay North deposits, and the Cu-PGM Marathon deposit); 2) layered Ti-Fe(-V) deposits in the Duluth Complex Early Gabbro Series; and 3) Nb-U(±Th±REE) in alkaline intrusions in Ontario. Magmatic mineral deposits related to the MRS Rift Stage include large contact-type disseminated Cu-Ni-PGE sulfide deposits and small but potentially economic Ti-Fe(-V) oxide ultramafic deposits along the basal section of the Duluth Complex. With diminished volcanism and increased sedimentation during the Late/Post-Rift Stages, hydrothermal fluids became an

increasingly important component of mineralization. Deposits that formed during this time frame are thought to include: 1) chalcocite in basalt (e.g., 543S); 2) copper sulfide veins (e.g., Coppercorp); and 3) Cu-Mo breccia pipes in the Mamainse Point area, which all may have a hybrid magmatic/hydrothermal origin. Additional hydrothermal deposits within this time period are: 1) a complex group of metal-bearing veins in Ontario (e.g., Ag-bearing veins of the Mainland and Island Groups, unconformity Pb-Zn-Ba($\pm$ U) veins); and 2) stratiform Cu deposits in the Nonesuch Formation (e.g., White Pine and Copperwood). The final, major MRS mineralizing event occurred during the Compressional Stage and created the world-famous Keweenaw native Cu($\pm$ Ag) deposits, contained within the Rift Stage Portage Lake Volcanics. This space/time classification of MRS mineral deposits is outlined in a USGS Story Map^c.

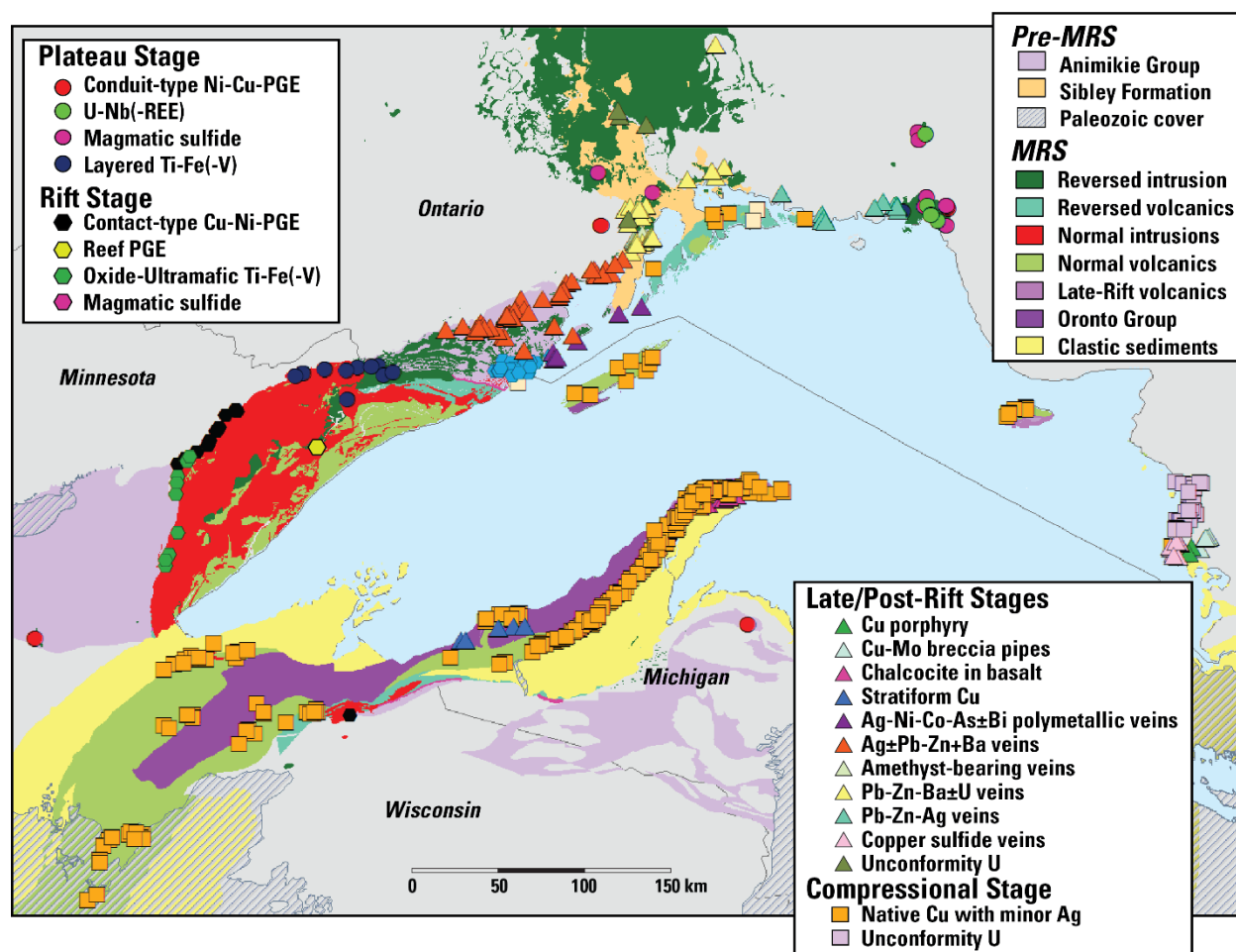


Figure 1. Simplified geologic map of the Lake Superior region, showing pre-MRS and MRS-related rocks, distinguished by stage, type, and magnetic polarity. Mineral deposits compiled from USGS and OGS databases have been classified by deposit type and put into a time-space evolutionary model for the MRS. Geology and mineral deposits taken from the USGS MRS geodatabase.

Nicholson, S.W., Cannon, W.F., and Schulz, K.J., 1992, Metallogeny of the Midcontinent rift system of North America: Precambrian Research, v. 58, p. 355-386.

^a <https://mrdata.usgs.gov/mrds/>

^b <https://www.mndm.gov.on.ca/en/mines-and-minerals/applications/ogsearch/mineral-deposits-mdi>

^c https://wim.usgs.gov/geonarrative/MRS_mineral_deposits/

Sulfur mobility in arc magma systems: Implications for porphyry ore deposits

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Porphyry ore deposits supply two-thirds of the world's Cu and nearly all of its Mo, as well as significant amounts of Au, Ag, and critical elements such as Re, Se and Te. These deposits form as a result of arc-related volcanism, when partial melts generated by dehydration melting of the subducting basaltic ocean crust percolate upwards through the mantle wedge and accumulate at the base of the crust in a process called underplating. As these mafic magmas fractionate, felsic melts segregate and ascend to the middle and upper crust where they form magma chambers that are thought to be the source of ore fluids in porphyry systems. However, a major problem with sourcing porphyry fluids from intermediate to felsic magmas is that mass balance calculations indicate that such silicic magmas cannot supply all of the S in porphyry ore deposits. The most plausible explanation for the excess S in porphyry deposits is underplating of middle to upper crustal silicic magma chambers by decompressing, volatile-saturated mafic magma that delivers volatiles such as S, H₂O, and Cl, and possibly metals into the overlying felsic magma.

This study explores the effects of underplating on volatile exchange between a mafic recharge magma and felsic host magma by simulating an underplating scenario. Diffusion-couple experiments were performed wherein a cylinder of mafic magma (basaltic andesite) was juxtaposed beneath a cylinder of felsic magma (dacite) and run under a range of pressure-temperature-composition-redox conditions relevant for upper crustal arc magma (porphyry) systems. The most intriguing finding is the development of a redox gradient of ~1.8 log units fO₂ at the mafic-felsic interface of the most oxidizing (FMQ+4) experiments, where the mafic melt is oxidized, and the felsic melt is reduced. Sulfur x-ray absorption near-edge structure (S-XANES) analyses also indicate complex S-speciation near the mafic-felsic interface in the most reducing (FMQ+1) experiment. Such a gradient affects the speciation of redox-sensitive elements such as S and moderates mass transfer from mafic to felsic melt, as well as affecting the metal-scavenging potential of an exsolved magmatic-hydrothermal volatile phase. Studying the effects of underplating in arc systems is paramount to understanding the source(s) and mechanisms responsible for the titration of volatiles and metals into ore forming environments and could help reconcile the excess sulfur problem in volcanic systems.

Multiscale Layering in the Black Sturgeon Sill, Nipigon, Ontario

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The basic petrology of the Nipigon sills was established by Richard Sutcliffe thirty years ago: “The diabase occurs primarily as ... 150 to 200 m thick sills with a textural stratigraphy indicating that the sills represent single cooling units. Compositional variation in the sills indicates that they crystallized from several magma pulses.” (Sutcliffe, 1987) “Fractionation in the sills is attributed to flowage differentiation and movement of residual liquids ... toward the top of the sections.” (Sutcliffe, 1989). The current study has confirmed and amplified these interpretations of sill-scale processes.

A continuous drill core through the Black Sturgeon sill (Zieg & Wallrich, 2018), a 250 m Nipigon group (Hollings et al., 2007; 2010) mafic intrusion, has yielded far more detailed stratigraphic variations than were previously available. With this newly-available data, Sutcliffe’s original model can be shown to apply at multiple scales. Specifically, although textural evidence for “non-unit” a cooling history remains elusive, smaller-scale magma batches can be recognized within the larger-scale magma pulses. Additionally, there is compositional evidence for upward movement of evolved liquids within any sub-section of the sill. These patterns have been traced down to a scale on the order of tens of centimeters, with individual textural and mineralogical discontinuities visible on the thin section scale.

The relationship between classical igneous layering and the observed compositional and textural variations is unclear. Much of the data from the Black Sturgeon sill suggests that olivine (and plagioclase) concentrations in this system reflect the injection of antecryst-laden magma. A similar type of analysis on a more traditionally layered intrusion might shed light on the extent to which the processes that controlled layer formation in the BSS also contributed to layer formation in other systems.

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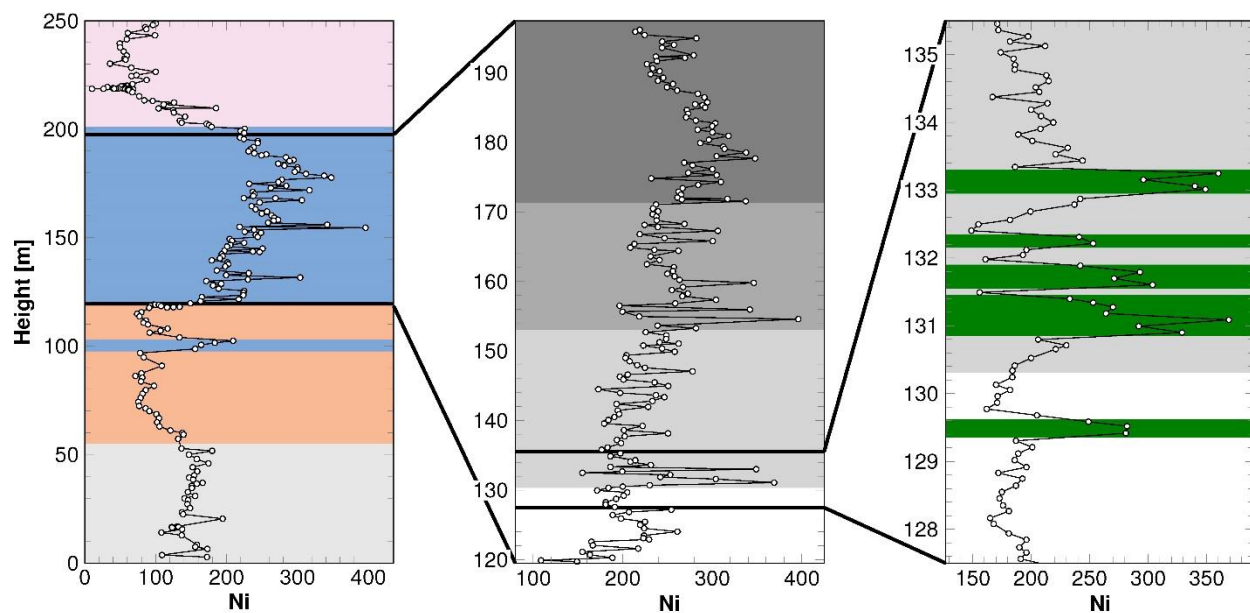


Figure 1. Compositional profiles. Higher Ni concentrations coincide with olivine-dominated portions of the system, regardless of scale. Distinct compositional layering can be recognized at all three scales.

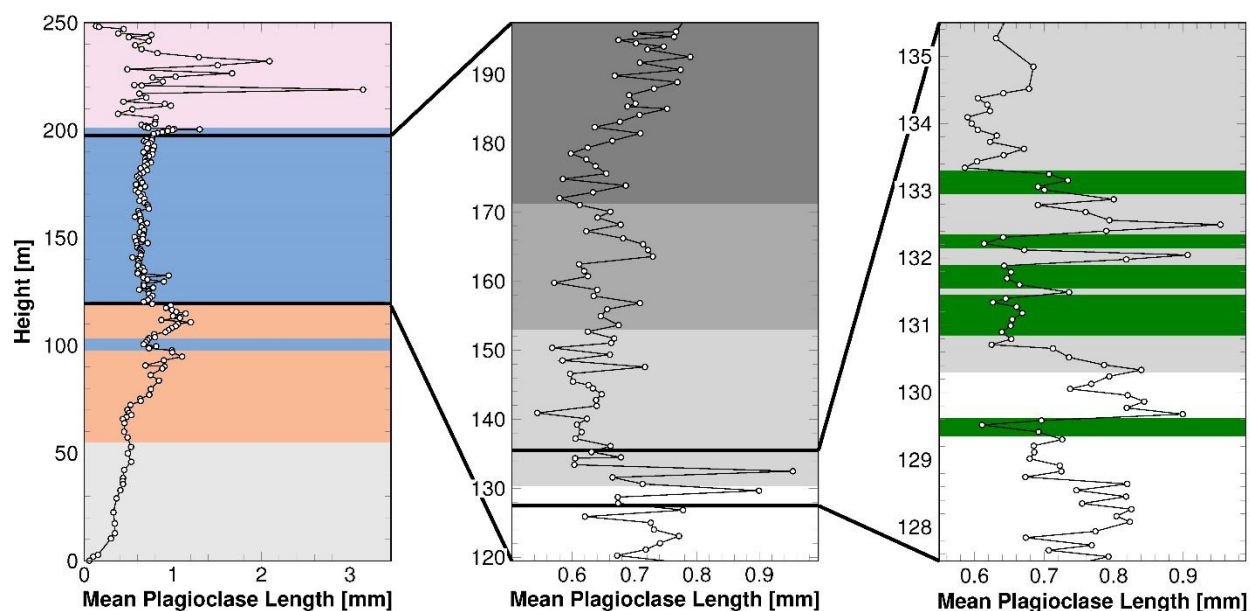


Figure 2. Textural profiles. Mean plagioclase length is typically lower in parts of the system that have accumulated olivine. This pattern can be traced down to olivine accumulations less than a meter thick. Although textural variations can be recognized at all three scales, there is little clear evidence for discrete cooling units. Rather, textural variations apparently reflect different magma batches (crystal cargo).