



Institute on Lake Superior Geology

62ND ANNUAL MEETING

May 4-8, 2016

Duluth, Minnesota

Sponsored by

PRECAMBRIAN RESEARCH CENTER

AND

DEPARTMENT OF EARTH AND ENVIRONMENTAL SCIENCES

AT THE UNIVERSITY OF MINNESOTA DULUTH

Meeting Co-Chairs

James Miller, Christian Schardt, and Dean Peterson

Proceedings Volume 62

Part 1 – Program and Abstracts

Edited by Christian Schardt and Jim Miller

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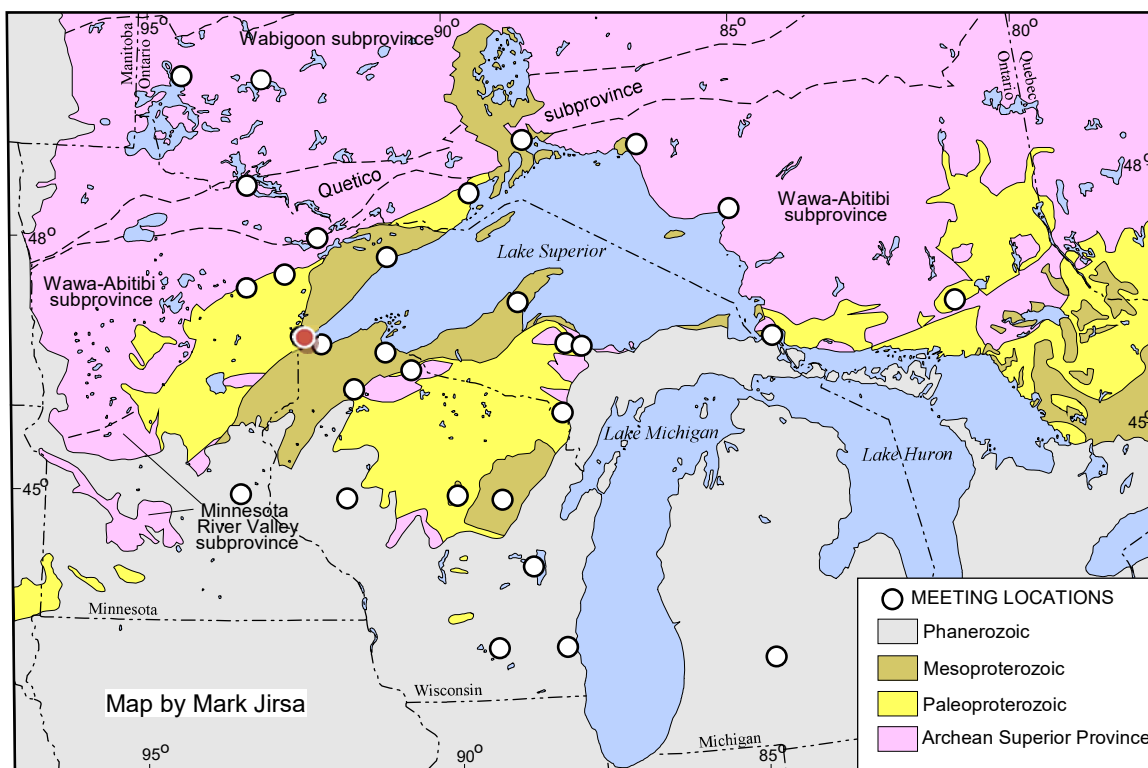
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Some figures in this volume were submitted by authors in color, but are printed grayscale to conserve printing costs. Full color imagery will appear in the digital version of the volume when it is available on-line at <http://www.lakesuperiorgeology.org>.

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Institutes on Lake Superior Geology, 1955-2016



#	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

<u>#</u>	<u>Date</u>	<u>Place</u>	<u>Chairs</u>
23	1977	Thunder Bay, Ontario	M.M. Kehlenbeck
24	1978	Milwaukee, Wisconsin	G. Mursky
25	1979	Duluth, Minnesota	D.M. Davidson
26	1980	Eau Claire, Wisconsin	P.E. Myers
27	1981	East Lansing, Michigan	W.C. Cambray
28	1982	International Falls, Minnesota	D.L. Southwick
29	1983	Houghton, Michigan	T.J. Bornhorst
30	1984	Wausau, Wisconsin	G.L. LaBerge
31	1985	Kenora, Ontario	C.E. Blackburn
32	1986	Wisconsin Rapids, Wisconsin	J.K. Greenberg
33	1987	Wawa, Ontario	E.D. Frey & R.P. Sage
34	1988	Marquette, Michigan	J. S. Klasner
35	1989	Duluth, Minnesota	J.C. Green
36	1990	Thunder Bay, Ontario	M.M. Kehlenbeck
37	1991	Eau Claire, Wisconsin	P.E. Myers
38	1992	Hurley, Wisconsin	A.B. Dickas
39	1993	Eveleth, Minnesota	D.L. Southwick
40	1994	Houghton, Michigan	T.J. Bornhorst
41	1995	Marathon, Ontario	M.C. Smyk
42	1996	Cable, Wisconsin	L.G. Woodruff
43	1997	Sudbury, Ontario	R.P. Sage & W. Meyer
44	1998	Minneapolis, Minnesota	J.D. Miller & M.A. Jirsa
45	1999	Marquette, Michigan	T.J. Bornhorst & R.S. Regis
46	2000	Thunder Bay, Ontario	S.A. Kissin & P. Fralick
47	2001	Madison, Wisconsin	M.G. Mudrey & Jr., B.A. Brown
48	2002	Kenora, Ontario	P. Hinz & R.C. Beard
49	2003	Iron Mountain, Michigan	L. Woodruff & W.F. Cannon
50	2004	Duluth, Minnesota	S. Hauck & M. Severson
51	2005	Nipigon, Ontario	M. Smyk & P. Hollings
52	2006	Sault Ste. Marie, Ontario	A. Wilson & R. Sage
53	2007	Lutsen, Minnesota	L. Woodruff & J. Miller
54	2008	Marquette, Michigan	T. Bornhorst & J. Klasner
55	2009	Ely, Minnesota	J. Miller, G. Hudak, & D. Peterson
56	2010	International Falls, Minnesota	M. Jirsa, P. Hollings, & T. Boerboom, P. Hinz & M.Smyk
57	2011	Ashland, Wisconsin	T. Fitz
58	2012	Thunder Bay, Ontario	P. Hollings
59	2013	Houghton, Michigan	T. 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

Sam Goldich and the Goldich Medal

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

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

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

Reference:

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

Prepared by various Goldich Medal Awardees, 2007



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	1997	Ronald P. Sage
1980	<i>not awarded</i>	1998	Zell Peterman
1981	Carl E. Dutton, Jr.	1999	Tsu-Ming Han
1982	Ralph W. Marsden	2000	John C. Green
1983	Burton Boyum	2001	John S. Klasner
1984	Richard W. Ojakangas	2002	Ernest K. Lehmann
1985	Paul K. Sims	2003	Klaus J. Schulz
1986	G.B. Morey	2004	Paul Weiblen
1987	Henry H. Halls	2005	Mark Smyk
1988	Walter S. White	2006	Michael G. Mudrey
1989	Jorma Kalliokoski	2007	Joseph Mancuso
1990	Kenneth C. Card	2008	Theodore J. Bornhorst
1991	William Hinze	2009	L. Gordon Medaris, Jr
1992	William F. Cannon	2010	William D. Addison & 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
		2015	Rodney J. Ikola

2016 GOLDICH MEDAL RECIPIENT

Mark Jirsa

Goldich Medal Committee

Serving through the meeting year shown in parentheses.

Mark Smyk (2016)	Ontario Geological Survey
Hélène Lukey (2017)	Cliffs Natural Resources
Shannon Zurevinski	Lakehead University

Citation for the Goldich Medal Award to **Mark A. Jirsa**

I am honored to be able to present the 2016 Goldich Medal to Mark Jirsa. I first met Mark in 1983, when I was hired for a six month stint at the Minnesota Geological Survey. The first time I walked into the MGS office I was immediately introduced to both Mark Jirsa and Jim Miller, and the three of us were quickly dispatched to northern Minnesota to conduct field mapping for an unusual project involving the Minnesota Waste Management Board. I soon realized that I was working with a mapping Zen-master, and was very fortunate to have started my career with not one, but two people who are now both at the forefront of their respective areas of expertise. It was also the beginning of a long friendship and comradery.

Mark's career has never strayed far from Lake Superior – he earned a B.S. degree from the University of Wisconsin – Eau Claire in 1976, and an M.S. from the University of Minnesota – Duluth 1980. His Master's thesis was on the petrology and tectonic significance of the interflow sediments in the Keweenaw North Shore Volcanic Group of Northeastern Minnesota. He worked a short time in northwestern Minnesota for Exxon Minerals, and then joined the Minnesota Geological Survey. As if the 'normal' work load of annual stints of field mapping, compilation, and publication of geologic maps and reports isn't enough, Mark is also the Technical Editor for every map and report that is published at the MGS. The wide range of topics for the things he reviews – including Precambrian, Phanerozoic, and Quaternary geology, as well as hydrostratigraphy, testifies to the breadth of Mark's geologic knowledge.

Mark has been a mainstay of the ILSG for many years – his first paper was in 1978 in Milwaukee, on the topic of his Master's thesis. He has probably attended every meeting since then. As most of you know, Mark has been one of the most active and involved members of the Institute on Lake Superior Geology for many years. He has co-chaired meetings in Minneapolis, International Falls, and Hibbing. He has led or co-lead 13 field trips starting with Eveleth in 1993 through the most recent 2014 meeting in Hibbing, and after this meeting we can bump that total up to 15. He has submitted over 30 abstracts for oral talks and posters, and has been session chair multiple times. He was the Secretary-Treasurer from 1994-2002, returned as Treasurer in 2005 and still is today. He has also led field trips for GSA meetings. If you have ever been on an ILSG trip that Mark is taking part in, you also know he has his nose right on the outcrop talking to the leaders and other participants about the rocks, not only for that stop, but for how they tie into the rest of the world. If you are a new young member of ILSG you should stick close to Mark and ask any question you want because he will fully engage you, and to him there is no such thing as a 'stupid question'.

However, the Goldich award is for more than just involvement with the ILSG. It is also about one's contribution to the geology of the Lake Superior region. In the latter, Mark has contributed a great amount. His work has focused mainly on deciphering the complex



geology of the Archean rocks in both northern Minnesota and in the Minnesota River Valley, but he has also contributed a great deal to understanding the Paleoproterozoic terranes of Minnesota, including the east-central Minnesota batholith and environs, the Sioux Quartzite, the Biwabik and Gunflint Iron Formations, and the Sudbury ejecta deposits in Minnesota. In all of these cases his work has benefited not only Minnesota, but has applications elsewhere in the Lake Superior region. He has authored or co-authored more than 60 maps and reports published by the MGS, has authored or co-authored numerous publications in refereed journals, and selflessly agrees to give presentations to the public on a wide variety of topics pertaining to his work

Mark's latest focus is on unraveling the Timiskaming-type assemblages in northern Minnesota, which has given him cause to lead nine Precambrian Research Center capstone projects aimed at tracing and deciphering these assemblages. These capstone projects have given dozens of aspiring geologists the opportunity to map with a great mentor. He always found a way to sandwich these capstone projects in between all the other contractual mapping obligations of the MGS.

Mark first started at the Minnesota Geological Survey in 1979, as a Junior Geologist, and one of his first projects was making a geologic map of Paleozoic strata of the Twin Cities basin. Fortunately for us hard rock types, he quickly moved on to what he loves, Precambrian rocks. Mark has an uncanny knack for field mapping (especially picking out graded beds!) and accompanying drill core logging. His ability to unravel the structural attributes of everything from a single outcrop to an entire greenstone belt never ceases to amaze me. Equally as amazing and inspirational to me is his tireless work ethic, be it long days in the field or dark winter days in the office. I've never known him to knock off a day of field work because of any type of weather conditions – more than once I've been back indoors, warm and dry, for several hours due to atrocious field conditions, but I won't see Mark until after dark when he comes in stomping mud off his boots telling me about some great thing he discovered that day.

Subsequent to my being hired full-time at MGS in 1987, I have worked almost continuously with Mark on a wide variety of mapping and drilling projects throughout all of the different Precambrian terranes of Minnesota. Early on I had the job of being his field assistant, which was great fun since my main task was helping peel outcrops – and boy did we peel! This led to other larger mapping projects where we divided up map areas, drilling projects that went through entire winters, and independent mapping projects. During every one of these, and continuing to this day, Mark has always set the bar when it comes to initiating projects, field work, and interpreting the rocks – from the outcrop through map compilation and publication. More than once Mark would have some idea for a grand mapping project for which my initial reaction was “Really? You think we can do that?”, then a couple of years later there it was - a finished project.

The year 1983 was 33 years ago. Since I am currently 56 years old, that means I have known Mark for well over half my life. We have spent months living out of the same motel room, driving to and from field work, to ILSG meetings, etc. I don't know if the feeling is mutual, but I had a great time through all of it. And my conclusion after having lived half my life with the guy is that he is most deserving of this medal.

Terry Boerboom
Precambrian Geologist
Minnesota Geological Survey

In Memoriam



Leon Wayne Gladen, 82, of Hibbing, died April 23rd, 2016. He was born in Bemidji, MN on April 25th, 1933, to Leonard and Hattie (Holmberg) Gladen. Leon grew up on the family farm in Bemidji and he served in the U.S. Army during the Korean War. He was a graduate of UMD and he held a Master's Degree in Geology. He worked as a geologist for the Minnesota Department of Natural Resources for ten years and later for Lehman & Associates out of Minneapolis. Leon and Bernice (Grzybowski) were united in marriage on July 1, 2001 in Kenai, Alaska. Leon and Bernice enjoyed traveling the world together for his work assignments. He enjoyed reading, hunting, collecting fly fishing rods, and gardening.

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 2015, the ILSG Board of Governors awarded three awards from the Joe Mancuso Student Research Fund. The winners were:

Amanda Van Lankvelt

University of Massachusetts-Amherst, Department of Geosciences
Current degree program: PhD candidate (Advisor: M.L. Williams)
Determining the Deformation Age of the Baraboo Syncline
Award: \$500

Detaya Johnson

University of Wisconsin-Milwaukee, Department of Geosciences
Current degree program: Bachelors of Science (Advisor: Dyanna Czeck)
Geochemical analysis of deformed metaconglomerates
Award: \$500

Laura Cuccio

Utah State University, Department of Geology
Current degree program: MS Candidate (Advisor: James Evans)
Evaluating the nature of sedimentary rock-crystalline basement interface and its control on hydrologic processes.
Award: \$500

Doug Duskin Student Paper Awards

Each year, the Institute selects the best of student presentations and honors the presenters with a monetary award. Funding for the award is generated from registrations of the annual meeting, and from generous donations to the fund in honor of Doug Duskin—an exploration geologist and long-time friend of the Institute. The 2012 ILSG Board of Directors approved adding Doug’s name to the award to acknowledge his contributions, and distribute those donations in a manner that would have pleased him. The Duskin Student Paper Committee is appointed by the Meeting Chair. Criteria for best student paper—last modified by the Board in 2001—follow:

- 1) The contribution must be demonstrably the work of the student.
- 2) The student must present the contribution in-person.
- 3) The Student Paper Committee shall decide how many awards to grant, and whether or not to give separate awards for poster vs. oral presentations.
- 4) In cases of multiple student authors, the award will be made to the senior author, or the award will be shared equally by all authors of the contribution.
- 5) The total amount of the awards is left to the discretion of the meeting Chair in conjunction with the Secretary, but typically is in the amount of about \$500 US (increase approved by Board, 10/01).
- 6) The Secretary maintains, and will supply to the Committee, a form for the numerical ranking of presentations. This form was created and modified by Student Paper Committees over several years in an effort to reduce the difficulties that may arise from selection by raters of diverse background. The use of the form is not required, but is left to the discretion of the Committee.
- 7) The names of award recipients shall be included as part of the annual Chair’s report that appears in the next volume of the Institute.

Student papers will be noted on the Program.

2016 Student Paper Awards Committee

Karl Everett – KEA Associates

Dyanna Czeck - University of Wisconsin-Milwaukee

Tim Kroeger – Bemidji State University (MN)

Michael Zieg – Slippery Rock University (PA)

Dorothy Campbell – Ontario Geological Survey

Board of Directors

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

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

Rob Cundari (2015-2018) – Ontario Geological Survey

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

Allan Blaske (2013-2016) – AECOM

Pete Hollings - Secretary (2013-2016) – Lakehead University

Mark Jirsa – Treasurer (2011-2014) – Minnesota Geological Survey

Local Committee

Jim Miller – General Meeting Chair
Department of Earth and Environmental Sciences
University of Minnesota Duluth

Christian Schardt – Technical Program Chair
Department of Earth and Environmental Sciences
University of Minnesota Duluth

Dean Peterson – Field Trip Chair
Peterson Geoscience LLC and
Precambrian Research Center
University of Minnesota Duluth

Session Chairs

Robert Lodge – University of Wisconsin – Eau Claire

Gerry White – Ontario Geological Survey, Thunder Bay, ON

Ben Drenth – U.S. Geological Survey, Denver, CO

Jeff Lynott – Foth, Green Bay, WI

Latisha Brengman – University of Minnesota Duluth

Esther Kingsbury Stewart – Wisconsin Geological and Natural History Survey

Field Trip Leaders

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

1) GLACIAL GEOLOGY OF THE LAURENTIAN UPLANDS

Phil Larson – Vesterheim Geoscience PLC

Howard Mooers – Dept. of Earth and Environmental Sciences, UMD

2) NEOARCHEAN GEOLOGY OF THE WESTERN VERMILION DISTRICT

Mark Jirsa, Amy Radakovich, Terry Boerboom - Minnesota Geological Survey

3) Cu-Ni-PGE DEPOSITS OF THE DULUTH COMPLEX

Mark Severson – Tech American

Andrew Ware – PolyMet Mining

Kevin Boerst – Twin Metals Minnesota

Steve Monson-Geerts – Natural Resources Research Institute, UMD

5) GEOLOGY OF THE ENDION SILL ALONG THE DULUTH LAKEWALK

Jim Miller - Dept. of Earth and Environmental Sciences, UMD

6) GEOLOGY AND TROUT FISHING ALONG AMITY CREEK, DULUTH

Dean Peterson – Peterson Geoscience LLC

George Hudak - Natural Resources Research Institute, UMD

7) ARCHEAN AND PROTEROZOIC GEOLOGY OF THE GUNFLINT TRAIL

Mark Jirsa - Minnesota Geological Survey

8) KEWEENAWAN GEOLOGY OF THE HOVLAND AREA

Terry Boerboom – Minnesota Geological Survey

John Green - Dept. of Earth and Environmental Sciences, UMD

9) DULUTH HARBOR GEOLOGIC HISTORY BOAT CRUISE: QUATERNARY TO ANTHROPOCENE

Irv Mossberger, Meghan Blair, Eric Dott – Barr Engineering

Andy Breckenridge – University of Wisconsin - Superior

Todd Kremmin - Dept. of Earth and Environmental Sciences, UMD

Sponsors

The following organizations and individuals made general contributions to the 62nd Annual Meeting. We thank them for their commitment to the Institute on Lake Superior Geology. All of the funds contributed this year go toward travel awards for student registrants.



INDIVIDUAL CONTRIBUTORS TO STUDENT TRAVEL SCHOLARSHIPS

WILLIAM EVERETT	JOHN BERKLEY
HENRY DIERLEV	STEVE HOAGLUND
ALLAN MACTAVISH	RYAN DAYTON
MARY ARTHUR	DAN COSTELLO
HARVEY THORLIEFSON	DANIEL ROMANELLI
GORDON MEDARIS, JR.	ERIC DOTT

With an especially generous donation provided by
RON SEAVOY

Report of the Chair of the 61st Annual Meeting

Dryden, Ontario

The 61st ILSG was held in Dryden, Ontario on May 19-24, 2015. The meeting was chaired by Robert Cundari (Ontario Geological Survey) and Peter Hinz (Ministry of Northern Development and Mines) with considerable assistance from the organizing committee (Mark Smyk, Al MacTavish and Pete Hollings). The meeting was attended by a total of 123 delegates including 31 students. Special thanks to individuals who provided financial support for the meeting (Mary Arthur, Steve Baumann, Leonard Espinosa, Gordon Medaris Jr., Allan MacTavish, Jim Miller and Paul Weiblen) as well as the Thunder Bay Branch of the Canadian Institute of Mining and Metallurgy (CIM) for its generous donation.

The two-day technical session began on Thursday May 21st which focused on Midcontinent Rift-related geology and special topics including an extended oral presentation summarizing research to date on the Sudbury Impact Event in the Lake Superior Region. Technical talks continued through Friday morning with talks focusing largely on Archean geology. A total of 21 talks were given, 8 of which were presented by students. A total of 24 posters were displayed, 9 of which were presented by student authors. The 2015 Goldich Medal was awarded to Rodney J. Ikola from Esko, Minnesota. Thomas Waggoner presented the award during the annual banquet citing Rodney's many contributions to the geoscience and mining community of Minnesota. The evening banquet speaker was Steve Beneteau – Senior Diamond Advisor / Chief Gemmologist for the Province of Ontario and the Manager of the Diamond Sector Unit for the Ontario Ministry of Northern Development and Mines. The title of his talk was: ***“Ontario’s Diamonds: A Journey from Mine to Market”***.

The meeting offered three multi-day field trips, three one-day field trips and three half-day field trips covering the Archean Geology of northwestern Ontario. Three pre-meeting field trips were offered on Tuesday May 19th and Wednesday May 20th, including Red Lake Geology (2-day) led by Andreas Lichtblau and Carmen Storey (Ontario Geological Survey), a Western Wabigoon Subprovince Transect (Dryden to Meggisi Lake) led by Mark Puumala and Dorothy Campbell (Ontario Geological Survey) and the Geological Setting of the Thunder Lake Gold Deposit led by Treasury Metals Inc. personnel. Three half-day trips were offered on Friday May 22nd, including Classic outcrops of the Dryden Area led by Peter Hinz (Ministry of Northern Development and Mines), Gold Occurrences of Van Horne Township led by Steve Meade (Ontario Geological Survey) and the Unique mineralizing event at the Pidgeon Molybdenum Occurrence led by Craig Ravnaas (Ontario Geological Survey). Three post-meeting field trips were offered starting Friday afternoon running through Sunday May 24th, including the Historic Pickle Lake Camp (1.5-day) led by Mark Smyk (Ontario Geological Survey), Pete Hollings (Lakehead University) and Neil Pettigrew (Fladgate Exploration Consulting Corp.), the Ghost Lake Batholith and Related Pegmatites led by Shannon Zurevinski (Lakehead University) and the Mattabi/Sturgeon Lake Historic VMS Camp (2-day) led by George Hudak (University of Minnesota Duluth).

The Institute's Board of Directors met on Thursday May 21st to discuss the business of the Institute. The meeting was attended by meeting co-chair Robert Cundari, Treasurer Mark Jirsa, Secretary Peter Hollings and board members Jim Miller (2014 chair), Theodore Bornhorst (2013 chair) and Al MacTavish (2012 chair). Secretary Hollings took the minutes of the Board meeting that are as follows:

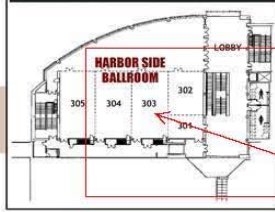
1. Accepted report of the Chairs for the 60th ILSG, Hibbing, Minnesota; as printed in the Proceeding Volume (Miller), and minutes of last Board meeting, May 15, 2014 (Hollings)
2. Received, discussed, and accepted 2014-2015 ILSG Financial Summary (Jirsa).
3. Received, discussed, and accepted 2014-2015 report of the Secretary (Hollings).
4. Approved Rob Cundari as on-going ILSG Board member
5. Approved Duluth as the site for the 62nd annual ILSG meeting. The meeting will be hosted by Jim Miller and Christian Schardt.
6. Discussed and approved replacing Bernhardt Saini-Eidukat as the "member from academia" on Goldich Committee (end of term 2015) with Shannon Zurevinski
7. Discussed student research grants. It was agreed that the application deadline will be switched to April 1 with results announced by April 30 each year. The next competition will be held in 2016. Jirsa to provide a list of all recipients of these awards so their attendance at the Annual Meeting can be tracked.
8. Jirsa to investigate the possibility of obtaining Director's insurance including the cost and what would be covered. Also to investigate the implication of turning the Institute into a LLC.
9. Jirsa to develop a budget template for Meeting Chairs to help with the reporting of expenses and revenue when submitting the financial summaries to the Treasure

The chairs would like to thank all those who assisted with the meeting including the organizing committee, the field trip leaders, the session chairs, service providers and those who provided support behind the scenes. The chairs would also like to thank those who participated in the meeting including the field trip attendees and the oral and poster presenters for their enthusiastic involvement with the Institute.

Respectfully submitted,

Robert Cundari and Peter Hinz
Co-chairs, 61st Institute on Lake Superior Geology

HARBOR SIDE THIRD LEVEL



DECC

Duluth Entertainment Convention Center

FLOOR PLANS

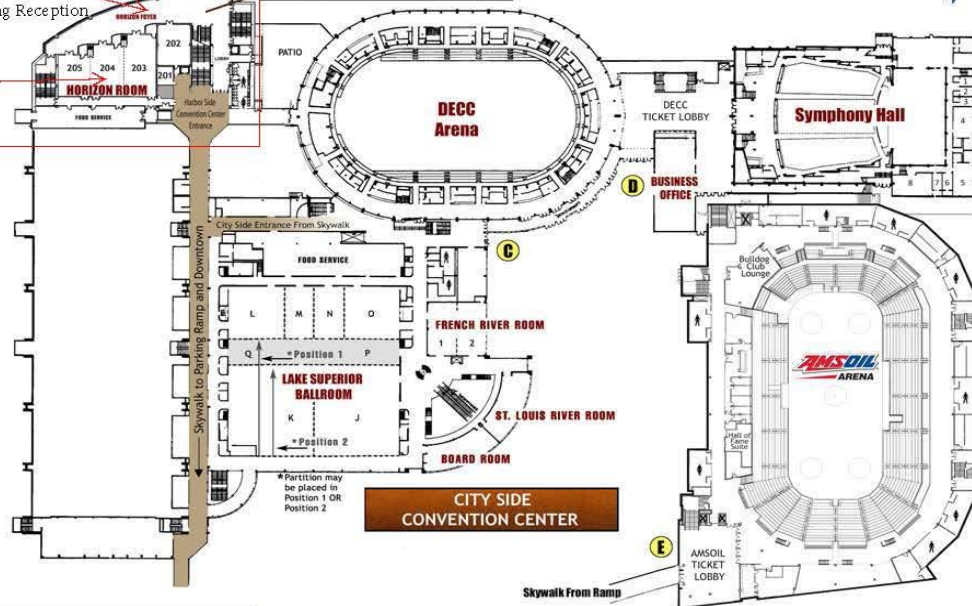
Annual Banquet Room

SKYWALK LEVEL

Poster Displays and
Welcoming Reception

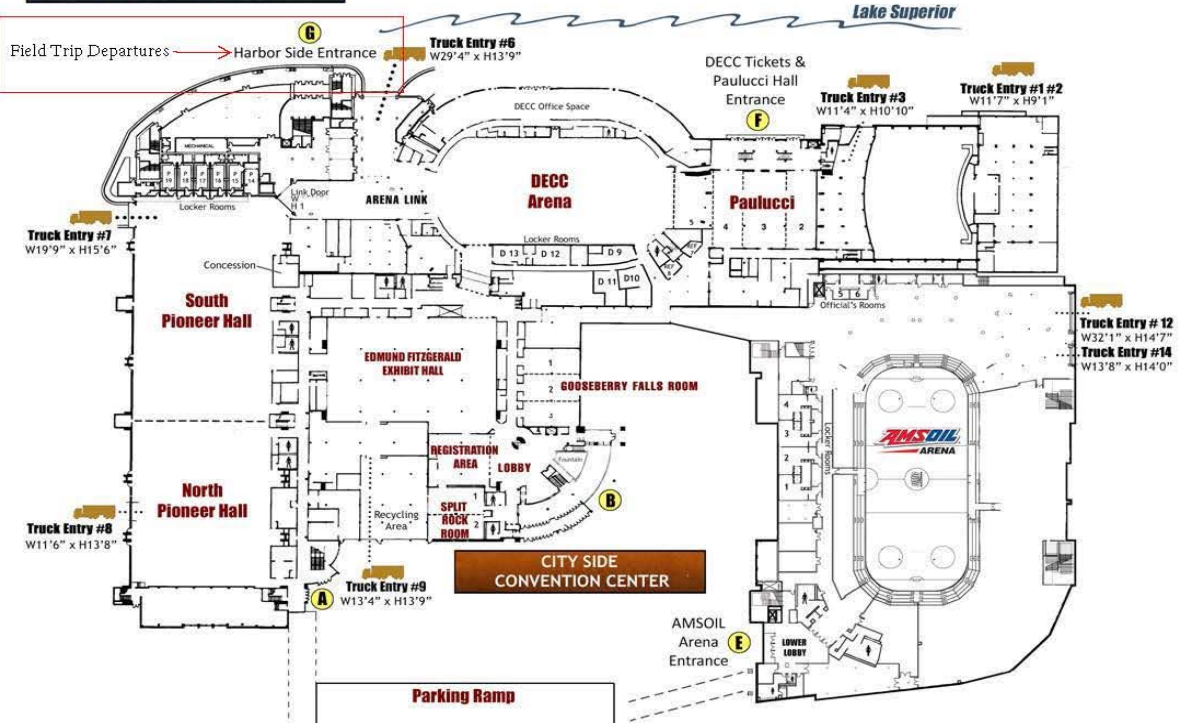
Technical
Sessions

HARBOR SIDE CONVENTION CENTER



GROUND LEVEL

Field Trip Departures → Harbor Side Entrance



TECHNICAL PROGRAM

WEDNESDAY MAY 4, 2016

All trips leave from the Harbor Side entrance (G) of the Duluth Entertainment and Convention Center

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

1) GLACIAL GEOLOGY OF THE LAURENTIAN UPLANDS

Phil Larson – Vesterheim Geoscience PLC

Howard Mooers – Dept. of Earth and Environmental Sciences, UMD

2) NEOARCHEAN GEOLOGY OF THE WESTERN VERMILION DISTRICT

Mark Jirsa, Amy Radakovichm Terry Boerboom - Minnesota Geological Survey

3) Cu-Ni-PGE DEPOSITS OF THE DULUTH COMPLEX

Mark Severson – Tech American

Andrew Ware – PolyMet Mining

Kevin Boerst – Twin Metals Minnesota

Steve Monson-Geerts – Natural Resources Research Institute, UMD

1:00pm - 5:30pm **HALF-DAY PRE-MEETING FIELD TRIP**

5) GEOLOGY OF THE ENDION SILL ALONG THE DULUTH LAKEWALK

Jim Miller - Dept. of Earth and Environmental Sciences, UMD

4:00 pm - 10:00 pm **Registration** (Horizon Foyer)

7:00 pm - 10:00 pm **Welcoming Reception** (Horizon Foyer)

Poster Session (Horizon Foyer and Room 202)

THURSDAY MAY 5, 2016

Asterisk * denotes a student eligible for Best Student Paper Award

7:30 am - noon **REGISTRATION**

8:00 am **OPENING REMARKS**

Jim Miller and Christian Schardt, Co-Chairs, 2016 ILSG

TECHNICAL SESSION I

Session Chairs:

Robert Lodge – University of Wisconsin – Eau Claire

Ann Wilson – Ontario Geological Survey

1A) PETROLOGY AND METALLOGENESIS OF ARCHEAN AND PALEOPROTEROZOIC IGNEOUS RX

8:10 **Dave Peck, Lionnel Djon, Cameron McLean, Gary DeSchutter, Jill Maxwell, Kelsey Privett, Denis Decharte, Chris Roney, Michelle Huminicki, & Bob Stewart**

The Lac Des Iles PGE-Cu-Ni deposit, Canada: an organized mega-breccia unit?

8:25 **M. L. Djon*, G.R. Olivo, J.D. Miller, D.C. Peck, and B. Joy**

PGE Mineralization in the Northern Ultramafic Center of the Lac des Iles Complex, Ontario: Evidence of Magmatic and Hydrothermal processes

8:40 **Erik Haroldson*, Brian Beard, Aaron Satkoski, Clark Johnson, and Philip Brown**

U-Th-Pb isotopes of the Reef Deposit; a Au-Cu occurrence in central Wisconsin

8:55 **Ashley Quigley*, Thomas Monecke, Eric Anderson, Nigel Kelly, and Patrick Quigley**

Setting of volcanogenic massive sulfide deposits of the Paleoproterozoic Penokean volcanic belt

9:10 **Robert Lodge, Geoffrey Pignotta, Brigitte Gélinas, Kelly Schwierske, and George Hudak**

Volcanological, Geochemical, and Geochronological Comparisons of the Gafvert Lake Sequence in Minnesota and Shebandowan Assemblage in Ontario

9:25 **G. Gamelin*, V. Stinson, Yuanming Pan, and M. Nadeau**

A comparative study of mafic and felsic lithologies from the Borden Belt and adjacent greenstone belts in the Wawa-Abitibi Terrane

9:40 **Brigitte Gélinas* and Peter Hollings**

The Geology and Geochemistry of the Laird Lake Property, Red Lake Greenstone Belt, Ontario

9:55 **COFFEE BREAK AND POSTER SESSION**

1B) PRECAMBRIAN GEOCHRONOLOGY / ARCHEAN SEDIMENTATION AND STRUCTURE

- 10:15 **Michael Mudrey**
Continued Evaluation of the Dilatancy Model for Discordant Uranium-Lead Age Determination of Zircon
- 10:30 **Ben Frieman*, Yvette Kuiper, Nigel Kelly, and Thomas Monecke**
Provenance and tectonic evolution recorded by successor basins in the Abitibi-Wawa terrane: Insights from new U-Pb LA-ICP-MS analyses of detrital zircon
- 10:45 **Sophie Kurucz* and Philip Fralick**
Giant Domes of the Mosher Carbonate, Steep Rock, Ontario
- 11:00 **Matthew Svensson* and Philip Fralick**
The Badwater gabbro as an analogue for the weathering of Martian basalts
- 11:15 **Victoria Stinson*, Yuanming Pan, Gleceria Gamelin, and Matthew Nadeau**
A re-examination of the Kapukasing structural zone
- 11:30 **Tracy Carson*, Brittany Deley, and Mary Louise Hill**
Microstructural comparison of the Hardrock Project at Geraldton, Ontario and the Coffee Gold Project, Yukon
- 11:45 **LUNCH BREAK**
ILSG BOARD MEETING

TECHNICAL SESSION II

Session Chairs:

Ben Drenth – U.S. Geological Survey, Denver, CO
Jeff Lynott – Foth, Green Bay, WI

2A) MIDCONTINENT RIFT GEOLOGY AND MINERALIZATION

- 1:15 **Klaus Schulz and Suzanne Nicholson**
The Geochemistry of the Siemens Creek Formation and the Nature of Early Midcontinent Rift Basaltic Magmatism in the Western Lake Superior Region
- 1:30 **Mark Smyk, Peter Hollings, and Philip Fralick**
A Preliminary Investigation of Enigmatic Igneous Rocks on Big Powder Island, Northern Lake Superior: A Possible Mesoproterozoic Magmatic Event
- 1:45 **Sean O'Brien*, Peter Hollings, and Jim Miller**
Petrology, geochemistry and sulphur isotopes of the Crystal Lake gabbro and Mount Mollie dyke, Northwestern Ontario
- 2:00 **Robert Cundari, Peter Hollings, David Good, and Sarah Davis**
Geochemistry and petrogenesis of volcanic rocks in the Coldwell Alkaline Complex; new insights from the Wolfcamp Lake volcanic rocks
- 2:15 **David Good, Robert Linnen, and Iain Samson**
The Cu/Pd diagram and metal/sulfur variation as an exploration tool: Examples from the Coldwell Alkaline Complex, Ontario

- 2:30 **Robert Mahin and Steven Beach**
The Eagle East Magmatic Nickel-Copper Discovery
- 2:45 **Connor Mulcahy*, Jim Miller, Robert Mahin, Steven Beach, and Bob Nowack**
*Emplacement and Crystallization History of Ni-Cu-(PGE) Sulfide-mineralized
Peridotites in the Eagle Intrusion, Upper Michigan*
- 3:00 **Christian Schardt**
*Metal isotopic signatures in the Duluth Complex associated with magmatic Cu-Ni-
PGE mineralization*
- 3:15 **COFFEE BREAK AND POSTER SESSION**

2B) ENVIRONMENTAL GEOLOGY RELATED TO MINING AND EXPLORATION

- 3:35 **Alex Brown**
*Unique characteristics of sediment-hosted stratiform copper mineralization resulting
from exceptional latent volcanic heat at White Pine, northern Michigan*
- 3:50 **Robert Seal, Perry Jones, Nadine Piatak, and Laurel Woodruff**
*Potential value of pre-mining baseline oxygen, hydrogen, and sulfur isotopic data
from surface waters for proposed large mining projects in northern Minnesota*
- 4:05 **Andrew Manning, Richard Wanty, and Jean Morrison**
*Preliminary groundwater age and chemistry data from cover overlying Duluth
Complex Ni-Cu-PGE deposits, NE Minnesota*
- 4:20 **Nadine Piatak, Robert Seal, Perry Jones, and Laurel Woodruff**
*Copper toxicity and dissolved organic matter: Resiliency of mineralized watersheds
in northern Minnesota and Michigan*
- 4:35 **Andrea Reed, Barry Frey, and Kevin Hanson**
*Expanding the historical exploration document collection at the Minnesota
Department of Natural Resources: the Polaris Joint Venture exploration program*
- 4:50 **George Hudak, Monson Geerts Stephen, Larry Zanko, Sara Post, and Euan
Reavie**
*The Minnesota Taconite Workers Health Study: Environmental Study of Airborne
Particulate Matter - 2015 Update*

6:00 **RECEPTION/POSTER SESSION – CASH BAR** (Harbor Side Foyer)

7:00 **ANNUAL BANQUET** (Harbor Side Ballroom)

- Announcement of 63rd Annual Meeting Location
- 2016 Goldich Award Presentation to Mark Jirsa
- Banquet Presentation - **Peter Clevenstine**, Asst. Director of Minerals, MN DNR
“Managing Minnesota's Mineral Resources and the DNR’s Conservation Agenda”

FRIDAY MAY 6, 2016

Asterisk * denotes a student eligible for Best Student Paper Award

8:00 OPENING REMARKS, UPDATES

Jim Miller and Christian Schardt, Co-Chairs, 2016 ILSG

TECHNICAL SESSION III

Session Chairs:

Latisha Brengman –University of Minnesota Duluth

Esther Kingsbury Stewart– Wisconsin Geological and Natural History Survey

3A) PROTEROZOIC TECTONICS AND SEDIMENTATION

8:10 Paul Bedrosian

Making it and breaking it in the upper Midwest: Constraints on continental assembly and rifting from EarthScope2

8:25. Esther Kingsbury Stewart and Jeffrey Mauk

Sequence stratigraphy and basin evolution of the Mesoproterozoic Nonesuch Formation, Ashland syncline, northern Wisconsin

8:40 V.J.S. Grauch, Michael Powers, and Eric Anderson

Progress on 3D modeling of the Midcontinent Rift System in the western Lake Superior region and an isopach map of the Oronto Group

8:55 Robyn Jones* and Philip Fralick

Sedimentology of a pre-vegetation prograding deltaic assemblage: the Mesoproterozoic Kama Hill and Outan Island Formations, Ontario

9:10 Philip Fralick and Kamil Zaniwski

Sedimentology of a Pre-Vegetation Floodplain Assemblage: the Mesoproterozoic Hele Member of the Sibley Group, Ontario

9:25 Julie Bartley, John Berger, Tanner Eischen, Sydney Firmin, and Lindsey Reiners

Hypersaline conditions for stromatolite growth in the Rossport Formation (Mesoproterozoic, Ontario)

9:40 Richard Ojakangas

What Happened in Northern Minnesota Between 2700 Ma and 1900 Ma? The Answer Is in the Pokegama Formation: A Multicycle Sedimentary History!

9:55 COFFEE BREAK AND POSTER SESSION

3B) GUNFLINT IRON FORMATION AND BARABOO QUARTZITE

10:25 William Cannon, Laurel Woodruff, and Stacy Saari

Traces of the Sudbury meteor impact in the western Gogebic Iron Range, northern Wisconsin

10:40 Ruby Reid-Sharp* and Mary Louise Hill

Characterizing deformation of Gunflint Formation in contact with Archean basement rocks east of Thunder Bay, Ontario

- 10:55 **Carli Nap* and Philip Fralick**
Mesoproterozoic Alteration of the Paleoproterozoic Gunflint Formation: Analogies with Martian Blueberries
- 11:10 **Esther Kingsbury Stewart, Eric Stewart, and Matthew Lamb**
Discovering hidden folds and faults in the Precambrian: new insights into Baraboo-interval stratigraphy and deformation in southern Wisconsin
- 11:25 **Gordon Medaris, Jr.**
Quantifying Mass Fluxes of Potassium in Weathering and Metasomatism of Paleosols
- 11:40 **LUNCH BREAK**

TECHNICAL SESSION IV

10 YEAR ANNIVERSARY OF THE PRECAMBRIAN RESEARCH CENTER AT UMD

- 1:15 **Jim Miller, Dean Peterson, and George Hudak**
Ten Years of Educating the Next Generation of Precambrian Field Geologists
- 1:30 **Dean Peterson, Jim Miller, and George Hudak**
The PRC's Precambrian Field Camp - A Decade of Training Students Geologic Mapping of the Canadian Shield
- 1:45 **George Hudak and Dean Peterson**
Future Directions for the Precambrian Research Center
- 2:00 **Mark Jirsa**
Nine years of capstones: A summary of PRC field camp capstone projects in the Neoarchean Knife Lake Group and associated rocks, central BWCAW, Minnesota
- 2:15 **UPCOMING FIELD OPPORTUNITIES**
BEST STUDENT PAPER AWARDS
STUDENT TRAVEL AWARDS
- 3:00 **END OF TECHNICAL SESSION**

4:00 pm POST-MEETING FIELD TRIPS

6) GEOLOGY AND TROUT FISHING ALONG AMITY CREEK, DULUTH

Dean Peterson – Peterson Geoscience LLC

George Hudak - Natural Resources Research Institute, UMD

7) ARCHEAN AND PROTEROZOIC GEOLOGY OF THE GUNFLINT TRAIL

Mark Jirsa - Minnesota Geological Survey

8) KEWEENAWAN GEOLOGY OF THE HOVLAND AREA

Terry Boerboom – Minnesota Geological Survey

John Green - Dept. of Earth and Environmental Sciences, UMD

SATURDAY MAY 7, 2016

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

9) DULUTH HARBOR GEOLOGIC HISTORY BOAT CRUISE: QUATERNARY TO ANTHROPOCENE

Irv Mossberger, Mehgan Blair, Eric Dott – Barr Engineering

Andy Breckenridge – University of Wisconsin - Superior

Todd Kremmin - Dept. of Earth and Environmental Sciences, UMD

POSTER PRESENTATIONS

Asterisk * denotes a student eligible for Best Student Paper Award

Eric Anderson, V.J.S Grauch, and Michael Powers

Reprocessed seismic data image geology and structure near the Douglas fault on the Bayfield Peninsula, Wisconsin

Kira Arnold* and S.E. Zurevinski

An Investigation of the Ney's Lookout Lamprophyric Dyke, Marathon, ON

Kristofer Asp* and Christian Schardt

An Investigation of Ni and Cu Isotopic Fractionation in Basal Duluth Complex Cu-Ni-PGE Mineralization, Northeastern Minnesota

Steven Baumann, Alexandra Cory, and Sandra Dylka

Lithological sedimentary divisions of the Copper Harbor Formation in Gogebic and Ontonagon Counties, Michigan

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

The occurrence of Li, B, Sn, and W in the Nine Mile Pluton, Wausau Syenite Complex, Marathon County, Wisconsin

William Cannon

Mobilization of silica by flash heating of silica gel beneath the Sudbury Impact Layer, Baraga Basin, Michigan

Val Chandler and Amy Radakovich

Utility of the horizontal-to-vertical spectral ratio (HVSr) passive seismic method for determining Quaternary sediment thickness and bedrock elevation in north-central Minnesota: Fun with little control and generally poor data

Jonathan Clark, Kristen Eshler, Patrick Groff, Taylor McClendon, Alexander Rode, Emily Salings, Kristen Spinelli, Kyle Vander Wyst, Aiden Walsh, Kristofer Asp, and Phillip Larson

Bedrock Geology of the Devilfish Lake Area, Cook County, Minnesota

Sarah Davis*, Peter Hollings, and Rob Cundari

Mineralogy and Geochemistry of the Wolfcamp Lake Basalts

Brittany Deley* and Mary Louise Hill

Origin of the gold-hosting porphyry at Geraldton, Ontario

Benjamin Drenth and Chad Ailes

Re-digitized public aeromagnetic data for parts of the west-central Upper Peninsula, Michigan

Benjamin Drenth, Raymond Anderson, Klaus Schulz, Joshua Feinberg, Val Chandler, and William Cannon

Progress on Geophysical Mapping of the Northeast Iowa Intrusive Complex

Simon Dolega* and Philip Fralick

Geochemistry of deep and shallow water Archean banded iron formations, and their post-depositional implications in the western Superior Province, Canada

Esprey Essig*, Howard Mooers, and Karen Gran

3D Geological Mapping Using Terrestrial LiDAR at Soudan Underground Mine

F. Glass

Evidence in the Eastern Canadian Shield of regular fault patterns of crustal origin for the loci of some mineral deposits and late-stage intrusive events.

Michael Felzan * and Marcia Bjørnerud

Multi-stage development of breccias in the Baraboo Quartzite, Rock Springs, Wisconsin

Carol Finn, Michael Zientek, Paul Bedrosian, Benjamin Bloss, Bethany Burton, Dean Petersen, and Heather Parks

Geophysical Imaging of Layered Mafic Complexes and Relation to Platinum Group Element Exploration

Carlin Green*, Robert Seal, William Cannon, and Nadine Piatak

Quantitative abundance and preliminary morphological characterization of amphiboles in the Ironwood Iron-Formation, Gogebic Iron Range, Wisconsin

Gregory Guenther* and Esther Kingsbury Stewart

Paleocurrent interpretation of the Cambrian Elk Mound group using geophysical optical borehole image (OBI) logs from two new boreholes, Dodge county, Southern Wisconsin

Samuel Helmuth* and Robert Lodge

A New Rusk County: Producing an new Precambrian geological map from new field observations and compilations of historic geological/geophysical datasets

Benjamin Hinks*, Joyashish Thakurta, Robert Mahin, and Steve Beach

Geochemical and petrological studies on the origin of Ni-Cu sulfide mineralization at the Eagle and Eagle East intrusions in Marquette County, Michigan

Sheree Hinz* and Peter Hollings

Preliminary Observations of the Ultramafic Metavolcanic Rocks in the Eastern Portion of the Shebandowan Greenstone Belt, northwestern Ontario

Nathaniel Jackson*, Bruno De Moura Meres, and Robert Lodge

Lithostratigraphy and Ore Petrology of the Eisenbrey Zn-Cu-Pb Deposit, Rusk County, Wisconsin

Shiyun Jin and Huifang Xu

Incommensurately modulated structure of plagioclase as an indicator of cooling history of igneous rock

Detaya Johnson* and Dyanna Czeck

Geochemistry of Seine River metaconglomerates from Mine Centre, Ontario: interpreting fluid flow and volume changes during deformation with implications for strain analysis

Alexandra Kozlowski* and S.E. Zurevinski

Mineralogy and petrology of the diamondiferous Madonna Dyke, Marathon, ON

Timothy Kroeger

Preliminary Report on the Palynology of the Gervais Formation (Pleistocene), Red Lake County, Minnesota

Matthew Lamb* and Esther Kingsbury Stewart

A comparison of Baraboo-Interval (Late Paleoproterozoic) Iron-Formation, Southern Wisconsin

Crystal Lambert* and John Swenson

Millennial-scale shoreline bluff retreat rates in the western arm of Lake Superior

Matthew Matko* and Christian Schardt

Small scale microanalysis of rock and mineral textures and its relationship to mineral separation

S. Metteer* and S.E. Zurevinski

Mineralogy and Petrology of the Rabbit Foot Dyke, White River, ON

Jim Miller, Aaron Balles, Ellie Brown, Ryan Helms, Greta Penzel, and Luke Smith

*Geology of the Cherokee Lake area of the Boundary Waters Canoe Area, Cook County, MN
- 2015 Precambrian field camp capstone mapping*

D. Nikkila*, R.H. Mitchell, and S.E. Zurevinski

Investigations of the Layered Series Nepheline Syenite within Center II of the Coldwell Complex, Marathon, ON

Maile Olson* and Robert Lodge

Ore Petrography and Precious Metals of the Primary Flambeau Massive Sulfide Ore

Mark Puumala and Seamus Magnus

A preliminary evaluation of the structural controls on gold mineralization in the Jackfish Lake area, northwestern Ontario

Lindsey Reiners*, Tanner Eischen*, and Julie Bartley

The building blocks of stromatolites: Comparisons across time and environment

Tyler Sager* and Nigel Wattrus

Evaluating H/V analysis of passive seismic data as a means to map sediment thickness in the Duluth-Superior harbor

Andrew Sasso* and Joyashish Thakurta

Geochemical and Petrological Comparisons of Peridotite Units in Marquette County, Michigan

Ruth Schulte, Nadine Piatak, Robert Seal, and Laurel Woodruff

Acid-Generating and Acid-Neutralizing Potential of Silicate Rocks from the Basal Mineralized Zone of the Duluth Complex, Minnesota

V. Smith* and S. Zurevinski

The Mineralogy, Petrography and Geochemistry of the Anderson Lake Pegmatite Occurrence

Matthew Svensson* and Stephen Kissin

Source of Native Iron in Canadian Arctic Artifacts

Margaret Upton, Ryan Puzel, Jaron Christenson, Morgan Kent, Steven Spreitzer, and Mark Jirsa

Geologic mapping of Neoproterozoic and Proterozoic rocks near Kekekabic Lake, northeastern Minnesota, by students of the Precambrian Research Center's 2015 field camp

Gerrit VanderWaal* and Christian Schardt

Influence of mineral liberation on metal leaching and dissolution rates in ore material and associated host rock

Blake Wallrich* and Michael Zieg

Small-Scale Petrographic Variations in a Nipigon Diabase Sill

Zacharie Zens* and Robert Lodge

Geochemistry and Petrography of the Volcanic Strata Hosting the Flambeau Cu-Zn-Au Deposit in Rusk County, WI: A Re-examination of Wisconsin's Only Past-Producing Volcanogenic Massive Sulfide Mine.

Michael Zieg and Blake Wallrich

Evidence for Episodic Emplacement History of a Nipigon Diabase Sill

Michael Zientek, Klaus Schulz, Laurel Woodruff, William Cannon, Suzanne Nicholson, Lukas Zürcher, Heather Parks, and Connie Dicken

Assessment of Undiscovered Nickel-Copper-Platinum Group Element (Ni-Cu-PGE) Resources Related to Conduit-Type Mineralization in the Midcontinent Rift System, Michigan, Minnesota, Ontario, and Wisconsin

ABSTRACTS

Reprocessed seismic data image geology and structure near the Douglas fault on the Bayfield Peninsula, Wisconsin

ANDERSON, Eric D., GRAUCH, V.J.S., POWERS, Michael H.,
US Geological Survey, MS 964, PO Box 25046, Denver, CO 80225 USA

A prominent gravity low lies over the Bayfield Peninsula in northern Wisconsin. The mapped bedrock geology includes sedimentary rocks of the Oronto and Bayfield Groups that overlie Midcontinent rift-related volcanic and intrusive rocks. The nearly 100 mGal amplitude anomaly has been interpreted to reflect low density Archean granite that is surrounded by higher density basalt (White, 1966; Allen and others, 1997), informally called White's Ridge (Figure 1). Reprocessed seismic reflection data are helping to understand the geology and structures that are encompassed by the gravity low.

Seismic reflection data acquired in 1984 were obtained for portions of several lines on the Bayfield Peninsula (Figure 1). Initially, only stacked time-series sections were available. The raw shot records were obtained for two lines within the western gradient of the gravity low and reprocessed using modern seismic data processing techniques. New stacking velocities were determined and used to create a new migrated time section and convert it to depth. The results show significantly more detail than was evident in the original time sections. These reprocessed data provide new insights about the geology to depths as great as 12 km.

The reprocessed seismic lines run north-south and east-west for a total of about 65 line km. The north-south line is perpendicular to the mapped Douglas fault and confirms that it is south-dipping, thrusting Keweenaw volcanic rocks over as much as 3.7 km of younger, south-dipping Bayfield and Oronto Group rocks to the north. At approximately 1 km depth, an anticlinal structure is evident south of the mapped Douglas fault. The velocity model indicates that the anticlinal structure is within the sedimentary rock package that overlies the volcanic rocks. North of the Douglas fault, both seismic sections indicate the Oronto Group increases in thickness towards the fault. The reprocessing of the east-west line has revealed several significant reflections in what was previously considered as reflection-poor Archean gneiss. These events are at depths from 9 to 12 km and may indicate the presence of layered strata of unknown origin at the easternmost end of the seismic line. The reprocessed data show in both lines a wavy texture in parts of the volcanic rocks. This texture is not evident in the vintage time sections. In the east-west line, the wavy texture is more pronounced where the volcanic rocks are in unconformable contact with the overlying Oronto Group. In the north-south line, the wavy texture only appears at depth in the volcanic rocks north of the Douglas fault. This texture may be due to heterogeneity in the physical properties and/or layering of the volcanic rocks or be the expression of local intrusive activity.

The new seismic observations are being integrated into broader scale gravity and magnetic models that span the gravity low over the Bayfield Peninsula. Preliminary models indicate that relatively low density pre-rift rocks can explain the gravity low. The seismic data add considerable detail to the geologic model and are helping to define stratigraphic and structural relationships between the lithologies at depth.

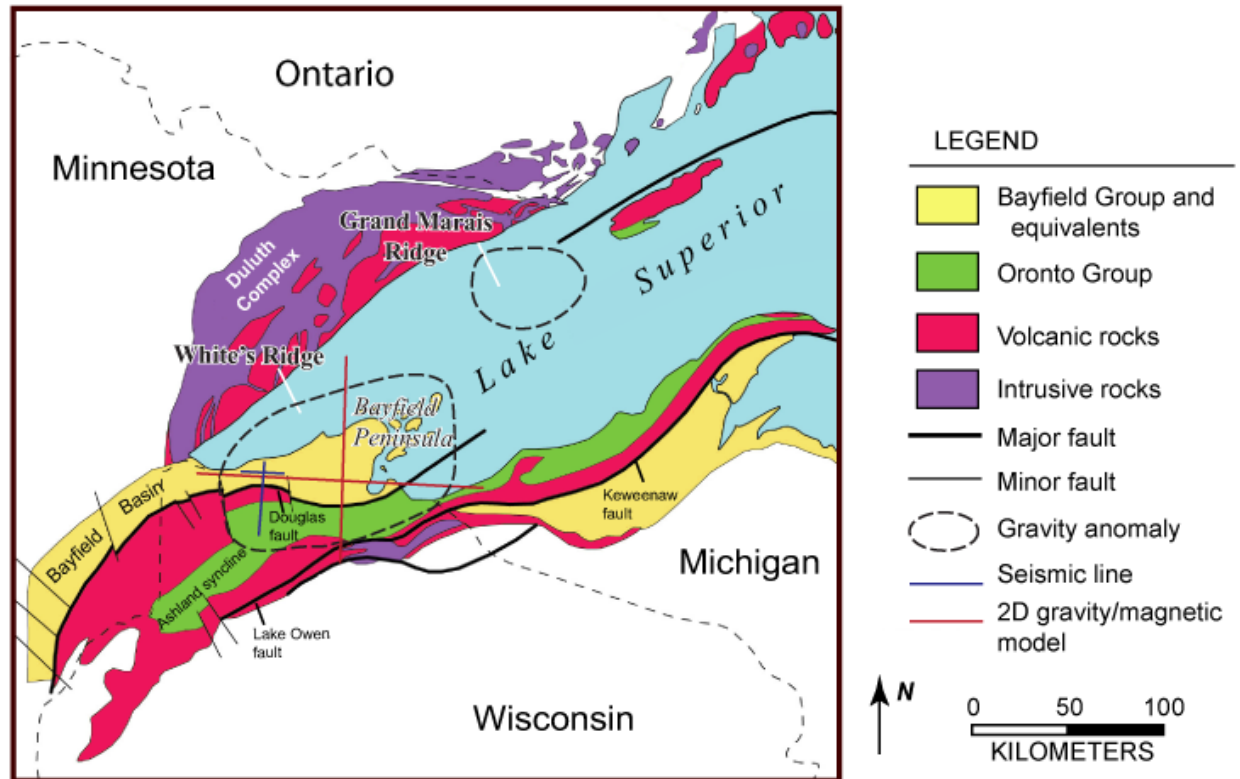


Figure 1: Generalized geology map of western Lake Superior showing location of reprocessed seismic data within the western gradient of the gravity low that overlies the Bayfield Peninsula. Anomalous gravity lows occur at both White's and Grand Marais Ridges. The seismic lines provide detailed subsurface images that are being integrated with 2D gravity and magnetic models to help characterize the source of the gravity lows.

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An Investigation of the Ney's Lookout Lamprophyric Dyke, Marathon, ON

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The Coldwell Complex of the Superior Province is known to host multiple lamprophyric dykes varying from ultramafic to alkaline affinities (Heaman and Machado 1992). The 1108 +/- 1 Ma age of the Coldwell complex and close spatial proximity supports a strong relationship to the magmatism of the Keweenaw Midcontinent Rift. The Ney's Lookout dyke is located within the Center II portion of the Coldwell Complex, crosscutting assimilated syenites. This area of Center II is highly brecciated and assimilated, which is interpreted to be representative as evidence of the cauldron collapse (Mitchell and Platt 1978). The lamprophyre is devoid of diamonds, and has not been thoroughly analyzed other than brief field assessments. The objective of this research is to complete a mineralogical assessment of the lamprophyre dyke in order to characterize and classify the lamprophyre according to the IUGS classifications of lamprophyre-clan rocks.

The main minerals that comprise the lamprophyre are euhedral zoned pyroxene phenocrysts and flow-aligned anorthoclase laths in a fine-grained groundmass composed of biotite, pyroxene, amphibole and feldspars. The pyroxene phenocrysts are poikilitic with inclusions of biotite, amphibole and relic olivine similar to the groundmass. Relic chloritized olivine phenocrysts are present in the groundmass and as inclusions in pyroxenes. The pyroxenes present in the sample are classified as diopside with minor augite. Mineralogical compositions of the Ney's Lookout amphibole classify as Ferroan Paragasic Hornblende. When compared to other lamprophyres within the Coldwell Complex, there were mineralogical and textural similarities between Ney's Lookout Lamprophyre and local sannaite, such as porphyritic texture and mantling of amphiboles on pyroxene (Mitchell et al. 1991). Aside from minor variances in modal mineralogy, the lamprophyre best resembles a sannaite under the alkaline lamprophyre classification.

The chill margin along the dyke is a fine-grained rim with no contact metamorphism present, interpreted as representing a moderate emplacement temperature. Laths of anorthoclase are directionally aligned in the lamprophyre and are interpreted as flow textures. Zonation in the pyroxene is distinct in the phenocrysts, representing increasing Cr and Ti outward toward the rim with increased Fe in the core and decreasing amounts in the rim. Uralitization is the alteration of pyroxene phenocrysts to amphibole around the outer rim. The zonation and uralitization often occur from magma mixing events. The Ney's Lookout Sannaite Lamprophyre, has intruded into an area of highly brecciated and assimilated country rock. As well, the Little Pic River fault, a North-South trending fault, is located to just to the West of the lamprophyre. It is likely that the Ney's Lookout lamprophyre was emplaced along planes of weakness similar to other lamprophyres in the area.

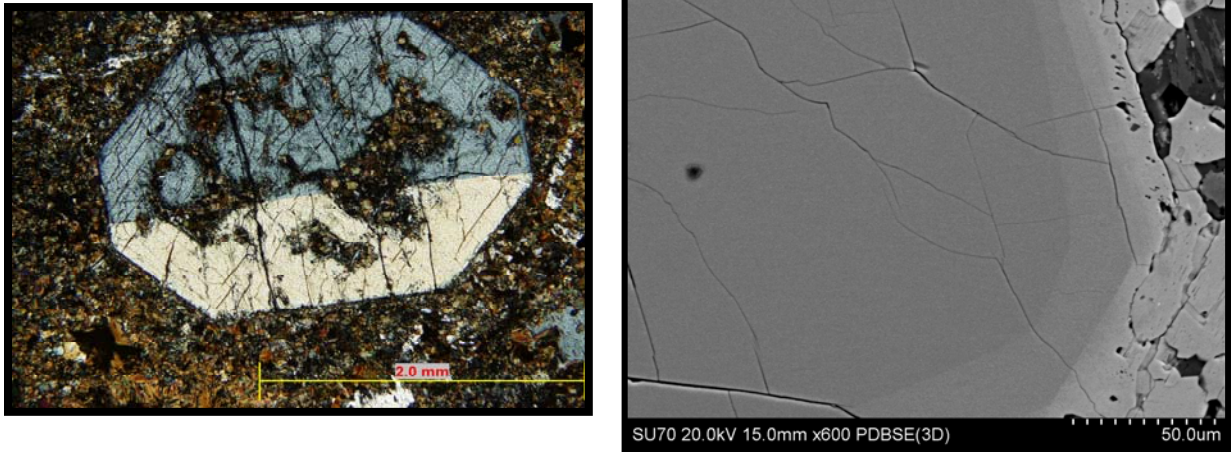


Figure 1. A. Pyroxene phenocrysts present in the lamprophyre dyke are poikilitic and euhedral with simple twinning. B. The distinct zonation of pyroxene phenocrysts with a Fe rich core. Cr and Ti wt. %'s increase towards the rim. Al wt. % varies between zones, with no distinctive trend.

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An Investigation of Ni and Cu Isotopic Fractionation in Basal Duluth Complex Cu-Ni-PGE Mineralization, Northeastern Minnesota

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Cu-Ni-PGE magmatic sulfide-style mineralization occurs along the western margin of the Duluth Complex in northeastern Minnesota. Previous studies have demonstrated a notable fractionation of ⁶⁰Ni and ⁵⁸Ni in terrestrial materials, including both primary and secondary phases, with a total range of 2.1 ‰ [1 – 5]. Additional work has indicated a fractionation of ⁶⁵Cu and ⁶³Cu, with pronounced differences between primary copper sulfides and secondary copper phases in a variety of magmatic deposit types [6, 7]. Prior to this research, no $\delta^{60/58}\text{Ni}$ or $\delta^{65/63}\text{Cu}$ values have been measured in Duluth Complex rocks. The primary goal of this study is to measure Ni and Cu isotope values in a variety of Duluth Complex samples, and develop a possible model for the $\delta^{60/58}\text{Ni}$ and $\delta^{65/63}\text{Cu}$ isotopic systems in this geologic terrane. A secondary goal is to determine whether or not Ni and Cu isotope values in surface material could be used as an exploration tool for identifying Cu-Ni-PGE mineralization at depth.

Based on the findings of previous studies, samples were collected to determine the isotopic differences between sulfide-bearing and sulfide-barren material. The potential effects of weathering were also taken into account by collecting samples at the surface in addition to unweathered, primary mineralized drill core. Samples were collected from a variety of locations in the basal Duluth Complex, including glacial till beds and surface outcrops in the vicinity of the Spruce Road, Maturi, Serpentine, Mesaba, and NorthMet deposits. Drill core from the Birch Lake, Wyman Creek, and Wetlegs deposits, along with those listed previously, was provided by several companies, including Duluth Metals/Twin Metals, Teck, PolyMet, and Encampment Minerals. Several pieces of drill core were also obtained from the MN DNR core facility in Hibbing, MN.

A detailed characterization of till, weathered surface, and primary drill core samples revealed three main sources of nickel in Duluth Complex material: silicate, sulfide, and secondary oxide. The 24 $\delta^{60/58}\text{Ni}$ values have an overall range from -0.97 to 0.22 ‰, but are correspondingly distinct in each type of material: silicate (-0.03 ‰ average), sulfide (-0.36 ‰ average), secondary oxide (-0.50 ‰ average). Further geochemical and microprobe work, along with the isotopic values, indicate two main stages of Ni fractionation in basal Duluth Complex rocks: a high temperature stage during crystallization, and a low temperature stage during surficial weathering. High-T fractionation is defined by a preferential incorporation of ⁵⁸Ni into sulfide, while silicates, especially olivine, are reflective of the Bulk Silicate Earth value [3]. Low-T fractionation results in a preferential incorporation of ⁵⁸Ni into secondary oxide, while ⁶⁰Ni possibly enters solution and leaves the system [1; 5].

The 22 measured Duluth Complex $\delta^{65/63}\text{Cu}$ values have an overall range from -1.28 ‰ to 0.36 ‰, with an overall average of -0.35 ‰. This range is roughly similar to the magmatic sulfide values measured by [6], but are a significant departure from values measured in other deposit types. Specifically, deposits containing abundant secondary copper phases, including Cu-carbonates and hydroxides, are significantly more enriched in ⁶⁵Cu, with values up to 2.41 ‰ reported [7]. Due to the lack of observed secondary Cu minerals in project samples, it is possible that the low-T fractionation of ⁶⁵Cu into secondary phases may not occur as readily in the basal Duluth Complex. Accordingly, the only indicated fractionation in the Duluth Complex is a high

temperature fractionation, where ^{63}Cu is preferentially incorporated into Cu sulfides during crystallization.

Based on the measured isotopic values, there are distinct differences between sulfide-bearing and sulfide-barren material at the surface that may indicate the presence of mineralization at depth. There is potential for these isotopic systems to be used as an exploration tool, but further research is required to fully evaluate the processes associated with these systems.

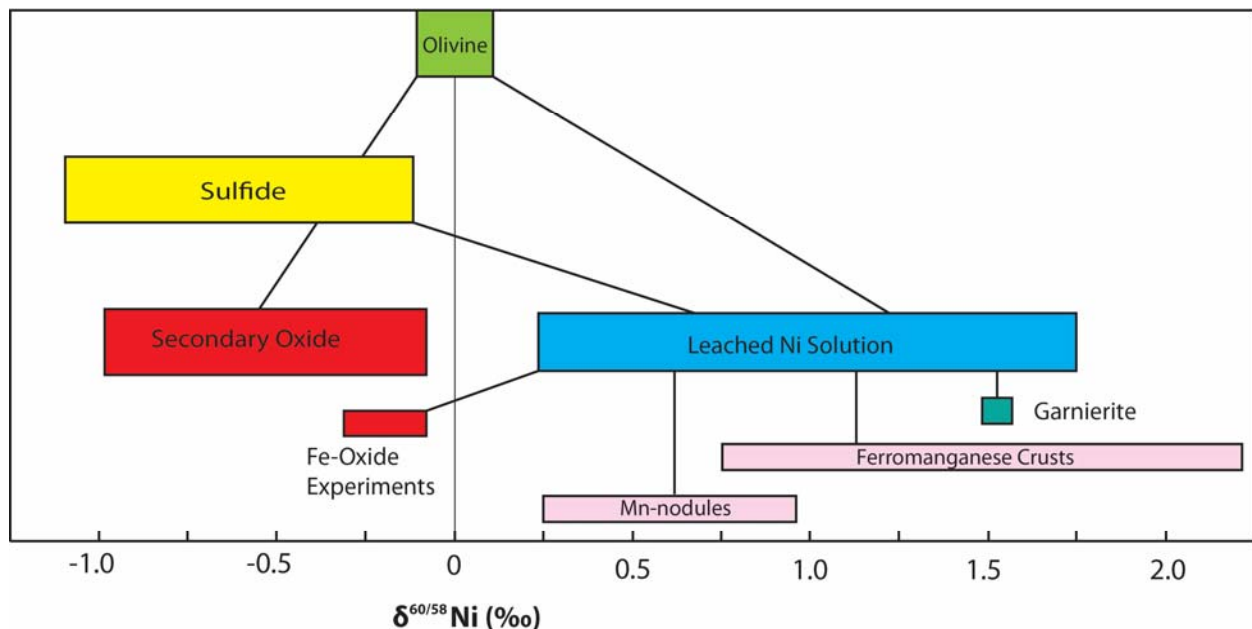


Figure 1: Developed model for Ni isotopic fractionation in the basal Duluth Complex. Primary fractionation occurs at high temperatures during the crystallization of olivine and sulfide, while secondary fractionation leads to a preferential incorporation of ^{58}Ni into secondary oxides. Also during secondary fractionation, ^{60}Ni enters solution, and may be incorporated into other secondary phases including ferromanganese crusts and secondary Ni silicates (garnierite).

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Hypersaline conditions for stromatolite growth in the Rosspport Formation (Mesoproterozoic, Ontario)

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The Mesoproterozoic Rosspport Formation of Ontario, Canada is approximately 1.4 billion years old (Franklin et al., 1980) and is generally interpreted to have been deposited in an intracratonic basin, most likely a rift-related lake (Rogala et al., 2005). While the Rosspport consists dominantly of sandstone and shale, the Middlebrun Bay Member, in the middle of the formation, is a carbonate unit. The Middlebrun Bay Member, in exposures on the Channel Islands and along the North Shore of Lake Superior, consists of massive limestone and cherty, stromatolitic carbonate. Key features of these carbonates suggest an interval of low lake level, low clastic influx, high salinity, and local conditions suitable for microbialite development. They provide an important environmental constraint on conditions in this lake, and additionally suggest environments in which complex, carbonate-precipitating microbial communities could thrive.

The presence of a massive, recrystallized limestone on Copper Island suggests of hypersaline, evaporite-producing conditions. This unit is devoid of stromatolites or microbial laminae and has an unusual bright white color lacking internal structure (Fig. 1) with a coarsely recrystallized texture. These features suggest dissolution and replacement of a primary, soluble phase such as an evaporite mineral. The presence of large sandstone clasts let down from the overlying bed is reminiscent of collapse breccia associated with dissolution of that primary mineralogy (Fig. 2). Additionally, geochemical data suggest broad similarity with other Proterozoic carbonates interpreted as calcitized evaporites (Manning-Berg and Kah, 2013). Based on these data, we interpret the massive carbonate exposed on Copper Island as a calcitized evaporite, probably deposited originally as gypsum and replaced by calcite during diagenesis (Firmin and Bartley, 2014).

Previous work on the Rosspport Formation suggests that the Middlebrun Bay Member formed when lake levels and clastic influx were low (Rogala et al., 2007). Combined with an evaporite interpretation of the massive carbonate unit, we suggest the Middlebrun Bay interval may have been deposited during a period of increased aridity in the region. In this model, stromatolites would have formed in a hypersaline lake environment during intervals of low clastic influx.



Figure 1



Figure 2



Middlebrun Bay stromatolites have low-relief stratiform to columnar morphology (Figure 3). Early diagenetic chert is locally abundant, and the meso- to micro-scale texture suggests *in situ* precipitation of microbial laminae and rapid cementation of stromatolite form.

Stromatolites occur in lacustrine environments throughout geologic history, commonly under conditions of high alkalinity or high salinity (e.g., Gomez et al., 2013). During the Mesoproterozoic, though, stromatolites are more often associated with marine environmental conditions (Kah et al., 2009) and only occasionally occur in association with indicators of elevated salinity (e.g., Neudert and Russell, 1981). The Middlebrun Bay stromatolites, therefore, provide an important datum in space and time, allowing comparison of their morphology, texture, and fabric in relation to the features of younger, more commonly hypersaline stromatolites and contemporaneous, normal-marine forms.

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Lithological sedimentary divisions of the Copper Harbor Formation in Gogebic and Ontonagon Counties, Michigan

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The sedimentary assemblage of the Copper Harbor Conglomerate shows four to five distinct sedimentary units (with interbedded volcanics) exposed for a length of approximately 35 miles along Lake Superior in Gogebic and Ontonagon Counties. 7.5' quadrangle scale mapping in 2014 to 2015 led to the recognition of four distinct sedimentary facies extending from the North Ironwood east along Lake Superior to at least the White Pines 7.5' quadrangles (see figure 1). A fifth sedimentary unit at the top of the formation exists in the Black River Harbor 7.5' quadrangle east to the Carp River East 7.5 minute quadrangle.

The five sedimentary units can be lumped into two main facies. The lower two units are conglomerate dominated (Units 1 and 2), while the upper three units are dominantly sandstones (Units 3, 4, and 5). These two basic facies appear to be separated by an unconformity, where the contact is exposed along the Black River.

The basal unit of the lower facies (Unit 1) is reddish brown to brown, massive, clast supported, polyomitic orthoconglomerate about 1700 to 3000 feet thick. The clasts are well rounded and range in size from pebbles to boulders ($\leq 14''$ in diameter). Lithic arkose makes up the majority of the matrix at $<15\%$ of the rock. Along the Black River this unit contains about 480 feet of volcanics at about the halfway point within the unit, informally called the "Black River Flows". These flows are dominantly andesite with some beds of sedimentary rock. The flows are stratigraphically lower in section than the base of the Lake Shore Traps.

Unit 2 overlies Unit 1 in a gradational to intertonguing relationship over about 200 feet, except where the Lake Shore Traps are present. The Lake Shore Traps separate the two units with sharp contacts. Unit 2 is a deep red to reddish brown, thick bedded, clast supported, polyomitic sandy orthoconglomerate. The clasts are all well rounded and generally larger than in Unit 1 ($\leq 22''$ in diameter). Lenses of deep red, medium to coarse grained, lithic arkosic arenite exist within the unit and are $\leq 4'$ thick by ≤ 50 feet wide. Unit 2 is about 700 to 2800 feet thick.

Unit 2 is separated from the upper facies (Unit 3) by a sharp contact, which is a probable unconformity. This unconformity separates the two main facies. Unit 2 thickens at the expense of Unit 3 in the Carp River West and East quadrangles. Unit 3 is deep purplish gray to brown, thin to medium cross bedded, fine to coarse grained, arkosic arenite. It contains beds of polyomitic sandy diconglomerate with well rounded clasts $\leq 8''$ in diameter. Ripple marks are very common on bedding planes. Unit 3 is 800 to 3000 feet thick.

Unit 3 grades up into Unit 4 over about 30 feet. The lithology of Unit 4 closely resembles the Freda Formation. It is deep red mottled pale yellow brown becoming purplish near the top, medium bedded to cross bedded, fine to coarse grained, arkosic arenite. The unit fines up section. It contains isolated thick beds of polyomitic sandy paraconglomerate, with clasts $\leq 6''$ in diameter. Ripple marks are common. Unit 4 has the most consistent thickness at 1000 to 1700 feet.

Unit 5 shows an intertonguing and gradational contact with Unit 4. Gradation is over about 20 feet. Unlike the lower four units, it is not continuous throughout the area. It exists as a large lens extending about 21 miles from the North Ironwood to Carp River East quadrangle. It is a deep purple to dark gray, laminated to massive, sandy shale, with some polyomitic sandy paraconglomerate beds. Clasts are $\leq 3''$ in diameter. The sandy parts of the unit are mostly coarse lithic arenites. It is the thinnest of the units at 0 to 400 feet thick. The top of the unit is locally covered, except in the Carp River East quadrangle, where the top is gradational with the overlying Nonesuch Formation. The top of the Copper Harbor Formation at Nonesuch Falls along the Little Iron River (White Pine quadrangle), resembles Unit 5 and may be equivalent. However, complex local folding and faulting makes a definite correlation difficult.

Units 1 and 2 thin dramatically on the east side of the Porcupine Mountains and pinch out altogether just south of the mountains (at about 46.76° by -89.62°). However, lithologies resembling Units 1 and 2 appear to be traceable on the north shore of the Keweenaw Peninsula, where Unit 1 can be traced along with a facies change in Unit 2. At Horseshoe Harbor (47.473° by -87.809°) Unit 2 includes more continuous beds of sandstone with shale, along with

stromatolites. The thinning of Units 1 and 2 observed around the Porcupine Mountains may just be a local phenomenon caused by the extremely thick Porcupine Volcanics.

The four to five fold division of the Copper Harbor Formation is persistent and traceable from about -90.19° (North Ironwood quadrangle) to -89.57° longitude (White Pine quadrangle) along Lake Superior. The four to five fold division west of longitude -90.19°, begins to break down. West of longitude -90.28° (in the Little Girls Point quadrangle), the Copper Harbor Formation appears to be undivided. The Copper Harbor pinches out entirely in Copper Falls State Park, north of Mellen, Wisconsin.

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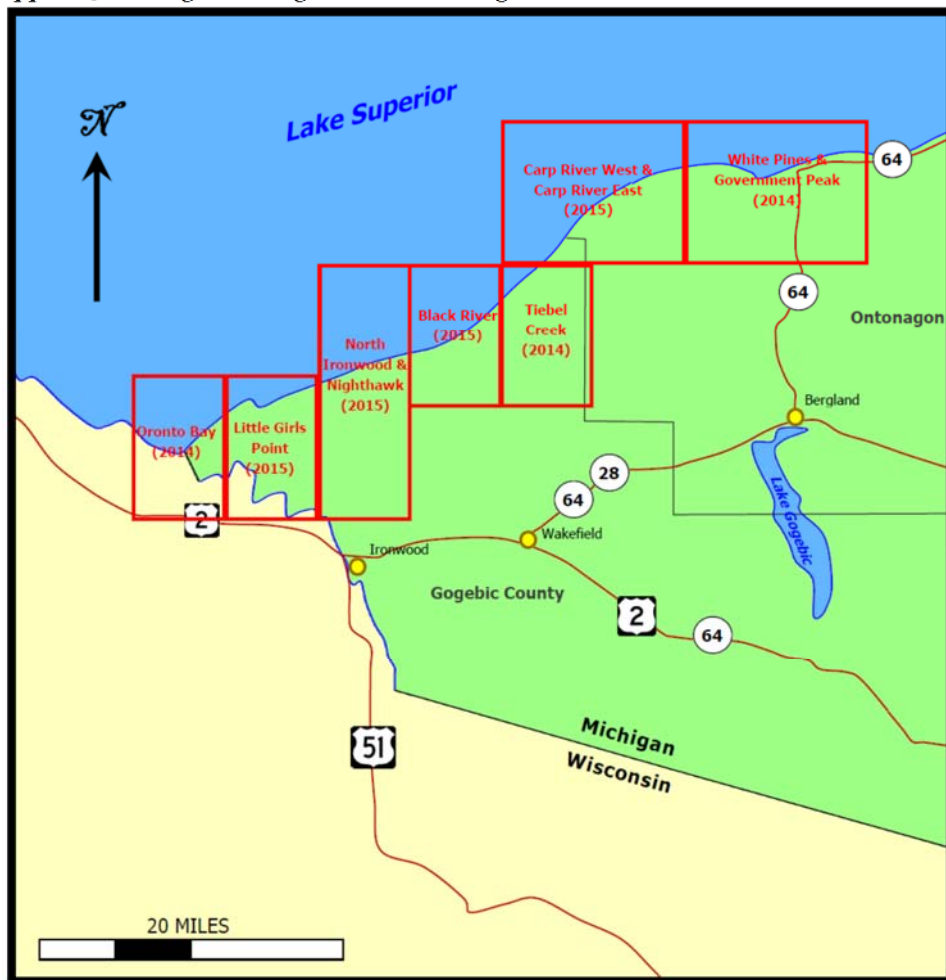
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Figure 1: Mapped Quadrangles in Gogebic and Ontonagon Counties



Making it and breaking it in the upper Midwest: Constraints on continental assembly and rifting from EarthScope

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The North American mid-continent presents a window into craton growth and stabilization as well as the 1.1 Ga rifting event that nearly tore Laurentia apart. Unique to this region is the preservation of this tectonic collage, largely unmodified by subsequent tectonic events, which permits examination of if and how such events are preserved in the continental lithosphere. Focusing on the upper Midwest, I will discuss the implications of a three-dimensional resistivity model derived from EarthScope magnetotelluric data [Bedrosian, 2016].

The resistivity model reveals the distribution of highly conductive Penokean age meta-sedimentary rocks in Minnesota, Michigan, and Wisconsin. These rocks are correlated with meta-graywackes of the Michigamme Formation in MI and WI, and with graywackes of the Virginia and Rove Formations in MN. The electrical signature of these rocks is unique throughout the entire mid-continent region. Their high conductivity is attributed to metallic sulfides and in some cases graphite. The former is considered a potential source of sulfur for certain types of mineral deposits found in the region. A more detailed magnetotelluric survey, in addition to a reconnaissance airborne electromagnetic survey, is being carried out to map these rocks in greater detail. An isolated sliver of similarly conductive rocks is mapped in the subsurface in northwest Iowa (sub-parallel to the Spirit Lake Tectonic Zone); I speculate that Penokean-age rocks may be preserved further west than currently assumed.

The Paleoproterozoic structural collage was interrupted by the 1.1 Ga Mid-continent Rift System (MRS). The type electrical signature of the MRS is found in Iowa, where a resistive medial horst is imaged, flanked by deep sedimentary basins filled with Bayfield and Oronto Group equivalent sediments. A distinction is observed between the moderately conductive Oronto Group and the highly conductive Bayfield Group.

Translating this basic picture to the Lake Superior graben, a pronounced west to east asymmetry is seen, with the Thiel fault being the most obvious division. The asymmetry is taken to reflect the different geometric response of each half of the basin to compression during the Grenville orogeny [Cannon, 1994]. The orientation of the rift-bounding faults in relation to the stress field at the time is speculated to have resulted in a greater degree of compression in the western half of the Superior graben than in the eastern half. Additionally, there appears to be a horst and graben geometry across each half of the Superior graben.

At a much larger scale, the resistivity of the mantle lithospheric beneath the region is surprisingly heterogeneous. The spatial pattern of these variations bears little resemblance to the crustal imprint of past tectonic events or to the direction of North American absolute plate motion. I argue that these resistivity variations reflect differing degrees of hydration (metasomatism) preserved within the lithosphere. Lithospheric hydration in the upper Midwest is speculated to have occurred during MRS magmatism. This interpretation is consistent with geochemical and isotopic analyses of MRS basalts and their inferred mantle sources [Nicholson et al., 1997].

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Unique characteristics of sediment-hosted stratiform copper mineralization resulting from exceptional latent volcanic heat at White Pine, northern Michigan

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Most studies of copper mineralization hosted by basal greybeds of the Nonesuch Formation at White Pine, Michigan, have concluded that the main-stage sediment-hosted stratiform copper (SSC) mineralization resulted from an upward influx of cupriferous brine from a coarse-grained footwall aquifer, the Copper Harbor Conglomerate (White and Wright, 1966; Brown, 1971). An early diagenetic timing is interpreted mainly from textural evidence that copper deposited largely by replacement of *in situ* fine-grained syndiagenetic pyrite (Fig. a), that infiltrations of ore-forming brine would have been relatively rapid before advanced compaction and lithification of the basal fine-grained Nonesuch strata, and that main-stage mineralization pre-dated later structurally controlled mineralization (Mauk, 1993).

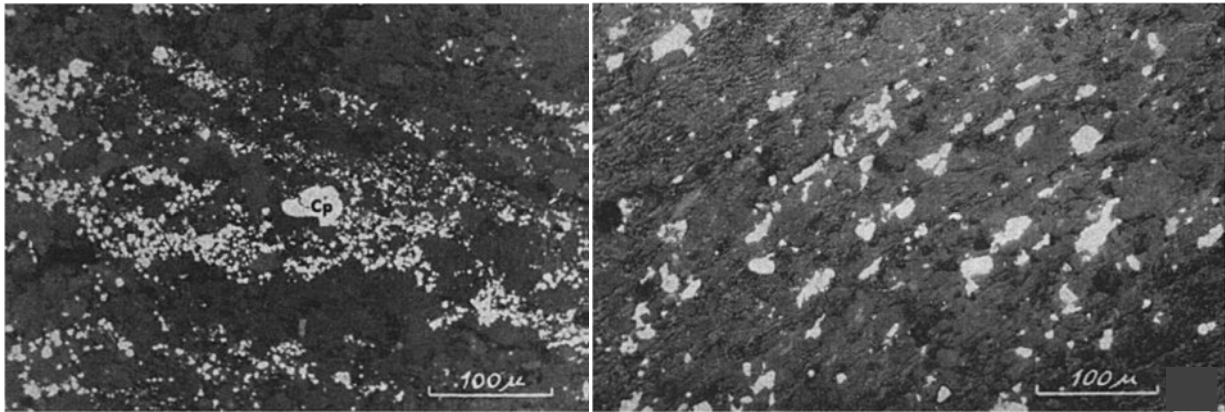
Curiously, the replacement of fine-grained disseminations of euhedral pyrite by cupriferous sulfides at White Pine is clearly visible in a transition zone at the top of the cupriferous zone (cms in width), but not within the cupriferous zone proper (meters in width) where disseminated chalcocite (Fig. b) occurs with a grain-size considerably greater than that of disseminated pre-ore pyrite found above the cupriferous zone. The only strong visual evidence for chalcocite replacement of pyrite within the cupriferous zone is the occurrence of chalcocite nodules which presumably were initially syndiagenetic pyrite nodules; commonly, the chalcocite nodules are surrounded by halos of hematite which probably represent iron released during pyrite replacement. Curiously too, the White Pine deposit is unique in that most other SSC deposits world-wide exhibit fine-grained euhedral pyrite replacements within their cupriferous zones. Also, the White Pine copper mineralization is composed virtually only of disseminated chalcocite with a remarkably narrow transition ($\text{Py} \rightarrow \text{Cp} \rightarrow \text{Bn} \rightarrow \text{Cc}$) into overlying pyritic strata (Fig. c), whereas most SSCs world-wide exhibit gradual copper-iron sulfide transitions over the breadth of their cupriferous zones.

The recent proposal (Brown, 2013, 2014) that the upwardly infiltrating cupriferous brine at White Pine was warmed to $\sim 100^\circ\text{C}$ by latent heat from the underlying buried Porcupine Volcanics dome (Fig. d) could offer explanations for the unique character of the White Pine SSC deposit: a) the anomalously warm ore-stage environment could have resulted in a more rapid and complete reaction through the $\text{Py} \rightarrow \text{Cp} \rightarrow \text{Bn} \rightarrow \text{Cc}$ sequence to form uniquely chalcocitic mineralization rapidly within the cupriferous zone proper while the copper front advanced upward through the basal Nonesuch graybeds; b) under warm conditions, fine-grained chalcocite could have recrystallized to coarser-grained chalcocite; and c) the preservation of fine-grained zoned replacement textures and pseudomorphs after pyrite euhedral along the top of the cupriferous zone could represent replacements of pyrite at low temperatures prevailing toward the end of the main-stage copper mineralization event.

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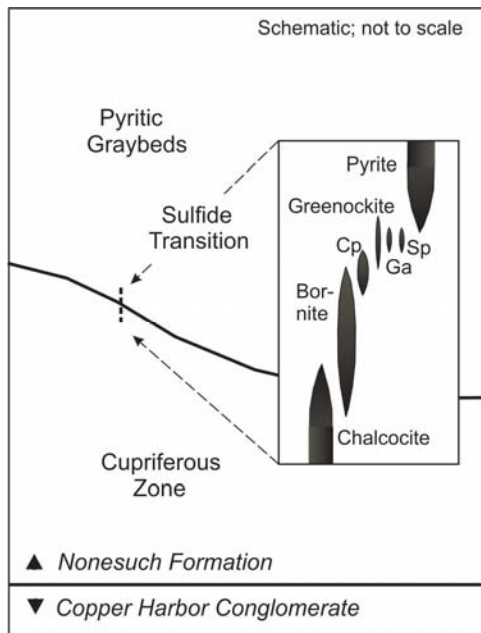
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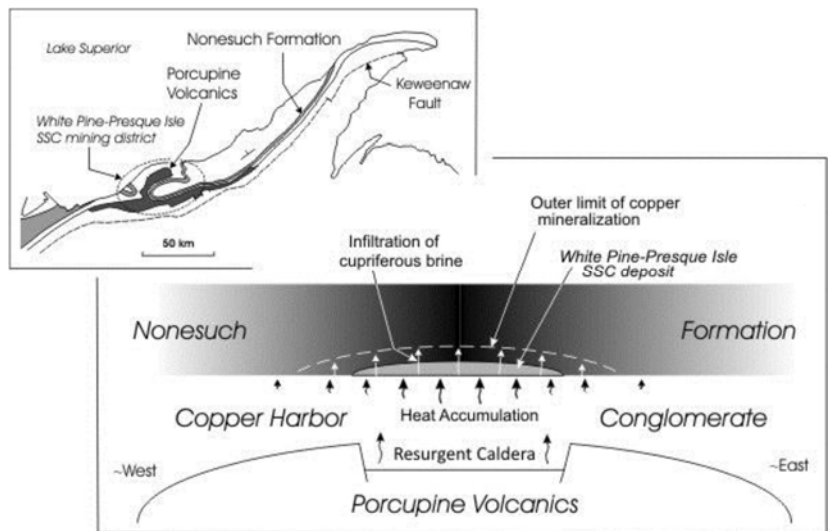


a) Disseminated very fine-grained pyrite (some framboidal) in Nonesuch graybeds above the cupriferous zone, White Pine deposit. (Relatively coarse grain of pre-ore stage chalcopryite (Cp) in center of view).

b) Fine-grained chalcocite (white) of the cupriferous zone, basal Nonesuch graybeds. Chalcocite grain-size decidedly greater than that of pyrite in a). Note also the absence of pseudomorphs after euhedral pyrite.



c) Narrow pyrite to chalcocite transition (Py→Cp→Bn→Cc) at the top of the cupriferous zone, White Pine-Presque Isle district.



d) Schematic illustration of Porcupine Volcanics dome contributing latent volcanic heat during early diagenetic infiltrations of Cu-bearing brine into basal Nonesuch graybeds, White Pine-Presque Isle district. See Brown (2014) for further explanations.

The occurrence of Li, B, Sn, and W in the Nine Mile Pluton, Wausau Syenite Complex, Marathon County, Wisconsin.

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The Nine Mile Pluton is the youngest (≈ 1505 Ma, Dewane & Van Schmus, 2007) and most silicic of the four intrusions comprising the Wausau Syenite Complex, and is primarily composed of granite and quartz monzonite. Over the last several decades we have developed considerable data on the behavior of some minor elements during the formation of this complex, notably Li, B, Sn and W, which are addressed here. Identification was via electron microprobe (EMP), X-ray diffraction (XRD), energy dispersive spectrometry (EDS) and direct coupled plasma spectroscopy (DCPS) as indicated.

Although overall sparse, Li mineralization has been identified in several areas of the pluton, associated with pegmatites and greisens exposed in quarrying operations exploiting easily excavated “rotten granite” or grus. In the former Wimmer pits and adjacent operations, the Li-mica zinnwaldite, $\text{KLiFe}^{2+}_2\text{Al}(\text{Al}_2\text{Si}_3\text{O}_{10})$ (an intermediate composition between siderophyllite and polyolithionite), has been identified (EMP, DCPS) from several fractionated pegmatites, associated with columbite- pyrochlore- and euxenite-group minerals. Additionally, approximately 2 gms of elbaite tourmaline (XRD, EMP), $\text{Na}(\text{Li}_{1.5}\text{Al}_{1.5})\text{Al}_6(\text{Si}_6\text{O}_{18})(\text{BO}_3)_3(\text{OH})_3(\text{OH})$, were found in a large (2.4x2.2x0.4 m) miarole in a pegmatite located in the former

Thurber pit (later Wimmer #3). Zinnwaldite (EMP, DCPS) has also been found in several pegmatites in the former Koss pit in the central portion of the pluton (associated with cassiterite, columbite-, euxenite- and pyrochlore-group minerals); in greisenized pegmatites and aplites in the former Maguire Pit in the south-central portion of the pluton (associated with cassiterite, ferberite/huebnerite, topaz, cryolite, prosopite and other minerals), and in a greisen-related episyenite and vein assemblage in the Ladick operation (associated with cassiterite, pseudobrookite, monazite, molybdenite and other minerals) in the southwest portion of the pluton. Overall, Li contents in Nine Mile Pluton pegmatite wall zones reach 10-20 ppm, while in the granite itself Li contents range from below detection limit to 4 ppm (DCPS).

Boron minerals are extremely rare in the Wausau Complex, having only been found as the aforementioned elbaite tourmaline, and a few grams of schorl tourmaline (EMP) found in a small miarole (5 cm diameter) in the former Wimmer pit #2. This scarcity is probably a consequence of very low boron levels in the Complex. In general, DCPS analysis of Nine Mile Pluton pegmatite wall zones indicate B contents ranging from below detection limit to 3 ppm, and of the granite itself from below detection limit to 1 ppm, although DCPS analysis of the wall zone of the elbaite-bearing pegmatite indicated anomalous B contents of 12-15 ppm.

Sn mineralization is not abundant in the Nine Mile Pluton, but is relatively widespread.

Cassiterite, SnO_2 , has been found as apparent epitaxial overgrowths on ilmenite in a small miarolitic granite body on the western side of the former Wimmer Pit #3 in the NE portion of the pluton (EDS). Tantalian cassiterite (EMP) was found in a small fractionated pegmatite nearby where it was closely associated with columbite-group minerals, U-rich pyrochlore, a U-niobate mineral and hafnian zircon, and was also identified (EDS, EMP) from a fractionated pegmatite exposed by workings in the former Koss Pit in the central portion of the pluton. Sparse cassiterite has also been found as red-brown grains in chloritized biotite from an euxenite and fluorite-rich pegmatite exposed in the Kafka operation in the western portion of the pluton (EDS), and in a

thin quartz-pyrite vein briefly exposed in the floor of the Red Rock Southwest Pit in the southwest portion of the pluton (EDS). Cassiterite was abundant in greisenized pegmatites and aplites exposed by workings in the former Maguire Pit in the southern portion of the Nine Mile Granite (EDS, EMP), and tantalian cassiterite (EMP) was common in the greisen-related episyenite and vein assemblage in the Ladick quarry briefly described above. It is interesting that several analyzed cassiterites have elevated tantalum contents of 0.3 to 0.4 wt% Ta₂O₅, while their Nb₂O₅ contents are much lower, suggesting that Ta is more compatible in cassiterite than Nb.

Tungsten mineralization is very limited within the Nine Mile Pluton, and has only been found in the greisenized pegmatites and aplites that were exposed in the former Maguire Pit briefly described above. “Wolframite” (sensu lato) was common as crystals to about 1.5 mm, and varied from Fe-rich ferberite, FeWO₄, to Mn-rich huebnerite, MnWO₄, often within the same crystal (EMP). Small grains of a Pb-tungstate mineral, probably either raspite or stolzite (EDS, EMP, both Pb(WO₄)), were present as inclusions in ferberite. Closely associated columbite-(Fe) in some cases contained up to 12 wt.% WO₃ (EMP), resulting in tungstenian columbite-(Fe). Such high-W columbites are likely disordered, and may be “wolframoixiolite”, (Nb,W,Ta,Fe,Mn)₂O₄ (MINDAT, accessed 03/2016), but due to limited amounts of material this hypothesis has not been confirmed. Finally, scheelite (EMP), CaWO₄, was noted as small grains in heavy mineral separates from several dikes, and ferberite pseudomorphs of octahedral to cubic morphology were found in one dike (No. 5), and are likely ferberite replacements of scheelite.

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Mobilization of silica by flash heating of silica gel beneath the Sudbury Impact Layer, Baraga Basin, Michigan

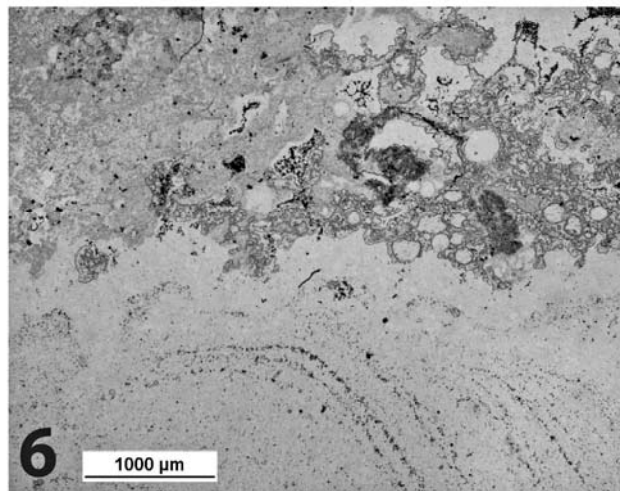
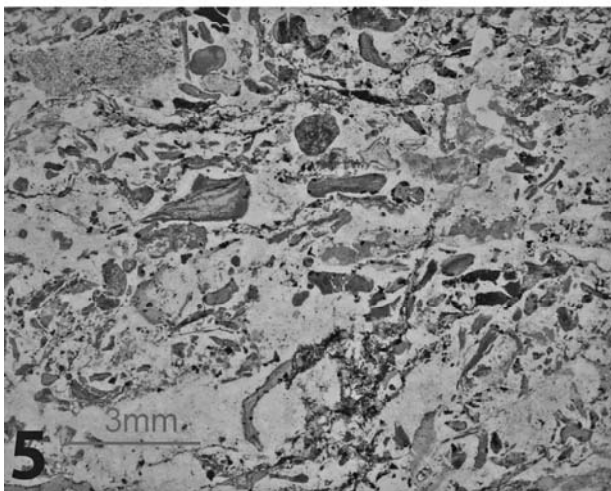
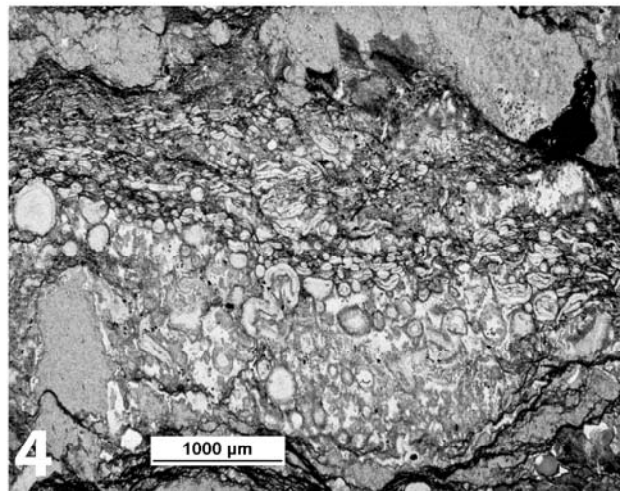
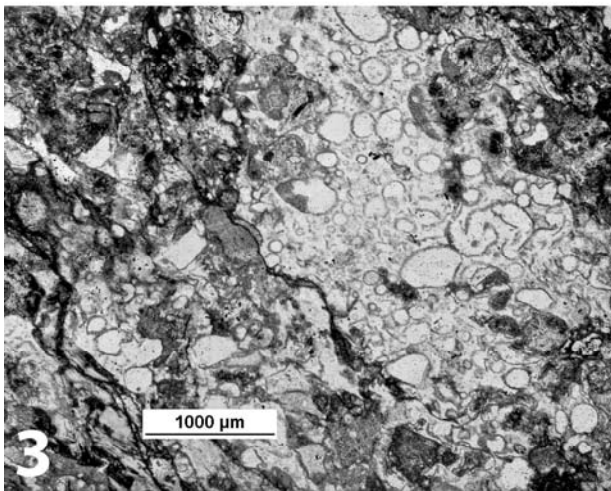
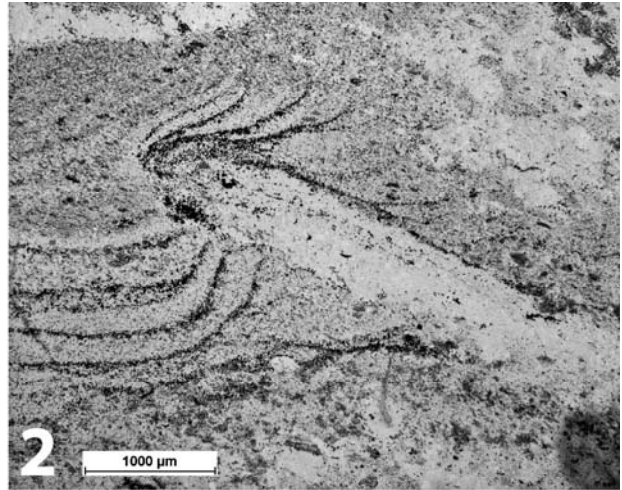
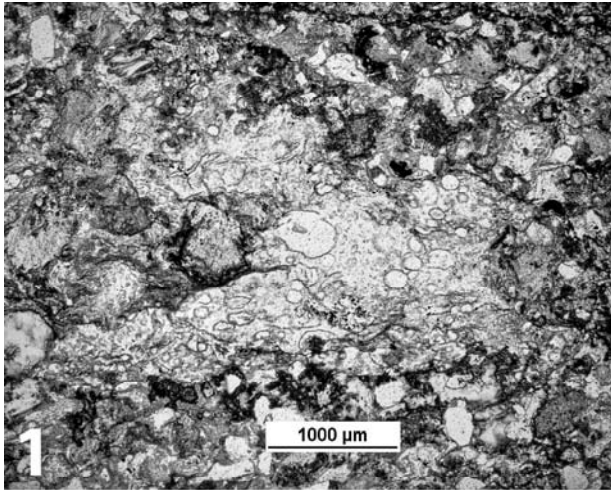
CANNON, W.F.

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The Baraga Basin in northern Michigan is a structural depression in which sedimentary rocks of the Paleoproterozoic Baraga Group are preserved. The section includes ejecta-bearing rocks of the Sudbury Impact Layer (SIL) deposited 1,850 million years ago (Cannon and others, 2010). At the time of the Sudbury impact, the area of the Baraga Basin was covered by a shallow, perhaps intertidal, sea in which chemical sediments, now interlayered chert, carbonate minerals, and minor iron minerals were accumulating. The ejecta layer in this area, about 500 kilometers west of the impact site, is typically a few meters thick and consists mostly of impact glass in the form of spherules and shards and some interlayers rich in accretionary lapilli. The SIL was deposited across the area from a fast-moving curtain of ballistic ejecta that, in some of the area, was transformed into a base surge that incorporated parts of the underlying rock units into the ejecta-bearing layer. A distinguishing feature of the SIL in the Baraga Basin is the prevalence of a very siliceous matrix surrounding ejecta particles. The SIL also contains many particles that are themselves very siliceous, many of which are highly amygdular. Both features suggest an unusual involvement of silica in the deposition of the ejecta layer.

Some of the uppermost beds of the sedimentary sequence at the time of the impact may have been silica gel. Gels can contain more than 90 wt. % water. When these gels came into contact with newly deposited high temperature ejecta, or were fragmented and incorporated into it, flash heating by the hot ejecta resulted in explosive release of steam and generation of silica-rich fluids that infused much of the ejecta layer. Most ejecta particles appear to have been solid during deposition, but flattened and stretched forms suggest that they were hot enough to have been soft and easily deformed. The presence of soft gels is shown microtexturally by siliceous (now cherty) inclusions in the ejecta that are distorted as indicated by both their external shape and internal features (Fig. 1). Especially compelling textures are shown by slivers of hardened silica that sharply penetrated into gelatinous clasts (Fig. 2). Many chert clasts have an unusual internal structure consisting of closely spaced amygdules whose outlines are shown by a film of sericite grains, but are otherwise entirely a recrystallized mosaic of fine quartz grains (Fig. 3). The term “popcorn chert” seems appropriate for them in that they appear to have formed by flash vaporization of their original high water content to produce these once highly vesicular silica masses. Commonly the amygdules are moderately to strongly flattened parallel to bedding (Fig. 4). Some samples show arcuate films of sericite grains that may be fragments of broken bubble walls (Fig. 5) suggesting that boiling also produced independent hollow structures that were later collapsed and broken. A well preserved contact of the base of the ejecta with underlying chert, seen in one drill hole, appears to have preserved this flash boiling in progress (Fig 6). The cusped and discordant upper contact of chert containing thin magnetite laminae is overlain by a selva of popcorn chert that may have formed *in situ* as chert gel was converted to a silica-steam mixture upon heating from the overlying ejecta. These features, together, suggest that a substrate of hydrous silica played an important role in determining the character of the SIL in the Baraga Basin.

Cannon, W.F, Schulz, K.J., Horton, J. Wright, Jr., and. Kring, David A., (2010) The Sudbury impact layer in the Paleoproterozoic iron ranges of northern Michigan, USA: Geological Society of America Bulletin, v. 122, p. 50-75.



1. Irregular mass of highly vesicular chert surrounded by glassy ejecta. 2. Sliver of chert that penetrated and deformed a clast of chert-magnetite gel. 3. Fragment of popcorn chert in glassy ejecta. Amygdules are outlined by a coating of sericite. 4. Fragment of popcorn chert whose upper half is compressed and highly flattened. 5. Films composed mostly of sericite in a siliceous matrix. These curved films may be the walls of broken bubbles. 6. Upper contact of chert with magnetite lamellae and overlying glassy ejecta. Popcorn chert at contact.

Traces of the Sudbury meteor impact in the western Gogebic Iron Range, northern Wisconsin

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Rock layers containing ejecta particles and other indications of the 1850 Ma Sudbury meteor impact have been observed in core from 12 drill holes along 40 km of the Gogebic Iron Range in northern Wisconsin. This ejecta-bearing material, found about 650-700 km west of the impact site near Sudbury, Ontario, is distinct from other occurrences of the Sudbury Impact Layer around the Lake Superior region. It occurs in multiple beds of reworked ejecta that commonly have ultra-potassic compositions. Ejecta-bearing material is found in two types of deposits: 1- thick (up to 20 m) debris flows of coarse breccia, and 2- multiple thinner (0.02- 2 m) turbidite beds throughout the lower 25 m of the Tyler Formation (Fig.1).

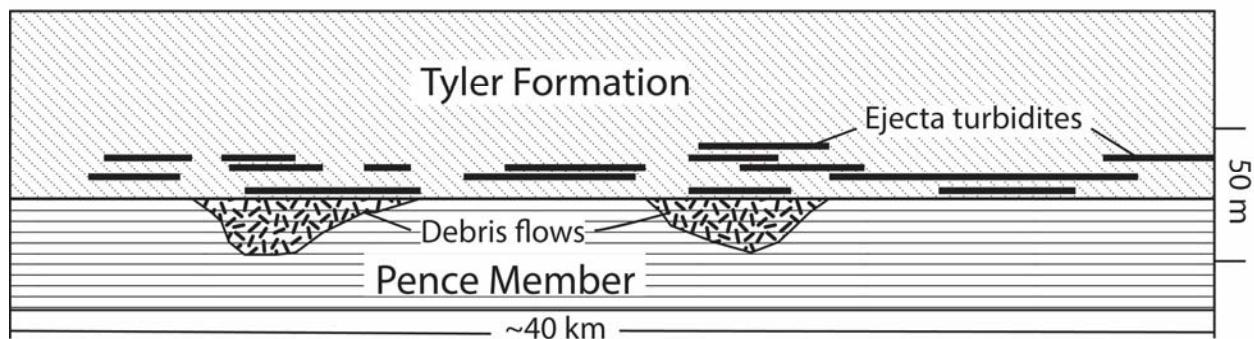


Figure 1. Stratigraphic relationships of ejecta-bearing beds to the regional stratigraphy of the Gogebic Iron Range. The Pence Member of the Ironwood Iron Formation is an even-bedded, generally moderately magnetic, iron formation containing minor units of granular iron-formation. The Tyler Formation, in its lower part, is laminated argillite and shale containing variable amounts of carbon and pyrite. It contains thin units of chert and magnetic chert in some drill holes.

Debris flows- Three drill cores contain coarse breccia from 10-20 m thick at the contact of the Pence Member of the Ironwood Iron Formation and Tyler Formation. They appear to be three separate units because breccias are absent in intervening drill holes. Where breccia is present, the thickness of the underlying Pence Member is less than in drill holes without breccia, suggesting that the debris flows incised their own channels into the Pence. The flows consist of a mixture of apparently local rocks and ejecta, including accretionary lapilli, and altered impact glass. They are massive to crudely bedded. A sparse set of quartz grains with shock metamorphic features (Fig. 2A) is a definitive indication of a relationship to the Sudbury impact.

Turbidite beds- Ejecta-bearing beds that appear to be turbidites are interbedded with laminated shale and siltstone of the lower 25 m of the Tyler Formation. The number of beds varies from 0 to 8 in various drill holes and the beds vary in thickness from a few cm to 2 m. Many beds have prominent normal size grading. These beds cannot be correlated either in number or thickness between closely spaced drill holes showing that they are individual tongues of material with limited lateral extent, at least along the current strike of the iron range. The occurrence of multiple ejecta-bearing beds leads to the obvious conclusion that they are

reworked material derived from the original ejecta blanket. These beds were commonly identified as tuff on drill logs, but a suite of features characteristic of ejecta, including a sparse but well developed suite of impact shocked quartz grains (Fig. 2B) indicate a link to the Sudbury event.

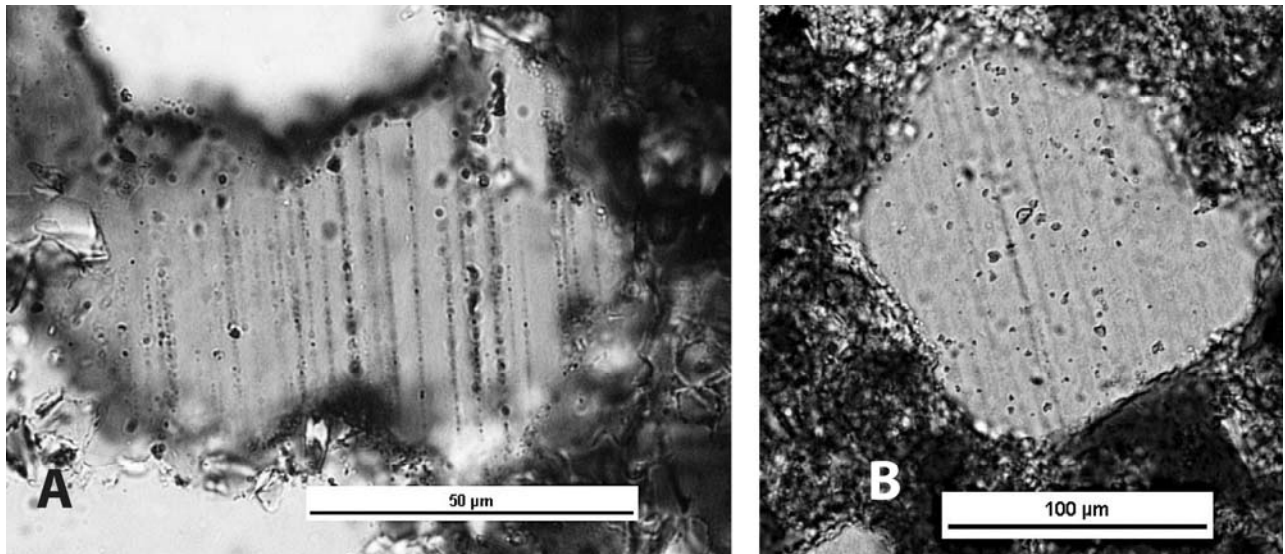


Figure 2. Examples of quartz grains with relict planar deformation features indicative of intense shock. A-from a debris flow; B-from a turbidite bed.

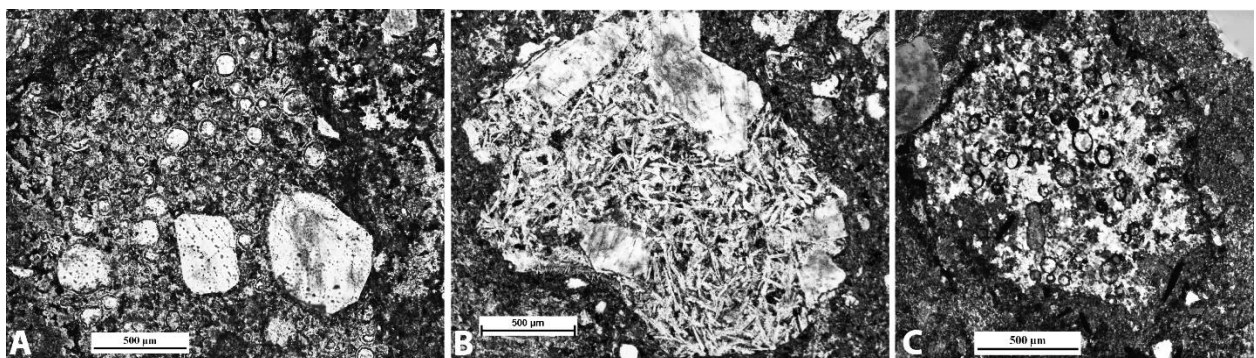


Figure 3. A-microcline phenocrysts in a vesicular glass fragment, B-microcline phenocrysts in a quench-textured microcline-rich fragment, C-amygdular glass fragment composed almost entirely of fine-grained mosaic-textured microcline.

Both types of beds have ultra-potassic compositions. K_2O ranges from 8.4 to 13.0 wt. % in five samples analyzed. The K content results both from abundant small phenocrysts and fragments of microcline, and from a finer mosaic of microcline that overprints original textures of clasts. The phenocrysts are a very early component of the ejecta, being enclosed both in accretionary lapilli and glass fragments (Fig. 3A, B). The finer microcline may be secondary-a result of seafloor K-metasomatism akin to formation of K-bentonites in younger volcanic ash. Individual clasts of K-rich ejecta indicate that they were altered before being incorporated into the present beds. The ejecta-bearing beds record a set of processes including: 1) deposition of an original ejecta blanket in a shallow marine setting probably not far from the current study area, 2) alteration of the ejecta to K-rich partly consolidated sediments, and 3) remobilization of the metasomatized ejecta to produce the debris flows and multiple ejecta-bearing turbidite beds.

Microstructural comparison of the Hardrock Project at Geraldton, Ontario and the Coffee Gold Project, Yukon

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The Superior Province of the Canadian Shield and the North American Cordillera both host extensive gold mineralization. These regions are distant from each other and very different in age, but the similarities between microstructures within gold-hosting units are striking. Separate microstructural studies were done on gold-hosting units in the Coffee Gold Project south of Dawson, Yukon and the Hardrock gold project at Geraldton, Ontario and the results are compared. The focus in each project is to examine the microstructures within gold-hosting rock units to determine the protolith of the host and assess structural control on gold mineralization. Based on mineralogy, each study concludes that a felsic igneous rock is the likely protolith to the gold-hosting lithology. Each study finds similar styles of deformation resulting in microstructures typical of a mylonite. The microstructures include a foliation defined by parallel alignment of muscovite and rigid porphyroclasts of feldspar in a fine-grained groundmass. Together, these observations lead to the conclusion that the host for gold mineralization in each study is a deformed felsic plutonic rock.

Both gold-hosting lithologies have similar mineralogy consisting dominantly of feldspar, quartz and muscovite. Rigid porphyroclasts of plagioclase are situated within a groundmass composed of <0.1mm quartz, feldspar and muscovite. Plagioclase is the dominant feldspar in both studies. Feldspar is present both in the groundmass and as rigid porphyroclasts. The plagioclase porphyroclasts commonly have asymmetrical tails, indicating non-coaxial strain, and commonly contain deformation twins. Sericite alteration on porphyroclasts is evidence for the presence of hydrous metamorphic fluids. In the Geraldton study these rigid porphyroclasts are fractured. Quartz is common within the groundmass in both studies, and late quartz veins are abundant within the Yukon study. Undulose extinction and subgrain boundaries indicate dislocation creep in quartz. Dimensional preferred orientation of muscovite defines the foliation and muscovite bends around the rigid porphyroclasts.

The Coffee Gold Project is hosted within the Yukon–Tanana Terrane bounded between the Tintina and Denali Faults and along strike of the Teslin Fault, this area is located within the Tintina Gold Province. The study examines three zones, Kona, Supremo and Latte. In each of the zones a felsic plutonic rock with varying degrees of deformation was interpreted to be the protolith. The Kona zone is mapped as granite and is the least deformed of the three zones. The Kona zone's mineralogy consists of feldspar, quartz, sericite and biotite with an average grainsize of approximately 2.5mm. Deformation in the Kona zone includes undulose extinction, subgrain boundaries and serrated grain boundaries in the quartz as well as sericite alteration of feldspars. Supremo and Latte zones show increased deformation with the development of a foliation bending around rigid porphyroclasts and deformation features in quartz and feldspar. Quartz microstructures such as subgrain boundaries, serrated grain boundaries and undulose extinction are common and indicate deformation by dislocation creep. Rigid porphyroclasts of feldspar are common providing a minimal original grainsize of ~3mm. Deformation twins observed within feldspars provide further evidence of deformation. The Latte zone is mapped as biotite schist, however biotite is present in only small amounts. The mineralogy in the Latte zone

consists dominantly of quartz and feldspar suggesting a felsic igneous protolith. A relationship between deformation and gold mineralization is observed; as deformation increases the gold mineralization increases. Gold mineralization based on published assay values was lowest in the Kona zone and increased in the more deformed Latte and Supremo zones. The protolith of all three zones is likely a deformed felsic plutonic rock with varying degrees of metamorphism and deformation.

The Hardrock Project is located within the Beardmore-Geraldton belt. The Beardmore-Geraldton belt lies between the Wabigoon and Quetico subprovinces and it is comprised of multiple fault-bounded metavolcanic and metasedimentary belts. The Hardrock Project is one of several past-producing gold mines situated within the Beardmore-Geraldton gold camp. The Beardmore-Geraldton gold camp is bounded by major steeply dipping structures that are comparable to structures in the Tintina Gold Province. Mineralogy and microstructure of the “porphyry” within the Hardrock Project are consistent with a deformed felsic plutonic rock similar to the Latte and Supremo zones in the Coffee Gold Project. The Latte and Supremo zones in the Coffee Gold Project have mylonitic features that are comparable to the “porphyry” at the Hardrock Project. The “porphyry” is known to have significantly more mineralization than its protolith, Croll Lake stock, suggesting that gold mineralization is related to deformation. This is similar to deposits within the Tintina Gold Province such as the Coffee Gold Project. The Beardmore-Geraldton belt may be an older Cordilleran-type gold province with structural controls on gold mineralization similar to the Tintina Gold Province.

This comparison gives insight into the similarities of shear-zone-hosted gold deposits. In both examples, mylonitized felsic plutonic rock hosts gold mineralization.

Utility of the horizontal-to-vertical spectral ratio (HVSr) passive seismic method for determining Quaternary sediment thickness and bedrock elevation in north-central Minnesota: Fun with little control and generally poor data

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Work continues in Minnesota on using the horizontal-to-vertical-spectral ratio (HVSr) passive seismic method to help map the thickness of Quaternary glacial sediments and the topography of the bedrock surface. A total of 570 passive seismic stations have been acquired in and around Becker, Cass, Hubbard, and Wadena Counties in north-central Minnesota as part of the County Geologic Atlas (CGA) program of the Minnesota Geological Survey (MGS). This area is characterized by thick and complex glacial sequences, widely scattered drillhole control, and, unfortunately, generally poor HVSr data. Ideally a HVSr spectrum yields a large-amplitude, singular peak that represents the bedrock surface (Chandler and Lively, 2014; Lane and others, 2008). In north-central Minnesota, the observed HVSr spectra instead commonly consist of low-amplitude and multiple peaks, where recognition of bedrock signatures is difficult when observing spectra individually. The cause of the poor signal quality is unknown, but could be related to a highly irregular bedrock surface or to the complexity of the overlying glacial sequences. In areas with these types of issues we have made increased use of multi-station spectral cross-sections that have been converted to approximate elevation sections (Fig. 1). This conversion uses a power-law calibration that is based on observed HVSr results at control points, usually consisting of water wells or seismic refraction soundings. Due to the lack of a sufficient number of control points in the study area, a generalized calibration is used, which is based on 303 widely distributed control points in Minnesota. More refined sections may eventually be possible with locally derived calibrations, but our generalized approach produces useful sections that readily allow lateral correlation of HVSr features within a framework of available geologic control.

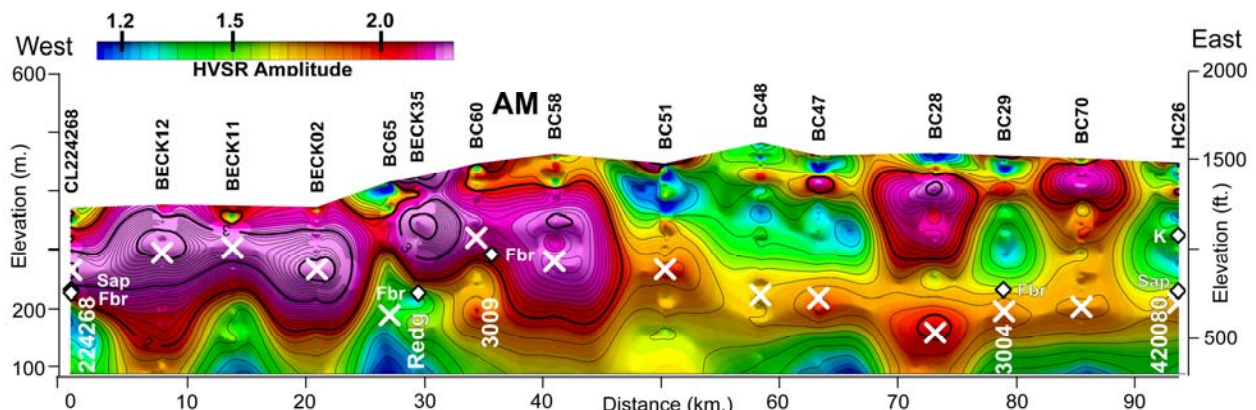


Figure 1. Color HVSr section across central Becker County. West end of profile located at UTM 252686E/5203087N; East end of profile located at UTM 335129E/5210337N) White X's designate HVSr-based estimates of the bedrock surface. White diamonds indicate bedrock horizons at control points, either drill-holes with well number (6 digit label), or seismic refraction sites (4 digit label). Bedrock horizons are: K, the top of Cretaceous sediments; Sap the top of saprolite; and Fbr the top of fresh bedrock. Individual stations are labeled in black. AM approximates the western margin of the Alexandria Moraine. Vertical scale is elevation and horizontal scale is cumulative distance between successive stations. 50X vertical exaggeration.

Using the cross-sectional approach as a guide, viable maps have been produced that estimate the elevation and depth of the Precambrian bedrock surface that underlies the study area. Trough- like depressions in the Precambrian surface are indicated beneath northeastern and central Becker County and beneath northeastern Wadena and eastern Hubbard Counties, where total depths are 500-1000 ft. (150-300 m). These depressions are known to locally contain Cretaceous strata, but the HVSr method cannot discriminate the soft Cretaceous rocks from the glacial sediments. Broad rises in the Precambrian surface are indicated near the junction of Becker, Hubbard, and Wadena Counties, and much of southern and eastern Cass Counties. These preliminary interpretations have been largely corroborated by follow-up seismic refraction profiling and test drilling. The results of this study indicate that when used with the proper precautions, the HVSr method can be useful for bedrock depth and elevation studies, even under less-than-ideal conditions.

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Bedrock Geology of the Devilfish Lake Area, Cook County, Minnesota

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Grout and others (1959) has heretofore been the primary published work investigating the contact between the reversed polarity lower northeast sequence of the North Shore Volcanic Group (NSVG) and the early magmatic stage of the Duluth Complex (DC) in the vicinity of Devilfish Lake, and by extension the eastern limit of the Mesoproterozoic Duluth Complex, Minnesota, USA. Geologic mapping and gravity surveying by the Precambrian Research Center Field Camp in the summers of 2014 and 2015 provides additional detail to better contextualize Grout's pioneering work with more recent understanding of the geological and geophysical nature of the DC, NSVG, and Midcontinent Rift as a whole (e.g. Miller et al., 2012). Targeted mapping addressed 1) understanding the contact between the DC and hangingwall lower northeast sequence NSVG volcanic rocks, 2) identifying small-scale mafic intrusive dikes and sills cross-cutting the NSVG and/or DC, and 3) infilling state-wide gravity station coverage along roads and trails constructed since prior gravity surveying in the late 1960s.

In this area, volcanic rocks of the ~1108 Ma lower northeast series of the NSVG form an ~9 km thick, shallow, southwest-dipping sequence overlying the Paleoproterozoic Rove Formation. The base of the sequence is composed of relatively primitive tholeiitic basalts of the Grand Portage lavas, and is capped by the relatively evolved basaltic andesites, andesites, icelandites, and rhyolites of the Hovland lavas. The Hovland lavas are characterized by abundant feldspar phenocrysts. This study recognizes a sequence of thick-bedded, relatively evolved, aphyric basalts and basaltic andesites intermediate to the Grand Portage and Hovland lavas, herein named the *Esther lavas*. The Grand Portage and Esther lavas successively truncate against the DC toward the west.

The base of lower northeast sequence was subsequently intruded by the Crocodile Lake gabbro (CLG) and Cucumber Lake granophyre (CL); these intrusions have been correlated with the ~1109 Ma Poplar Lake intrusion. A general lack of volcanic or sedimentary xenoliths in the CLG and CL suggest they intruded as sheet-like bodies along the basal contact of the NVSG with the underlying Rove Formation, with little incorporation or removal of wall rock, suggesting the pinch-out of the Grand Portage and Esther lavas may be a primary characteristic reflecting original volcanic basin geometry.

The contact between the DC (CL) and overlying NSVG is much more irregular than indicated by previous mapping, consistent with a relatively shallow, southward-dipping contact. Hornfelsed NSVG volcanic rocks immediately overlying this contact form a prominent linear trend of hills immediately south of the contact, and apophyses of granophyre are common in the hornfels. Overall, the contact between the DC and NSVG appears to mirror the dip of flows within the NSVG.

Mapping identifies at least four mafic intrusive phases with distinct mineralogy and geochemistry cross-cutting the NSVG and DC. Sill-like(?) gabbroic intrusions cross-cutting the Esther lavas are the only pre- or syn-DC intrusions recognized by this mapping. Multiple mafic intrusive phases cross-cutting the DC occur as dikes in both NW-SE and SW-NE trending structures. E-W oriented, normal polarity dikes (*Chester dikes*) contains abundant anorthosite xenoliths, suggesting correlation with the ~1096 Ma Beaver River diabase. Mafic dikes cross-cutting the CLG display both coarse-grained and chilled, aphanitic textures, suggesting multiple intrusive events during the cooling of the CLG.

Previous to this study, state-wide gravity data indicated an ~45 mgal gradient in the Bouguer anomaly over ~5 km between points collected over the Rove Formation (north) and the contact between the CLG and CL intrusions and hangingwall NSVG volcanics (south). Infill surveying of this gap suggests that the CLG and CL intrusions are southward-dipping sheet-like bodies. Truncation of this E-W oriented gradient coincident with the eastern extent of the DC suggests intrusion of the CLG/CL was controlled in part by subsidence along a rift-perpendicular tear fault. Mapping results support the hypothesis that the early, eastern extent of the DC was emplaced as sheet-like intrusions at the base of the lower northeast sequence NSVG volcanic pile. The NSVG pile may preserve pinch-out of individual volcanic units reflecting original basin geometry. Multiple geochemically, texturally, and mineralogically distinct mafic dikes cross-cutting both the early DC and NSVG attest to a heretofore unrecognized long and complex history of post-early magmatic stage igneous activity in this sector of the Midcontinent Rift.

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Geochemistry and petrogenesis of volcanic rocks in the Coldwell Alkaline Complex; new insights from the Wolfcamp Lake volcanic rocks

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Recent work carried out on volcanic rocks present within the Coldwell Alkaline Complex has unveiled new insights into the genesis of Midcontinent Rift-related volcanic rocks along the North Shore of Lake Superior, Ontario. Coldwell Complex volcanic rocks display broadly similar trace element patterns to basalt type I and II (*cf.* Nicholson et al. 1993) suggesting eruption in the early magmatic stage of the Midcontinent Rift (Good et al. 2015; Cundari et al. 2012). This is supported by the intrusion of the Eastern Gabbro suite into Upper and Lower metabasalt units at 1108 ± 1 Ma and the intrusion of centre II syenites into the Coubran Lake and Wolfcamp Lake basalts at $1109^{+8.4}$ Ma (Heaman and Machado, 1992). Good et al. (2015) proposed three distinct basaltic packages present within the Coldwell Complex, listed here as progressively more evolved units based on Mg number and Ni abundance (Figure 1a); the Lower meta-basalts (LMB), the Upper meta-basalts (UMB) and the Coubran Lake basalts (CLB).

The Wolfcamp Lake basalts (WLB) represent a fourth unit in this sequence more evolved than previously recognized volcanic units in the Coldwell Complex. WLB display an average TiO_2 content of 1.86 compared to 0.86 for the CLB, 1.15 for the UMB, and 1 for the LMB suggesting the Wolfcamp rocks are distinctly different and more evolved than those suites (Figure 1b). The WLB also exhibit the highest total alkali abundance of all four volcanic units present within the Coldwell complex. WLB display greater LREE abundances compared to the CLB but lack a negative niobium anomaly suggesting the LREE-enrichment is not due to crustal contamination. Additionally, SiO_2 content for the WLB is too low to be explained by contamination of continental crust.

The CLB were interpreted to be the volcanic equivalent of the Two Duck Lake gabbro based on trace element abundances by Cundari (2012). Trace element abundances for the Geordie Lake gabbro trend towards the WLB suggesting a co-genetic relationship whereby the WLB may represent the volcanic equivalent of the Geordie Lake gabbro. Gd/Yb_n ratios for the WLB are broadly similar to those for the CLB suggesting a similar depth of partial melting. The extreme LREE enrichment exhibited by the WLB compared to the CLB may be due to lower degrees of partial melting although it should be noted that field evidence such as a reddish staining of alkali material suggests that WLB have been altered by syenite intrusions which may have contributed to the LREE content of these rocks. A number of mechanisms may be responsible for the LREE enrichment characteristics observed in the Coldwell Complex volcanic rocks, notably the CLB and the WLB. Extreme LREE enrichment may be controlled by apatite accumulation, suggested by a positive correlation between Th and Gd with P_2O_5 although LREE abundances may be too high to be accounted for entirely by apatite. An alternative mechanism for generation of LREE enriched volcanic rocks may be partial melting of an enriched mantle source suggesting a possible relationship with Coldwell syenitic intrusions. Further work is required to develop the relationships between the volcanic units present within the Coldwell Complex, most notably, the relationship between the Coubran Lake and Wolfcamp Lake volcanic units. Modelling of fractional crystallization of average Coubran basalt composition trending toward Geordie Lake gabbro and Wolfcamp basalt may explain the petrogenesis of these units and establish the magmatic relationship between them.

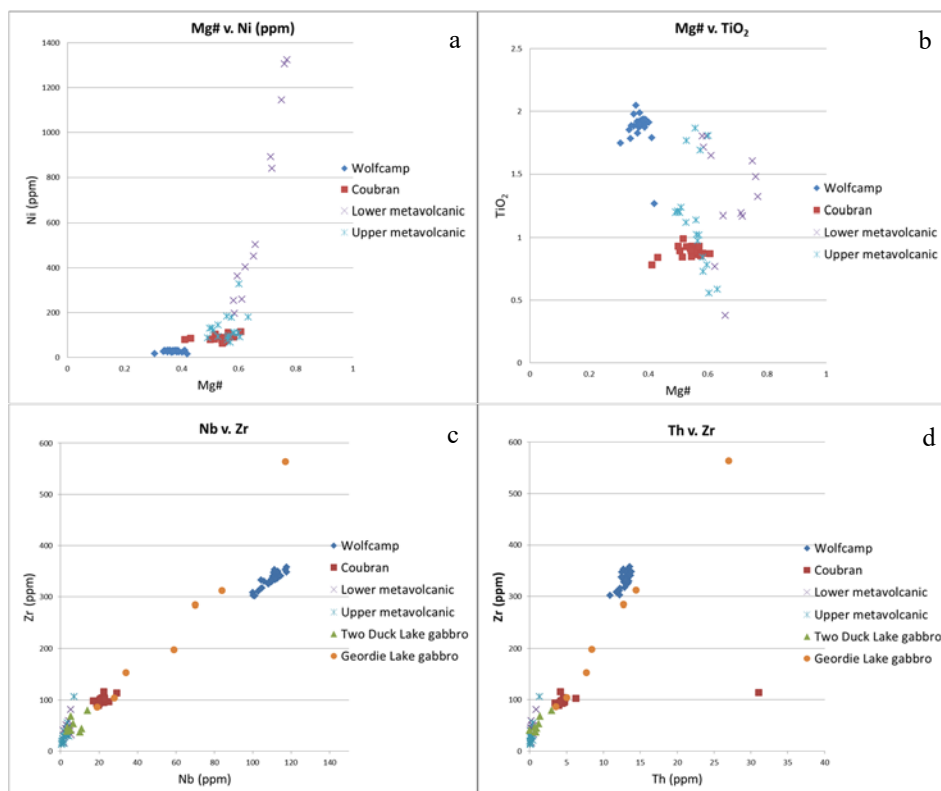


Figure 1: Major and trace element abundances of Coldwell Complex volcanic units compared to Coldwell Complex intrusive units.

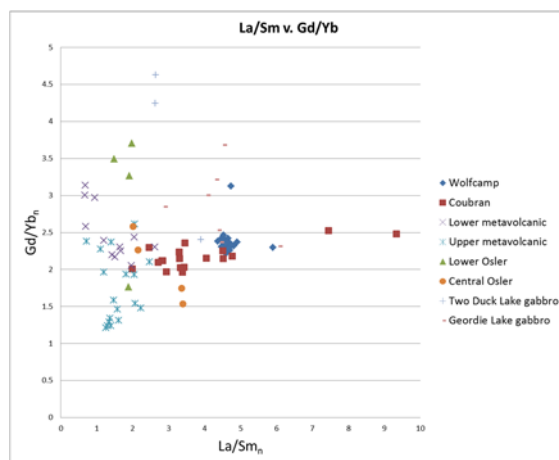


Figure 2: La/Sm vs. Gd/Yb plot of Coldwell Complex volcanic units compared to Coldwell Complex intrusive units.

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Mineralogy and Geochemistry of the Wolfcamp Lake Basalts

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The Wolfcamp Lake Basalts are Midcontinent Rift-related volcanic rocks (Walker et al., 1993) that have been linked with other MCR volcanic rocks such as the Coubran Lake, Penn Lake, Bamooos Lake and Foster Island volcanic units along the north shore of Lake Superior which have all been interpreted to be roof pendants within the Coldwell Complex (Puskas, 1967; Walker et al., 1993).

Basalts of the Wolfcamp Lake volcanic unit are exposed in two main areas bisected by the TransCanada highway northwest of Marathon, Ontario. The entire unit is approximately 2 km east-west by 4 km north-south with one large exposure northeast of the highway east of Wolfcamp Lake and a second exposure south of the TransCanada highway cropping out as large cliffs, railway cuts and outcrops on the north shore of Lake Superior near Port Munroe. Flow thicknesses are generally 2-4 m with variations present locally. The main lithology comprises basalt flows which are dominantly ophitic or sub-ophitic. The mineralogy is dominated by feldspars (primarily plagioclase), olivine and pyroxenes. Alteration minerals including hornblende, sillimanite, chlorite, biotite, opaques (primarily magnetite) are present in all samples at concentrations from 3% up to 40%.

All of the samples of the Wolfcamp Lake basalts show very consistent trace element geochemistry with OIB-like characteristics on primitive mantle normalised plots. They are characterised by negative zirconium, hafnium and titanium anomalies with no negative niobium anomalies observed. The Wolfcamp Lake basalts were compared to the closest volcanic rocks which are the Coubran Lake Basalts, but differences were observed when compared to other volcanic rocks in the area.

When compared to the three types of basalts identified in the Coubran Lake unit the Wolfcamp Lake basalts lack the strong negative niobium anomaly displayed by the Coubran Types A and B which was interpreted to be the result of contamination (Fig. 1). The Wolfcamp Lake Basalts also show lower Mg numbers than the Coubran Lake Basalts indicating that the former are more evolved. This suggests that the Wolfcamp basalts are uncontaminated MCR magmas despite their more evolved compositions.

The Wolfcamp Lake basalts are broadly similar to those of the Lower Osler volcanic rocks, with similar LREE patterns and no negative niobium anomaly (Fig. 2). However, the Osler volcanics display a lower La/Sm_n ratio on a Gd/Yb_n vs La/Sm_n diagram (Fig. 3) indicating a more primitive composition compared to the Wolfcamp Lake Basalts.

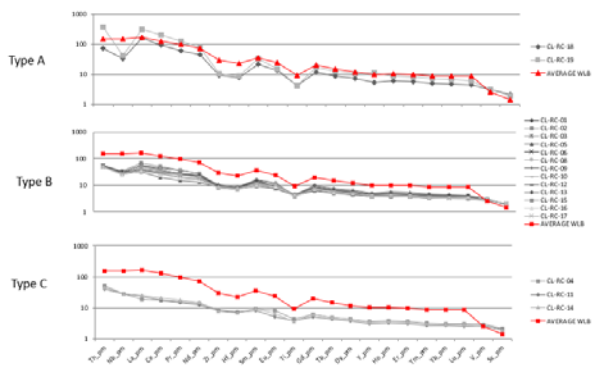


Figure 1: Spider plots comparing geochemistry of Average Wolfcamp Lake Basalts to Coubran Lake Basalt Types A, B and C. Comparative data from Cundari (2012).

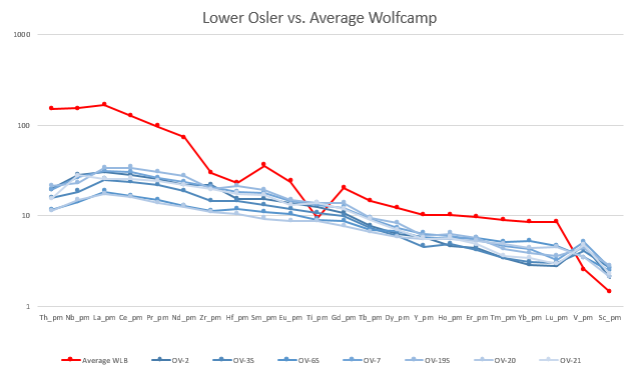


Figure 2: Spider Plot comparing Wolfcamp Lake Basalts to the Lower Osler Volcanics. Comparative data from Hollings et al. (2007).

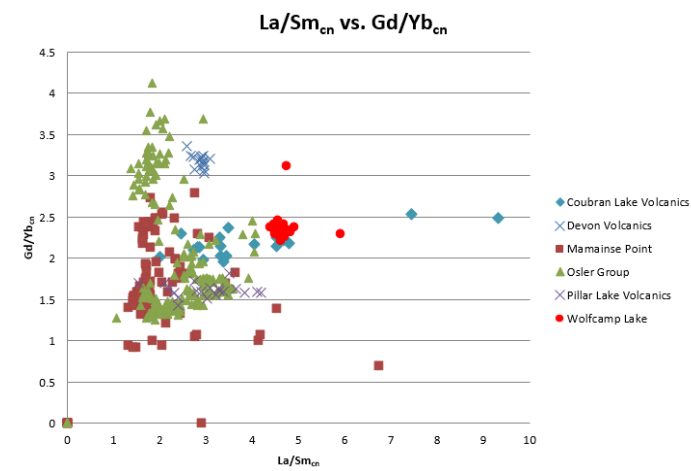


Figure 3: Plot of La/Sm vs Gd/Yb showing Midcontinent Rift volcanics. Normalizing values from Sun and McDonough (1989). Comparative data from Cundari (2012).

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Origin of the gold-hosting porphyry at Geraldton, Ontario

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The lithologic unit known as the “porphyry” at Geraldton, Ontario is host to widespread gold mineralization, but its origin is poorly understood. The porphyry occurs within the Beardmore-Geraldton greenstone belt in the Superior Province of the Canadian Shield. Gold was first discovered in the Beardmore-Geraldton belt in 1917, and production occurred between 1930 and 1970 at 20 mines throughout the belt, producing 4.1 million ounces of gold (www.premiergoldmines.com, 2016). Exploration is currently active again in the Beardmore-Geraldton belt.

Microstructural analysis was done on samples from the “porphyry” to better understand its origin. Samples from the porphyry contain approximately 1mm porphyroclasts of plagioclase within a groundmass composed of approximately 0.1mm grains of quartz, plagioclase, and muscovite. The fine-grained groundmass is formed as a result of grain size reduction by dislocation creep. The plagioclase porphyroclasts commonly have asymmetrical tails, and muscovite crystals tend to bend around the porphyroclasts. Asymmetrical tails are an indication of non-coaxial strain. Plagioclase porphyroclasts are commonly fractured with calcite infilling the fractures. The presence of calcite indicates a CO₂-bearing fluid phase. Sericite alteration occurs on porphyroclasts indicates the presence of H₂O-bearing metamorphic fluids. Plagioclase commonly contains deformation twins. Undulose extinction and subgrain boundaries indicate dislocation creep in quartz. The porphyry also has a well-developed foliation defined by parallel alignment of muscovite. Based on microstructural analysis, it appears that the most likely protolith for the porphyry is a felsic plutonic rock. The microstructures are typical of a mylonite. Characteristic features of mylonitic rocks include a strong foliation produced by the parallel alignment of minerals, the presence of a fine grained matrix produced by grain size reduction mechanisms with porphyroclasts, and the presence of a certain asymmetry.

Approximately 30km east of Geraldton, near Longlac, Ontario, is a 150 km² elliptical, granodiorite intrusion, the Croll Lake stock. This intrusion is the nearest felsic and plutonic rock to the porphyry at Geraldton. The Croll Lake stock is also deformed. Deformational features in quartz include undulose extinction, subgrains and serrated grain boundaries. Plagioclase commonly contains deformation twins. Evidence for deformation of the stock increases westward toward its margin where it resembles the porphyry. Microstructural analysis of the porphyry and the Croll Lake stock suggest that the “porphyry” is a mylonitized fragment of the Croll Lake stock.

PGE Mineralization in the Northern Ultramafic Center of the Lac des Iles Complex, Ontario: Evidence of Magmatic and Hydrothermal processes

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The Archean Lac des Iles Complex in northwest Ontario consists of a mafic complex (South LDI complex) and a predominantly ultramafic complex (North LDI complex). The South LDI complex is ~6 km long and 1.5-2.5 km wide and comprises the Mine block intrusion, South LDI intrusion, and Camp Lake Intrusion. The Mine Block Intrusion is the best known of the individual intrusions within the LDIC due to the presence of significant Pd-rich platinum group element (PGE) mineralization that has been mined since 1993 (Lavigne and Michaud 2001). The North LDI complex is a composite, tadpole-shaped, intrusive body with dimensions of 6 km by 4.5 km and featuring a preponderance of ultramafic over mafic cumulate rocks that are distributed in two centres: the Southern Ultramafic Centre and the Northern Ultramafic Centre (Sutcliffe and Sweeney 1985). Various exploration programs conducted over a 50 year span have identified PGE occurrences with >1 g/t Pd+Pt. The best documented of these ultramafic-hosted PGE occurrences are in the Sutcliffe Zone, which consists of four subparallel, stratiform PGE-enriched horizons exposed within the Northern Ultramafic Centre (NUC).

Detailed field mapping, petrographic studies, and lithogeochemistry of recently acquired drill cores indicate that the 4 km diameter, >1900m-thick, lopolith-shaped NUC can be subdivided into an Eastern Marginal Zone and a Layered Series. Furthermore, the Layered Series can be divided into fourteen cyclic units defined by cumulus mineral paragenesis of two general types. Cyclic unit type A (CUA) displays a cumulate stratigraphy of Ol+Sp (dunite) → Ol+Opx+Cpx±Sp (olivine-websterite) → Cpx+Opx (websterite) → Pl+Opx±Cpx (gabbro-norite). Cyclic unit type B (CUB) displays a simpler cumulate sequence of Ol+Sp (dunite) → Ol+Cpx (olivine clinopyroxenite). Cyclic unit boundaries are sharp between similar types but also where CUA overlies CUB. In contrast, where CUB overlies CUA, the contact is gradational and is marked by the complex hybrid unit. Within individual cyclic units, cyclical cryptic variation in mg# of olivine (Fo) and pyroxenes (En) shows a progressive upward decrease followed by an abrupt to gradual increase at or just below cyclic unit boundaries. Olivines of CUB rocks have lower Ni concentrations and higher Fo contents than olivines in CUA rocks. CUA and CUB samples are further distinguished by having different abundance ranges in incompatible elements, and Zr/Y and Ce/Yb ratios. Djon et al. (submitted) interpreted CUA and CUB type cyclic units to have formed from two compositionally distinct parental magmas. CUA parental magmas would have been enriched in Si, Ni and incompatible trace elements and depleted in Ce/Yb ratio relative to CUB parental magmas. The cyclical cryptic variation within the NUC cyclic units is suggested to have formed by crystal fractionation within individual magma inputs randomly interrupted by alternating recharge of CUA or CUB magmas.

The PGE-enriched horizons occur exclusively in four of the CUA-type cyclic units and show very different enrichment patterns depending on whether it is sharply overlain by another CUA unit or is capped by hybrid zone below a CUB unit (Fig. 1). The upper three PGE-enriched zones occur in CUA-6, -8 and -11 (which are overlain by the hybrid units and CUB) and are hosted in websterite and/or gabbro-norite units. They form 15-20m-thick disseminated zones, where the PGE grades gradually increase toward the top of the cycle and rapidly decrease into the hybrid unit. The lowermost PGE-enriched zone occurs halfway through the CUA-5, which is overlain by CUA-6. It is hosted in olivine websterite and websterite cumulates, and forms 10-15m-thick zone in which PGE grades slowly decrease toward the top of the cycle (Fig. 1).

The host rocks show weak to moderate hydrothermal alteration with variable proportion of mainly actinolite-tremolite, serpentinite, and chlorite. The primary PGE mineralization is commonly found in association with disseminated and blebby sulfide (0.2-2 vol%; mainly pyrrhotite, chalcopyrite, and pentlandite with minor cubanite, troilite, and cobaltite) and locally with primary hydrous phase (fluorine-bearing magnesiohornblende). In altered rocks, the primary sulfides have been partially replaced by chalcopyrite, pentlandite, sphalerite, heazlewoodite, and chalcocite. Palladium occurs either in solid solution with primary pentlandite and cobaltite or as Pd-telluride; however, Pd-bearing minerals containing mainly Pb and to lesser extent Ge, Sn, Bi, Rh, and Ag (e.g. zvyagintsevite; Pb-bearing palladium telluride) occur at the margin of secondary sulfides (e.g. heazlewoodite, pentlandite) and altered chrome-spinel, along pyroxene fractures, or included in serpentine and amphibole. Pt-bismuthotellurides and sperrylite commonly occur associated with primary sulfides at sulfide-silicate contacts and, minor laurite is found enclosed in chrome-spinel. In general, PGE enrichments are related to increases in total S, Cu and Zr contents and a decrease in Mg:Fe ratios of pyroxenes. The mineralized zones averaging 0.358 ppm Pd+Pt (643 ppm Pd+Pt in 100% sulfide), Pd/Pt and Pd/Ir ratios ranging from 0.9 to 3.5 and 35 to 537, respectively, and a wide range of S/Se ratios (500-6000). The highest PGE (Pd+Pt) grades up to 11 ppm (4377 ppm in 100% sulfide) are found in serpentinized olivine websterite, which yield an average Pd/Pt ratio of 3.5 and a S/Se ratio of approximately 2.000.

Our data suggest that magmatic crystal fractionation leading to early sulfur saturation and late concentration of base and precious metals in a volatile-rich fluid and possibly magma mixing can be accounted as dominant process for the different PGE occurrences throughout the CUA-type cyclic units. The PGE contents could have been enhanced during a post-magmatic stage by hydrothermal fluids which have interacted with early-formed assemblages resulting in dissolution and redistribution of PGE.

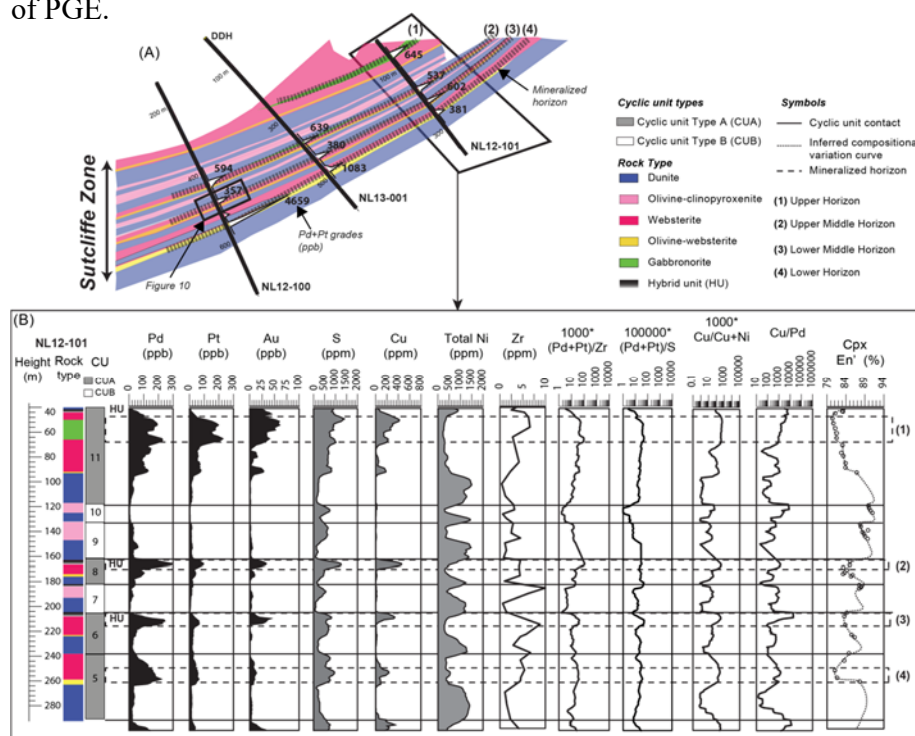


Figure 1: (A) Detailed cross-section of the Sutcliffe Zone within the Layered Series showing the distribution of the PGE enriched horizons with their stratigraphic Pd and Pt concentrations. (B) illustrates the stratigraphic location of the PGE-rich horizons throughout the cyclic unit types from drill hole NL12-101, in relation with the variation of modal rock type, the whole rock concentrations of selected PGE and trace elements (from North American Palladium Ltd database) and the average enstatite (En') content of clinopyroxene (Cpx) from (Djon et al., submitted)

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GEOCHEMISTRY OF DEEP AND SHALLOW WATER ARCHEAN BANDED IRON FORMATIONS, AND THEIR POST DEPOSITIONAL IMPLICATIONS IN THE WESTERN SUPERIOR PROVINCE, CANADA

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Geochemical studies have been conducted on banded iron formations for over 40 years to attempt to better understand their synthesis, depositional environment and ocean chemistry. Previous studies have made assumptions that the geochemistry of the iron formation reflects the exact geochemistry of seawater during time of formation (Konhauser et al. 2011; Planavsky et al. 2014). These studies have not taken to account the possibilities of a post depositional mechanism, such as diagenesis and metamorphism, which can affect the mobility of elements and can alter interpretations inferred from geochemical analyses.

Several locations containing Archean banded iron formations have been chosen for this study. They include the banded iron formations of the Beardmore-Geraldton Belt, Wabigoon Subprovince, Lac-St Joseph of the Uchi Subprovince, Shebandowan Greenstone Belt of the Wawa Subprovince, Weagamow – North Caribou Greenstone Belt of the Sachigo Subprovince, Red Lake Greenstone Belt of the Uchi Subprovince and the Steep Rock Group of the Wabigoon Subprovince. These locations were chosen based on their differences in age, depositional environment and differences in metamorphic grade.

Geochemical analyses were conducted using an Inductively Coupled Plasma Optical Emission Spectrometer and Inductively Coupled Plasma Mass Spectrometer at Lakehead University. Preliminary results show that the Na/K ratio is greater in the magnetite-rich samples and lower in the hematite-rich samples (Figure 1). This is consistent for all the iron formations chosen for this study. The differences in the Na/K ratio cannot reflect the original geochemistry of seawater because the magnetite and hematite layers form by the same mechanism, the precipitation of ferric hydroxides. During diagenesis, magnetite will form where organic carbon reduces some of the iron (Drever, 1974). Changes in the Na/K ratio within the iron formation indicate that there has been element mobility after deposition either by diagenesis or regional metamorphism. Therefore, any geochemical conclusions inferred from banded iron formations without taking into account element mobility must be questioned.

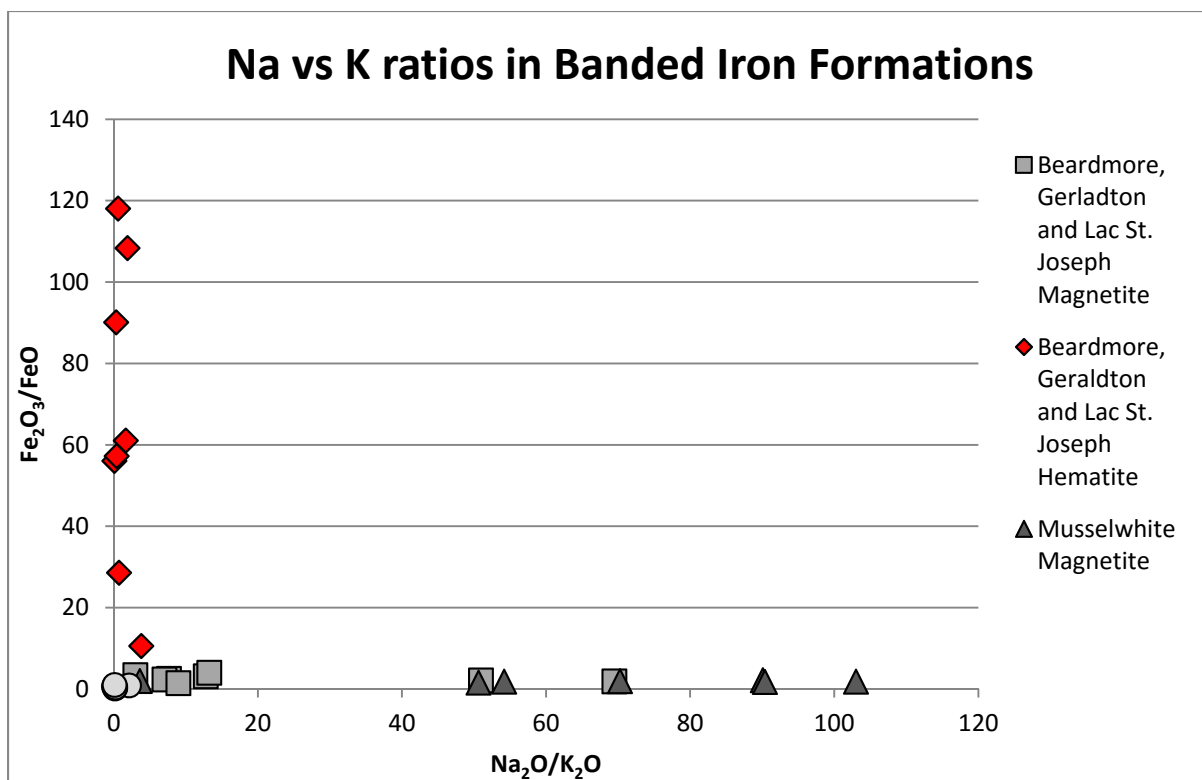


Figure 1: Ratio scatter plot showing how Na and K concentrations vary with the mineralogy of the iron bearing phase in the iron formations studied.

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Progress on Geophysical Mapping of the Northeast Iowa Intrusive Complex

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Large amplitude gravity and magnetic highs over northeast Iowa are interpreted to reflect a buried intrusive complex composed of mafic/ultramafic rocks, the northeast Iowa Intrusive Complex (NEIIC), intruding Yavapai Province (1.8-1.72 Ga) rocks. The age of the complex is unproven, although it has been considered to be Keweenawan (~1.1 Ga). Because only four boreholes reach the complex, which is thought to be covered by 200-700 m of Paleozoic sedimentary rocks, geophysical methods are critical to developing a better understanding of the nature and mineral resource potential of the NEIIC. An initial airborne data collection campaign in the region of Decorah, IA, included high-resolution magnetic and gravity gradient data. Geologic interpretation of those data (Drenth et al., 2015) highlighted circular magnetic and gravity gradient highs thought to represent an alkaline ring complex or a mafic anorogenic intrusive complex, concepts that may be applicable to other similar anomalies over the broader NEIIC. Interpreted northeast trending dikes, thought to be Keweenawan, are also critical to understanding the age of the NEIIC and country rocks.

A large (~22,700 line km) follow-up aeromagnetic-only survey was flown during the fall of 2015 over the southern half of the NEIIC, in the region of Cedar Rapids, Waterloo, and Manchester, IA. Those data are here presented publicly for the first time, in the context of other older geophysical datasets in the region. No rigorous interpretive effort has yet been made, and much ground gravity data remains to be acquired in the region, but the aeromagnetic data show many interesting features that are similar to those observed in and interpreted from the Decorah geophysical data: Large circular aeromagnetic anomalies are consistent with significant individual intrusive complexes, and numerous northeast trending linear anomalies are consistent with dikes of possible Keweenawan age. Follow-up geochronologic and paleomagnetic work may also help to clarify the geologic relations.

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Re-digitized public aeromagnetic data for parts of the west-central Upper Peninsula, Michigan

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The public aeromagnetic database (Daniels et al., 2009) for Michigan's west-central Upper Peninsula (UP) is widely regarded as unsuitable for intermediate- and detailed-scale geologic mapping and mineral exploration applications. There are several limitations of the data, including being available only in a native analog format, being acquired with too wide of a line spacing and too high of a terrain clearance, and being digitized at a much lower level of detail than shown on original contour maps. This abstract describes an ongoing effort to re-digitize aeromagnetic data from original contour maps in the greatest detail possible. To date, the Michigan F (Case and Gair, 1965), E (U.S. Geological Survey 1967a, 1967b, and 1967d), and C (U.S. Geological Survey 1967c and 1967d) surveys in the west-central UP have been re-digitized.

Each survey was a fixed-wing total-field aeromagnetic survey flown at a nominal terrain clearance of 150 meters (Daniels et al., 2009). The Michigan C survey was flown in 1948 with 533 m line spacing along N-S lines, the F survey was flown in 1950 with 400 m line spacing along N-S lines, and the E survey was flown in 1949 with 400 m line spacing along E-W lines. After removal of an unspecified base level, the acquired data were interpolated onto contour maps with a minimum contour interval of 50 nT. A subsequent digitization effort from the contour maps followed at an unknown time, and the resulting digitized data are those publically available today from the USGS (e.g., Daniels et al., 2009). However, that digitization effort inexplicably sampled the contour maps along only every other flightline, effectively simulating surveys with double the actual line spacing. This resulted in poor geologic resolution. The same problem plagues several other vintage aeromagnetic datasets acquired in the central and western UP.

We have re-digitized each of these aeromagnetic datasets in their entirety, sampling each contour from the original contour map and effectively capturing all of the available detail. The results are a much more effective representation of the region's geology. Several known geologic features in the region are well represented, including the Marquette and Menominee iron ranges, dike swarms, blocks of Archean rocks, and the plutons hosting the Eagle and Eagle East deposits.

However, the recovered data still have several major and minor limitations that must be considered by interpreters. First, the surveys were flown at too wide a line spacing and too far above the ground for detailed-scale geologic mapping and mineral exploration. Second, the minimum contour interval of 50 nT shown on the original contour maps means that more subtle anomalies and geologic details undoubtedly present in the original flightline data will never be recovered. Third, the exact terrain clearance of the magnetometer was not recorded, and in several localities may have varied significantly from the nominal 150 meter clearance. Finally, the base level removed from the magnetic data wasn't recorded, meaning that the total-field intensity and formal total-field anomalies cannot be calculated.

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3D Geological Mapping Using Terrestrial LiDAR at Soudan Underground Mine

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Light Detection and Ranging, or LiDAR, data technology, has the potential to revolutionize the way we visualize and interpret 3 dimensional relationships in space. Conceptualization of underground geology and mine workings can be particularly challenging. This study evaluates the use of terrestrial LiDAR to visualize the physical setting and geology at Soudan Underground Mine, which today serves as a historical State Park, physics laboratory and point of significant geological interest.

Using a Faro Focus 3D laser scanner, courtesy of Karen Gran and the University of Minnesota Duluth's Department of Earth and Environmental Sciences, 3D point clouds and associated photographs have been collected on at the 27th level at Soudan. These point clouds provide submillimeter resolution and spatially accurate representations of anything in range of the laser beam. These individual scans are then stitched together in the Faro Scene[®] software using a combination of spherical target, plane, and point recognition approaches with an error of less than 2 mm. Data collection, stitching and rendering of these point clouds is ongoing. The goal of this project is to create a working 3 dimensional model of the underground drift workings at Soudan using LiDAR that can serve as a platform for various applications. Geology of the Soudan Mine mapped by Thompson (2016), Peterson and Patelke (2003), and Vallowe, Thalhamer, Rhoades, and Peterson (2010) are overlain on the 3D imagery.

The scope of this project uses modelling as a tool to clearly visualize the spatial relationships among mapped geologic units in 3D space. The Soudan Iron Formation is an Algoma-type banded iron formation (BIF) on the southern end of the Ely Greenstone Belt. Originally chemically deposited as magnetite with chert in association with mafic volcanics, the Soudan Iron Formation was later hydrothermally altered to rich hematite ore through metasomatism and syntectonic deformation. Interpretations and details of its genesis have caused ongoing geological debates, many of which depend on structural and resulting geochemical controls. We evaluate the use of 3D mapping as a geological interpretive tool at Soudan Mine.



Pictured to the left are 3D rendered point cloud representations of the 27th level at Soudan Mine

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Multi-stage development of breccias in the Baraboo Quartzite, Rock Springs, Wisconsin

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The ca. 1650 Ma Baraboo Quartzite contains localized zones of breccia in which angular fragments of the red to purple quartzite are engulfed in a stockwork of coarse white vein quartz and subsidiary kaolinite. The time of formation of these breccias relative to the formation of the Baraboo Syncline is not well constrained because the highly competent quartzite experienced little internal deformation, and thus there are no clear cross-cutting relationships between the breccias and folding-related mesoscale structures. At two breccia localities, muscovite that appears to be in textural equilibrium with the vein quartz and kaolinite has yielded $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of 1405 ± 5 Ma and 1459 ± 3 Ma (Medaris et al., 2002), broadly consistent with $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 1460 to 1484 Ma obtained from muscovite that lies parallel to cleavage planes in the Seeley Slate, which overlies the Baraboo Quartzite but is only known from drill core samples (Medaris et al., 2009). Fluid inclusion analyses of the white vein quartz, combined with the equilibrium coexistence of quartz + kaolin + muscovite, constrain the conditions of breccia formation to 200-280° C and 0.5-2 kbar, or about 2-8 km depth (Medaris et al., 2011).

The most extensive brecciated zone in the Baraboo Range occurs on the north limb of the syncline near the town of Rock Springs, WI, extending from the west side of Ablemans Gorge to the Rock Springs Quarry east of the Baraboo River. At this location, the brecciated zone is at least 50 m thick, >3 km long, and approximately parallel with the vertical, ENE-striking bedding. We recently obtained permission to collect samples at the Rock Springs Quarry, where the brecciated zone is well exposed on the south wall of the main pit. Here it is clear that the white vein quartz breccia in fact overprints two other distinctive types of broken and veined rock. The older of these are cm-scale bands of fragmented host quartzite and greyish vein quartz, the latter recognizable in thin section because of its significantly larger grain size and elongate grain shapes. Grain boundary textures suggest that the host rock had already been metamorphosed to quartzite at the time of this early fragmentation. Broken zircon grains occur in these early breccias, and in one thin section, two halves of what seems to have been a single original grain can be seen on opposite walls of the brecciated zone. This suggests that the initial failure along these zones occurred under transient stresses high enough to fracture zircon, a famously tough mineral. The vein quartz in these oldest breccia bands exhibits kink-like deformation lamellae, indicative of quasi-ductile deformation and temperatures just below the onset of quartz plasticity (ca. 350°C). This is close to the peak metamorphic temperature inferred from the absence of biotite in the Seeley Slate (Medaris et al. 2011).

These deformed early breccias are in turn cut by distinctive black, hematite-rich veins that occur in three different geometries. The most common form is a mesh-like framework around cm-size fragments of host quartzite. In these occurrences, the hematite-rich zones coincide with areas of very fine, apparently cataclasized, quartz grains much smaller (0.1 mm) than the grain size typical of the host quartzite (>1 mm). The hematite occurs as tiny (<0.1 mm) needle-like crystals that ‘decorate’ the edges of the quartz grains. In many instances, white (late-stage) vein quartz clearly cuts across this black, hematitic cataclasite. The second mode of occurrence of the hematite-rich material is as planar zones – apparently bounded by tensile fractures – that show no contrast in grain size with the adjacent, unmineralized host quartzite. As in the cataclastic zones, hematite occurs as very fine fibrous crystals that fill interstitial spaces around and between quartz grains. The third geometric mode of the hematitic material is as selvages around quartzite fragments that are enclosed in a matrix of white (late) vein quartz. Here the black material seems to have adhered to the edges of clasts when they were separated by the emplacement of the coarse vein quartz. The textural similarities of the hematite in these three types of occurrence suggest that it formed under the same conditions, involving a fluid of distinct composition, over a limited period of time.

Finally, the white vein quartz was emplaced in complex three-dimensional networks that cut through not only the two earlier types of broken/mineralized rock but also previously unfractured host quartzite. This stage of brecciation and fluid flow affected a much larger mass of rock than the earlier two and involved large dilatant strains. In representative hand specimens, the white vein quartz constitutes as much as 40% of the rock volume. The fragments of host quartzite have a wide range of sizes (mm to m scales) and morphologies, ranging from tabular to equant to highly irregular three-dimensional shapes. Crescentic and splinter-like clasts suggest energetic spallation from the walls of the veins. Although the separated clasts have a ‘jigsaw’-like appearance, it is difficult in most cases to fit the pieces back together by matching their shapes or truncated internal features.

This could indicate significant translation and/or rotation of the fragments within the zone prior to the formation of the vein quartz. Fluid inclusions are very abundant in the vein quartz and typically occur in parallel planar arrays within a given crystal, pointing to episodic growth over many cycles of fluid infiltration. In some cases, the vein quartz occurs as zoned, phantom, and terminated prismatic crystals up to 5 cm long, growing into open space or into masses of kaolin. In thin section, the vein quartz shows sweeping undulose extinction, indicating that it too experienced significant deviatoric stress after its crystallization (van Lankvelt and Bjørnerud, 2010).

Collectively, these observations suggest that brecciation and veining at Rock Springs occurred in several distinct stages, involving different modes of deformation and fluids of varying composition, over a protracted period of time. First, an early period of brittle failure, apparently at very high – possibly co-seismic -- stresses, fractured the host quartzite and even cracked detrital zircon grains. An early generation of quartz veins were precipitated into the fractures, and these veins then became the locus of quasi-ductile deformation at temperatures close to the inferred metamorphic peak of 350°. Next, a period of cataclasis along anastomosing shear fractures created cm-scale zones of finely comminuted quartz grains. These cataclasized zones acted as conduits for an iron-rich fluid that infiltrated the rock and was overpressured enough to create additional pathways for itself through hydrofracturing. Next, a large volume of rock, including but extending beyond the previously fractured area, was pervasively broken into fragments whose varied and complex shapes suggest violent, implosive failure. Silicic fluids at temperatures of 200-280°C then flowed repeatedly through this brecciated rock, eventually enclosing the clasts in a matrix of white, fluid inclusion-rich quartz and lesser kaolinite. Finally, continuing stresses caused slight deformation of the vein quartz.

The temporal relationships between these inferred events and the regional folding is not clear. The parallelism of the Rock Springs breccia zone with bedding in the Baraboo Quartzite could indicate that flexural slip during the main folding event played a role in the formation of the breccia. The Rock Springs breccia occurs within an especially massive stratigraphic interval of the quartzite, with little interbedded phyllite (Van Hise Rock being the notable exception). Perhaps at some point in the folding process, bending stresses became so great within the stiff quartzite beam that it failed along a bedding-parallel zone. Failure then allowed overpressured fluids to rush into the fragmented rock, leading to further fracturing and successive stages of veining. The source of the fluids, and in particular the iron-rich fluid that left the unusual hematite veins, is not known. The Baraboo Quartzite as a whole – one of Earth's earliest 'red bed' sequences -- owes its color to oxidized iron, so the iron could have been scavenged from the host rock itself. Alternatively, a little-known iron formation, the Freedom Formation, lies stratigraphically above the Baraboo Quartzite and Seeley Slate and occurs (in the subsurface) in the core of the Baraboo syncline (Roe and Bjørnerud, 2012). If the formation of the hematite-rich areas post-dated the folding and rotation of bedding in the north limb to its present vertical orientation, fluid flow from the Freedom Formation might have been lateral rather than downward.

Another fundamental question is whether all the breccias in the Baraboo district (and other Baraboo-interval quartzites) are of the same age and origin or whether they reflect only local stresses and fluid flow. The 1400-1460 Ma ages of muscovite from other breccia localities as well as the Seeley Slate suggest that deformation and metamorphism at Baraboo were linked to Wolf River Batholith magmatism. In any case, it seems the Baraboo breccias have a more complex story to tell than previously thought and may provide a new window into the processes that contributed to the formation of the still-enigmatic Baraboo Mountains.

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Geophysical Imaging of Layered Mafic Complexes and Relation to Platinum Group Element Exploration

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Layered ultramafic to mafic intrusions such as the Duluth Complex are economically important because they can host magmatic ore deposits containing economic concentrations of nickel, copper, titanium, vanadium and platinum-group elements (PGE's). Because most new discoveries lie under cover, modern exploration for PGE's relies heavily on understanding the geophysical signature of the entire magmatic system in which buried deposits form. Geophysical surveys and methods of analysis provide higher resolution views of the environments in which PGE's develop than were previously available. Combined analysis of potential field and electromagnetic data can provide constraints on the volume of the intrusion, its extent under cover, possible locations of sulfide mineralization. These data can also effectively map small-scale (~3 meters) structures within layered intrusions that host PGE-bearing magmatic ore deposits. Previous interpretations of aeromagnetic and gravity data helped map the geology of the Duluth Complex under cover and confirmed that the complex consists of multiple intrusions (Chandler, 1990; Chandler et al., 1998; Miller et al., 2001). The advent of new filtering, imaging, and modeling techniques will allow us to refine these earlier interpretations, and new high resolution magnetic and electromagnetic (EM) data provide detailed views of the Kawishiwi intrusion. For example, the tilt derivative of the aeromagnetic data significantly enhances small scale features, such that linear aeromagnetic anomalies in the Poplar Lake and Misquah Hills intrusions, Duluth Complex, possibly related to layering, can be observed. In other intrusions, like the Stillwater Complex, the linear aeromagnetic anomalies primarily relate to boundaries between major stratigraphic units and olivine-bearing rock layers altered to a mixture of serpentine and magnetite. Gravity highs characterize the exposed and interpreted buried extent of several intrusive components of the Duluth Complex (Chandler, 1990; Chandler and Ferderer, 1989; Chandler and Lively, 1998). Two dimensional modeling of the Duluth Complex indicate that the Complex thickens to the southeast (Chandler and Ferderer, 1989; Chandler and Lively, 1998). Similar to the Bushveld (Cole et al., 2013; Finn et al., 2015a) and Stillwater Complex layered mafic intrusions (Finn et al., 2015b), modeling of the gravity data constrained by other geophysical data, may help constrain the 3D extent of the Duluth Complex. Existing gravity data over the Kawishiwi intrusion indicate that the Cu-Ni-PGE deposits along its base align along a gravity gradient indicating a density contrast between basement and mafic intrusive rocks (Condor Consulting Company, 2011, internal report). Stochastic inversion of the EM data aids in enhancing low resistivity features that could indicate undiscovered deposits. Existing MT data images the configuration of low resistivity sulfides within the Animikie basin adjacent to the Duluth Complex (Bedrosian, 2016), important because the degree of reaction and assimilation of the Animikie rocks with the mafic magmas resulted in a variety of mineralization zones. In addition, the Animikie basin may have influenced the extent of the Duluth Complex as the Transvaal basin did for the Bushveld intrusion (Finn et al., 2015a).

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Sedimentology of a Pre-Vegetation Floodplain Assemblage: the Mesoproterozoic Hele Member of the Sibley Group, Ontario

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Descriptions of fluvial systems operating prior to significant terrestrial macrophyte vegetation have concentrated on assessing the impact of plant evolution on channel style; this is probably in part due to the scarcity of well developed floodplain successions in fluvial assemblages of these ages. This study describes wet, pre-vegetation floodplain deposits and processes observed and inferred from a continuous succession of drill core through an extensive, 1.4 Ga, delta-top channel-floodplain assemblage forming a portion of the Sibley Group, Ontario, Canada. Sub-aerial deposits are dominated by flaser, wavy and lenticular bedded, fine-grained sandstones, siltstones, and mudstones, with abundant small mudstone rip-up clasts. Soft-sediment deformation of these units is ubiquitous, with loading and injection features being the most prominent. Thicker medium-grained sandstone beds, representing crevasse splays, commonly have poorly developed protosols in their upper portions. Well-laminated sediments with wave ripples, and only rarely containing rip-up clasts and soft sediment deformation, were deposited in floodplain ponds. These deposits differ from post-vegetation floodplain sediments in having: (i) better preservation of layering without rootlet bioturbation; (ii) dominance of rippled sand on the floodplain, probably due to lack of vegetation-induced baffling and thus higher velocities of overbank flows away from the levees; (iii) large-scale generation of small, intraformational clasts caused by intense drying of the thin upper layer of sediment due to the lack of shade; (iv) desiccation crack fills consisting of peds and locally derived intraclasts, probably transported by overland flow during rainfall events that did not result in sediment delivery from the main channels; (v) ubiquitous soft-sediment deformation features in sub-aerial deposits denoting a groundwater table very close to the surface; and (vi) well-laminated, commonly oxidized sediment that accumulated in floodplain ponds attributable to low levels of organic loading, though some green pond sediments indicate that microbial microflora, and probably microfauna, did exist in these ponds. These attributes are the direct result of the lack of macrophyte vegetation, and produce floodplain assemblages that are distinctly different from those currently forming in similar climatic settings.

Provenance and tectonic evolution recorded by successor basins in the Abitibi-Wawa terrane: Insights from new U-Pb LA-ICP-MS analyses of detrital zircon

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Understanding the detrital zircon provenance of syntectonic successor basins can provide insight into the processes related to amalgamation of the Superior Province. The aim of this study was to investigate the provenance of successor basins in the southern Abitibi subprovince (SAS), which comprises the southeastern most extent of the Superior Province. To establish the provenance of sedimentary rocks in successor basins of the SAS we have utilized statistically robust U-Pb dates of detrital zircon grains obtained by laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS). The results were compared to detrital zircon data from successor basins in the Wawa subprovince from Lodge et al. (2013) to establish the characteristics of provenance throughout the Abitibi-Wawa terrane. The Abitibi-Wawa terrane (Stott et al., 2010) is one of the largest, best-exposed, well-studied, and economically well-endowed Archean greenstone belts in the world. The Abitibi and Wawa subprovinces occur to the east and west, respectively, of the Paleoproterozoic Kapuskasing uplift in Ontario.

In recent years, extensive high-resolution, U-Pb zircon geochronology coupled with new and existing mapping has revealed a characteristic lithotectonic progression for the development of the Abitibi-Wawa terrane (e.g., Ayer et al., 2002). The research, primarily focused on the SAS, indicates that construction of the terrane was dominated by bimodal volcanism in a subaqueous environment from ~2750 to ~2695 Ma. The termination of submarine volcanism at ~2695 Ma was marked by the onset of regional tectonism, which progressively localized along major regional deformation zones and resulted in the formation of orogenic gold deposits. Synchronous with tectonism was the development of thick sedimentary successions in successor basins. In the SAS, two distinct types of successor basins are recognized based on sedimentological, structural, and geochronological constraints: the ~2695-2685 Ma, submarine, turbidite-dominated Porcupine assemblage and the ~2680-2670 Ma, largely subaerial, coarse clastic-dominated Timiskaming assemblage. The Timiskaming assemblage is typically fault- and/or unconformity-bounded, represents a critical temporal and structural marker unit, and commonly hosts orogenic gold deposits.

To establish the provenance of successor basins in the SAS a representative set of sixteen samples was collected from across the subprovince. Sampling targeted well-constrained localities with a variety of stratigraphic relationships, spanning many of the major structural zones and mining camps in the SAS. To evaluate the detrital zircon date distributions of samples from these successor basins, probability density (PDF) and cumulative distribution (CDF) functions were calculated. These data provide a robust characterization of the provenance of Porcupine and Timiskaming assemblage sedimentary rocks. The PDFs for all of the samples display similar principal populations of detrital zircon grain dates that are dominated by ~2800-2650 Ma results. However, primary differences between Porcupine and Timiskaming assemblage detrital zircon populations were indicated by differing proportions of older, pre-2800 Ma dates. The CDF calculations indicate that zircon grains with pre-2800 Ma dates comprise ≤5% of the Porcupine assemblage data and ~10-15% of the Timiskaming assemblage data. Similar to SAS

samples, Wawa detrital zircon samples (Lodge et al., 2013) are predominately composed of grains with 2800-2650 Ma dates. Furthermore, the Wawa data displays a similar proportion of pre-2800 Ma dates to Porcupine assemblage samples (i.e., <5%), but also contain a relatively high proportion of ~2650 Ma and younger zircon grains. Lodge et al. (2013) interpreted the young dates as a result of metamorphism, and therefore they may not reflect primary depositional differences in provenance between the southern Abitibi and Wawa subprovinces. The Wawa successor basins display sedimentological characteristics that are ‘Timiskaming like’ (i.e., dominated by coarse clastic sedimentary rocks), although the maximum age of deposition is locally well-constrained by detrital zircon geochronology to be ~2690 Ma (Lodge et al., 2013). Consequently, despite broad similarities to the Timiskaming assemblage in the SAS, the Wawa successor basins appear to be the same age as, and contain detrital zircon provenance that is most comparable to, the Porcupine assemblage in the SAS.

In general, the provenance of SAS detrital zircon samples indicates that the successor basins are dominantly composed of local detritus, consistent with geochemical and sedimentological studies (e.g., Feng and Kerrich, 1990; Cocoran and Mueller, 2007). However, the occurrence of pre-2800 Ma detrital zircon grains may be indicative of provenance from adjacent subprovinces, as the SAS does not contain rocks in this age range (e.g., Ayer et al., 2002). Therefore, we interpret these data as an indicator of exhumation and erosion of an emergent hinterland to the north (i.e., the Winnipeg River, Marmion, and Opatika subprovinces). Potential sources for pre-2800 Ma grains also occur to the south in the Minnesota River Valley terrane. However, these rocks also contain zircon grains with ~3500-3300 Ma dates (Bickford et al., 2006), which are not observed in the SAS data. In the SAS, it is well-established that the Porcupine and Timiskaming assemblages were deposited at different times based, in part, on the ages of the youngest detrital zircon grains they contain (e.g., Ayer et al., 2002). Our data additionally indicates that Timiskaming assemblage rocks contain a higher abundance of zircon grains with pre-2800 Ma dates relative to Porcupine assemblage rocks. This suggests that detritus from the hinterland was more prevalent during the later stages of tectonism at ~2680-2670 Ma, supporting models that invoke north to south propagation of the tectonic front.

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A comparative study of mafic and felsic lithologies from the Borden Belt and adjacent greenstone belts in the Wawa-Abitibi Terrane

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The Borden Belt in the Kapuskasing Structural Zone of the Superior Province of Canada contains schists and gneisses that reached upper amphibolite to granulite facies of metamorphism. Whole rock geochemistry and trace element analyses indicate igneous protoliths of sub-alkaline affinity, ranging from ultramafic to felsic compositions. Igneous tectonic geochemical signatures are preserved which indicate shallow mantle melting environment and crustal input, characteristic to arc-subduction zone magmatism. The Wawa-Abitibi Terrane can be defined as a tectonostratigraphic terrane, by comparing trace element geochemistry and field relationships of the Borden belt, Michipicoten Greenstone Belt, and the southern Abitibi Greenstone Belt in Ontario. All three belts share similar geochemical signatures which indicate lithologies associated with the formation and progression of a mature volcanic arc in a shallow marine setting within the Wawa-Abitibi Terrane.

The Geology and Geochemistry of the Laird Lake Property, Red Lake Greenstone Belt, Ontario

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The Laird Lake property is situated on what has been previously interpreted as the angular unconformity 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 (Corfu and Wallace, 1986; Corfu and Andrews, 1987; Stott and Corfu, 1991). The Balmer assemblage is characterized by mafic tholeiites, ultramafic flows, local banded-iron formations and minor felsic volcanic rocks, whereas the Confederation comprises mafic to felsic volcanic rocks with a calc-alkalic affinity (Parker, 2000; Sanborn-Barrie et al., 2001, 2004). Contrary to previous interpretations, the Laird Lake property displays metamorphic assemblages up to amphibolite grade facies which are attributed to regional metamorphism, rather than being related to the metamorphic aureole of the Killala-Baird batholith (2704 ± 1.5 Ga) north of the field area (Sanborn-Barrie et al., 2004; Dubé et al. 2000). Multiple gold occurrences are found on the property and generally occur within 200 m of the interpreted unconformity. The occurrences are hosted by multiple rock types with some of the highest recorded values from grab samples of quartz veins (101.90 g/t), banded-iron formation (35.34 g/t), altered mafic volcanic rocks (38.57 g/t) and quartz-feldspar porphyritic crystal-tuff (>0.1 g/t; LeBlanc, 2015).

This study will develop an integrated model for the geology and gold mineralization of the Laird Lake area by 1) characterizing the primary host rocks and 2) investigating the nature, timing and origin of the Au-mineralization. Mapping and sampling of the various rock types in the field area at surface and within five drill cores that intersect the gold bearing zone will provide the geological constraints for this study. Petrographic and SEM analysis will characterize the textures and mineralogy of the rocks, whereas whole rock geochemistry will be used to characterize their composition in order to differentiate the Balmer and Confederation assemblages. Quartz vein samples (barren and mineralized) will be analyzed for oxygen isotopes and fluid inclusion work will be conducted if possible. Additionally, Sm-Nd isotope analyses will be conducted on carefully selected samples in order to acquire information on the source of the host rocks to help establish the tectonic history of the area, and last, a geochronology sample of a felsic volcanic unit within the Balmer assemblage will be dated by U-Pb zircon analysis.

Previous models suggest that the Balmer and Confederation assemblages cannot be distinguished in the field, however, observations made over the field season indicate that the two assemblages show clear differences. The Balmer comprises a fine-grained, aphyric mafic metavolcanic, locally pillowed, with various amounts of biotite and carbonate alteration and banded-iron formation. The Confederation was observed to have phenocrystic (feldspar and/or amphiboles) and rare aphyric mafic metavolcanic rocks intercalated with intermediate and felsic metavolcanic rocks. The mafic to felsic metavolcanic rocks were not observed to have pillows and display much weaker alteration than the Balmer. Both Balmer and Confederation rocks show a dominant east-trending fabric with increasing foliation observed when approaching the unconformity.

Detailed mapping at the “Gold Bearing Zone” trench and whole-rock geochemistry indicates that the outcrop is part of the Balmer assemblage with aphyric mafic metavolcanic tholeiites and banded iron formations. Known gold occurrences at the trench are localized within a banded iron formation cut by a gold-bearing shear. This relationship would suggest a

sulphidation reaction in order to precipitate the gold, samples of which have yielded values up to 35.34 g/t over 2m (LeBlanc, 2015).

Primitive mantle-normalized trace element profiles for Balmer and Confederation volcanic units show distinct trends that support the subdivision of assemblages within the field. As expected, the Balmer mafic volcanic rocks show a tholeiitic signature, with two distinct trends; trend 1 has a low Th/Nb ratio and a weak negative Ti anomaly whereas trend 2 has a more LREE depleted profile with a distinctly higher Th/Nb ratio and a stronger negative Ti anomaly. The Balmer ultramafic volcanic units equally show two trends; trend 1 is enriched in LREE while trend 2 is depleted in LREE. Both show high Th/Nb ratios with flat HREE. The Confederation assemblage volcanic rocks show calc-alkaline signatures with enriched LREE, flat HREE, high Th/Nb ratios and strong negative Ti anomalies, all indicative of rocks formed above a subduction zone.

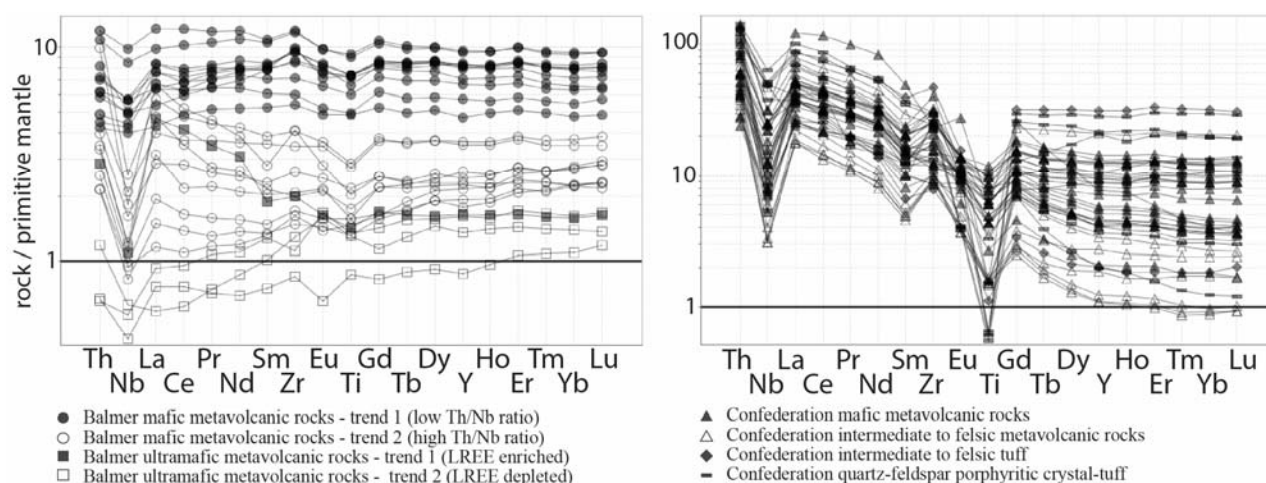


Figure 1: Primitive mantle-normalized trace element profiles for Balmer and Confederation assemblage metavolcanic rocks (normalization factors are after McDonough et al. 1992). (A) Balmer assemblage. (B) Confederation assemblage.

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Evidence in the Eastern Canadian Shield of regular fault patterns of crustal origin for the loci of some mineral deposits and late-stage intrusive events

Glass, F., Quebec

Qualitative analysis of aeromagnetic data and examination of other data sets (geomorphology, mapped outcrops) have been used to determine the presence of interpreted lineaments at known mineral occurrences or late-stage intrusive events (mapped or aeromagnetic observation). These lineaments are thought to represent ductile or brittle fault traces and to have origin within the crust.

The prevalence of particular fault-trace orientations is consistently regular over a large area of the Canadian Shield. The age of the dated mineral deposits or intrusive events associated with particular fault traces or fault loci vary from 2,7 Ga to 1,1 Ga.

Within a 1 000 km map block area or greater, the inter-relationship of certain mineral deposits and late-stage intrusive events appears to consistently correlate to specific geographic orientations. Within the boundary of a smaller block (100 km or smaller in size) anywhere inside the larger block, the inter-relationship between local deposits or nearby late-stage intrusives, coincides with some of those lineaments evident at the regional scale. In addition, there are also different orientations, not necessarily observed with extensive continuity, unequivocally present. These features of local extent are, however, oddly present, with near exact correlation to specific regional orientations, over a similarly large area of the Canadian Shield.

In order to explain the origin of the above observations requires likely two different depths for the far and local stress fields or, more plausibly, a single cause for the stress field possibly acting on two crustal layers, the near-surface one delaminated from the deeper crust below.

Prior to at least 1,1 Ga, the Canadian Shield appears to have behaved as a single rigid crustal block. (The Mount Polley alkaline complex has a N27W faulted boundary to the west; the Labrador Trough to the M7 earthquake (1929) in the St-Lawrence (Quebec Embayment Structure) is at N27W).

10 slides have been prepared showing repetitions of a few common lineament orientations (all flat-map representations) with a final slide illustrating the necessity to use polar projection (spherical maps) over large regional distances. All 11 slides are presented on one poster.

The Cu/Pd diagram and metal/sulfur variation as an exploration tool: Examples from the Coldwell Alkaline Complex, Ontario

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Mapping out variations in Cu/Pd, Cu/S and Pd/S through a Ni-Cu-PGE sulphide deposit provides important insight to the mechanisms acting during deposit formation. For instance, the Cu/Pd diagram has been used: to illustrate PGE depletion by previous sulphide segregation (Barnes et al., 1993); to estimate R-factors required to form deposits in the Duluth Complex (Thériault and Barnes, 1998); and as an indicator of extreme PGE enrichment (Barnes and Ripley, 2016). We propose here that patterns and features shown by a large data set on the Cu/Pd diagram can provide insight into the cumulative history of the deposit, particularly in a magma-conduit setting where intrusive bodies formed by build up of multiple sills.

This study compares spatial and compositional relationships for 15,000 assays from 11 mineralized zones within the Marathon, Geordie Lake, and Area 41 deposits and the Four Dams and Redstone occurrences located within the 1.1 Ga Midcontinent Rift related Coldwell Alkaline Complex. The deposits are proposed to be co-genetic and, except for Geordie Lake, exhibit common petrologic features indicating formation in a magma conduit setting at or just above the contact between mafic meta-volcanic rocks and the Archean basement (Good et al., 2015). The Geordie Lake deposit is located closer to the middle of the complex and was cut by syenitic rocks during Cycle I of the Coldwell intrusive event. The host rocks for the deposits consist of some combination of ophitic gabbro and pegmatite; apatitic clinopyroxenite; or augite troctolite. Mineralization consists predominantly of disseminated assemblages of chalcopyrite $\pm$ pyrrhotite $\pm$ bornite.

Trends for metal abundances across mineralized intervals in all zones, except for the W Horizon at Marathon, show a correlation between Cu, Pd, Pt and S. But metal tenor (metal/S) and/or Cu/Pd in these sections commonly exhibit saw-tooth patterns that change gradually up through intrusions with sharp steps occurring within and between individual zones. Mineralized intervals that exhibit increasing Cu, S and Pd with decreasing Cu/Pd are consistent with models for accumulation of sulphides from magma with similar R-factor. Step-like changes in Cu/Pd or Cu/S within a zone are interpreted to represent contacts between individual pulses of sulphide-bearing magma with an inherent R-factor attribute.

Taken together, the range of Cu/Pd for all samples in a mineralized zone represents the cumulative history of individual magma pulses. Contouring the data for each zone by point density defines a characteristic shape and trend line for the zone, the slope of which is dependent on the total range of R-factors for the accumulated magma pulses. Shallow-dipping trend lines, such as that observed for the Geordie Lake deposit and the Marathon footwall zone, indicate a simple intrusive history with magma pulses having a limited range of R-factors. Steeply negative trend lines extending from the Pd-depleted to the Pd-enriched fields represent magma pulses with a very broad range of R-factors and indicate a very dynamic intrusive history, as is the case for data from the W horizon and the top unit at Area 41. The latter relationship shows there is a spatial, and possibly a temporal, relationship between the most copper-rich and Pd-rich zones at Marathon and Area 41.

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Progress on 3D modeling of the Midcontinent Rift System in the western Lake Superior region and an isopach map of the Oronto Group

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Efforts are underway to develop a three-dimensional (3D) model of the structure and configuration of sedimentary and volcanic basins related to the Midcontinent Rift System (MRS) in the western Lake Superior region (Fig. 1). The current efforts build on a 3D model previously developed in the 1990s (Allen et al., 1997) and concepts developed by many other previous workers. Technical advances in modeling capabilities, expanded and improved geophysical data coverage, and renewed interest in the mineral resources of the MRS provide the motivation for new attempts at 3D digital modeling of the MRS. An improved 3D model of the area helps visualize geologic relations, provides mechanisms to test hypotheses about tectonic history and the spatial distribution of mineralization, and helps identify areas where more detailed analysis is required.

Our 3D model is regional and intended to show broad variations in geology. Only three generalized, MRS-related geologic packages are represented, following Allen et al. (1997). The packages, from oldest to youngest, are 1) undivided Keweenaw plutonic and volcanic rocks, 2) Oronto Group sedimentary rocks, and 3) Bayfield Group and equivalent sedimentary rocks. A fourth package represents undivided pre-rift rocks (basement). In addition, three major fault systems are modeled: the Douglas, Lake Owen, and Keweenaw fault systems (Fig. 1).

The modeling strategy involves digitizing the bases of the geologic packages, fault locations, and general orientation data along 2D sections and from geologic maps. The 3D modeling software then connects the digitized points into surfaces and volumes in 3D space, using simple geologic rules for stratigraphic and onlap relations and for the lateral extents of the influences of faults. Digitized points from the previous 3D model (Allen et al., 1997) serve as a guide, but we are re-evaluating geophysical data and making sure that updated geologic concepts have been incorporated. In particular, we are revisiting the analyses of available seismic-reflection sections with modern software and developing new gravity and magnetic models to substantiate the interpretations. For example, we have applied modern re-processing techniques to proprietary seismic-reflection data in the Bayfield Peninsula to document previously unpublished results and provide a better image of the geology. We are also developing root-mean-square velocity maps for analog seismic-reflection sections to establish depths to strong reflections. Some of these new depth interpretations are revealing discrepancies between interpreted seismic sections where they cross each other, which merit further work.

An isopach map of Oronto Group thickness constructed from the 3D model (Fig. 2) illustrates the tremendous thickness of sediments that were deposited within present-day, western Lake Superior during post-magmatic subsidence and before Bayfield basin formation. The thickest parts of the basin are generally located in between White's and Grand Marais ridges, respectively. A significant observation is the broad asymmetry of the Oronto basin in western Lake Superior, with the thickest part of the basin (>12 km) near the south shore adjacent to the Porcupine Mountains. The asymmetry is present in similar, previous maps (e.g., Allen et al., 1997), but is more pronounced in our map. The broad, southeast-deepening asymmetry next to the Porcupine Mountains contrasts with isopach thicknesses and previous workers' interpretations of GLIMPCE seismic line C (Fig. 2). Along line C, the thickest Oronto Group is concentrated within a narrow (~25-km) zone adjacent to the south shore. The local thickening next to the Douglas fault at the southeast side of White's Ridge is present in both our and Allen's model, derived independently from informal observations of proprietary seismic data.

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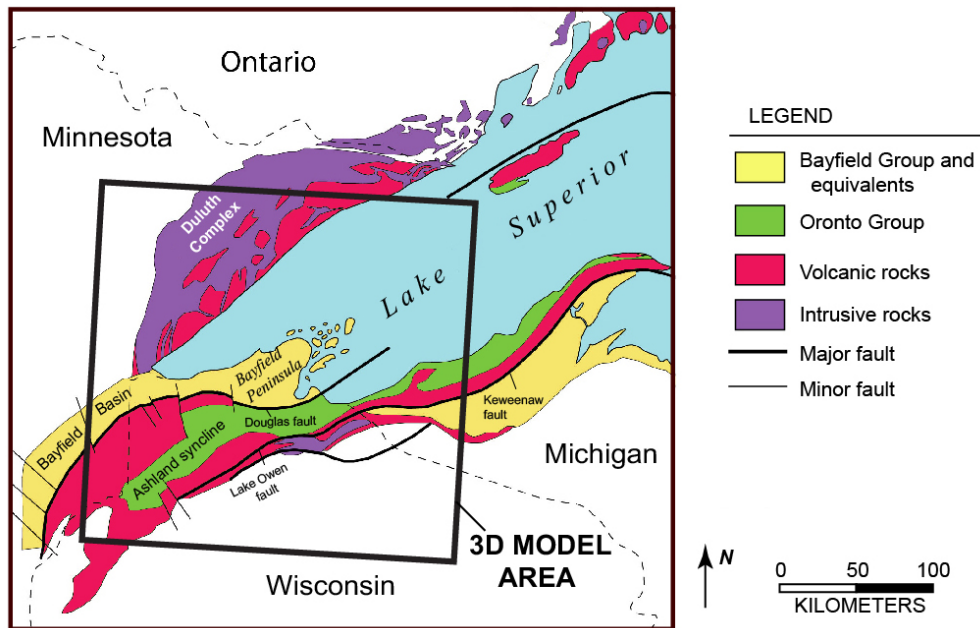


Figure 1: Generalized rock units of the Midcontinent rift system in the western Lake Superior region and area covered by the 3D model. Geographic boundaries are shown by dashed lines.

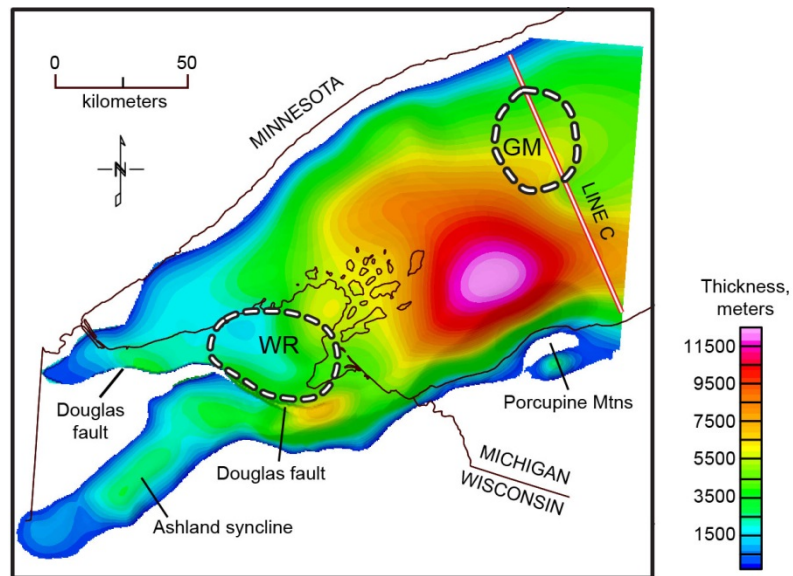


Figure 2: Isopach map of the Oronto Group from the 3D model, shown as a color-shaded relief image with illumination from the west. Gravity lows interpreted as basement highs (Allen et al., 1997): White's Ridge (WR) and Grand Marais Ridge (GM). Location of GLIMPCE seismic line C is indicated by red and white line.

Quantitative abundance and preliminary morphological characterization of amphiboles in the Ironwood Iron-Formation, Gogebic Iron Range, Wisconsin

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The western portion of the Gogebic iron range in northern Wisconsin constitutes one of the largest undeveloped iron resources of the Lake Superior region (Cannon et al., 2007). Knowledge of mineralogical changes related to metamorphism in the Gogebic iron range will be essential to planning for potential future resource development, especially solid mine waste management practices. The purpose of this study is to document the distribution and morphological character of amphibole minerals in the Ironwood Iron-Formation related to the thermal impact of the Mellen Intrusive Complex (MIC).

The Paleoproterozoic Ironwood Iron-Formation is the principal iron-bearing unit in the Gogebic iron range. The Ironwood has five named members (from the base upward): Plymouth, Yale, Norrie, Pence, and Anvil (Anvil Member is absent in the western Gogebic iron range) (Cannon et al., 2007). The Ironwood contains ferruginous chert, Fe-oxides, Fe-silicates, and Fe-carbonates in granular or oolitic wavy and finely laminated beds. Contact metamorphism related to the Mesoproterozoic MIC had the combined effects of increasing the magnetite content and progressively changing the silicate mineralogy of the Ironwood Iron-Formation (Cannon et al., 2007).

Three drill holes, selected for study based on the completeness of their stratigraphic section and location relative to the MIC contact, were examined to determine variability in mineral assemblages with changes in metamorphic grade. The drill holes are oriented east-west, increasing in distance from the MIC eastward. Drill hole A is approximately 2 km from the contact, B is approximately 3.2 km from the contact, and C is approximately 4.7 km from the contact.

Samples were selected from lithologic sub-units within the 4 different members to create a representative sample suite for each member. A separate topical set of samples was also chosen from areas of particular interest to elucidate amphibole paragenesis. A few samples were also collected from the underlying Palms Formation. All samples were examined by optical microscopy and scanning electron microscopy (SEM), and analyzed by powder X-ray diffraction (XRD) using Co K α radiation. Quantitative estimates of mineral abundances were calculated from XRD data using the Rietveld method.

The three drill cores show a well-defined progression from low-grade metamorphic conditions in the easternmost drill hole (A) to high-grade metamorphic conditions in the westernmost drill hole (C). Figure 1 displays the mineral distribution in the representative suite of samples from each drill hole. Samples are shown at the drill hole depth from which they were taken. Drill hole A primarily exhibits low-grade metamorphism characteristics (as described in Klein, 1983). Quartz is commonly present in major amounts. Magnetite typically ranges from approximately 10 to 40 weight percent (wt. %) but is absent in a small number of samples. Siderite and members of the dolomite-ankerite series are common and make up significant portions of the total rock volume. Chlorite-group minerals are commonly present in trace to minor amounts. The presence of Fe- and Mg-carbonates and trace amounts of Fe-silicates such as stilpnomelane are indicative of the low-grade metamorphic conditions. Amphiboles were not detected within the representative samples, but trace to minor amounts were found in several of the topical samples from the Norrie and Plymouth members.

Central drill hole B commonly contains amphiboles of the grunerite-cummingtonite series, diagnostic of medium-grade metamorphic conditions (see Klein, 1983). These amphiboles are present in each member of the Ironwood, ranging in quantities from 3 to 65 wt. %. Magnetite and quartz remain the most common minerals. The near-complete absence of Fe- and Mg-carbonates is due to metamorphic reactions of these minerals with quartz, producing members of the grunerite-cummingtonite and actinolite-tremolite series along with calcite. Chlorite-group minerals remain common but at diminished amounts.

Drill hole C has indications of high-grade metamorphism, such as the appearance of pyroxene, fayalite, and garnet. Quartz and magnetite continue to be common. Members of the grunerite-cummingtonite and actinolite-tremolite series remain common and are present from trace amounts up to approximately 40 wt. %. Chlorite-group minerals become rare at these conditions.

Research on amphibole morphology and mineral chemistry is ongoing. Examination of thin sections using petrographic microscopy and SEM reveals a range of amphibole crystal habits and grain sizes. Distinctions in primary morphological classifications of individual amphibole crystals, based on degree of elongation of one or more dimensions and aspect ratio, is underway. Very fine-grained crystalline aggregates composed of grains less than 10 μm in size, as well as large single crystals up to 5.5 mm also have been observed.

The distribution of a variety of amphiboles in the Ironwood Iron-Formation has been documented by powder XRD and SEM-EDS (energy dispersive spectroscopy). Quantitative mineral abundance estimates show that the presence of amphiboles is dependent on the proximity to the MIC. Preliminary microscopic investigation reveals a range of crystal habits and geometric variability. These will be characterized in more detail in continuing studies, which will include electron probe micro-analysis to determine quantitative mineral chemistry.

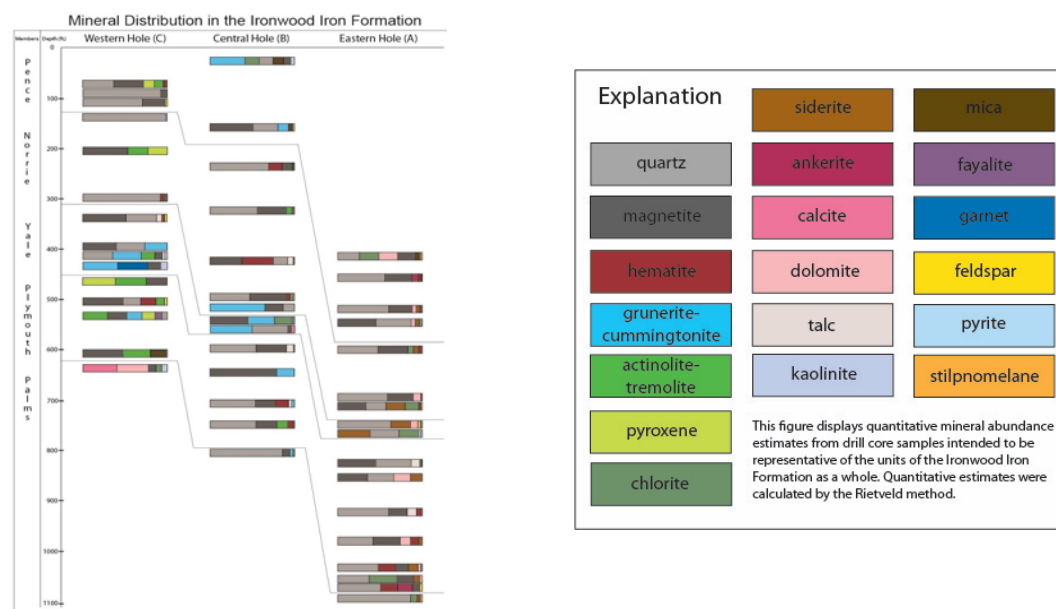


Figure 1. Mineral distribution in weight percent in the Ironwood Iron-Formation.

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PALEOCURRENT INTERPRETATION OF THE CAMBRIAN ELK MOUND GROUP USING GEOPHYSICAL OPTICAL BOREHOLE IMAGE (OBI) LOGS FROM TWO NEW BOREHOLES, DODGE COUNTY, SOUTHERN WISCONSIN

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Paleocurrents measured from cross-beds in sandstone indicate sediment transport direction or the flow direction of water at the time of deposition. Characterizing variation in paleocurrent direction through a stratigraphic succession is one tool for investigating evolution of depositional environment through time. In southern Wisconsin the Cambrian Elk Mound Group is comprised of, from oldest to youngest, the Mount Simon Formation sandstone, Eau Claire Formation shale, and Wonewoc Formation sandstone. In south-central Wisconsin the Eau Claire Formation undergoes a facies change from shale to sandstone. Here the Elk Mound Group is present mostly in the subsurface so it is understood primarily through observation of drill core, drill cuttings, and downhole geophysical logs. The purpose of this study is (1) to test the validity of using measurements from optical borehole image (OBI) logs to measure paleocurrents in sandstones present in the subsurface and (2) investigate how paleocurrent direction varies through two thick, sandstone-dominated intervals of the Elk Mound Group in Dodge County, Wisconsin.

OBI logs are oriented, down-hole images taken from drill site boreholes. The images return as 360 degree unwrapped digital representations of the borehole, and these images record sedimentary structures like cross-beds, laminations, and bedding planes. We use Wellcad software to measure the strike and dip of cross-beds and laminations from the Elk Mound Group that were imaged with OBI logs from two boreholes that the Wisconsin Geological and Natural History Survey drilled in Dodge County in 2015. The Slinger site encountered 243 feet (74 m) of Elk Mound Group sandstone before hitting Precambrian iron-formation. The Westphal 2 site encountered 422 feet (129 m) of Elk Mound Group sandstone and did not hit Precambrian basement. We compare OBI logs to drill core collected at each site. We compare our paleocurrent measurements to existing published data. Finally, we use elemental data collected using a handheld x-ray fluorescence (XRF) instrument at one foot intervals along each core to subdivide the Elk Mound Group. We observe how paleocurrent measurements vary between each of these preliminary subdivisions of the Elk Mound Group.

The paleocurrent directions we measured from OBI logs are consistent with published data for the Elk Mound Group (Michelson et al., 1973; Driese et al., 1981; Hagadorn et al., 2002). Published data report primarily south-directed paleocurrent directions with a secondary bimodal direction for the Elk Mound Group. At the Slinger and Westphal 2 study locations, we subdivide the Elk Mound Group into four informal units based on changes in elemental concentrations of Al, Ti, Zr, and K. The lower two units are characterized by southwest-directed paleocurrents. Paleocurrents become bimodal in the upper two units. Based on the similarity with published paleocurrent data, we conclude that paleocurrents may be measured accurately from OBI logs. Furthermore, the change in paleocurrent direction we observe from southwest in the lower Elk Mound Group to bi-modal in the upper Elk Mound Group likely reflects a change in environmental conditions that control sediment transport and deposition. Measuring paleocurrent direction from OBI logs is therefore a useful tool to aid subdivision of seemingly monotonous, thick packages of sandstone that are present in the subsurface.

We acknowledge Dr. Prajukti Bhattacharyya, University of Wisconsin-Whitewater, for her assistance with this project.

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U-Th-Pb isotopes of the Reef Deposit; a Au-Cu occurrence in central Wisconsin

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The Reef deposit, located within the Wausau Volcanic complex (WVC), is a vein hosted Au-Cu occurrence historically calculated to contain ~454,600 tons grading 0.262 opt gold, 0.25 opt silver and ~0.28% copper located approximately 15 miles east of Wausau, Wisconsin. The Ladysmith-Rhineland volcanic complex (LRVC), adjacent to the North of the WVC within the Pembine-Wausau volcanic subterranean, is known to contain many volcanogenic massive sulfide (VMS) deposits, several of which are considered to be economically viable to mining (DeMatties 1996). The Reef deposit has been described in the past as a lode gold or shear-zone hosted gold deposit (DeMatties 1996) separating it genetically from the VMS deposits to the north, along with a physical separation of the hosting volcanic complex (WVC vs. LRVC). The Reef deposit has also been described as the root zone of a Cu-Zn or Zn-Cu VMS deposit (Scott 1988) and although there are no known VMS deposits of economic interest, the WVC is known to host minor VMS mineralization (DeMatties 1996). An orogenic lode gold deposit could potentially be associated with various tectonic events in the history of central North America including; ~1700 Ma Yavapai, ~1600 Mazatzal or even anorogenic magmatic activity of the ~1510 Ma Stettin syenite complex or the ~1470 Ma Wolf River Batholith.

The Reef deposit consists of seven mineralized zones which consist of Au-Cu bearing quartz-sulfide veins hosted in primarily basaltic material (mafic metavolcanics and gabbroic intrusions) (Kennedy and Harding, 1990). Whilst ore zones of quartz-sulfide veins are also cross-cut by similar gabbroic intrusives it is unclear when the Au mineralization was deposited. The zones trend northeast, dip to the northwest and are closely associated with felsic intrusions (Kennedy and Harding 1990). Felsic dikes and sills are intermingled with the host gabbro intrusives as a swarm of granophyric to porphyritic, locally aplitic units. The deposit area is flanked to the west and northwest by dominantly basalt of massive and pillowed flows and mafic tuff. Felsic intrusions flanking the deposit are concentrated in the western and southeastern areas adjacent to the deposit.

U-Th-Pb isotopes analyses were made of sulfide phases which were micro-drilled from drill core selections and aliquots of coarse reject from split drill core assay material, previously split and crushed by Aquila Resources. The coarse reject samples are referred to as 'whole rock' (WR) samples. WR and sulfide (chalcopyrite, pyrite and pyrrhotite) $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ values range from 15.732 to 22.897, 15.222 to 16.058 and 35.139 to 41.794 respectively (Fig 1). Pb isotope values indicate a source region for sulfides at Reef similar to that of the Flambeau VMS deposit. The age of volcanogenic massive sulfide deposits in the LRVC have been estimated at ~1860 Ma (DeMatties 1996) and a Pb-Pb isochron for Reef of 1925 ± 92 Ma does overlap the estimate. Measured $^{238}\text{U}/^{204}\text{Pb}$ (μ) values range from 0.185 to 4.45 for sulfides and 1.016 to 14.202 for WR samples. $^{232}\text{Th}/^{204}\text{Pb}$ (ω) values range from 0.0436 to 3.084 for sulfides and 0.623 to 19.051 for WR samples. Only some μ and ω values support highly radiogenic Pb values to have been derived from in-situ decay (Fig 2). Samples are either subject to later coincident uranium and thorium loss, or lead addition from a high μ source.

A genetic model for the Reef deposit remains elusive; but a primary association with the Penokean orogen has been established.

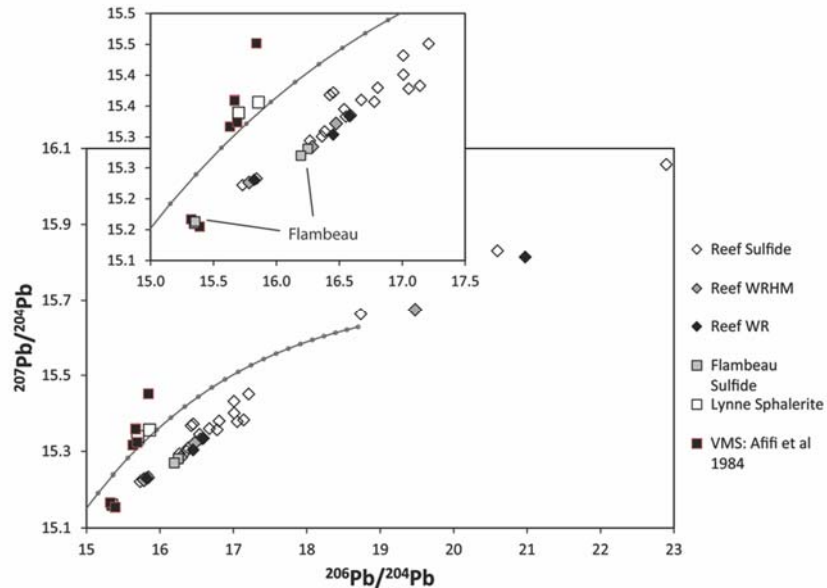


Figure 1 – $^{207}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$ plot of results from the Reef deposit and the Flambeau and Lynne VMS deposits. Smaller plot is inset with same data plotted. WR = Whole Rock; WRHM = Whole Rock Hand Magnetic fraction. Dark filled squares are previously published values for VMS deposits (Afifi et al 1984). Curve plotted is lead evolution from Stacey and Kramers (1975).

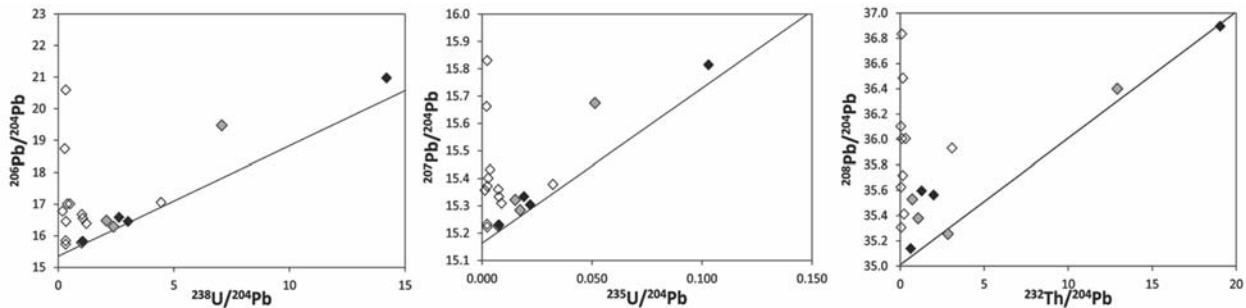


Figure 2 - plots investigating the in-situ decay of U-Th in Reef deposit samples. Symbols are same as figure 1. Reference isochron of 1925 Ma is shown in each plot.

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A New Rusk County: Producing an new Precambrian geological map from new field observations and compilations of historic geological/geophysical datasets

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Precambrian rocks of the Penokean Orogeny within the Wisconsin Magmatic Terrane host world-class volcanogenic massive sulfide deposits (VMS) near the southern limit of the Canadian Shield (DeMatties, 1994). This is a Paleoproterozoic juvenile and continental arc sequence consisting of mafic to felsic volcanic assemblages, sedimentary sequences, and associated plutonic rocks that are about 1.8-1.9 billion years old (Schulz & Cannon, 2007). These deposits are significant sources of metals such as zinc, copper, lead, silver and gold in the form of sulfide minerals. The size and concentration of VMS deposits in Wisconsin gives the region potential to become a world-class mining district. However, a thick cover of glacial deposits and Paleozoic sedimentary strata limit the Precambrian exposure in the region and make regional tectonic and metallogenic interpretations of the Precambrian geology difficult. The primary objective of this project was to create a new geologic map of the Precambrian geology in Rusk County, Wisconsin, describing the distribution and petrologic characteristics of the Precambrian bedrock beneath this cover by compiling historic geological and geophysical datasets with new field observations and combining these observations with modern geochemical data and interpretations.

There were two phases of mapping related to this project. The first phase included sampling rocks from drill core, which was collected during mineral exploration and mining activities, in regions in the county where no bedrock exposure exists. These uppermost parts of these drill cores were described and sampled. The second phase involved field mapping and sampling of Precambrian rock outcrops in the rivers, road cuts, and quarries throughout Rusk County. All samples were processed and analyzed via XRF to determine their major and minor element geochemistry and thin sections from select samples were used for petrographic analysis.

The volcanic and tectonic insights gained through petrographic and geochemical interpretations were compiled and geospatially integrated with historic geologic maps published through the Wisconsin Geological and Natural History Survey (Mudrey et al. 1987) and aeromagnetic geophysical surveys available through the USGS (Daniels & Snyder, 2002) to better constrain the Precambrian lithostratigraphic units beneath Cambrian and Quaternary cover. This integration of field mapping, drill core sampling, and data compilation of geological and geophysical datasets in ArcGIS created a new and improved geological map of the Precambrian rocks of Rusk County (Figure 1). In addition, petrographic and geochemical interpretations of these rocks will add a new layer of understanding that will significantly improve our tectonic, volcanological, and metallogenic framework of the Precambrian bedrock in Wisconsin.

Based on aeromagnetic geophysical patterns, distribution of various volcanic, plutonic, and sedimentary rocks, and geochemical domains throughout Rusk County, we subdivided the Precambrian geology into four supracrustal units: (1) Blue Hills Metasedimentary Unit, (2) Thornapple Metavolcanic Unit, (3) Flambeau-Jump River Metavolcanic Unit, and (4) Weyerhaeuser-Forks Metavolcanic Unit. The Blue Hills Metasedimentary Unit underlies the northwestern portion of the county and has abundant outcropping quartzite and phyllite. The Thornapple Metavolcanic Unit is located throughout the north-central portion of the map forming a moderately magnetic geophysical domain and hosts the Zn-Cu-Pb Eisenbrey VMS

deposit. Bedrock exposures and core samples observed included primarily intermediate volcanic assemblages with lesser basalt, rhyolites, and iron formation forming. The lower magnetic portion of the southeastern part of the county is predominantly mafic to intermediate volcanic assemblages that hosts the Flambeau Cu-Au VMS deposit. Lastly, the Weyerhaeuser-Forks Unit underlies the highly-magnetic areas in the southwest and northeast parts of the map. Here, alkali basalts and associated intrusions have been discovered. The aeromagnetic geophysical surveys also allowed us to better identify felsic plutonic bodies in the mapping area.

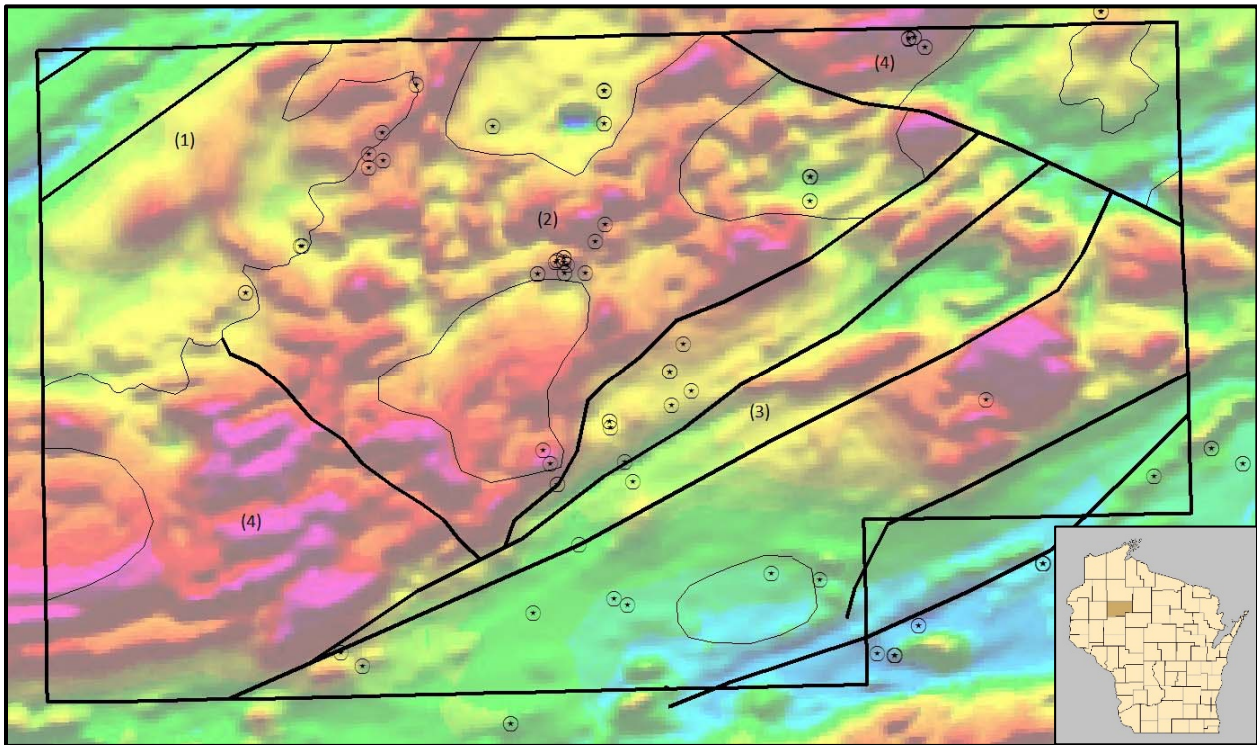


Figure 1: Preliminary Precambrian geology of Rusk County, Wisconsin, showing major faults (bolded lines) and contacts (thin lines) shown in relation to the airborne magnetic geophysical map for the state (Daniels & Snyder, 2002). Circles in mapping area show where core and field samples have been collected and analyzed. Numbers 1 through 4 correlate to approximate location of supracrustal units described in text.

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Geochemical and petrological studies on the origin of Ni-Cu sulfide mineralization at the Eagle and Eagle East intrusions in Marquette County, Michigan

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The Eagle deposit is a small, high-grade Ni-Cu-bearing sulfide deposit located in the north central portion of Michigan's Upper Peninsula in Marquette County. The Eagle and the Eagle East intrusions, separated by 600m, are parallel to the east-west trending Marquette-Baraga dike swarm that is associated with ~1.1 Ga Midcontinent Rift System magmatism (Ding et al. 2010). Recently, in 2014 a discovery was made within the Eagle East intrusion. Drilling by Lundin Mining Corporation intersected a small section of high grade sulfide minerals near the base of the intrusion. The purpose of this study is to characterize the magmatic sulfide deposit at Eagle and its relationship to the surrounding country rocks. The relationship between Eagle sulfide ores and the newly discovered Eagle East sulfide ores have also been analyzed.

Petrographic analysis has shown that Eagle and Eagle East sulfide mineralization consists of three minerals: pyrrhotite, pentlandite and chalcopyrite. Olivine crystals tend to host sulfide minerals, indicating that an immiscible sulfide liquid must have formed prior to olivine formation. Rare earth element (REE) analysis from peridotite samples at Eagle and Eagle East confirms that the intrusions are very similar. The REE diagram depicts similar concentrations and patterns of REEs with shallow slopes for the two intrusions, indicating low degrees of crystal fractionation and high degrees of partial melting that formed the magmas at Eagle and Eagle East.

Sulfur isotope analysis was also performed on sulfide ores from Eagle, Eagle East, Michigamme Formation rocks and Archean basement rocks. The three intrusive sulfide zones (disseminated, semi-massive, and massive) for both intrusions are within the range of 0‰ to 5‰. Michigamme Formation rocks display $\delta^{34}\text{S}$ values from 6‰ to 20‰. Archean basement rocks display a wide range of sulfur isotope values from -11‰ to 7‰. The $\delta^{34}\text{S}$ values reported from the main sulfide ore bodies of Eagle and Eagle East are indicative of slight enrichment of ^{34}S , most likely caused by interaction and mixing of mantle-sourced sulfur (0‰) with surrounding crustal-sourced sulfur. Country rock contamination $\delta^{34}\text{S}$ signatures found within the immiscible sulfide liquid may have been averaged or totally erased through interaction of mantle magmas with the crustal sulfide liquid. $\delta^{34}\text{S}$ signatures could have additionally been altered by the mixing of sulfur from the two crustal sources, Archean and Proterozoic rocks. Archean rocks typically have a range of high and low $\delta^{34}\text{S}$ values from -11‰ to 7‰, while Proterozoic rocks have high $\delta^{34}\text{S}$ values of 6‰ to 20‰. Mixing of sulfur sourced from Archean rocks with sulfur sourced from Proterozoic Michigamme Formation rocks could have averaged the $\delta^{34}\text{S}$ signatures seen in the ore bodies to ~3.5‰.

Previous researchers Ding et al. (2012) determined $\delta^{34}\text{S}$ values at the Eagle deposit for disseminated and massive sulfides ranging from 0.3‰ to 4.6‰, while semi-massive sulfides were characterized by $\delta^{34}\text{S}$ values ranging from 2.2‰ to 5.3‰. The $\delta^{34}\text{S}$ values of sulfide ores hosted in the intrusion are much lower than would be expected if assimilation of crustal-sourced sulfur had occurred. Ding et al. (2012) attributed the low $\delta^{34}\text{S}$ values within the Eagle intrusion

to mantle-sourced sulfur (0‰) coming into contact with sulfide liquid that had higher $\delta^{34}\text{S}$ values attributed to crustal rock assimilation and depleting the $\delta^{34}\text{S}$ values closer to 0‰.

However, since the $\delta^{34}\text{S}$ values within intrusive sulfides at both Eagle and Eagle East in this study are so similar, it is proposed that mixing of crustal-sourced sulfur from the Michigamme Formation rocks and Archean basement rocks could have additionally averaged the $\delta^{34}\text{S}$ values seen within the intrusions to a range between 0‰ to 5‰. Mixing of sulfur derived from crustal rocks and the interaction of mantle-sourced sulfur could have averaged the $\delta^{34}\text{S}$ values seen within the ore bodies from that of crustal contamination signatures.

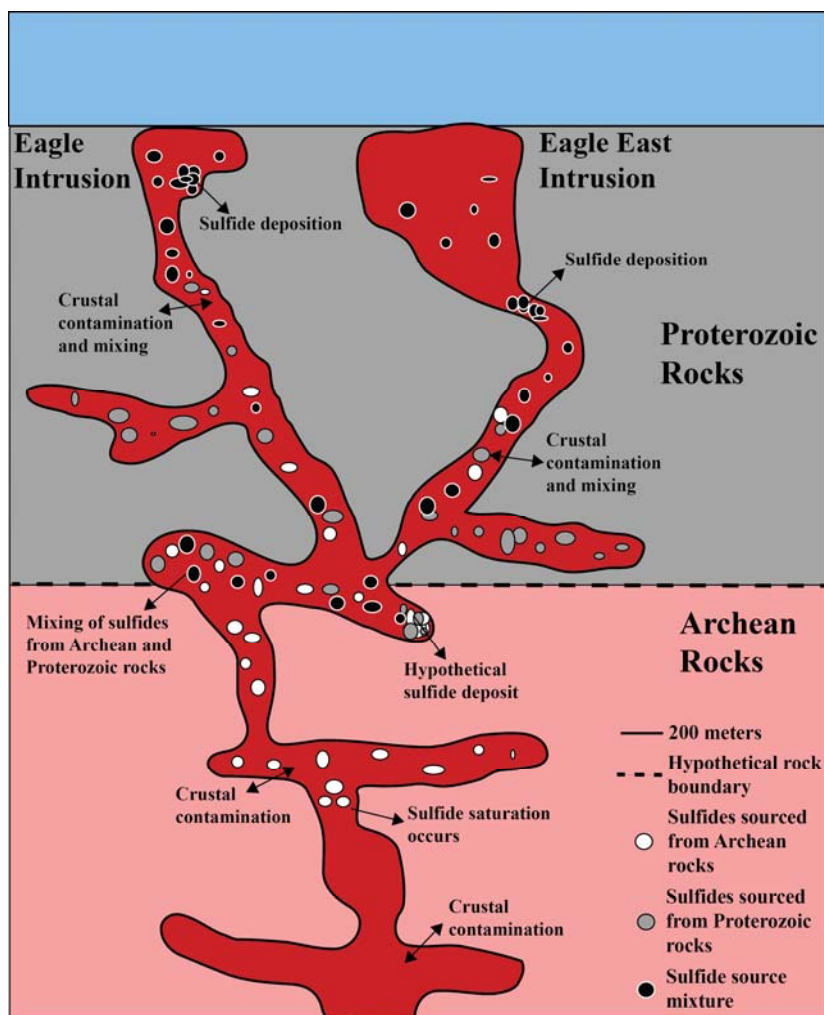


Figure 1: Hypothetical diagram illustrating a model for the mixing of sulfur from Archean and Proterozoic sources, resulting in $\delta^{34}\text{S}$ values between 0‰ to 5‰ for sulfides hosted within the Eagle and Eagle East intrusions.

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Preliminary Observations of the Ultramafic Metavolcanic Rocks in the Eastern Portion of the Shebandowan Greenstone Belt, northwestern Ontario

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The ultramafic metavolcanic rocks in the eastern portion of the Shebandowan greenstone belt are located within Conmee Township (Fig. 3), which is part of the larger Wawa-Abitibi terrane (Stott et al., 2010). The Shebandowan greenstone belt has been divided into three main assemblages based on geochronological studies by Stott and Corfu (1998) and Lodge (2012), namely; the Greenwater assemblage (circa 2720 Ma), the Kashabowie assemblage (circa 2695 Ma) and the Shebandowan assemblage (circa 2690 to 2680 Ma).

This study focuses on the ultramafic metavolcanic rocks of the Greenwater assemblage that are best exposed in the Bateman trenches dug by Linear Metals in 2008 and the Freewest and Dawson trenches (Fig. 3). These trenches display near continuous stratigraphic sections including spinifex-textured flows, massive flows, flow breccia and quenched autobreccia (Lodge, 2014). Other rock types in this assemblage include mafic, intermediate and felsic metavolcanic rocks, as well as metasedimentary rocks.

Preliminary field observations include the identification of preserved macroscopic primary volcanic textures, despite the greenstone belt being metamorphosed to greenschist facies. The macroscopic textures and associations are important because on a microscopic scale, all primary mineralogy has been altered and metamorphosed. Spinifex texture is widely observed throughout the map area; this texture is formed through undercooling of a very hot magma and is a critical feature of komatiites (Fig. 2). Associated with the spinifex-textured komatiite in the Linear Metals trenches is a unit with polyhedral jointing analogous to columnar jointing in basaltic flows (Arndt 2008). In several localities an ultramafic volcanic breccia with spinifex-textured angular fragments in a glassy groundmass is present (Fig. 1). These macroscopic textures are difficult to put into context with the surrounding units because of the gaps in the trenches where contacts should exist.

Preliminary geochemical analyses show that these rocks have lower than normal MgO for a true komatiitic rock, with an average of 11.2 wt% but some samples showing up to 27wt% MgO. The SiO₂ content is also higher than normal for a typical komatiite, with an average of 50%, with some samples as low as 40wt%. The Ni content fits well with the typical komatiite composition with an average of 607ppm and average Cr content of 1133ppm. This suggests that the ultramafic rocks in the study area are predominantly komatiitic basalts with rare komatiites. Both komatiites and komatiitic basalt display spinifex texture.

Further mapping will be completed in the summer of 2016 in order to correlate the units over a wider area. Petrographic studies are underway and geochemical data will be analyzed once obtained. By combining detailed petrographic studies with whole-rock geochemical data this study will investigate fractionation trends, mixing and crustal contamination signatures to understand the evolution of the komatiites. This study will produce a detailed map of the komatiites and develop a model for the formation of these rocks.



Figures 1) Spinifex texture in ultramafic rock, from Linear Metals trench 2) Ultramafic breccia from Freewest trench

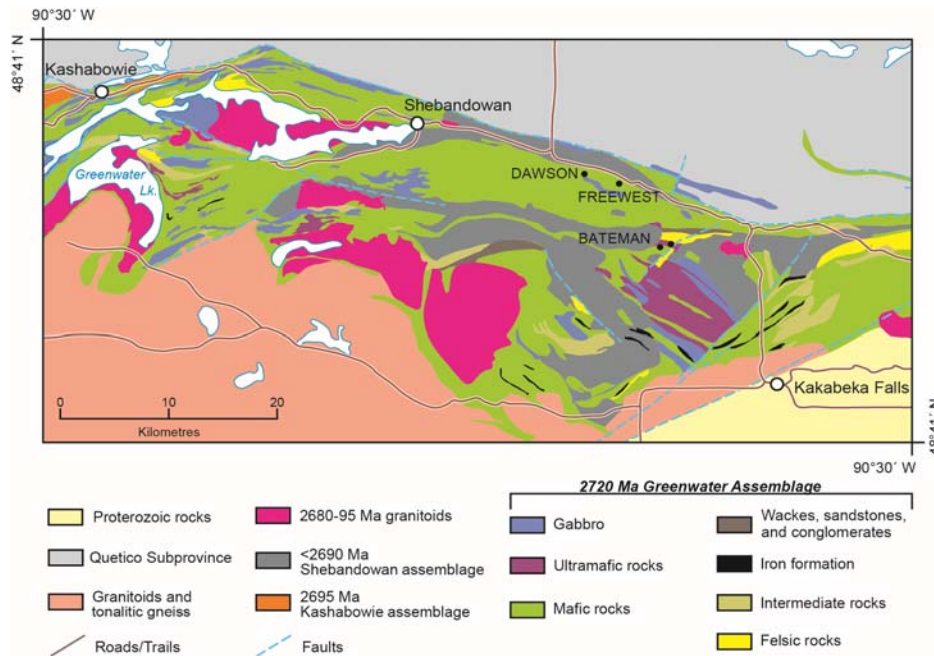


Figure 3) Regional geology map showing the location of study areas within Conmee Township in relation to the Shebandowan greenstone belt. Bedrock geology modified from Santaguida (2001a, 2001b) and Lodge et al. (2015).

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The Minnesota Taconite Workers Health Study: Environmental Study of Airborne Particulate Matter - 2015 Update

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The Natural Resources Research Institute (NRRI) conducted a detailed characterization of mineral dust in northeastern Minnesota. The purpose of this research was to evaluate the effects of present emissions from taconite mining and processing on air quality throughout the Mesabi Iron Range (MIR) (Figure 1) by characterizing airborne mineral particulate matter (PM) within currently operating taconite processing plants, in MIR communities surrounding taconite mining/processing operations, and in population centers in Minnesota not associated with taconite mining. Characterization studies of age-dated lake sediments were also conducted to determine the composition of past PM deposition. NRRI's sampling and characterization work represents the community/environmental component of the Minnesota Taconite Workers Health Study, a broad University of Minnesota (UM) research effort involving both the NRRI and the School of Public Health.

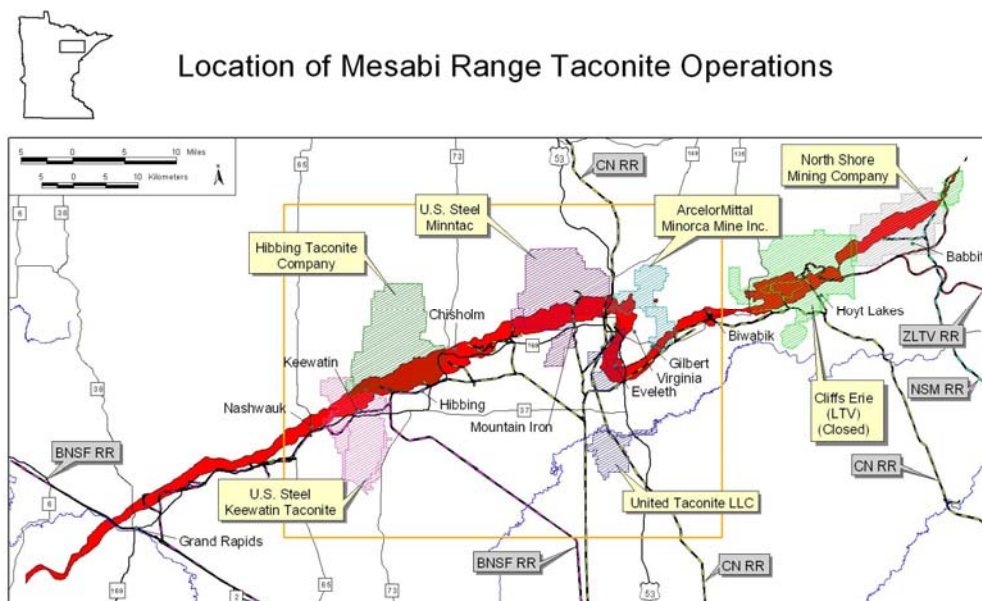


Figure 1. Locations of taconite processing plants on the Mesabi Iron Range being sampled during this study (after Oreskovich and Patelke, 2006)

Air sampling was performed within taconite operations, MIR communities, and non-MIR communities by NRRI scientists during both winter and summer seasons from 2009-2012. Sampling was conducted at four process locations within taconite operations, including: 1) secondary crushers; 2) magnetic separators/concentrators; 3) agglomerators/ball drums; and 4) kiln/pellet discharge areas. Community sampling took place on centrally-located rooftops of public buildings, or in the case of the northern most background site, in a remote sampling location to evaluate the air quality away from the MIR. Sampling and analytical techniques for all project work are described in detail in several reports that are in preparation. NRRI's research methods do not produce exposure data, and are not meant to provide data for regulatory purposes.

NRRI has evaluated the physical (gravimetric, morphology, concentration), mineralogical, and chemical characteristics of the PM obtained from sampling at the taconite operations and MIR/non-MIR communities. This included analysis of 55 taconite plants; 73 northeastern Minnesota community and 6 Minneapolis samples. Age-dated lake sediment cores were collected from Silver Lake in Virginia, MN, on the central MIR, and “North-of-Snort” Lake on MIR’s eastern end, near Babbitt, MN, and 36 analyses were completed. The results provide historical data regarding potential mineralogical inputs from iron mining and processing from ~1840 (which pre-dates iron mining on the MIR) to the present, including the natural ore mining to taconite mining transition period.

Community results are as follows:

- measured particulate matter concentrations for PM_{2.5} in all MIR communities have been below 12 µg/m³, and for total PM have been below 16µg/m³;
- particulate matter concentrations on the MIR are similar to those in the two NE Minnesota background sites (Duluth NRRI, Ely Fernberg site), and are lower than those obtained in Minneapolis (UM Mechanical Engineering Building rooftop);
- mineral particulate matter in community air samples reflects the mineralogy of the Biwabik Iron Formation and other Minnesota rock types and geological materials;
- elongate mineral particles (EMP) are present in MIR community ambient air samples; however, asbestiform amphiboles were rarely observed (1 asbestiform amphibole EMP in ~22,800m³ of air).

Taconite plant results are as follows:

- plant environments can be dusty, with the most dusty environments associated with the agglomerator and kiln discharge areas;
- particulate matter levels (PM₁, PM_{2.5}, PM₁₀, and total PM) show a slight increase in the five MIR communities during plant/mine activity, but this increase is not statistically significant compared to when the plants were not operating.
- significantly higher concentrations of EMPs, including amphiboles, were detected in the eastern most plant compared with the other five plants, but the morphology of these structures more closely resembles cleavage fragments rather than asbestiform morphologies.

Lake sediment results are as follows:

- a water elutriation method developed by Webber et al. (2008) was effective for isolating PM_{2.5} particles from age-dated sediment intervals.
- the mineralogy of isolated PM_{2.5} EMPs reflects bedrock and glacial geology in the vicinity of both lakes.
- a portion of the insoluble PM within the sediment of the two MIR lakes is most likely attributable to atmospheric inputs (fugitive dust) generated by historic iron ore/taconite mining activity

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Lithostratigraphy and Ore Petrology of the Eisenbrey Zn-Cu-Pb Deposit, Rusk County, Wisconsin

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The primary objective of this research is to study the geological characteristics of the poorly understood Eisenbrey Zn-Cu-Pb deposit in Rusk County, Northwestern Wisconsin. Volcanogenic massive sulfide (VMS) deposits are significant sources of metals such as zinc, copper, lead, silver and gold in the form of sulfide minerals (Franklin et al. 2005). Despite the proximity of the Eisenbrey deposit to the better known, past-producing Flambeau Cu-Au VMS deposit, there has been essentially no research completed on the rocks hosting the Eisenbrey nor has there been any volcanic and tectonic linkages made to the strata hosting the Flambeau. Understanding the tectonic and metallogenic framework of the Eisenbrey and any potential genetic relationship to the Flambeau deposit will significantly improve our understanding of the Precambrian geology of northwestern Wisconsin (e.g. DeMatties 1996). The samples of the metalliferous ores and their host rocks are currently being analyzed to determine their petrographic and geochemical characteristics and to re-interpret the economic geology of this region.

Initial phases of research included visiting the outcrop exposures of the Paleoproterozoic rocks that host the deposit that are present along the Thornapple River approximately 4 miles northwest of the Flambeau deposit. The ore horizon is present as interlayered sulfide-bearing magnetite-chert iron formation and strongly foliated chloritic mafic units exposed with a total stratigraphic thickness of ~10 m. The ore horizon is hosted in variably silicified intermediate to felsic volcanoclastic rocks. These Paleoproterozoic rocks are intruded to the north and west by gabbro and pyroxenite dykes associated with the midcontinent rift.

The second phase of this research involved re-logging and sampling of historic drill core collected during mineral exploration (Figure 1). The ores and altered rocks are hosted within a thick pile of moderately foliated dacitic volcanoclastic unit consisting of tuffs and lapilli tuffs that have feldspar phenocrysts up to 3mm in size and composes 1-2% of the rock. These rocks are altered to an anthophyllite-magnetite±sericite schist that is generally fine grained and has a moderate foliation. This altered unit is variably mineralized and contains thin pyrite stringers and disseminations.

Based on lithostratigraphic associations, the Eisenbrey deposit is a bimodal felsic-type deposit. In addition, the presence of an ore horizon dominated by sphalerite, chalcopyrite, pyrite and pyrrhotite supports this classification (Franklin et al., 2005). However, massive to semi-massive ore are generally low grade and are composed of mostly pyrrhotite and pyrite with local abundances of chalcopyrite and sphalerite composing a combined 10% over 1-2 meters. Reflected light and scanning electron microscopy are currently being carried out on these ores. In addition to confirming the major ore minerals, trace amounts of silver telluride have been found.

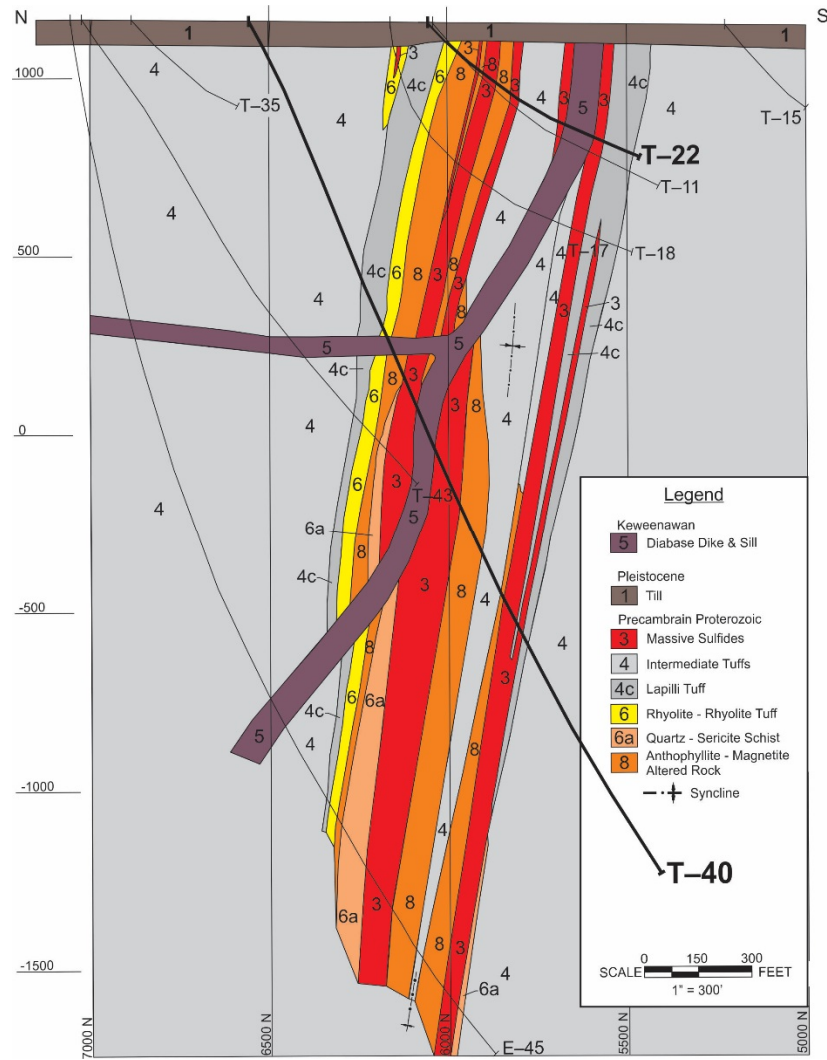


Figure 1: Representative cross section of the Eisenbrey VMS deposit showing location and stratigraphic context of holes logged for this study (bold lines and labels). Figure modified from LeBerge (1996).

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Incommensurately modulated structure of plagioclase as an indicator of cooling history of igneous rock

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Plagioclase feldspar is the most abundant group of mineral in the earth's crust. Intermediate plagioclase formed at low temperature display a highly ordered aperiodic structure, resulting in satellite diffractions with irrational indices (*e*-reflections), which has been an enigma for more than half a century since its first discovery in 1940 (Chao and Taylor 1940). Three plagioclase crystals of similar chemical composition from Duluth igneous complex were analyzed with single crystal X-Ray diffraction. The incommensurately modulated structure were solved in (3+1)D hyperspace. Detailed differences of the crystal structures were revealed, while the structures solved with only main reflections are basically the same as volcanic labradorite.

The plagioclase in troctolite (An₅₇) and gabbro (An₅₄) from Duluth Igneous complex has a modulation period of 42Å and 45Å respectively, which are significantly larger than the modulation period of a metamorphic plagioclase with similar composition (~30Å). The structures display density modulation with an amplitude of less than 10 mole%, which is hard to characterize accurately due to the limited second order satellite reflections (*f*-reflections). The plagioclase in the anorthosite with composition of about An₆₀, on the other hand, shows a modulation period of 40Å. The structure is obviously more ordered than the other two crystals, displaying a density modulation of 18 mole% in amplitude. The number of *f*-reflections collected is about triple of the troctolite sample and more than 10 times of the gabbro sample. The fitness of the refinement result and the experimental data is significantly better. The degree of orderliness characterized by the X-Ray diffraction data indicates a different origin of the anorthosite from the Duluth Layered Series. Thus the modulation period and amplitude of *e*-plagioclase may be used as an indicator of the cooling history of the host rock.

Chao, S.H. and Taylor, W.H. (1940) Isomorphous replacement and superlattice structures in the plagioclase feldspars, pp. 76-87.

Nine years of capstones: A summary of Precambrian Research Center field camp capstone projects in the Neoproterozoic Knife Lake Group and associated rocks, central Boundary Waters Canoe Area Wilderness, Minnesota

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An important mission of the University of Minnesota-Duluth's Precambrian Research Center (PRC) is training students to map the geology of Precambrian terranes. The Arrowhead region of Minnesota generally—and the Boundary Waters Canoe Area Wilderness specifically—contains some of the best localities for such mapping. Since its inception in 2006, the PRC has conducted 9 seasons of geologic field camps in the region (2007-2015), with an emphasis on the rock types, alterations, and structures that host much of the world's metallic mineral endowment. The training involves several weeks of mapping exercises, followed by a “capstone” project conducted in small groups with practicing geologists. These projects test student skills by creating new geologic maps in areas of poorly known geology, which benefits both students and mentor organizations. Students conduct field work for 7-8 days in remote locations, then

remarkably turn their observations into geologic maps during 4 days and present their results before an audience of academic, government, and industry professionals.

This presentation describes one set of capstone projects in the central part of the Boundary Waters Canoe Area Wilderness (BWCAW). The geology was mapped to varied levels of detail by the author and 41 students during 9 individual capstone projects. Although these capstones focused on lithologic and structural complexities of the Neoproterozoic Knife Lake Group (Fig. 1), the resulting maps provide details about other parts of the Wawa subprovince of the Archean Superior Province, rare diabasic dikes, unconformity-bounded Paleoproterozoic iron-formation, and the basal Mesoproterozoic Duluth Complex.

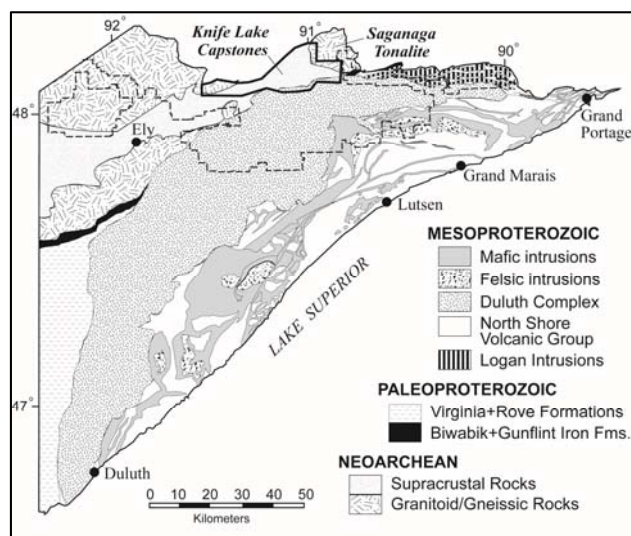


Figure 1. Generalized bedrock geologic map of NE Minnesota showing the area of capstone mapping projects (outline labeled “Knife Lake Capstones;” ~ area of Fig. 2). The Neoproterozoic unit labeled “Supracrustal Rocks” encloses both older volcanic sequences and younger, largely sedimentary ones. Outline of BWCAW is dashed.

Volcanic, sedimentary, and intrusive rocks of the Knife Lake Group comprise a Timiskaming-type extensional basin and its apparent wall- and floor-rocks. The geologic units are parceled into structural lozenges separated by anastomosing shear and fault zones (Fig. 2). Although rock types are comparatively pristine within each lozenge, correlation of units from one fault-bounded block to another is challenging. Nevertheless, these projects attempt to “unstrain” the rocks within each lozenge to reveal stratigraphic variations that may reflect fluctuations in original basin geometry and progressive erosional dissection of basin wall rocks. Understanding the lithologic details and the apparent post-depositional tilt of individual lozenges of rock is essential to this objective. An integrated depositional and tectonic model of the basin is evolving using Gruner’s (1941) work, unpublished theses, and capstone mapping. Basin evolution appears to have involved early subaerial calc-alkalic volcanism synchronous with sediment deposition, uplift, erosion, and surface weathering that contributed alluvium to localized fault basins. This was followed by development of braided streams, and transitioned to subaqueous deltaic and turbiditic deposition. Strata containing clasts of the ca. 2690 Ma Saganaga Tonalite were deformed and metamorphosed at ca. 2680 Ma, which brackets basin development within a 10 Ma period.

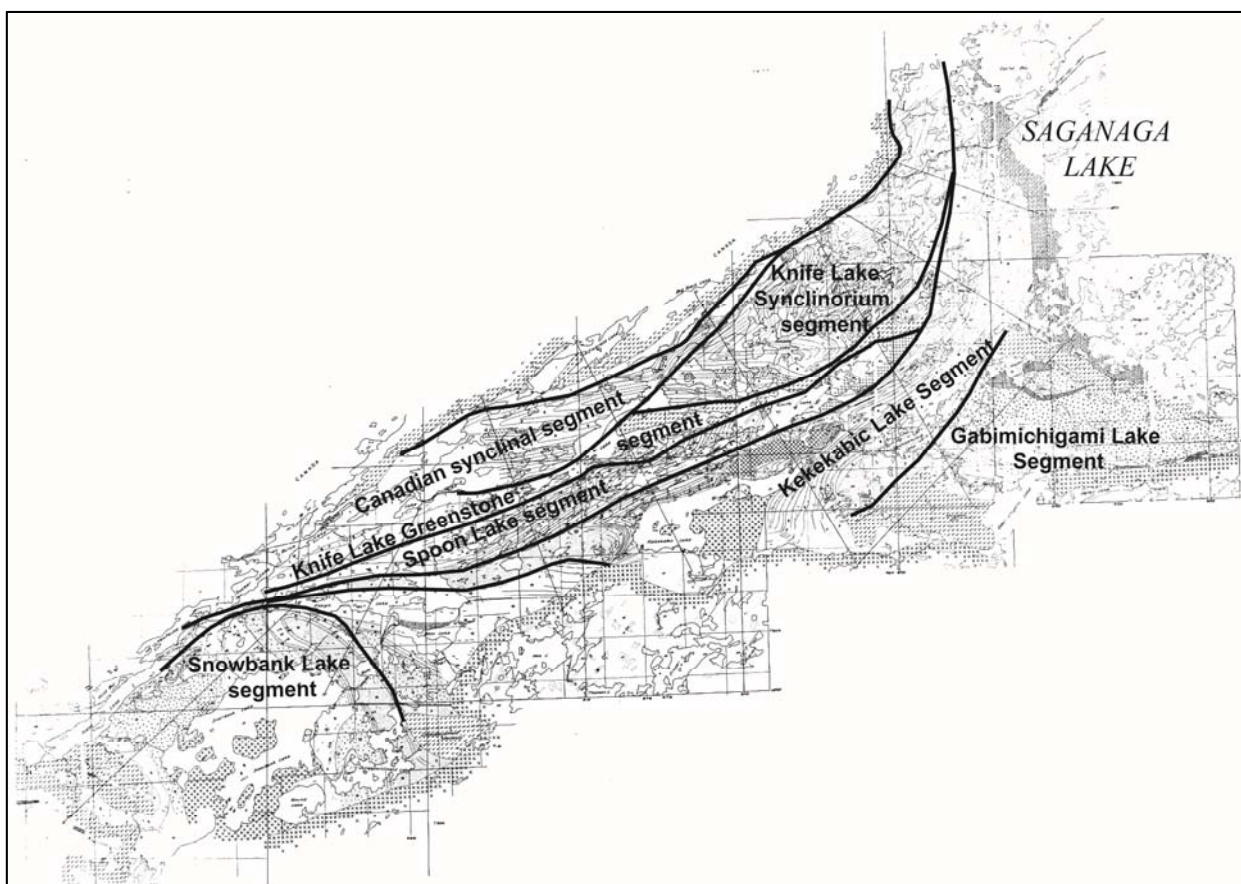


Figure 2 Historic geologic map of central BWCAW from Gruner (1941) showing fault zones that bound lozenges or segments of internally coherent strata. Bounding faults are modified from Gruner's work based on subsequent mapping.

Mapping funded in part by the Precambrian Research Center contributed to the following publications:

- Abstracts—Institute on Lake Superior Geology, 2008-2016. Lead authors/meeting years: Jirsa 2008, 2009, 2012; Fahrenkrog 2010; Birkmeier 2011; Korman 2013; Mulcahy 2014; Krogmeier 2015; Christenson 2016.
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Geochemistry of Seine River metaconglomerates from Mine Centre, Ontario: interpreting fluid flow and volume changes during deformation with implications for strain analysis

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Ductile shear zones are formed by tectonic plate interactions and are often thought to be deep-seated equivalents to faults. They can act as barriers or conduits for fluid flow, with many acting as both conduits for zone-parallel flow and barriers to cross-zone flow (e.g. Selverstone et al., 1991; Yonkee et al., 2013). Fluids have major impacts on deformation; they can alter deformation mechanisms, metamorphic reactions, and strain accumulation. Even though fluid is such an important factor in deformation, it is difficult to study due to its transient nature. Geochemical analyses may be used to interpret fluid conditions during deformation. In particular, major element geochemical analyses may be conducted to determine whether fluids assisted depletion of soluble elements resulting in volume changes (e.g. Newman and Mitra, 1993; Srivastava et al., 1995; Yonkee et al., 2003). This method has been used to demonstrate significant volume loss in some shear zones (e.g. up to 70% reported in Newman and Mitra, 1993) and none in others (Srivastava et al., 1995).

The Seine River metaconglomerates in the Rainy Lake region of northwestern Ontario, Canada are located in a wedge of deformed rocks between the Quetico Fault and the Seine River-Rainy Lake Fault. The metaconglomerates underwent ductile deformation and greenschist facies metamorphism. They have clasts with varied lithology including felsic to ultramafic volcanic and granitoid clasts. Selected samples were previously analyzed to determine strain magnitudes by Czeck et al. (2009); they demonstrated that different clast types had differing rheologies that resulted in a range of strain magnitudes. Strain magnitude also varied across the region (Fig. 1). In the most highly strained outcrops, significant carbonate alteration suggests that fluid flow was an important factor during deformation, and there may have been a symbiotic relationship between fluid localization and enhanced deformation.

Geochemical analysis and evaluation for fluid-rock interaction had not previously been performed on the Seine River metaconglomerates and was the focus of this study. Compositions of several clast types (granitoids, mafic volcanics, and felsic volcanics) were determined for a range of strain magnitudes using major and minor element X-Ray Fluorescence (XRF).

Results from 36 analyses were reviewed to see if there were significant changes in composition from low to high strain sites. These preliminary results show a high degree of variability amongst major constituents within the same clast type at individual sites. For a given clast type, the mean concentrations of all major elements are indistinguishable at low and high strains (Table 1). For example, in granitoid clasts, the mean concentration of SiO₂ is 70.43% (st. dev. of 4.17%) at low strain and 69.13% (st. dev. of 6.06%) at high strain.

The high variability and overlap of data for all major elements indicates that either A) there was no significant clast volume change between low and high strain regions or B) the geochemical signal of any volume change is masked by a large variability in initial compositions. So while there is clear evidence from alteration patterns that fluid flow differed between low and high strain outcrops, this did not result in measurable volume change with increasing strain. The inherent heterogeneity in metaconglomerates allows them to be extremely useful for strain analysis, but complicates geochemical characterization. In order to capture the variability within the population of clasts and determine the extent of fluid-assisted alteration in

deformation, we may require a larger sample size similar to the study by Yonkee et al. (2013) in deformed diamictites.



Figure 1. Seine metaconglomerates at a variety of strain magnitudes. A) Low strain (\$1 CAD for scale). B) Moderate strain (lens cap for scale). C) High strain with carbonate alteration (\$1 CAD for scale)

	Granitoid Clasts				Mafic Clasts				Felsic Clasts			
	Low Strain (n=6)		High Strain (n=7)		Low Strain (n=3)		High Strain (n=10)		Low Strain (n=6)		High Strain (n=7)	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Na ₂ O	5.36%	0.33%	5.51%	0.84%	5.25%	0.77%	4.34%	1.84%	4.54%	0.87%	5.30%	1.66%
MgO	0.62%	0.28%	0.58%	0.30%	1.59%	0.68%	2.33%	0.83%	0.76%	0.62%	1.07%	0.80%
Al ₂ O ₃	11.84%	0.48%	12.83%	2.32%	14.20%	0.60%	15.02%	1.54%	13.83%	3.05%	13.03%	2.24%
SiO ₂	70.43%	4.17%	69.13%	6.06%	63.98%	2.79%	63.64%	4.78%	63.21%	6.76%	72.35%	5.22%
P ₂ O ₅	0.05%	0.02%	0.11%	0.07%	0.11%	0.01%	0.14%	0.09%	0.06%	0.05%	0.09%	0.05%
K ₂ O	0.68%	0.36%	0.68%	0.30%	1.17%	0.63%	1.65%	1.30%	2.08%	1.44%	0.81%	0.75%
CaO	4.93%	1.25%	4.52%	2.11%	3.49%	0.66%	1.89%	1.18%	6.22%	4.38%	1.38%	0.98%
TiO ₂	0.21%	0.10%	0.31%	0.18%	0.71%	0.43%	0.76%	0.25%	0.25%	0.23%	0.53%	0.44%
Fe ₂ O ₃	1.47%	0.69%	1.95%	1.05%	5.01%	2.21%	6.31%	1.98%	2.16%	2.05%	3.27%	2.19%

Table 1. Results of XRF analysis. The compositional signatures of each clast type are highly variable. In all cases, the mean concentrations of elements are indistinguishable between low and high strain when the standard deviation is taken into account.

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SEDIMENTOLOGY OF A PRE-VEGATATION PROGRADING DELTAIC ASSEMBLAGE: THE MESOPROTEROZOIC KAMA HILL AND OUTAN ISLAND FORMATIONS, ONTARIO

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This study focused on the Kama Hill and Outan Island Formations of the Sibley Group located approximately 30 to 130 km east and northeast of Thunder Bay, Ontario. A lack of associated extrusive igneous rocks has resulted in an imprecise age for the unit of between approximately 1460 to 1339 Ma (Rogala, 2003; Franklin, 1978). A paleomagnetic pole position for the Sibley plots at 1400 Ma on the apparent polar wander path (Robertson, 1973) and further defines its age. The principle objective of this study was to more precisely understand the depositional environment of this section of the Sibley Group. Cheadle (1986) interpreted the Kama Hill Formation as a mud-flat environment, but Rogala (2003) and Rogala et al. (2007) believed it to be a prograding deltaic assemblage. Previous studies have found evidence of desiccation cracks in outcrop, as reported by Cheadle (1986) in the lower Kama Hill Formation. While other studies have interpreted the depositional environments as deltaic to fluvial; with fining upwards sequences as channel-fill deposits and coarsening upwards sequences as sub-aqueous distributary mouth bars (Rogala, 2003; and similar to Haszeldaine, 1984).

The lithofacies associations in this study were constructed based on four cored drill-holes within the Nipigon Plate and currently reside in the MNDM Conmee core library. Along with drill-core logging of the 340m thick interval, multiple thin sections were prepared to analyze the microstructures and grain arrangements.

The drill cores were cross-correlated and divided into different lithofacies associations (LA) based on grain-size and primary sedimentary structures: *fine-grained, silt-rich, rippled sandstone LA*; *cross-stratified LA*; *massive medium-grained sandstone LA*; *fine-grained sandstones LA*; *silt-rich, very fine-grained sandstone LA*, and *upper fine-grained LA*. The lower two thirds of the succession studied consists of two coarsening- and thickening-upward sequences, with the lower one terminating in distributary mouth bar sediments and the upper one overlain by a fluvial floodplain-channel assemblage.

Finally, there are desiccation cracks within the interval studied; however, they are located within areas in the upper third of the core interpreted as subaerial floodplain, where a sediment moisture deficit could easily occur. Also, the lower contact with the Rosspoint Formation was difficult to determine in some core and as the Rosspoint has mud cracks it may have led to confusion in the past. The most striking difference between this delta and modern examples is that the upper distributary mouth bar is mostly composed of massive, thick sandstones that appear to have been deposited by slurry flows down the distributary channels, and may be related to the lack of vegetation.

This study gives unique insight into the primary structures of deltas, the role that flora and fauna play within deltaic systems, and has determined that the Kama Hill and Outan Island Formations were formed in deltaic environments.



Figure 1: NB-97-04 depth: 489.75-495.64 m; shows possible mud crack located within the floodplain assemblage.



Figure 2: NB-97-04: 692.00 to 697.87m; mud-chip conglomerate between rippled sandstones located in the silt-rich lithofacies association.



Figure 3: He-02-02 depth; 166.3 to 170.8 m; nice ripple lamination with numerous mud drapes present, part of the fine grained lithofacies association.

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Mineralogy and petrology of the diamondiferous Madonna Dyke, Marathon, ON

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Diamondiferous intrusive lamprophyric dykes have been identified occurring just North of Lake Superior, near Marathon, Ontario. The Madonna Dyke is a diamondiferous occurrence that lies within the Superior Province within a region host to multiple alkalic and carbonatitic complexes, many of which are linked to the intrusive activity resulting from the Midcontinent rifting event at 1.1 Ga. The Madonna Dyke is a hypabyssal rock with medium- to fine-grained phenocrysts of pseudomorphed olivine, spinel, pyroxene, and amphibole set in a dark green to black altered groundmass of mainly calcite after melilite, REE-poor apatite, phlogopite and spinel. Pseudomorphed olivine occurs as microphenocrysts, phenocrysts and rare macrocrysts replaced by serpentine, magnetite and calcite. A few fresh olivine macrocrysts show mantle compositions ranging from Fo₉₁ to Fo₉₂. Clinopyroxenes are aluminous diopside with Al₂O₃ ranging from 3.11 to 14.47 wt.%. Groundmass mica show kinoshitalite – phlogopite compositions with up to 4 wt.% BaO and 20.9 wt.% Al₂O₃. Spinel-group mineral compositions follow Magnetic Trend #2 – the Titanomagnetite Trend, where spinels range in composition from aluminous magnesian chromites to titanian magnesian chromites to titanian chromites to members of the ulvöspinel-magnetite series. Spinel-group minerals occur as red chromium spinel phenocrysts to macrocrysts with magnesium-rich cores and iron-rich rims, often associated with olivine phenocrysts and macrocrysts. They also occur as fine-grained opaque groundmass titanomagnetites with altered cores, and as reaction products forming a necklace texture around olivine. Atoll spinels are present. Although the Madonna Dyke shows some textural and petrogenetic features of kimberlites, the mineralogy, including the presence of calcite after melilite and amphibole, are analogous with an ultramafic lamprophyre of Alnöitic affinity.

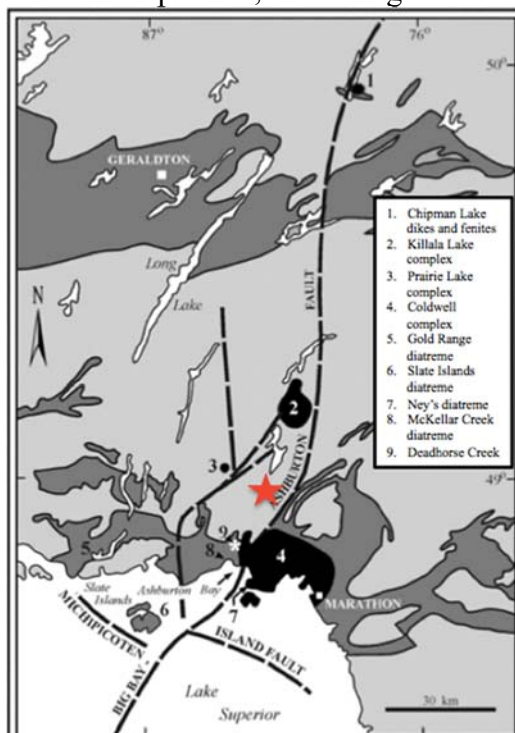


Figure 1: Regional map of the area north of Lake Superior between Terrace Bay and Marathon showing the alkaline complexes and structures of the area (after Smyk et al., 1993). The location of the Madonna Dyke is denoted by the red star.

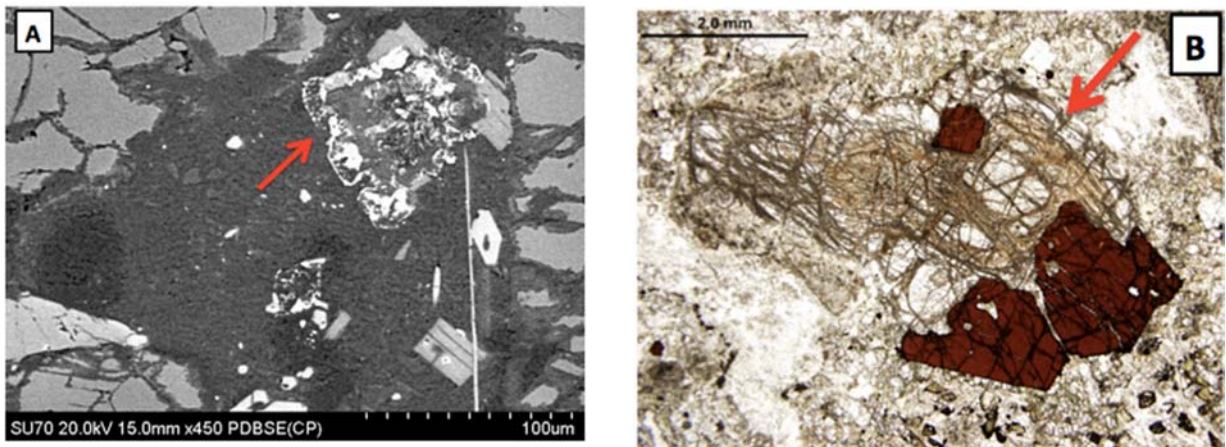


Figure 2: Microphotographs of the Madonna Dyke. (A) SEM-BSE image with red arrow pointing to an atoll spinel with a resorbed spinel core, calcite lagoon and magnetite rim. (B) Transmitted light PPL image of a pseudomorphed olivine macrocryst and reddish-brown chromium spinels.

Preliminary Report on the Palynology of the Gervais Formation (Pleistocene), Red Lake County, Minnesota

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The Gervais Formation (Harris and others, 1974) is the oldest glacial till stratigraphic unit exposed in northwestern Minnesota. The Gervais is exposed just above river level in a cutbank of the Red Lake River about 2 km northwest of the city of Red Lake Falls. The Gervais is described as very dark gray, unbedded, silty, clay loam that contains few pebbles and cobbles. The outcrop sampled is unusual because there are abundant wood fragments, small logs, insects, and mollusk fragments—concentrated in the lower portion of the formation. Reported radiocarbon dates for the organic materials are: >39,000, >39,900 (wood), >46,900 (coleopterous material) (Shotten and others, 1975). An Early Wisconsinan or pre-Wisconsinan age is suggested for the formation (Harris and others, 1974). Most of the pebbles within the Gervais Formation are carbonate rock although a few pebbles of coal were found. Harris and others (1974) suggested that the till of the Gervais Formation was derived largely from glacially modified lacustrine and fluvial sediment and the silts and clays were probably locally derived.

Five samples for palynological analysis were collected from the Gervais Formation. The samples were macerated using standard palynological extraction techniques (Doher, 1980). Palynomorph bearing residues were mounted on microscope slides using glycerine jelly as a mounting medium. All five of the samples from the Gervais Formation proved to be palyniferous. Palynomorph preservation ranges from excellent to moderately good.

Algal palynomorphs are common, including *Pediastrum*, multiple forms of peridinioid dinoflagellate cysts, chorate dinoflagellate cysts, and several additional palynomorph morphologies that are most likely produced by algae. Some of the algal forms are more typical of marine or marginal marine environments. Very few spores of ferns and mosses are present; they include spores that were probably produced by *Sphagnum*. Conifer grains are relatively common and include grains morphologically similar to *Pinus*, *Picea*, *Abies*, and *Thuja*. Angiosperm pollen is also common. In addition to pollen forms that would be typical of Pleistocene environments, angiosperm pollen forms that are stratigraphically restricted to the Upper Cretaceous and Paleogene are also present. Included are the form taxa, *Aquilapollenites* sp., *Tricolpites microreticulatus*, and *Retitrescolpites anguloluminosus*.

Overall, there is a mixture of palynomorphs that were most likely locally produced and palynomorphs that are reworked from Upper Cretaceous and Paleogene rocks. There is little obvious difference in preservation between grains that may represent local palynomorph production versus those that are reworked. The presence of pollen indicative of Upper Cretaceous and Paleogene rocks and the abundance of peridinioid and chorate dinoflagellate cysts strongly suggests that Upper Cretaceous and Paleogene rock materials were entrained by the glacier; such rocks are common to the west and northwest of the Red Lake Falls area in North Dakota and Saskatchewan where Upper Cretaceous and Paleocene aged marine and terrestrial rock units are exposed or subcrop beneath glacial materials. The clay-rich lithology of the Gervais Formation is also consistent with glacial transport of the shales and mudrocks from a northwesterly source area.

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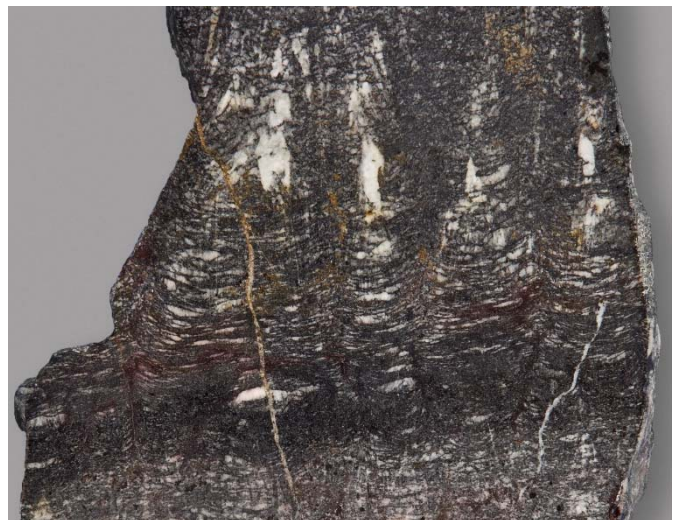
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Giant Domes of the Mosher Carbonate, Steep Rock, Ontario

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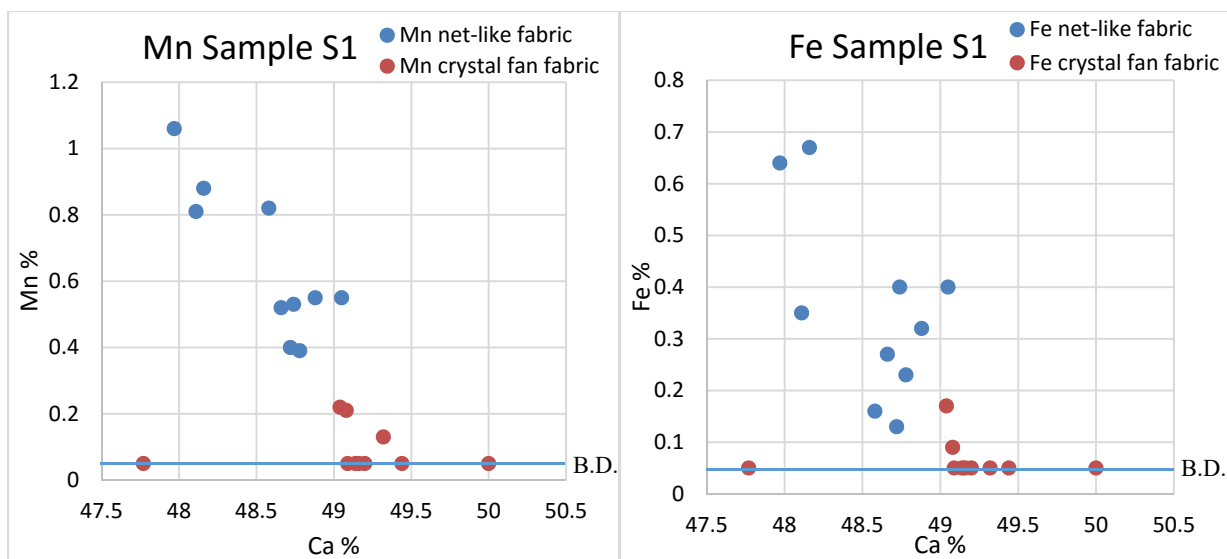
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The Giant Dome Lithofacies of the Mosher Carbonate is located within the Steep Rock Group, 5 km north of Atikokan in northwestern Ontario. The Mosher carbonate has been studied for over a century and is one of the most well preserved Archean carbonate sequences in the world (Grotzinger, 1989). The giant domes that constitute the uppermost 70m of the 500m thick carbonate sequence are referred to as the Elbow Point Member. The giant domes are meter-sized, elongate in shape, and are internally composed of alternating crystal fan fabric and cusped and net-like microbialite fabric. Crystal fan fabric consists of centimeter to decimeter tall radiating fans that have been argued to be originally aragonite that precipitated directly on the seafloor. Microbialites have been described by Sumner (1997) as being composed of draping, mat-like laminae, vertically oriented microbial support structures, and cement-filled voids. While both microbialite and crystal fan fabrics are common in the late Neoarchean to early Proterozoic, their occurrence with one another, and even as alternating lithologies, may be isolated to the Neoarchean. Therefore, the environmental factors that controlled the development of the giant domes, and their unusual internal composition, is not well understood.



The image on the left shows the giant domes of the Mosher Carbonate with a hat for scale. The image on the right shows the lithologies seen within the giant domes and their interbedded nature. Polished slab is 10cm wide.

The giant domes have been interpreted to have formed in a rimmed platform environment, where a fluctuating redox boundary resulted in the alternation in precipitation of aragonite and calcite (Fralick and Riding, 2015). Major element geochemical data suggests that the crystal fan fabric contains lower concentrations of Mn and Fe than adjacent fenestrate microbialite fabric, while Mg concentrations do not show any change in concentration. This trend may be a good indication that the primary mineralogy of the crystal fan fabric and fenestrate microbialite fabric is different. Similarly, cements that are interstitial and mantle the crystal fans contain relatively higher concentrations of Mg than the crystal fans themselves, indicating that the deposition of the fans and void-filling cements was not synchronous.



Atomic % of Mn and Fe vs. Ca for adjacent net-like microbialite and crystal fans. The net-like fabric displays higher concentrations of both Fe and Mn relative to the associated crystal fan fabric. B.D.=below detection.

There are also features that suggest periodic subaerial exposure of the giant domes. A well-preserved desiccation surface with a typical polygonal crack pattern can be seen on a sample that in cross-section displays cusped fenestrate fabric. The association of the support structures with the cracks that are expressed on the surface, leads to consideration of a desiccation related process in their formation. While there is an otherwise complete lack of preserved desiccation surfaces, Fe-rich red-brown surfaces that intervene between the interbedded layers of the giant domes at periodic intervals may represent desiccation or subaerial exposure surfaces that were later destroyed. Lastly, Fe- and carbon-rich dissolution surfaces separate some adjacent lithologies. These surfaces are continuous and can be seen to mark the boundary between crystal fan fabric and fenestrate microbialite fabric within certain samples. They are composed of microcrystalline quartz and zoned dolomite. The dissolution surfaces may represent hardgrounds that formed as a result of a hiatus in sedimentation and/or as result of early cementation and provided preferential fluid pathways for later silicification.

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A COMPARISON OF BARABOO-INTERVAL (LATE PALEOPROTEROZOIC) IRON-FORMATION, SOUTHERN WISCONSIN

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The Freedom Formation is part of the Baraboo-interval sediments that were deposited after ca. 1.71 Ga and later deformed by the 1.6 Ga Mazatzal Orogeny (Holm et al., 1998; Medaris et al., 2003). In the Baraboo Range of Sauk County, Wisconsin, the Freedom Formation conformably overlies the Seeley Slate, which conformably overlies the Baraboo Quartzite (Weidman, 1904). The Freedom Formation is only present in the subsurface and is known from 100-year-old drill cores that were recovered along the hinge of the Baraboo syncline (Sauk County). In Sauk County, the Freedom Formation is divided into two members: a lower iron-rich unit made up of finely-interbedded to interlaminated, hematite-rich micrite, chert, and silt- to clay-sized siliciclastic material and an upper member comprised of dolomitic micrite. Drill cuttings from three wells between 5 and 50 miles (8 to 80 km) east of the Baraboo Range recovered hematite- and magnetite-rich fine-grained sediments and quartzite, suggesting that the Freedom Formation is present, along with Baraboo-interval quartzite, in the subsurface across a broad area in southern Wisconsin. Additionally, a drill core recovered in 2015 by the Wisconsin Geologic and Natural History Survey encountered iron-formation beneath the Cambrian Elk Mound Group in the subsurface of Dodge County, some 50 miles (80 km) east of Baraboo.

The purpose of this research is to compare the Freedom Formation recovered from the Baraboo Range, Sauk County to the iron-formation recovered from drill core in Dodge County in order to better constrain correlation of Baraboo interval sediments. To accomplish this, we identify and log primary lithofacies from the Sauk and Dodge County drill cores. We also analyze thin sections from each lithofacies for mineralogical similarities. Lastly we collect elemental concentrations using a handheld Thermo Fisher Niton XL3t GOLDD+ X-ray fluorescence (XRF) analyzer on each core at 1 foot intervals to compare geochemistry with lithofacies observed through core logging.

We identify three main lithofacies in core from both locations: 1) gray to white, apparently massive carbonate, 2) laminated carbonate and gray siltstone, 3) laminated red (hematite-rich) siltstone, gray siltstone, and white to gray carbonate. In thin sections we observe a primary mineral assemblage of fine-grained carbonate, quartz, hematite, chlorite, and magnetite. The relative abundance of these minerals varies by lithofacies. Recrystallization is evident in thin section and core from both locations, but is more pronounced in the Dodge County location. Elemental XRF analyses broadly correlate with lithofacies for the Sauk County location, but the eight feet of iron-formation recovered from Dodge County did not provide enough material to meaningfully compare XRF analyses from both locations. From observation of core and thin section, we show that the Precambrian iron-formation recovered from drill core in Dodge County has similar lithofacies and mineralogy to the Freedom Formation of Sauk County. Based on these similarities, we conclude that the iron-formation from Dodge County is correlative with the Freedom Formation of Sauk County. Therefore, the Baraboo-interval sediments include an iron-formation that is laterally continuous over a more than 1,000 km² area in southern Wisconsin.

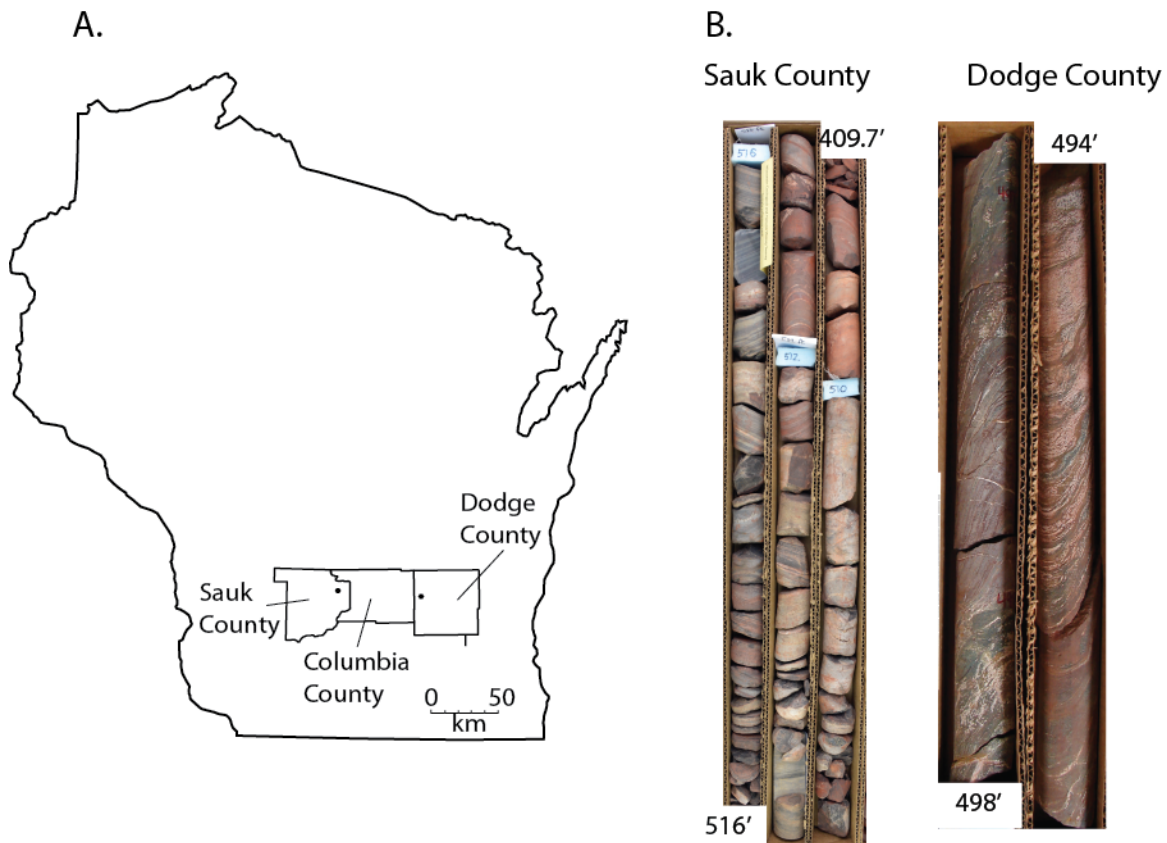


Figure 1. A. Location map. Dots show location of cores that recovered iron-formation in Sauk and Dodge counties. B. Core photographs showing examples of iron-formation recovered from each location.

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Millennial-scale shoreline bluff retreat rates in the western arm of Lake Superior

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In the far western arm of Lake Superior, shoreline bluff retreat is a significant problem for land-use planners and policymakers, who require knowledge of the bluff retreat rate. Previous studies of shoreline bluff retreat employ careful differencing of aerial photos, in combination with direct field observations (e.g., Johnson and Johnston, 1995; Swenson et al., 2006; NRPC; 2012). The large variability in retreat rate reported in these decadal-scale studies reflects the intrinsically stochastic nature of hillslope and coastal processes. By extension, these short-term studies downplay the importance of the well-documented, long-term rise in relative lake level (RLL) driven by differential uplift of the Lake Superior basin (e.g., Mainville and Craymer, 2005). On longer (geologic) timescales, this RLL rise is the fundamental driver for bluff retreat.

We developed a simple geometric-kinematic model of bluff retreat rate that addresses explicitly the role of RLL rise. Our model is motivated by the observation that the nearshore lake bottom is a surface of non-deposition and erosion (Kemp et al., 1978; Thomas and Dell, 1978). In the sequence-stratigraphic nomenclature, the lake bottom is a wave-cut transgressive ravinement surface, *sensu* Posamentier and Allen (1999). On the north shore, where the bluff material is Precambrian bedrock, this transgressive surface shows a very sparse cover lag of cobbles and boulders atop a clean (eroded) bedrock surface; on the south shore, where the bluffs are composed of unconsolidated glacial till, the scoured surface is located lakeward of a zone of littoral drift. With knowledge of the rate of RLL rise (V_z), the dip (α) of this transgressive surface constrains the long-term bluff retreat rate (V_x) (Fig. 1). Model predictions of bluff retreat rate hold for multi-century to millennial timescales and, as such, remove much of the variability that plagues short-term measurements. One limitation of our model is that it is tied explicitly to knowledge of the long-term rate of RLL rise, which is only moderately well constrained in the western arm of Lake Superior (Mainville and Craymer, 2005; Yu et al., 2013).

We applied our model to the extreme western arm of Lake Superior. With Duluth as the western boundary, our study area extended eastward to the mouths of the Knife and Brule rivers on the north and south shores, respectively. Our study area is well suited to analyze the importance of lithology in determining long-term bluff retreat rate: Bluffs on the north shore are composed of Keweenaw-aged igneous rocks of various lithologies, whereas those on the south shore are composed of relatively homogeneous Holocene-aged glacial till. Common to both coastlines was the history of RLL rise. Recent LiDAR data (NOAA, 2010; Fig. 1) provide high-resolution bathymetry for the north shore; on the south shore, we digitized the low-resolution NOAA navigation charts.

Preliminary results of our modeling efforts suggest that millennial-scale bluff retreat rates on the south shore are as much as an order of magnitude greater than those of the north shore; this result is not surprising, given the significant difference in bulk lithology between the coastlines. Using a widely accepted RLL rise rate of $2.5 \text{ mm} \cdot \text{a}^{-1}$ in the Duluth area (Mainville and Craymer, 2005), bluff retreat rates on the north shore average approximately $5 \text{ cm} \cdot \text{a}^{-1}$, with considerable variability that correlates broadly with lithology. In map view (Fig 1), this variability manifests itself as resistant headlands and erodible bays with tall escarpments. Thick felsic volcanic units show the greatest bluff retreat rates ($>7 \text{ cm} \cdot \text{a}^{-1}$), whereas mafic intrusives, e.g. the Endion Sill, are most resistant to erosion, e.g. the Endion sill. The correlation between retreat rate and

lithology is reduced by ‘buttressing’ effects, i.e. a strong mafic intrusive unit protecting or supporting an adjacent felsic unit.

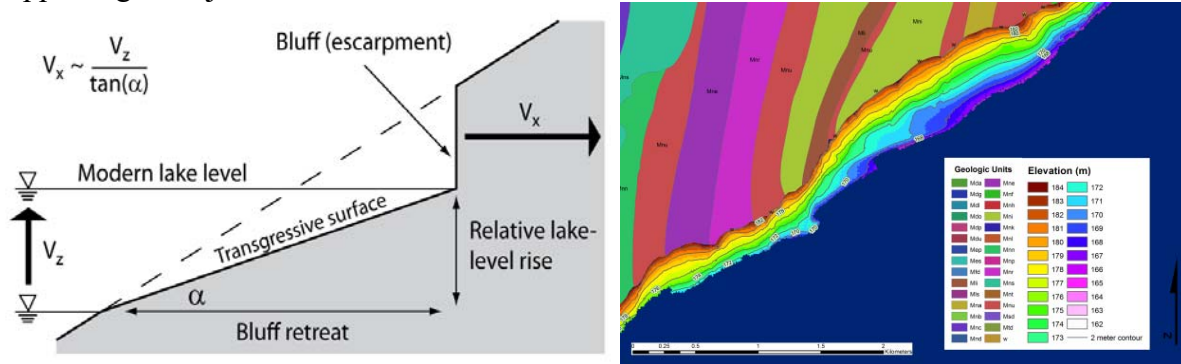


Figure 1. (Left) Cartoon illustrating relationship between transgressive surface, rate of RLL rise, and bluff retreat rate. (Right) Map of eastern Duluth shoreline, showing nearshore LiDAR-derived bathymetry (NOAA, 2010) and mapped bedrock units (Green and Miller, 2008).

Relatively low quality bathymetric data hinder somewhat the application of our model to the south shore, which consists of unconsolidated till. The relatively smooth coastline—lacking bays and headlands—and the generally planar offshore bathymetry together suggest little variability in bluff retreat rate with position along the coast. The primary difficulty in applying our model here is identifying the closure depth of the littoral zone—the region of active longshore sand transport—and, by extension, the nearshore extent of the transgressive surface. Our preliminary best estimate for the slope of the transgressive surface yields a millennial-scale bluff retreat rate of between 50 and 100 cm·a⁻¹. Our model predictions for long-term bluff retreat rates on both coastlines are within the ranges of values reported from decadal-scale studies (Johnson and Johnston, 1995; Swenson et al., 2006).

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Volcanological, Geochemical, and Geochronological Comparisons of the Gafvert Lake Sequence in Minnesota and Shebandowan Assemblage in Ontario

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The magmatic and tectonic evolution of Archean greenstone belts is complex and rocks are formed and modified by episodes of pre-deformation volcanic and plutonic events, syn-deformation orogenic magmatism and sedimentation, and post-orogenic plutonism. In addition to contributing to the understanding Archean magmatic and tectonic processes, unravelling the different episodes of the formation of these greenstone belts have important metallogenic implications. Many of the greenstone belts in the Superior province are host to a variety of base and precious metal deposits in a variety of deposit types. The well exposed Neoproterozoic greenstone belts in the westernmost part of the Wawa-Abitibi terrane present an excellent opportunity to study each of these phases of formation.

This study examines and compares the volcanic and plutonic rocks that are part of the syn-deformational Timiskaming-type assemblages in the Vermilion and Shebandowan greenstone belts in Minnesota and Ontario (Figure 1). The Gafvert Lake sequence of the Vermilion greenstone belt and the Shebandowan assemblage of the Shebandowan greenstone belt contain coeval volcanic assemblages that were deposited in D₂ transtensional basins formed during the accretion of the Wawa-Abitibi terrane to the rest of the Superior Province around 2690 Ma (Lodge et al, 2013). The interpreted geodynamic setting for these assemblages is similar to that of the Timiskaming group in the Kirkland Lake area that hosts several world-class lode gold deposits. The parallel settings between these areas have metallogenic implications and therefore it is critical to fully understand the characteristics of the Timiskaming-like assemblages in the western Wawa-Abitibi terrane to understand their potential precious metal endowments.

Newly acquired geochemical and geochronological data from the Gafvert Lake sequence and published geochemical data from the volcanic and plutonic assemblages in the Shebandowan greenstone belt (Gélinas et al. 2016) have allowed a more detailed comparison of the two assemblages. The most notable difference is that these two volcanic-plutonic deposits are compositionally distinct despite being coeval in formed in similar geodynamic settings. The Gafvert Lake sequence is notably more felsic with calc-alkalic, quartz-phyric volcanic and plutonic rocks dominating the strata. In contrast, the volcanic and plutonic rock in the Shebandowan assemblages are calc-alkalic to alkalic in composition with predominately andesitic volcanic compositions and monzonite to syenite plutonic suites. Geochemically, the Shebandowan assemblage are notably more enriched in their LREE and other incompatible elements relative to the Gafvert Lake Sequence, but are still significantly less alkalic than the volcanic and plutonic rocks that are found in the Kirkland Lake region. These compositional variations in the magmatic rocks are likely contributing to the relative differences in gold prospectivity in these greenstone belts.

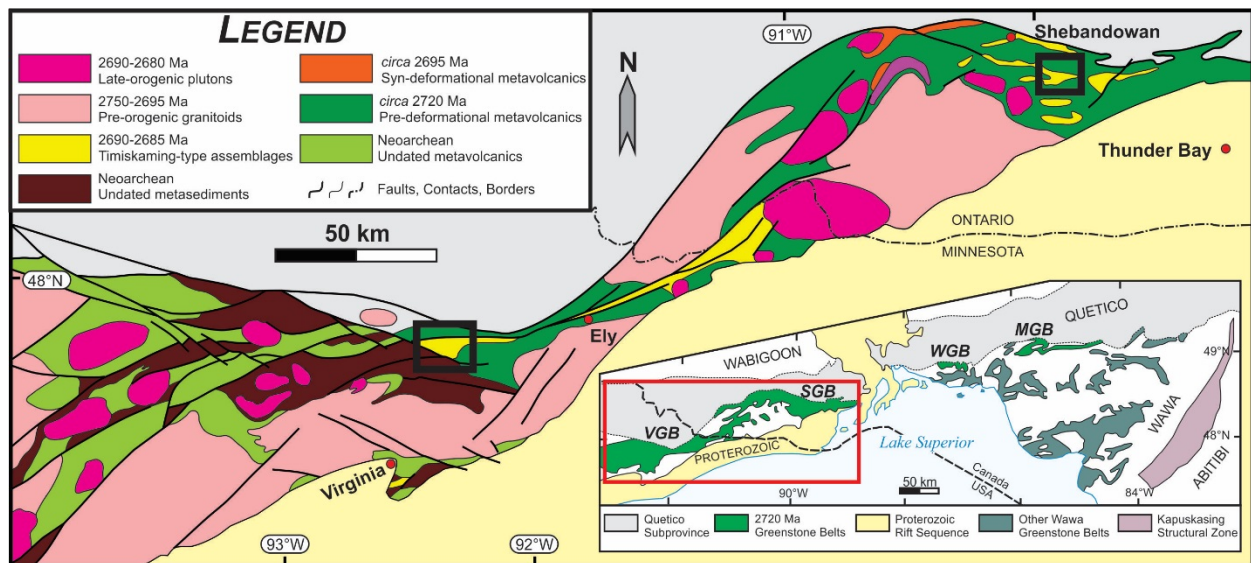


Figure 1: Regional geologic map of the Vermilion and Shebandowan greenstone belts in Minnesota and Ontario. Inset map shows location of these greenstone belts in relation to the western part of the Wawa-Abitibi terrane of the Superior Province. VGB, SGB, WGB, and MGB are referring to the Vermilion, Shebandowan, Winston Lake, and Manitowadge greenstone belts, respectively. Figure is modified from Lodge et al. (2013).

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The Eagle East Magmatic Nickel-Copper Discovery

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In June 2015, Lundin Mining Corporation announced the discovery of high grade magmatic nickel-copper mineralization similar in style to its 100%-owned Eagle deposit (5.2 MT reserves @ 3.12% Ni, 2.56% Cu), located in Michigan's Upper Peninsula. The new zone, Eagle East, is approximately two kilometers east of the Eagle mine and 950 meters deep. Assay highlights include:

- 30.85 meters of massive (MSU) and semi-massive sulphide (SMSU) with 5.23% Ni, 8.74% Cu, and 9.49 g/T combined Pt-Pd-Au. Included in this interval was 16.38 meters of MSU with 6.70% Ni, 13.59% Cu, and 16.43 g/T combined Pt-Pd-Au (DDH 14EA331I; 1,139.85m to 1,170.70m).
- 23.85 meters of MSU and SMSU with 5.34% Ni, 4.41% Cu, and 4.37 g/T combined Pt-Pd-Au, including 9.83 meters of MSU with 8.16% Ni, 7.10% Cu, and 5.14 g/T combined Pt-Pd-Au (DDH 14EA331H; 1,142.18m to 1,166.03m).

Eagle and the new Eagle East zone are hosted by separate 1Ga Midcontinent Rift-related ultramafic intrusions that intrude the Baraga Basin, a gently dipping syncline of Paleoproterozoic slates, shales, and greywackes. The intrusions are interpreted to be part of the plumbing system for the Keweenaw flood basalts that host the renowned native copper deposits. Massive sulphides at the Eagle East discovery consist of generally greater than 90% pentlandite, chalcopyrite, and pyrrhotite. Semi-massive sulphides consist of net-textured pentlandite, chalcopyrite, pyrrhotite, and silicates. Also present are magmatic breccias containing inclusions of basal cherts/quartzites and granitic Archean basement. The mineralisation is filling a sub-horizontal chonolith or conduit. Similar to the Eagle deposit, the new zone also contains horizontal MSU sills that intrude from the conduit laterally out into the surrounding metasediments. The discovery was made by applying a dynamic conduit model of magmatic sulfide mineralisation in which multiple deposits should exist along a main feeder dike. The nickel and copper tenors of the uneconomic mineralisation of Eagle East (aka Yellow Dog Peridotite) were known to be higher than that of Eagle. If mineralisation was found, the tenors predicted it could be higher grade than Eagle.

The drilling program involved attempting to trace the feeder dyke of from the lower portion of Eagle East into undrilled territory using directional drilling. Critical to the success of the program was the ability to use Devico directional drilling to steer each hole to a specific target and using of a single parent drill hole as a platform for multiple directional kick-off daughter holes. Semi-massive sulphides and magmatic breccias occupying the core of a 15 to 40 meter wide peridotite dyke were intersected early in the program and spurred further drilling along strike. Semi-massive sulphides continued to be intersected for over a 250 meter strike length to where thicker SMSU and high-grade MSU were encountered. The discovery drilling was made by using just two parent holes and a total of 15 kick-offs. The high grade zone has been traced for over a 60 meter strike length and is open in all directions. The project is still in an exploration and drill-out phase and the full extent of Eagle East has not been determined.

Preliminary groundwater age and chemistry data from cover overlying Duluth Complex Ni-Cu-PGE deposits, NE Minnesota

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The U.S. Geological Survey initiated a project in 2015 aimed at evaluating geochemical exploration methods for covered deposits in the northern Midcontinent Rift. A first round of soil and groundwater samples were collected in September from unconsolidated material overlying the Spruce Road, Wyman Creek, and Skibo deposits with the objective of determining effective sampling methodologies and characterizing the general geochemical signature of these deposits within the shallow cover. Twenty-seven water samples were collected, including 21 groundwater samples and 6 surface water samples. Groundwater samples were collected from mini-piezometers (plus one spring) having depths of mainly 0.5 to 1.5 m installed mostly in areas of suspected local groundwater discharge to wetlands. Five piezometers were installed along a flow-line-parallel transect ending at Filson Creek overlying the Spruce Road deposit. All samples were analyzed for major and trace element chemistry and stable isotopes of water (²H and ¹⁸O). Ten samples were also analyzed for groundwater age tracers, including dissolved noble gases (He, Ne, Ar, Kr, and Xe), ³He/⁴He ratio, tritium, and/or chlorofluorocarbons (CFC-11, -12, and -113). Age data were collected along with chemistry to survey the range of groundwater residence times in the cover and to investigate chemical evolution and metal transport processes along flow paths.

Groundwater conditions in the site area presented several challenges to obtaining well-constrained age determinations. For example, high DOC concentrations led to oxygen depletion in CFC sample bottles prior to analysis, resulting in CFC degradation and erroneously old computed CFC ages. However, difficulties with individual dating methods were overcome by utilizing multiple age tracers together, allowing samples to be sorted into the following age categories with reasonable confidence: <0.5 yr old; 0.5 to 2 yr old; 2 to 10 yr old, and 15 to 30 yr old. Water <0.5 yr old was distinguishable mainly based on heavy $\delta^{18}\text{O}$ values (-8 to -10.5‰ compared to -11 to -12‰; Levy et al., 2014) and warm noble gas recharge temperatures (9 to 15°C compared to 2 to 5°C), along with apparent ³H/³He ages of 0 yr, indicating 2015 spring or summer recharge. Water >2 yr old was distinguishable mainly based on apparent ³H/³He ages, with 15-30 yr old water containing substantial terrigenous ⁴He (produced from U-Th decay) and resulting low ³He/⁴He ratios 30 to 60% below atmospheric values. Tritium concentrations range from 7 to 10 TU, suggesting samples contained little pre-modern water >60 yr old.

Groundwater Cu concentrations range from <0.5 to 150 µg/L (median of 5.2 µg/L) and Ni from <1 to 348 µg/L (median of 5.5 µg/L), similar to concentrations reported for the site area in previous studies (Siegel and Ericson, 1980; Miller et al., 1992). Concentrations are generally greater at Spruce Road, where Cu and Ni medians are 21 and 19 µg/L, respectively. Groundwater Cu and Ni are roughly correlated with soil Cu and Ni concentrations at the piezometer location/depth, as expected. However, a relatively well defined negative correlation is apparent between Cu concentration and pH, as well as Ni and pH, suggesting that pH is another important control on Cu and Ni mobility in the groundwater system (Figs. 1A, B). Measured pH ranges from 5.7 to 8.6 (median of 7.2), and dissolved Cu and Ni concentrations are commonly observed to decrease as pH increases above the acidic range in mineralized settings

due to adsorption on negatively charged mineral surfaces. Figure 1C suggests that pH generally increases with age along flow paths, probably due to weathering of abundant mafic minerals (Fig. 1D). This increasing pH is the likely cause of an apparent decrease in Cu and Ni concentrations with greater age (Figs. 1E, F).

The observed negative correlation between Cu/Ni concentrations and age is significant because it may provide a limit on Cu/Ni concentrations and mobility within the deeper groundwater system in the site area, and must be taken into account in geochemical exploration approaches. It also corroborates the finding of Walton-Day et al. (1990) that discharging deeper, older groundwater in the cover may not be a primary contributor to enriched Cu and Ni concentrations in surface water in streams and wetlands in the Spruce Road area.

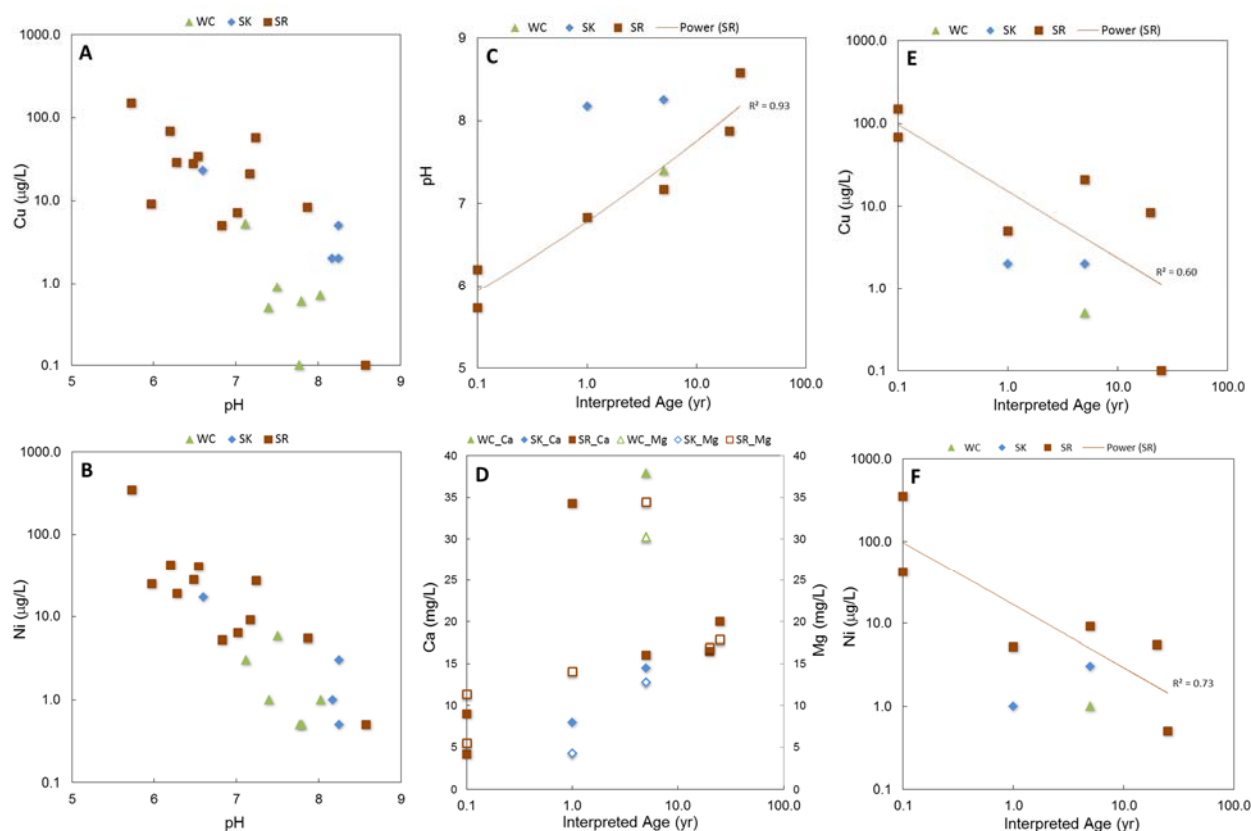


Figure 1. (A and B) Dissolved Cu and Ni concentration vs. pH. WC = Wyman Creek, SK = Skibo, SR = Spruce Road. (C) pH vs. interpreted groundwater age. Interpreted age is approximate midpoint of assigned age range referred to in text. Power law trend line is for Spruce Road samples. (D) Dissolved Ca (solid symbols) and Mg (open symbols) concentration vs. interpreted groundwater age. (E and F) Dissolved Cu and Ni concentration vs. interpreted groundwater age. Power law trend line is for Spruce Road samples.

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Small scale microanalysis of rock and mineral textures and its relationship to mineral separation

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Ore deposits form in a wide variety of geologic settings, and the processes involved in the formation of these deposits are well understood. Previous research along these lines has typically focused on more macro-scale processes such as fluid migration, chemical and metal transfer, and the associated physical and chemical changes that result (Cathles, 1981; Zientek, 2012). The ideas behind these processes have since been applied to large-scale features based on field observations, laboratory experiments, and theoretical assumptions to create models for the formation of these ore deposits. However, our understanding of how small-scale properties can influence the mineralization and alteration processes in these deposits is currently insufficient. Small-scale in-situ properties such as mineral grain size and shape variation, fracture dispersal, and the interconnectivity of pore space, along with the spatial distribution of these properties, may well play an important role in how ore deposits develop. Because mineralization styles such as disseminated, net-texture, or vein-style ores are all influenced by these properties it is important that they are investigated to see what influence they have on larger-scale processes (Prince *et al.*, 1995; Wennberg *et al.*, 2009; Holzheid, *et al.*, 2000; and Liu, *et al.*, 2014).

The primary goal of this project is to examine selected small-scale physical rock properties such as pore space, pore connectivity, fracture dispersal, as well as mineral grain size and orientation. Data collected from the examination of these properties will be used to create preliminary models for the physico-chemical formation of different mineralization and alteration styles. The investigation of these small-scale features will result in improved ore deposit models that take into account a greater set of formation variables. Materials were selected from a range of ore deposit types exhibiting different mineralization styles and/or alteration. Samples will be studied using a combination of analytical techniques such as X-ray Computed Tomography (xCT), Electro Pulse Disaggregation (EPD), and Mineral Liberation Analysis (MLA). xCT will be used to examine small cores taken from sample material to examine in-situ properties such as pore-space distribution, mineral grain morphology or fracture dispersal. EPD is being utilized as an alternative to traditional methods of material separation as this method is a touch-free way to liberate individual mineral grains. Electric pulses traveling through the material along zones of weakness, such as mineral grain boundaries or fractures, allow material disaggregation preferentially along these boundaries and preserve the original mineral grain morphology (Cabri *et al.*, 2008). MLA will be performed using a scanning electron microscope (SEM) on portions of the samples disaggregated by the electro pulse technique. The MLA will be employed to characterize the degree of ore mineral separation from gangue material and other ore minerals, grain shape patterns, and mineral grain size variation. Preliminary qualitative analysis of disaggregated material under a binocular microscope indicates that the EPD technology excels at separating ore minerals from silicate material and gangue, while preserving the original crystal morphology. The separation of individual ore minerals from each other in the case of massive ore will need to be assessed using the MLA technique because visual observation through the binocular microscope is not adequate. Samples of the disaggregated material will be scanned using an optical particle analyzer to assess the preserved crystal morphology.

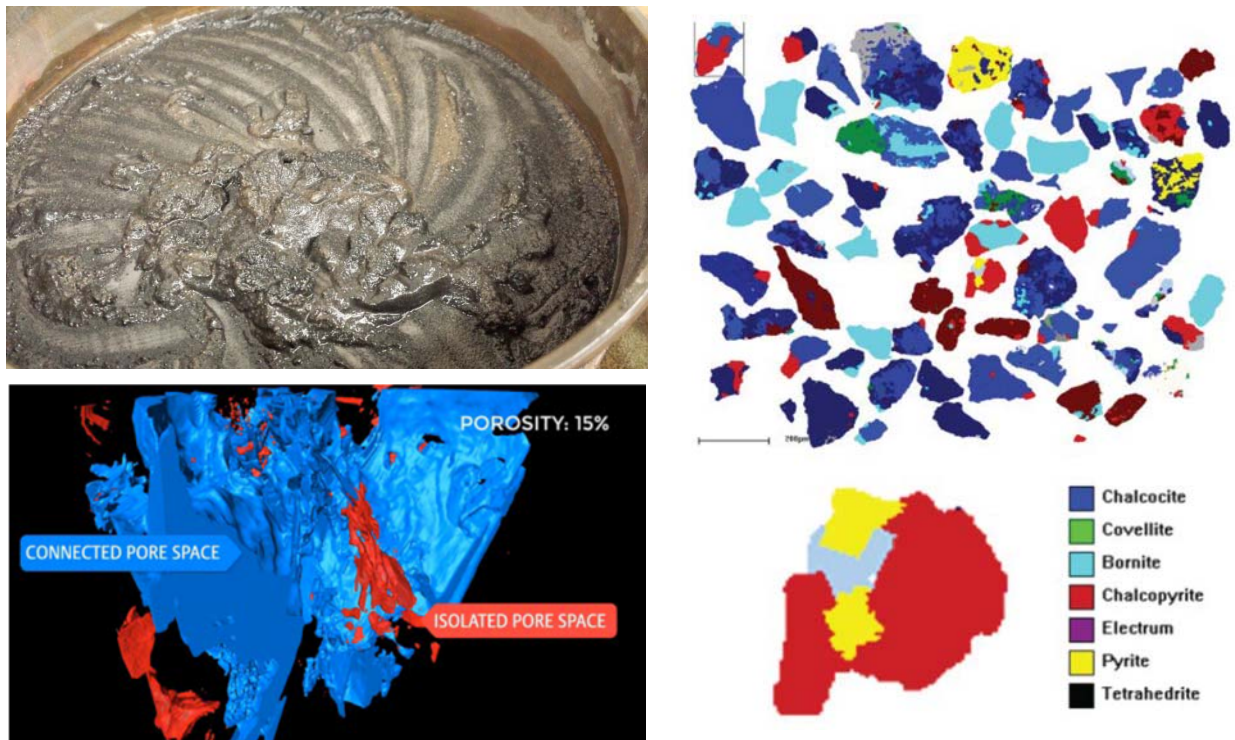


Figure 1) A sample of chromite ore disaggregated using EPD technology (top left). Sample image of a porosity analysis from a sample run through an xCT (bottom left) A sample grain mount after an MLA has been performed (right).

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Quantifying Mass Fluxes of Potassium in Weathering and Metasomatism of Paleosols

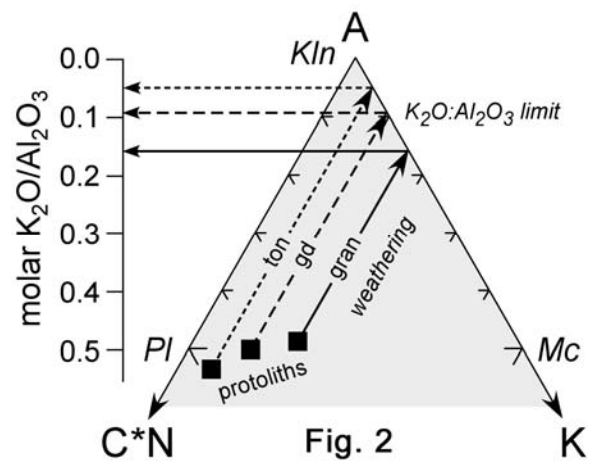
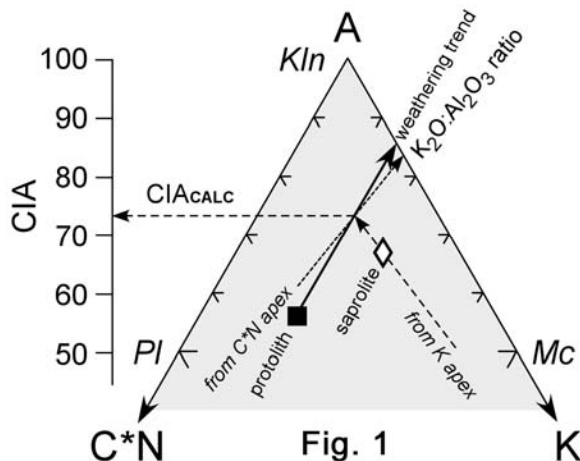
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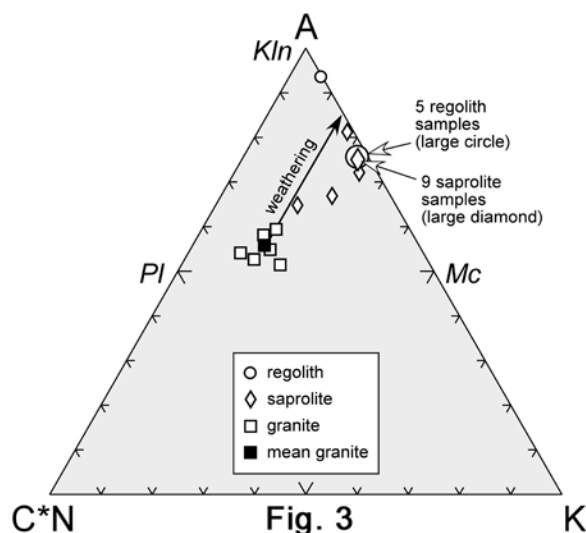
Paleosols provide significant insights into ancient climates, and weathering mass fluxes can be used to evaluate various climofunctions such as mean annual precipitation (MAP), mean annual temperature (MAT), and atmospheric $p\text{CO}_2$. However, the chemical compositions of many paleosols have been modified by potassium metasomatism, and such modification must be taken into account when calculating mass fluxes associated with weathering.

Method - The Chemical Index of Alteration (CIA) is a good measure of degree of weathering, attaining a value of 100 upon complete removal of labile oxides (Nesbitt & Young, 1982; $\text{CIA} = 100 \times \text{molar Al}_2\text{O}_3 / [\text{Al}_2\text{O}_3 + \text{CaO}^* + \text{Na}_2\text{O} + \text{K}_2\text{O}]$, where CaO^* is CaO in silicate minerals). It has been demonstrated that modern weathering produces chemical trends subparallel to the A-C*N side of an A-C*N-K plot (Nesbitt & Young, 1984; Fig. 1). The compositions of many paleosols are displaced from weathering trends towards the K apex, as illustrated by the saprolite in Fig. 1, which is a result of potassium metasomatism subsequent to weathering. The original CIA value (CIA_{CALC}) for the metasomatized saprolite can be determined by constructing a line from the K apex through the measured saprolite composition to intersect the weathering trend. A second line is then constructed horizontally from the point of intersection to the vertical CIA scale on the left, giving the original CIA value (Fedo et al., 1995). In an analogous manner, the pre-metasomatic K_2O content of the saprolite is determined by constructing a line from the C*N apex through the CIA intersection point on the weathering trend to the A-K side of the figure, where the molar $\text{K}_2\text{O}:\text{Al}_2\text{O}_3$ ratio is given (Fig. 1). The pre-metasomatic K_2O content of the saprolite is then calculated from this ratio and the measured Al_2O_3 content of the saprolite, converting molar values to wt. % (Medaris et al., 2015).

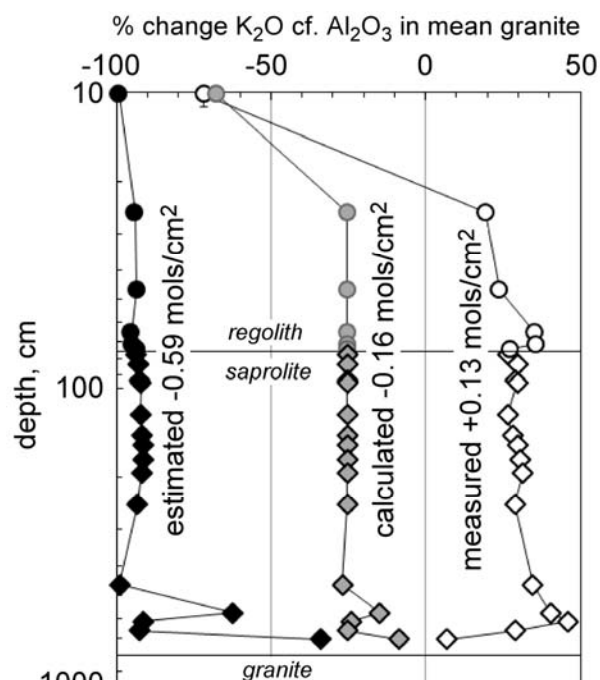


However, K_2O values calculated in this manner are only minima, because after complete removal of plagioclase, further weathering with removal of K feldspar may have proceeded along the A-K side of the figure toward the A apex. Note that the difference between minimum calculated K_2O contents and possible actual contents is a function of lithology (Fig. 2), where the difference between the two decreases with a decrease in original K feldspar content, e.g. progressing from granite to granodiorite to tonalite.

Application - The Baraboo paleosol is a mature, 800 cm-thick weathering profile that developed by intense weathering of Baxter Hollow granite at ~1700 Ma, which resulted in complete removal of both plagioclase and K feldspar from the paleosol and corresponding absence of detrital K feldspar in the overlying Baraboo Quartzite (Driese & Medaris, 2008). With one exception, all saprolite and regolith samples are displaced from the weathering trend due to ~1460 Ma potassium metasomatism (Fig. 3). Relative to the Al_2O_3 content of mean granite protolith, ~30% K_2O was added to the paleosol (Fig. 4), which integrated over the entire profile, amounts to 0.13 mols/cm² K_2O . The calculated amount of K_2O removed by weathering, following the method described above, was ~25%, corresponding to 0.16 mols/cm².



Because both plagioclase and K feldspar were completely removed by weathering, the actual % change of K_2O may be taken as equal to that of Na_2O , yielding an estimate of 0.59 mols/cm² K_2O removal over the profile (Fig. 4).



Atmospheric $p\text{CO}_2$ - Calculated atmospheric $p\text{CO}_2$ is a function, among other things, of the total mass flux of weathering. Despite the large relative difference between calculated and estimated weathering fluxes of K_2O , this difference has little effect on calculated $p\text{CO}_2$, because the flux of K_2O is small compared to the combined flux of SiO_2 , MgO , CaO , and Na_2O ($\Sigma = -5.03$ mols/cm²). Thus, $p\text{CO}_2$ for calculated and estimated K_2O fluxes is 18.1 vs. $19.0 \times \text{PIAL}$, respectively. Calculated $p\text{CO}_2$ is much more sensitive to duration of weathering and paleosol removal by erosion than to the uncertainty in K_2O flux, e.g. an increase in weathering duration from 10^5 to 10^6 years corresponds to a reduction in $p\text{CO}_2$ from 19.0 to $1.9 \times \text{PIAL}$, and $p\text{CO}_2$ prior to 10% erosion was $26.4 \times \text{PIAL}$, rather than a post-erosion value of $19.0 \times \text{PIAL}$.

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Mineralogy and Petrology of the Rabbit Foot Dyke, White River, ON

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Diamond-bearing macrocrystic, and xenolithic rocks have been identified near the town of White River, Northwestern Ontario. Initial assessment of these rocks has led to their being classified “melnoite”, a term used to describe potentially diamondiferous ultramafic lamprophyres.

Olivine occurs as two distinct phases within the rocks of the Rabbit Foot Dyke; macrocrystal olivine and groundmass olivine. Macrocrystal olivine ranges in Mg/(Mg+Fe) from Fo□□ to Fo□□, while phenocrystal and groundmass olivine ranges from Fo□□ to Fo□□. Phlogopite compositions range from Ba-phlogopite to tetraferriphlogopite. Spinel-group minerals commonly have chromite cores with titanomagnetite rims. Spinel compositions follow the “Magmatic trend 2”, the titanomagnetite trend. Spinel-group minerals can be observed displaying atoll textures. Spinel and perovskite are commonly spatially related, and are observed surrounding larger macrocrysts such as olivine in a necklace texture. Perovskite compositions are relatively pure CaTiO□, lacking any REE concentrations. In at least one outcrop of xenolithic rock, spherical magma clasts occur up to 10cm in diameter, with cores of fragmented olivine macrocrysts.

The rocks of the Rabbit Foot Dyke are in many ways analogous to kimberlite in texture and mineralogy, however, significant petrogenetic overlap with melnoites, or ultramafic lamprophyres, is evident. The macrocrystic and xenolithic rocks of the Rabbit Foot Dike are characterized here as kimberlite with melnoitic (ultramafic lamprophyre) affinity.

GEOLOGY OF THE CHEROKEE LAKE AREA OF THE BOUNDARY WATERS CANOE AREA, COOK COUNTY, MN - 2015 PRECAMBRIAN FIELD CAMP CAPSTONE MAPPING

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As a capstone mapping project for the 2015 Precambrian field camp, a crew of five students under the supervision of instructor Jim Miller conducted four days of field mapping bedrock geology in the Cherokee Lake area. This area is located in the Boundary Waters Canoe Area west of Brule Lake in Cook County, Minnesota. The area is accessible from the Caribou Trail, which heads north from Tofte to a canoe landing on Brule Lake. The 8-mile paddle and 4 portages totaling over 300 rods between the landing and Cherokee Lake started out with attempting a 5-mile paddle across the western half of Brule Lake into a strong wind and high waves. After a harrowing episode of one of our canoes being blown off course and “temporarily separated from the group - long story”, we took refuge on an island and resumed our trip to Cherokee Lake under much calmer conditions the next day.

The main objective of this capstone project was to conduct bedrock geologic mapping of intrusive igneous rocks to the northwest of the 2014 capstone projects on North and South Temperance Lakes (Beaver et al., 2014; Miller et al., 2015). That capstone mapping revealed that the footwall to the well differentiated Sawbill Lake intrusion, previously defined by capstone mapping in 2007 (Frost et al., 2007), 2009 (Blakely et al., 2009), 2010 (Brooker et al., 2010), and 2011 (Asp et al., 2011) and additional mapping by Ben Brooker for his MS thesis (Brooker and Miller, 2013), is composed of yet another as yet unnamed, well differentiated mafic layered intrusion. It was hoped that this footwall layered mafic intrusion defined in the Temperance Lakes area would project into the southern part of Cherokee Lake. This turned out not to be the case, as mostly Anorthositic Series and Felsic Series rocks of the Duluth Complex were found in the Cherokee Lake area.

Previous studies of the Cherokee Lake area include reconnaissance mapping by Grout et al. (1959) and Davidson (1977). Grout’s 1:100,000-scale map of Township 63 North, Range 4 West (Fig. XXIII, Grout et al., 1959) shows the area around Cherokee Lake to contain mostly gabbro with minor granophyric granite, intermediate rocks, and anorthositic gabbro. Davidson’s (1:24,000-scale) reconnaissance map of the Cherokee Lake 7.5’ quadrangle (Davidson, 1977) shows the dominant rock type to be anorthositic gabbro with minor areas of granophyric granite, intergranular granite, intermediate intrusives, metavolcanics, and olivine gabbro. The discovery that the gabbroic anorthosite mapped by Davidson in North and South Temperance Lakes (Davidson, 1977) and in Homer Lake (Davidson and Burnell, 1977) to the southeast was incorrect led to the suspicion that Davidson’s identification of gabbroic anorthosite in the Cherokee Lake area was also erroneous. Turns out Davidson got it right.

The 2015 capstone mapping project focused mapping shoreline exposures around the perimeter and along the many islands in Cherokee Lake. Overall, about 350 outcrops were mapped. Four general rock types were encountered in the area. In order of abundance, these were gabbroic anorthosite (90% of exposure), granophyric granite, diabase dikes, and mixed diabase/granophyre dikes. As is typical of Anorthositic Series rocks found elsewhere in the Duluth Complex, anorthositic rocks in the Cherokee Lake area are comprised of various modal types including gabbroic anorthosite, olivine leucogabbro, olivine gabbroic anorthosite and anorthosite. Most exposures show subophitic to ophitic textures with Cpx oikocrysts up to 5cm

diameter. Olivine, when present, ranges from small anhedral grains to poikilitic oikocrysts up to 3cm diameter. Fe-Ti oxides are typically subpoikilitic clots up to 0.5 cm diameter. Most rocks show some degree of foliation that is variably oriented on an outcrop scale.

Granophyric granite is salmon pink, fine- to medium fine-grained, intergranular to micrographic leucogranite, quartz monzonite, and quartz ferromonzodiorite. It contains 3-10% mafics (amphibole, oxide, and Fe-pyroxene). The large mass of granophyre east of Cherokee Lake is the western extension of the Misquah Hill granophyre of the Felsic Series of the Duluth Complex, which predates the Anorthositic Series (1108 vs. 1099Ma, Vervoort et al., 2007). Although smaller granite bodies north and west of Cherokee Lake were initially interpreted as Felsic Series equivalents (Miller et al., 2001), contact relationship observed in this study indicate that these granites cut the Anorthositic Series and are thus not part of the Felsic Series.

Small-scale intrusions cutting the Anorthositic Series rocks throughout the area include 1) thin (5-30 cm) granophyre dikes, 2) narrow (5cm-5m), very fine-grained, columnar-jointed diabase dikes, and 3) hybrid dikes of mixed diabase and granophyre. The hybrid dikes contain a mixture of medium fine-grained granophyre and aphanitic to fine-grained massive diabase, as well as intermediate hybrid lithologies. The felsic and mafic components commonly occur in sharp lobate contacts suggesting two-magma mixing. Locally, the diabase is cut by more angular apophyses of granophyre. This rock type is similar to late hybrid intrusions cutting the Sawbill Lake intrusion to the south (Brooker and Miller, 2013).

Plans for a future capstone mapping project in the area would be to map between Sawbill Lake and Cherokee Lake in order to better define the Sawbill Lake “footwall” mafic layered intrusion exposed in the Temperance Lakes.

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Continued Evaluation of the Dilatancy Model for Discordant Uranium-Lead Age Determination of Zircon

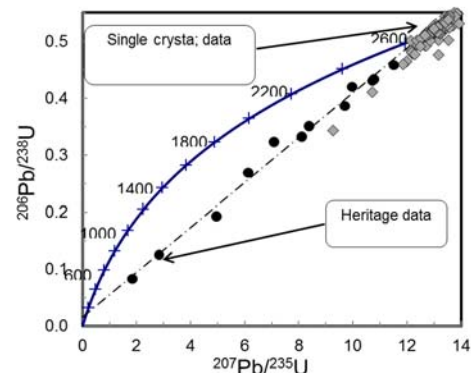
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The dilatancy model for lead loss in zircon explains the apparent linearity of data for suites of zircon plotted on a concordia diagram (Goldich and Mudrey, 1972; 1975). The lower intercept age of the discordia dates the approximate time of loss of lead through the escape of fluids which entered the metamict zircon. Time is required for the cumulative effects of U and Th decay to produce radiation damage. Uplift and erosion bring the zircon-bearing rock close to the surface and the resultant relief of pressure causes micro-fracturing and a concomitant increase in the volume or dilation of the rock. This, in turn, permits the entry of water and reactions between the water and the solid phase. Under these conditions some of the solution carrying radiogenic lead escapes. The zircon U-Pb ages become discordant.

The decay of uranium to lead yields decay equations which can be coupled by the construction of a concordia diagram, permitting the calculation of $^{206}\text{Pb}/^{238}\text{U}$, $^{207}\text{Pb}/^{235}\text{U}$, and $^{207}\text{Pb}/^{206}\text{Pb}$ ages. Substitution of uranium for zirconium leads to radiation damage in zircon that produces a complex of mixture of crystallites, and amorphous compounds. The extent of the damage depends on the original uranium and thorium content and the age of the mineral. Upon subsequent events, zircon can lose or gain both uranium and lead leading to the plot of data not in concordance, but commonly along a line from the original age to a lower intercept that has been variously interpreted.

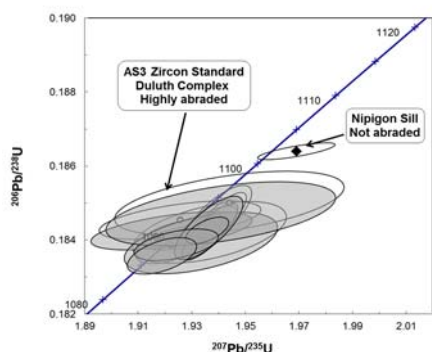
The figure 1 is a concordia diagram for the Rainy Lake district, Ontario and includes discordant heritage data (Hart and Davis, 1969), and modern single crystal concordant isotopic data (Lodge and others, 2013). The discordia line with an apparent Paleozoic lower intercept was rejected by Hart and Davis on the basis that its interpretation in the episodic lead-loss model requires an event at approximately 500 Ma for which there is no evidence. These same data, however, are subject to different interpretation in terms of the dilatancy model and may represent the exhumation of paleoplanes. Goldich and Mudrey submit that the excellent fit of the data to the 2,720-60 Ma chord clearly favors the dilatancy model in explaining the age discordance in the Rainy Lake district.



The non-analytical, or 'geologic,' reasons for discordance are (1) mixing of two or more populations of zircon, (2) Pb loss or U gain, (3) intermediate progeny product disequilibrium, and (4) initial Pb isotopic composition. Other factors such as the U isotopic composition of the sample may also be germane. Peterman and others (1986) illustrate the difficulty in interpreting of poly-episodic events in the Lake Superior region. Episodic lead loss may be by subsequent high temperature metamorphic or thermal events, or by low-temperature dilatancy and uplift.

Water, either as H_2O or as hydroxyl (OH^-) occurs both in the primary crystal structure, and in micro capillary channels and pores which result from radiation damage and stress release. The release of pressure during uplift and erosion results in expansion of the rock mass from micro fractures, rifting and jointing, particularly in quartz-rich rocks. This dilatancy permits

some of the water with dissolved radiogenic lead to escape. This low temperature lead loss model, occurs relatively late in the history of the zircon, and, therefore, the $^{207}\text{Pb}/^{206}\text{Pb}$ age commonly approaches the true age, provided the area is not reburied under a significant stratigraphic sequence.



Time since crystallization and uranium concentration determine the extent of dilatancy. As shown in figure 2, U/Pb analyses on abraded and HF leached single zircons of AS3 of the Duluth Complex containing approximately 100 ppm U (Min and others, 2000) yield a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1097 Ma. Also is plotted an unabraded zircon from a Logan Sill near Lake Nipigon (Davis and Sutcliffe, 1985) with approximately 3000 ppm U and an $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1107 Ma. The unabraded zircon has not had sufficient time for dilatancy, although the uranium content is high.

The Illinois-Deep-Hole-Project, drilled three deep core holes along the Illinois Wisconsin state line (Coates and others, 1983). The zircon discordia upper intercept and the whole rock Rb/Sr are in agreement, 1,430 Ma (Peterman and others, 1986). The lower intercept of the discordia gives an apparent age of 180 Ma. Zimmerman (1986) reports an apatite fission track age of 140 Ma at the Precambrian surface at 614 m, suggesting very strongly that the lower discordia intercept is a geologically interpretable event of uplift and exposure of the Mesoproterozoic granite.

I estimate that based on in situ stress and strain measurements (Engelder, 1993, p.267), the depth at which dilatancy is occurs is greater than 200 m but less than 1000 m.

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Emplacement and Crystallization History of Ni-Cu-(PGE) Sulfide-mineralized Peridotites in Eagle Intrusion, Upper Michigan

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The Eagle deposit and associated Eagle East prospect near Marquette, MI, are small, high-grade orthomagmatic Ni-Cu-(PGE) sulfide deposits hosted in ultramafic intrusive rocks associated with the Midcontinent Rift (Ding et al., 2010). The Eagle deposit is currently being developed by Lundin Mining Corporation. This study, which is the focus of the lead author's MS thesis at UMD, has four main goals: 1) to determine the number of magmas involved in Eagle's genesis, 2) to test an emplacement model for Eagle proposed by Lundin geologists, 3) to determine the petrogenesis of enigmatic "pyroxenite" inclusions (actually melagabbro) in parts of the Eagle intrusion, and 4) to determine the emplacement and crystallization history of the Eagle East intrusion. This talk will report on data that address the first and second goals.

With the exception of pyroxenite inclusions, the host rock of the Eagle intrusion is generally characterized by Lundin geologists as peridotite, which they subdivide into four grades of sulfide mineralization (mineralization unit types): < 5 vol% poorly mineralized (Per); 5-25% - disseminated (MPer), 25-75% - semi-massive (SMSU), and > 75% - massive sulfide (MSU). Petrographic work on silicate mineralogy conducted by Ding et al. (2010) defined four main modal rock types in Eagle and Eagle East – dunite, feldspathic peridotite, melatroctolite and melagabbro. However, they used a non-traditional classification scheme that did not discriminate between pyroxene types and did not factor in textures. In this study, petrographic observations of 121 samples from three Eagle drill cores and three Eagle East drill cores reveal that most samples representing all four mineralization types modally classify as a feldspathic lherzolite to feldspathic olivine websterite. Interpreting cumulate nomenclature from mineral habits and modes, the samples uniformly classify as olivine-clinopyroxene-orthopyroxene cumulates with variable amounts of intercumulus plagioclase, hornblende, Fe-Ti oxide, and apatite (OCpH to OCpH [α, f, a] in the cumulate code nomenclature of Miller et al., 2002).

In evaluating the number of magmas involved in the formation of the Eagle intrusion, Ding et al. (2010) interpreted variations in incompatible trace element ratios to indicate the involvement of at least two to as many as four compositionally distinct parental magmas. However, reevaluating the lithogeochemistry of the peridotitic rocks in terms of mixtures of cumulus minerals and postcumulus minerals (=trapped liquid), the range of incompatible trace element ratios can be attributed more simply to a single parental magma type. Orthocumulates, which contain elevated amounts of trapped liquid (now represented by intercumulus plagioclase, amphibole, Fe-Ti oxide, and apatite), should have incompatible trace element ratios closer to their parental magmas. In contrast, adcumulates, with little to no trapped liquid component, would be expected to have incompatible trace element ratios more reflective of the partition coefficients of their cumulate mineralogy. As shown in Figure 1, the variation of incompatible trace element ratios such as Zr/Y correlates well with the amount of Eu, Ti, and P, which are all elements associated with intercumulus minerals. Using the mineral-liquid partition coefficients reported by Bedard (1993) and taking the Zr/Y and La/Yb ratios of 6.5 and 5.0, respectively, for orthocumulates as approximating parental magma ratios (green ovals, Fig. 1), Zr/Y and La/Yb were calculated for adcumulates ranging in Ol:Cpx:Opx mode from 80:15:5 to 10:60:30 (black ovals, Fig. 1). It is noteworthy that samples with more abundant sulfide are more likely to be hosted in adcumulates. This may indicate that low density intercumulus silicate melt was displaced by the infiltration of high density sulfide liquid.

Lundin geologists have developed a two-stage emplacement/mineralization model based on spatial relationships of the three styles of mineralization. They speculate that initial pulse was intruded into a narrow Y-shaped conduit as a sulfide-oversaturated ultramafic magma that then experienced density driven settling of sulfide liquid to create the massive sulfide unit (MSU) in the neck of the intrusion and the disseminated mineralization in the upper parts of the intrusion. This was followed by emplacement of an olivine porphyritic magma along the margin of the still molten massive sulfide resulting in the creation of the semi-massive body adjacent to the massive sulfide and projecting upward into the disseminated lherzolite. While the trace element data suggest that a single parental magma composition was likely involved in the creation of the Eagle intrusion, it is still possible that this magma was emplaced more than once.

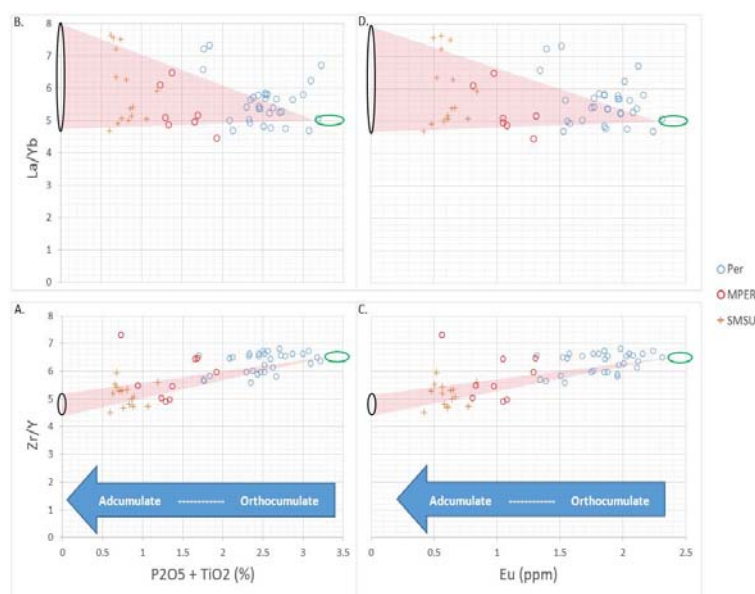


Figure 1) Zr/Y and La/Yb vs. $\text{TiO}_2 + \text{P}_2\text{O}_5$ (A & B) and vs. Eu (C & D) for Eagle samples. Ti, P and Eu are taken as proxies of intercumulus minerals of Fe-Ti oxide, apatite, and plagioclase, respectively, and give a qualitative measure for the amount of trapped liquid in Ol-Cpx-Opx cumulates. The green ovals represent estimated trace element ratios for the parent magmas approximated by orthocumulates. The black ovals represent the compositional range of trace element ratios of adcumulates in equilibrium with such parental magmas based on experimentally determined mineral-liquid partition coefficients (Bedard, 1994). Pink areas indicate the range of trace element ratios that might be expected in orthocumulates to adcumulates generated from a single magma composition.

Another possible test off whether two major magma pulses were involved in the creation of the Per-MPer-MSU sequence and the SMSU is to evaluate whether the Ni content of olivine is different between the two mineralized suites. While the presence of euhedral olivine phenocrysts in the SMSU suggest that olivine crystallized prior to sulfide liquation in the second pulse, the timing of olivine crystallization and sulfide liquation in the initial pulse is not clear. If sulfide liquation occurs before olivine begins to crystallize, Ni should be strongly depleted in olivine. Electron microprobe analyses of olivine from all four mineralization types show undepleted Ni abundances (Fig. 2). This implies that, if there were two pulses of magma, olivine crystallized prior to sulfide liquation in both. As shown in Figure 2, almost all analyses of olivine within a particular sample show a positive correlation between Ni abundance and Fo content, which is consistent with Ni depletion due to fractional crystallization of olivine. With the exception of one sample, the positive correlation Ni and Fo, especially from SMSU and MSU samples, indicates that olivine did not re-equilibrate with enclosing sulfides. This contrasts with Li et al's (2007) analyses of olivine in mineralized rocks from Voisey's Bay which show evidence of re-equilibration by their negative Ni-Fo trends.

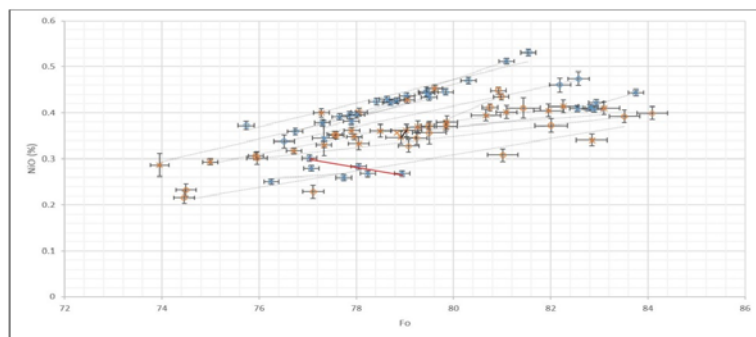


Figure 2) Ni-Fo trendlines by sample for all samples analyzed in the study. Orange points denote semi-massive sulfide, blue points denote disseminated sulfide. Red trendline shows the only negative Ni-Fo trend indicative of olivine-sulfide re-equilibration.

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Mesoproterozoic Alteration of the Paleoproterozoic Gunflint Formation: Analogies with Martian Blueberries

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NASA's Opportunity rover landed on Meridiani Planum in summer of 2004 with the intention of studying a rich concentration of hematite in much finer detail than what the preliminary images from the orbiting Mars Global Surveyor could possibly allow. Small, diagenetic, 4mm spherules composed primarily of hematite were discovered embedded in sand blasted bedrock, arming the scientific community with further evidence for a past presence of water on Mars (NASA, 2012). This thesis is an attempt at providing a terrestrial analogue for the formation of Martian spherules by using hematite-rich concretions observed in the minimally metamorphosed, 1.8Ga Gunflint formation as proxy.

Approximately 40 minutes eastbound of Thunder Bay at intersections with Mirror Lake (ML) and West Loon (WL) road lie two recently exposed, iron oxidized grainstone outcrops standing ~2-3m vertically. Original deposition occurred in the Paleoproterozoic at 1,876Ma in a storm-dominated shallow shelf. The grainstone has a typical grey-green ankeritic to white chert colour with spherical to rhombic hematite-rich concretions averaging <2mm to 2cm in diameter present in thin layers oriented parallel to the shallowly dipping, lentic bedding or randomly distributed within lenses as independent concretions or hematitic masses. Three fundamental questions occur in response to these outcroppings: Why are these rocks so iron stained when compared with the upper cherty and shaley Gunflint at outcrops of nearby Pass Lake (PL) road?; How do these concretions form?; Is the mechanism responsible for the formation of these concretions a reasonable analogue for those observed on Mars? A scaling down approach to these queries consisted of site mapping and stratigraphic sectioning, qualitative and quantitative petrographic and SEM analysis, and quantitative geochemical analysis using data acquired from ICP-MS, ICP-AES and XRD techniques.

It is well known that the Gunflint is high in iron that precipitated out of seawater solution as an insoluble chemical precipitate. In the studied upper cherty member, individual grainstone grains have fine, iron-rich laminae that had precipitated onto the grain surface itself or were accumulated by rolling over an Fe-rich substrate. An implicit, unconformable upper contact with the Sibley group, present above and just tens of meters away from the Gunflint outcrop, which would have allowed for iron rich and potentially oxidative fluid migration into the underlying Gunflint. Large, centimeter scale, iron-rich fracture sets as well as very fine, micrometer scale capillary networks provide evidence for fluid migration. Variability in the red colouration, from blood red to maroon, can be differentiated on concentric layers of individual concretions, as well as overprinting masses, and is suggestive of multiple phases of redox fluid front migrations. It is by some combination of intrinsic and extrinsic iron combined with oxidation that gave these rocks their ultimate red colouration.

Hematite concentrations within the ML and WL outcrops are always associated with carbonates that are at varying stages of decay. These hematite-bearing carbonates have been identified through geochemical, XRD and SEM analysis to be of ferroan dolomite to ankerite in composition. They are often found nucleating on or within siliceous and hematite altered grains as rhombs, and commonly mimic the entire grain. Spherical concretions occur when several carbonate altered grains are enclosed by the growth of successive poikilitic carbonate and rarely

display a distinguishable nuclei: the appearance of framboidal pyrite central to a select group of concretions and scattered within the groundmass strongly suggests the influence of bacterial sulfate reduction (BSR) on carbonate growth. The variation in size, morphology and distribution of iron-bearing carbonates within individual grainstone lenses as concretionary spheres or masses, as well as the presence of framboidal pyrites, suggests that primary, hematite-poor carbonate concretion formation occurred in a shallow phreatic, anaerobic environment at some time after cementation and prior to compaction as the grainstone layers accumulated.

Gunflint hematite concretions differ in several ways to those observed on Mars. Negative weathering, original iron-carbonate composition, the promotion of growth by BSR and a lesser random to common bedding parallel stratigraphic distribution define the concretions observed at the terrestrial site whereas positive weathering, jarosite-hematite-alunite composition, spherulitic growth by supersaturation of Fe-rich fluids, and non-conformable growth over all stratigraphic units define the concretions at the Martian sites (Morris *et al*, 2010). Concretions preserve fluid chemistry and are blueprints for flow regimes and are as such important to the evolution of water on Mars and early Earth.

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Investigations of the Layered Series Nepheline Syenite within Center II of the Coldwell Complex, Marathon, ON

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The Coldwell Alkaline Complex is the largest alkaline intrusion in North America, and was emplaced during initial magmatism of the Keweenaw Midcontinent Rift (MCR) at 1.1 Ga. Located on the north shore of Lake Superior, the Coldwell Complex was emplaced along the Thiel fault (the northern component of the Trans-Superior Tectonic Zone), and is host to rare earth elements (REE), Cu, Ni, PGE, and other high field element mineralization. Emplaced from east to west, the oldest – termed “Center I” is host to gabbro and Fe-rich augite syenite; “Center II” hosts biotite-gabbro and nepheline syenite; and “Center III” is host to a variety of syenite. The focus of this study is to understand the magma systematics involved in the emplacement and crystallization of the different intrusive centers, specifically Center II. This involves field mapping, extensive sampling and mineralogical study of the complex syenites. There is an emphasis on identifying the REE minerals occurring in the nepheline syenites. This detailed assessment will help to understand the complex systematics of alkaline rocks in the Superior Province, and will assist with mineral exploration within the complex, which is currently underexplored for REEs.

Layered series nepheline syenite rocks display a cumulus texture perthitic feldspar, with post cumulus amphibole and associated pyroxene, biotite, and zeolites. The feldspar exhibits secondary albitization of an earlier alkali feldspar which has produced lamellae of albite (An% 0-4.43). Amphiboles dominantly plot in the hastingsite range; with zoning compositions displaying a trend to Fe and Mn enrichment with Mg, Ca, Ti depletion. Biotite are classified as annite with rare siderophyllite, and occur as alteration products associated with amphibole. REE analysis of the layered series has displayed elevated levels of LREE in apatite (La, Ce, Nd) along with Th and Y, and minor abundances of britholite-(Ce, La) and wohlerite. Massive syenites associated with the layered series at higher structural levels contain abundant wohlerite and britholite-(Ce, La) with apatite containing minor amounts of LREE. Pegmatites representing altered massive syenite; contain the most diverse suite of accessory minerals including: wohlerite, britholite, Nb-Al-Fe bearing titanite, U-bearing pyrochlore, zoned apatite, zircon, and minor sulphides. Apatite has proven to be a viable mineral for future tracer isotope analysis; dominantly forming 20-100µm (rarely up to 300µm) subhedral elongate to hexagonal crystals. Commonly displaying irregular to concentric zoning with an increased LREE rim composition, apatite is found disseminated in the feldspar groundmass or along fractures and grain boundaries of amphibole.

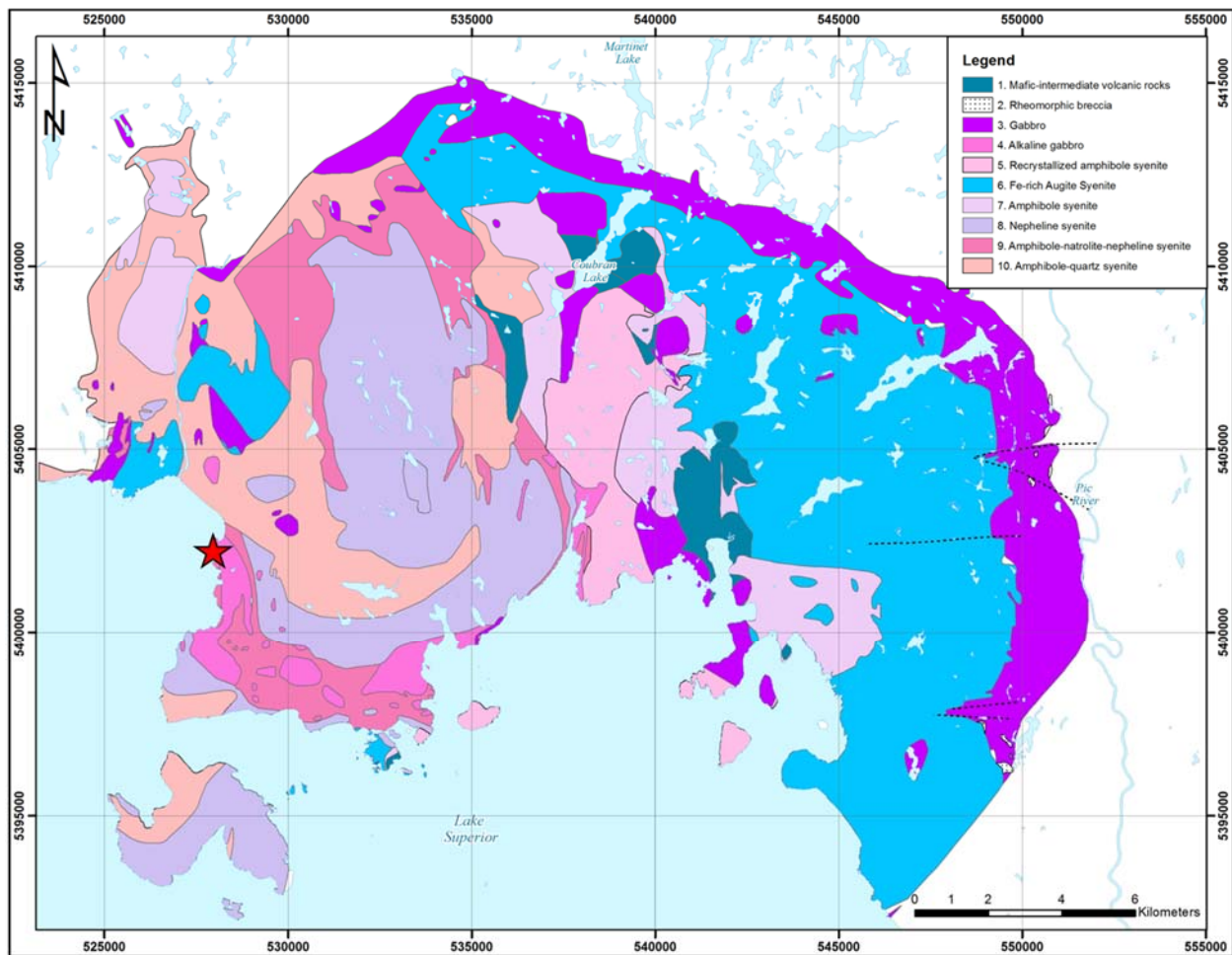


Figure 1: Geological Map of the Coldwell Complex (Note: Star represents sample area).

Petrology, geochemistry and sulphur isotopes of the Crystal Lake gabbro and Mount Mollie dyke, Northwestern Ontario

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The Midcontinent Rift (MCR) formed from ~1150 to 1087 Ma, with the majority of the igneous activity occurring in two pulses between ~1108-1105 Ma and ~1100-1094 Ma (Heaman et al., 2007). A magnetic polarity reversal is recognized by Davis and Green (1997) in MCR related volcanic and intrusive rocks during the gap in time between the main pulses. In this study two mineralized MCR-related intrusions, the Crystal Lake gabbro (CLG) and the Mount Mollie dyke (MMD), have been investigated using petrography, geochemistry and sulphur isotopes. The CLG is a “Y” shaped intrusion with a 5 km long north arm and a 3.75 km long southern arm (Fig. 1). The ~ 35 km long MMD extends east from the CLG (Fig. 1). The spatial relationship and similar rock types led to the belief that the two were co-genetic and/or contemporaneous, however, recent age dating has revealed that the CLG formed at 1099.6 ± 1.2 Ma and the MMD formed at 1109 ± 6.3 Ma (Heaman et al., 2007; Hollings et al., 2010). There are still unresolved issues with this age gap, most notably that both have the same paleomagnetic N-polarity, where one would expect a R-polarity for MCR related rocks that are older than 1105 Ma. This study will use petrography, whole rock geochemistry and sulphur isotopes in an attempt to resolve the conflicting evidence regarding the relationship between the CLG and MMD. Samples of the CLG were collected from an 828 m diamond drill core from the relatively little known about southern arm, whereas MMD samples were collected from a 1087 m diamond drill core.

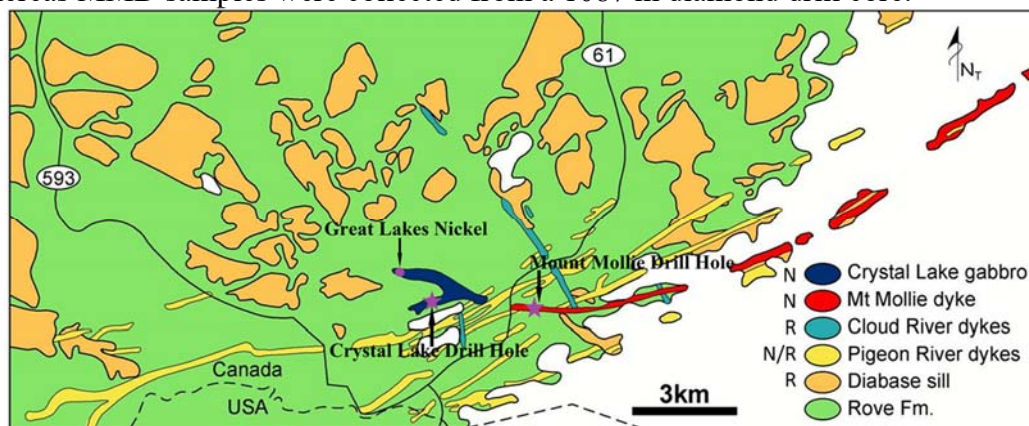


Figure 1. Generalized map and magnetic polarity of the Crystal Lake gabbro, Mount Mollie dyke and surrounding rocks within the Logan Basin (Cundari, 2013).

Petrographic studies have revealed that the CLG and MMD are mineralogically and texturally similar, with troctolite and sub-ophitic to ophitic olivine gabbro being the most abundant rock types. The bottom of the MMD hole begins with a sequence of troctolite to olivine gabbro with variable amounts of sub-ophitic to ophitic clinopyroxene. Around -600 m a ~15 m sequence of alternating very coarse- and medium-grained olivine gabbro. The next unit is a clinopyroxene bearing troctolite to gabbro sequence, with sub-ophitic to ophitic clinopyroxene at the bottom and intergranular clinopyroxene in the top 100 m of the sequence. The top 150 m of the drill core consists of granophyre, hornfels, and diabase units. The bottom of the CLG drill core consists of

shale of the Rove Formation and a thin 20 m fine-grained diabase unit. Next is a 100 m unit of medium- to coarse-grained troctolite and olivine gabbro with thin (mm) layers of fine-grained chrome spinel chadacrysts present 10 m above the base of this unit. A 75 m unit of fine-grained and plagioclase phyric diabase, petrographically similar to the 20 m diabase unit, separates two CLG units. The CLG units have chilled contacts with the diabase unit above and below, suggesting that it is significantly younger. The main CLG consists of a sequence of troctolite to gabbro with ophitic to sub-ophitic clinopyroxene with thin layers of chrome spinel chadacrysts near the base. The top 40 m of the hole consists of strongly altered sulphidic olivine gabbro.

The MMD and main gabbro unit in the CLG drill core show relatively smooth fractionation trends, with increasing concentrations of Fe₂O₃, SiO₂, Na₂O, TiO₂, Ba and V and decreasing concentrations of Al₂O₃, CaO, MgO and Ni from the bottom to the top of the hole; however, CaO values are constant in the CLG. In and around the very coarse-grained unit of the MMD, there are deviations from the smooth trends observed in the other units. This unit is currently being investigated using mineral chemistry to help explain these variations. The 20 m and 75 m thick diabases in the CLG drill hole are geochemically distinct from the CLG. This suggests that these units are likely from a separate source, consistent with the petrographic observation of chilled margins. To determine the role of crustal assimilation in the CLG, $\delta^{34}\text{S}$ was analyzed from the visible sulphides in various horizons of the drill core. The CLG had visible sulphides occurring at the top and bottom 10 to 50 m of both units. Overall the $\delta^{34}\text{S}$ ranged from 4.1 to 21.0 ‰, with higher values generally found in the lower unit. Due to the high variability of the $\delta^{34}\text{S}$ ~ -1 to 33‰ (Johnston et al., 2006) of the surrounding Rove Formation, which the CLG is assumed to have assimilated, it is difficult to determine the degree of assimilation. This is because a high degree of assimilation of a moderate $\delta^{34}\text{S}$ would yield similar results to a lower degree of a high $\delta^{34}\text{S}$ value material. Regardless, there is enough data to suggest that crustal assimilation played a role in the sulphur saturation history of the CLG.

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What Happened in Northern Minnesota Between 2700 Ma and 1900 Ma? The Answer Is in the Pokegama Formation: A Multicycle Sedimentary History!

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The Giants Range Batholith is the core of the Algonian Mountains in the area just to the north of the Mesabi Iron Range. This composite batholith, the Vermilion Complex, and the Saganaga Batholith were emplaced beneath volcanic arcs at about 2700 Ma by subduction processes. Except for 2100 Ma mafic dikes, there is no preserved geologic record in northern Minnesota until the sedimentary rocks of the Paleoproterozoic Animikie Basin, a foreland basin, at ~ 1850 to 1900 Ma.

Certainly erosion was going on, for the Algonian Mountains were essentially eroded away as topographic prominences by the time the Animikie Basin developed to the south of the mountains. This is a time span of about 800 million years. If we can assume that the Algonian Mountains were indeed respectable mountains, uplift and erosion must have generated thousands of feet of sediment. We also can reasonably assume that a significant portion of the detritus consisted of resistant quartz eroded from the granitic bodies that intruded into what was likely a volcanic roof, as documented by amphibolitic inclusions in the granitic outcrops. Based on regional relationships and cross bedding, we can assume that the paleoslope was to the south, toward and into the Animikie Basin. The lowest stratigraphic unit in the basin, the Pokegama Formation, less than 50 m thick in total, contains abundant detrital quartz only in its uppermost member, which was a quartz sandstone and is now a quartzite. Therefore the question is: “Where is the expected large quantity of quartz, the likely resistant detritus of 800 million years of erosion?”

At Blueberry Hill within the Hibbing Taconite complex of open pits, there is a conglomerate at the base of the Pokegama Formation, which overlies the Archean tonalite to granodiorite basement and underlies the Biwabik Iron Formation. The conglomerate is especially interesting in that it contains numerous rounded pebbles of quartz arenite, which consist of well-sorted and spherical unit quartz grains. At least a partial answer to the above question is that older quartz sands (pre-Pokegama) were transported, abraded, deposited, lithified, re-eroded, and redeposited during those 800 million years. The pebbles of quartz sandstone are therefore proof of a multicycle history of at least two cycles, and three counting the Pokegama. How many other undetected quartz sandstones may have been present but have been totally removed by erosion?

A cross bedding plot for the Biwabik Iron Formation is bimodal-bipolar, indicating a tidally influenced environment of deposition that is probably applicable to the Pokagama as well. Although the excellent rounding of resistant quartz grains also fits a tidal model, the total lack of vegetation on land during both Late Archean time and Paleoproterozoic time would have resulted in constant wind abrasion of sand-sized quartz grains by wind, the “best rounder” of sand grains. Therefore, the quartz grains (plus rare feldspar grains) were very likely well-rounded before they reached their final depositional site in the Pokegama Formation.



Rounded pebbles of quartz arenite in a basal conglomerate of the Pokegama Formation

Ore Petrography and Precious Metals of the Primary Flambeau Massive Sulfide Ore

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The Flambeau volcanogenic massive sulfide (VMS) deposit, near Ladysmith, WI, was the only one of several potentially economic deposits to be extracted in the Penokean Orogeny of Wisconsin. Northern Wisconsin is home to at least thirteen VMS deposits hosted within the Wisconsin Magmatic Terrane (DeMatties, 1994), a Precambrian juvenile arc sequence consisting of volcanic rocks, sedimentary sequences, and associated plutonic rocks that are about 1.8-1.9 billion years old (Schulz & Cannon, 2007). The Flambeau mine was considered as a copper-gold deposit because of the supergene-enriched zone that was the only portion of the ore body to be extracted. Interestingly, the enriched zone of the Flambeau deposit that was extracted accounted for ¼ of the total volume of ore and the primary ore was left in the ground. Following an initial surge of academic publications following the discovery and exploration of the Flambeau (e.g. DeMatties 1994), research largely ceased along with the mining and exploration activities. What research was done was predominantly carried out on the secondary enriched zone (e.g. Ross, 1997). Preliminary research indicates the primary ore body being more enriched in zinc and lead (Zens et al. 2015). This project is designed to examine the mineralogy, texture, and composition of the primary ore body, determine the base and precious metal phases that are present in the ore.

Petrographic and geochemical analyses of ore-forming minerals have helped constrain the nature and evolution of economic mineralization. The current phase of this research project has involved mineral analyses of polished thin sections of Flambeau ore samples. Using a Scanning Electron Microscope (SEM) in the Materials Science Center at UW – Eau Claire, the habit of gold, silver, empressite, electrum, and Sb-bearing alloy grains have been documented (Fig. 1). As expected with metamorphosed VMS ores, the main ore phases were euhedral pyrite, sphalerite, and lesser galena and chalcopyrite. Most of the thin section samples there are abundant sub-microscopic inclusions of galena, frequently found in pyrite, but also found in sphalerite and chalcopyrite. Bi-Ag-alloy has been observed with these galena inclusions. Various trace minerals found in the primary ore include monazite, barite, cinnabar, and cassiterite within the host mineral pyrite and to lesser extent sphalerite. Within sphalerite and pyrite, native silver, native gold, electrum, empressite, and Bi-Te-Sb alloys were identified. The primary gangue mineral phases are quartz and anthophyllite.

Research utilizing reflected light petrography and the SEM have improved the identification of precious metal ore minerals, their chemistry, and characterization of the precious metal mineral-hosts. The data gathered here is contributing to a larger study that is seeking a complete a geochemical and petrographic understanding of Wisconsin's VMS deposits and to fully characterize the Precambrian and economic geology of rocks hosting the Flambeau mine.

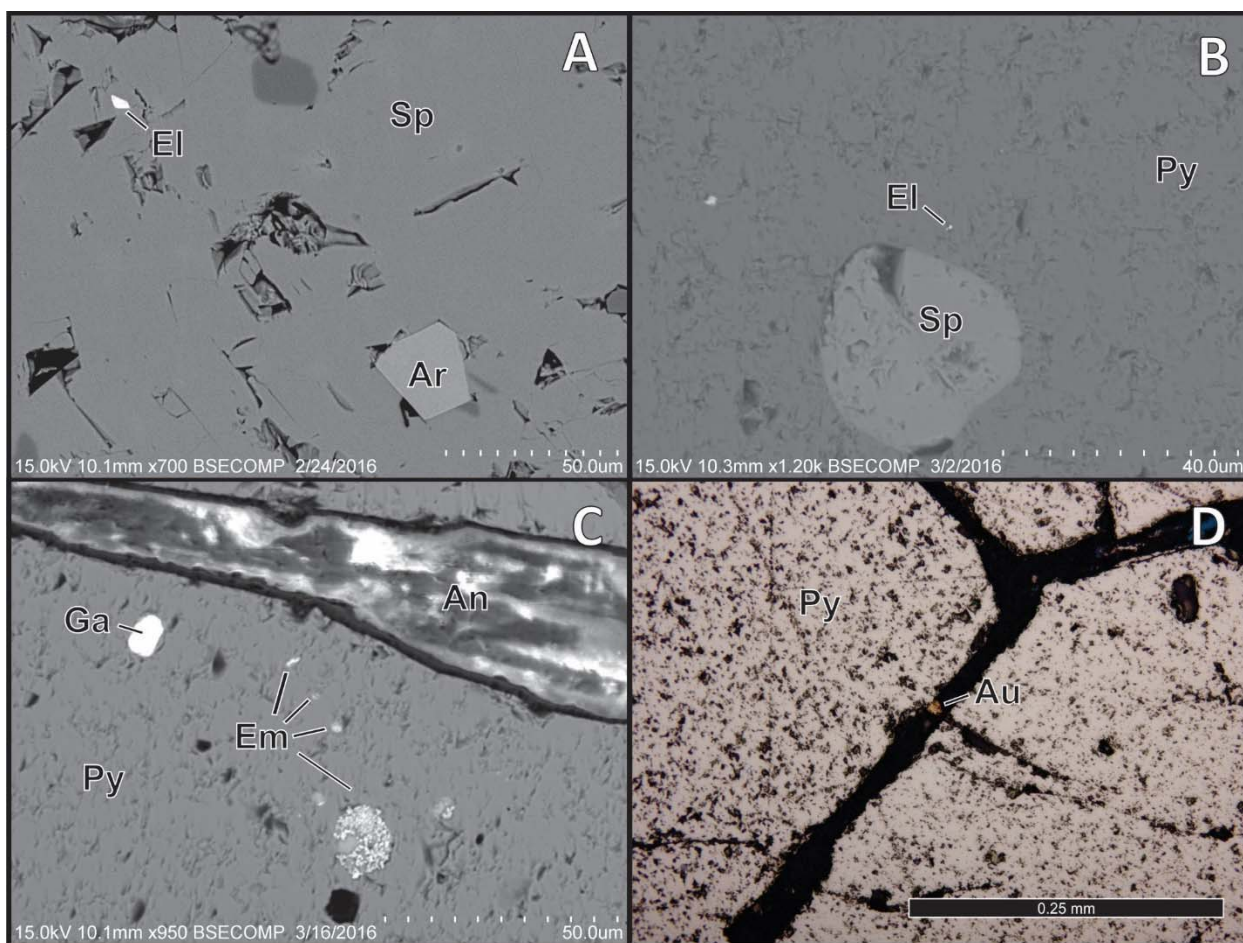


Figure 1: Various images showing mineral hosts of precious metals in the primary Flambeau ore body. Photos A-C are backscatter images from Scanning Electron Microscope. Photo D is photomicrograph from petrographic microscope. Mineral abbreviations: Sp – Sphalerite; Py – Pyrite; Ga – Galena; Au – Native Gold; El – Electrum ± Antimony alloy; Ar – Arsenopyrite; An – Anthophyllite; Em – Empressite (AgTe).

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THE LAC DES ILES PGE-CU-NI DEPOSIT, CANADA: AN ORGANIZED MEGA-BRECCIA UNIT?

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The Lac des Iles Intrusive Complex (LDI-IC), located in the Thunder Bay Mining District of northwestern Ontario, is one of several ~2.68 Ga mafic +/- ultramafic intrusive bodies that were emplaced into both the Eastern Wabigoon Terrane and the eastern part of the older Marmion Terrane of the western Superior Province. The LDI-IC consists of one mafic complex (South LDI complex) and one predominantly ultramafic complex (North LDI complex). All known mineral resources in the LDI-IC are hosted within the South LDI complex, with the vast majority occurring in the western part of the ~3 km long x 1.5km wide Mine Block intrusion (MBI). Historical PGE-Cu-Ni resources in the western MBI, including mined out and existing resources, now exceed 200 million tonnes at an average grade of >2 g/t Pd. This historical global resource includes approximately 50 million tonnes of higher-grade resources featuring average Pd grades in excess of 4 g/t over true widths of <5 to ~80m that commonly includes narrow widths (1-10m) of 'bonanza-grade' Pd mineralization (e.g., >10 g/t to 2-3 oz/t). Most of these resources occur within a small surface area having approximate, known dimensions of ~1 km N-S by 500m E-W by >2 km vertically. Recent insights stemming from 3D assay, whole-rock geochemistry, applied mineralogy, geophysical and structural logging data imply a dynamic, multi-stage mineralizing process. Previous research addressing LDI ore forming processes have typically cited one or both of the following: 1) magmatic sulfide collection of PGE and base metals; and, 2) magmatic volatile-related PGE localization and upgrading.

Over 50 years of exploration and twenty years of mining at LDI have generated a tremendous geoscientific database including over 500,000 assays and approximately 750,000 metres of exploration and definition drill core and logging. This database underpins several immutable facts relating to the geology, mineralogy, geochemistry and morphology of the PGE-Cu-Ni resources at LDI. These include:

1. Palladium tenors at LDI are amongst the highest documented from magmatic PGE-Cu-Ni deposits, typically exceeding several hundred ppm Pd and locally exceeding several thousand ppm Pd in 100% sulfide;
2. Pd:Pt and Pd:Au ratios increase with increasing Pd grade that, although documented in a small number of other intrusive bodies (e.g. Skaergaard intrusion, Keays and Tegner, 2016) remains an atypical feature of magmatic PGE-Cu-Ni deposits;
3. The highest Pd grades, although principally located along an inferred pre-magmatic regional feeder fault, locally follow other major faults as well as lithological contacts - especially those between vari-textured noritic rocks and earlier-formed intrusive units;
4. Semi-continuous brecciation of pre-existing rock units, including both early phases of the MBI and basement orthogneiss, occurred during the emplacement of fluid-rich noritic magmas and is interpreted as having been coeval with the formation of most of the highest grade PGE-Cu-Ni mineralization;
5. Palladium mineralization is commonly, but not universally, associated with disseminated Fe-Cu-Ni sulfide mineralization comprising a characteristic assemblage of pyrite + pyrrhotite + pentlandite + chalcopyrite +/- millerite with total sulfide mineral abundances generally falling in

the range of 0.5 to 2% but with local, narrow occurrences of net-textured and semi-massive sulfide mineralization;

6. Palladium principally occurs in Te-, Bi- and S-rich ore minerals displaying a wide range in texture, locking characteristics and mineral associations but having strong similarities to Pd-bearing minerals documented from other PGE deposits;
7. Recent studies of remanent magnetism in the LDI area indicate that the bulk of the PGE-Cu-Ni mineralization was formed after a reversal of the Earth's magnetic field such that both normally-polarized and reversely-polarized rocks are present in the South LDI-IC;
8. The Offset Fault separates the Roby and Offset structural blocks and is currently interpreted to be an oblique thrust fault – however, the timing of oblique slip movement along the Offset fault remains equivocal as does the relative timing of the currently defined major faults on the mine property and their relative importance in focusing and displacing mineralization; and,
9. Hydrous alteration associated with magmatic volatiles derived from fluid-rich noritic magma produced chlorite-amphibole +/- talc +/- epidote alteration along the contact between a pre-existing, largely unmineralized gabbroic unit (EGAB) and mineralized vari-textured noritic rocks. Although many altered structures and contacts are present in the MBI, only a few of these appear to have acted as “sinks” for PGE.

Taken together, these observations support an interpretation involving multiple injections of noritic to gabbronoritic magma into the proto South LDI-IC, with different pulses having distinctive geochemical and mineralogical characteristics. The earliest period of magmatism produced massive to layered, iron-enriched and locally oxide-saturated leuco- to ferro-gabbronorite and gabbronorite. The second magmatic episode produced massive to weakly layered norite and melanocratic norite featuring local PGE- and base metal sulfide enrichment. The final and principal ore-generating magmatic episode involved the emplacement of water-rich and sulfur-saturated noritic magma that produced a deeply-rooted and laterally- and vertically-extensive magmatic mega-breccia unit. The latter comprises a varitextured leuconorite to melanorite matrix and both cognate and basement-derived fragments of variable size and exhibiting a wide range in alteration intensity and degrees of resorption and partial melting. Although the mega-breccia unit is focused along the main north-south feeder structure it locally tracks along other major faults and intersects most of the pre-existing major rock units in the MBI.

With deeper drilling currently confined to the western MBI, the extent (and mineral potential) of the mega-breccia in the central and eastern parts of the intrusion remains unclear. Although having a chaotic appearance on the local scale, recent exploration findings suggest that the mega-breccia is well-organized on the deposit scale. Accordingly, vectoring to higher-grade subzones is becoming possible using routine exploration data including logging information, geochemistry, 3D structural interpretations and geophysical properties.

The favourable 3D continuity, thickness, PGE grades and sub-vertical orientation of the LDI PGE-Cu-Ni deposit provides strong motivation for future exploration in the region. The general category of contact-type PGE-Cu-Ni sulfide deposits should now be extended to include deeply-rooted, structurally-controlled magmatic mega-breccia systems like LDI. The higher-grade parts of these breccia systems are expected to occur in areas of maximum magma throughput, such as primary feeder conduits and structural intersections along these feeders. Narrow zones of high-grade PGE mineralization having low total sulfide content represent difficult exploration targets but should carry most of the value of a given mega-breccia system.

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Copper toxicity and dissolved organic matter: Resiliency of mineralized watersheds in northern Minnesota and Michigan.

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Copper (Cu) toxicity in surface waters was estimated in watersheds containing contrasting mineral-deposit types in the Duluth Complex (northern Minnesota) and in the Porcupine Mountains Cu district (western Upper Peninsula of Michigan); these waters contain high dissolved organic carbon (DOC) and low to moderate hardness, both of which mitigate metal toxicity. Mineral deposits in these areas are related to rocks of the Midcontinent Rift System. In the Duluth Complex, deposits include magmatic Cu-Ni (nickel)-PGM (platinum group metal) sulfide deposits in mafic rocks and iron (Fe) and titanium (Ti) oxide ultramafic intrusions. Mineral deposits in the Porcupine Mountains district are stratiform Cu deposits hosted by the Nonesuch Formation, which consists of gray to black shales and siltstones. This study compared aquatic life water-quality criteria for Cu calculated on hardness alone, which had been the standard regulatory procedure for the past few decades, and compared it to criteria based on the Biotic Ligand Model (BLM), a newer approach that has supplanted the hardness-based approach for Cu and incorporates major element chemistry, metal speciation, and organic carbon complexation.

Surface-water samples were collected along streams in three geologically distinct watersheds in the Duluth Complex: 1. Filson Creek where Cu-Ni-PGM mineralization occurs at the bedrock surface along the basal Duluth Complex; 2. Keeley Creek where Cu-Ni-PGM mineralization occurs only at depth; and 3. the upper St. Louis River in the vicinity of Fe-Ti oxide ultramafic intrusions, which occur at the subcrop beneath glacial cover. Samples were collected during low- and high-flow conditions between September 2012 and April 2014. In addition, surface-water samples were collected in September 2014 from several watersheds in the Porcupine Mountains; a short temporal variation in flow was examined due to a significant storm that occurred between sampling events. Sample locations included 1. upstream of, or not influenced by, the Nonesuch Formation, or 2. downstream of the Nonesuch (influenced) or downstream of mining impacted areas (impacted).

The geochemistry of the surface waters reflects underlying rock types, glacially transported unconsolidated materials, mineralization style within each watershed, and geochemical processes occurring in the streams. Waters from the Duluth Complex and the Porcupine Mountains are similar in composition in that they are generally oxidic, near neutral to slightly acidic (pH 5.0 to 7.6), and are characterized by moderate carbonate species concentrations (4 – 65 mg/L CaCO₃ as bicarbonate) and low sulfate concentrations (< 0.8 – 8 mg/L). Calcium (Ca), sodium (Na), magnesium (Mg), and silica (SiO₂) are the main dissolved major cations and the predominant dissolved trace elements include aluminium (Al), Cu, and Fe. Total dissolved solids, Ca, and Cu are generally lower in waters collected from the Duluth Complex compared to the Porcupine Mountains, whereas DOC, Fe, Al, and Ni are generally higher. Despite some variations in their chemistries, these watersheds display an atypical chemical signature when compared to most surface waters in the United States; the surface waters are rich in DOC (18 - 47 mg/L for Duluth; 2 - 22 mg/L for Porcupine Mountains) and have generally either low (10-53 mg/L CaCO₃ for Duluth Complex) or low-moderate hardness (21-135 mg/L CaCO₃ for Porcupine Mountains). The concentrations of major and trace elements vary seasonally and after large storm events with lower concentrations generally being found during higher flow conditions, consistent with dilution by rain or snowmelt. However, in the Duluth Complex watersheds, dissolved loads for major and trace elements are greater during higher flow conditions, likely from elements accumulating in wetlands and groundwater during dry and winter conditions and then being flushed downstream during higher flow.

The aquatic toxicity of most metals (i.e., Ag, Cd, Cr, Cu, Ni, Pb, Zn) is routinely assessed on the basis of hardness-based criteria that adjust for the protective effects of Ca and Mg ions. In 2007, a new guideline was adopted by United States Environmental Protection Agency for determining aquatic life criteria for Cu that relies on the BLM. The BLM evaluates the biological availability of metals in aquatic systems for several organisms (i.e., fishes, water fleas) and incorporates major element chemistry as well as additional water-quality characteristics including metal speciation and organic carbon complexation (Paquin et al., 2002); BLMs for metals other than Cu, including Ag, Cd, Ni, Pb, and Zn, are also being developed. Concentrations of metals in surface waters can be evaluated with regard to the hardness-based and BLM-based criteria using a hazard quotient (HQ), which is the ratio of the dissolved concentration of the metal in the sample to the criterion. Values above 1 imply toxic conditions, whereas those below imply non-toxic conditions. Hazard Quotients based on the hardness-based criteria for Cu are greater than 1 for most sites in Filson Creek and in most waters collected after the storm and, in a few, before the storm in the Porcupine Mountains (Figure 1A), which is a reflection of the low hardness of these waters. However, as shown in Figure 1A, HQs for Cu calculated based on the BLM model are significantly less than 1 for some of

these same sites, in particular for the Filson Creek watershed during low flow; for these sites, the hardness-based approach would predict toxic conditions, whereas the BLM model does not predict toxic conditions. The low HQs based on the BLM reflect the ability of DOC to complex Cu, rendering it unavailable biologically. In contrast, hardness-based HQs for a few sites in the Porcupine Mountains are lower than 1, whereas BLM-based HQs are greater than 1. The different results from the hardness-based and BLM-based approaches suggest that the former may be inadequate to describe metal toxicity especially in watersheds with high DOC and low to moderate hardness. The formation of Cu-DOC complexes significantly reduces the amount of dissolved Cu available to interact with the biotic ligand (the gill) of aquatic organisms. The protective effects of cations, such as Ca and Mg, competing with Cu to complex with the biotic ligand are likely not as important as DOC in many of these waters.

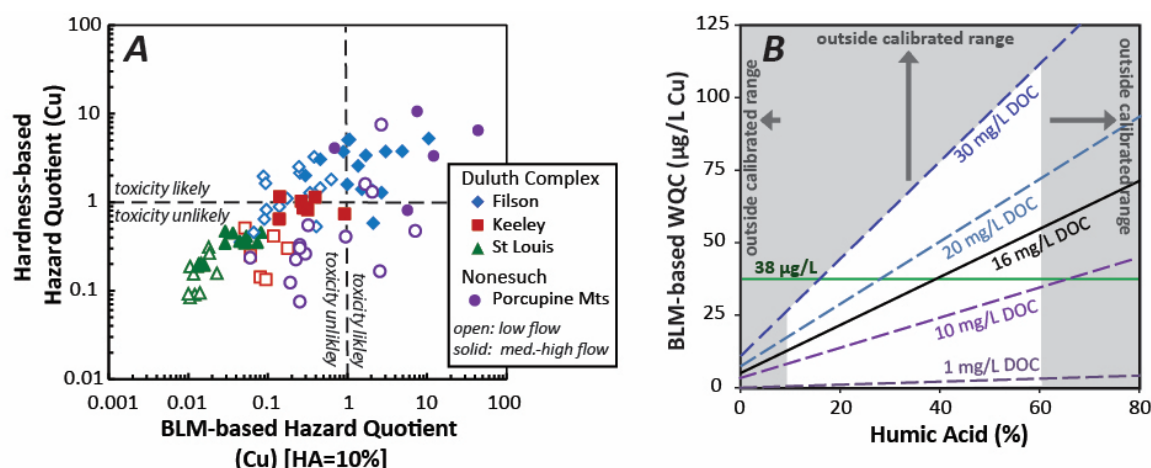


Figure 1. (A) Biotic Ligand Model (BLM)-based and hardness-based (HB) Hazard Quotients (HQ) of chronic toxicity for dissolved Cu in surface waters from the Duluth Complex and Porcupine Mountains. Open symbols are for waters during low flow conditions and solid symbols represent moderate to high flow conditions. (B) Fraction of humic acid (HA) and BLM-based chronic water quality criteria (WQC) for Cu for a site in the Porcupine Mountains. Dashed lines are WQC calculated for various DOC concentrations and percentages of HA for the same water chemistry. The solid black line is WQC for 16 mg/L DOC, the measured DOC value at the site. The green horizontal line represents the concentration of Cu measured at the site (38 µg/L). The gray-shaded area is outside the lower and upper calibrated ranges for DOC and HA for the BLM.

The composition of DOC also influences its ability to mitigate metal toxicity and is an input parameter for the BLM model. The humic acid (HA) fraction of DOC is assumed to be the reactive fraction available to complex with dissolved metals. As shown in Figure 1B for a site in the Porcupine Mountains, varying the DOC concentrations and HA fraction in the BLM model significantly changes the predicted chronic water-quality criteria for Cu; the fraction of HA has a greater influence on the criteria as total DOC concentrations are increased (i.e., steeper slope). Based on the measured DOC (16 mg/L) and Cu concentration (38 µg/L) at this site, if the HA fraction of the DOC is less than approximately 40%, the Cu concentration in the water exceeds the criterion, predicting toxic conditions, whereas if HA is greater than approximately 40%, the Cu concentration is less than the criterion. It is also noteworthy that there is a limited range of DOC and HA values for which the BLM is calibrated (Figure 1B); waters collected in the Porcupine Mountains fall within the DOC calibrated range (0.05- 29.6 mg/L), whereas numerous samples from the Duluth Complex exceed the upper limit.

Naturally-occurring concentrations of Cu at some sites currently exceed criteria prior to mining. The BLM approach to predicting aquatic water-quality criteria for Cu is likely needed for these waters in order to evaluate the effects of the high DOC and better predict resiliency to increased dissolved Cu concentrations. Additional investigations are needed to examine the composition of the DOC, which influences its ability to mitigate toxicity, as well as some of the limitations of the calibrated range for DOC concentrations in the BLM model.

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A preliminary evaluation of the structural controls on gold mineralization in the Jackfish Lake area, northwestern Ontario

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Jackfish Lake lies within the Wawa Subprovince, in the western portion of the Schreiber-Hemlo greenstone belt. The supracrustal rocks in this area have been assigned to the Schreiber assemblage (Williams et al. 1991), and include approximately equal proportions of metavolcanic and metasedimentary rocks (Walker 1967). These supracrustal rocks have been intruded by a number of late- to post-tectonic plutons, including the Terrace Bay batholith and the Santoy Lake pluton. No age determinations are available for the supracrustal or intrusive rocks in this portion of the greenstone belt. However, they are presumed to be Neoproterozoic, based on their stratigraphic relationship to rocks that have been dated elsewhere in the belt (Magnus and Walker 2015). Several late- to post-tectonic faults and shear zones occur in the Jackfish Lake area (Walker 1967). These structures include a major northwest-striking shear zone that was recently described by Magnus and Walker (2015) and occurs in the supracrustal rocks between the Terrace Bay batholith and Santoy Lake pluton (see Figure 1). Magnus and Walker (2015) also noted evidence of a late north-south-directed deformation event. As discussed below, this event may have played a role in the localization of gold mineralization at Jackfish Lake.

The Jackfish Lake area has a long history of gold exploration that dates back to 1873, when Donald McKellar reported the discovery of gold at Victoria Cape and Jackfish (Schnieders et al. 1996). Since that time, numerous gold occurrences have been found in the Terrace Bay batholith, and in the supracrustal rocks that surround the intrusion. These occurrences include the Empress Mine, which produced 112 ounces of gold during 1896-97 (Schnieders et al. 1996).

During 2015, work began on a study to examine the structural controls on gold mineralization in the vicinity of the Terrace Bay batholith. This paper presents the preliminary results of this work, which will be refined and expanded upon during a two year Ontario Geological Survey (OGS) – Lakehead University study set to commence in the summer of 2016. To date, field data have been collected from 11 gold occurrences in the Jackfish Lake area, near the eastern end of the Terrace Bay batholith. This field work has been complemented by the review of information that is on file for 20 other nearby gold and sulphide occurrences at the OGS Thunder Bay South Regional Resident Geologist's office. Based on a review of the information collected to date, gold has been found to occur in the following structural settings.

- Mineralized shear/fault zones that occur in supracrustal rocks near the margins of the Terrace Bay batholith.
- Quartz-carbonate vein systems that parallel the batholith-supracrustal rock contact and are located at or near the contact.
- Quartz-carbonate veins that occupy late brittle fracture systems within the batholith.

The most notable gold mineralized shear zone in the supracrustal rocks is known as the Empress structure (shown on Figure 1). It is a 15 to 25 m wide shear zone that strikes 70° with a moderate to steep dip toward the south. This structure hosts a number of gold occurrences, including the Empress Mine. The most significant gold values are obtained where the shear zone is at its widest and exhibits intense folding and quartz vein development. Fold axes in this structure plunge moderately toward the east.

The gold-mineralized contact- and batholith-hosted vein systems tend to have the following general characteristics.

- One grouping consists of narrow (generally less than 0.2 m wide), shallow-dipping (often north-striking) to near-horizontal veins. Many of these veins occur in en-echelon sets.

- The second grouping of veins is approximately north-striking with near-vertical dip. Vein widths are highly variable, ranging from a few millimetres to more than a metre.

All of the observations listed above suggest that gold mineralization is most likely to have been associated with a late north-south-directed compression event, such as that proposed by Magnus and Walker (2015). Gold generally appears to be associated with structural traps, both along the Empress structure (i.e., in zones of folding where dilatant structures have developed), and in the Terrace Bay batholith (brittle fractures).

In the Empress structure, structural traps are most likely to occur at the nose of significant folds, where quartz veining has occurred in dilatant zones. In the Terrace Bay batholith, the mineralized fracture-fill veins are most likely to have been “dead-end” fractures that were connected on one end to structures that acted as the primary gold bearing fluid conduits.

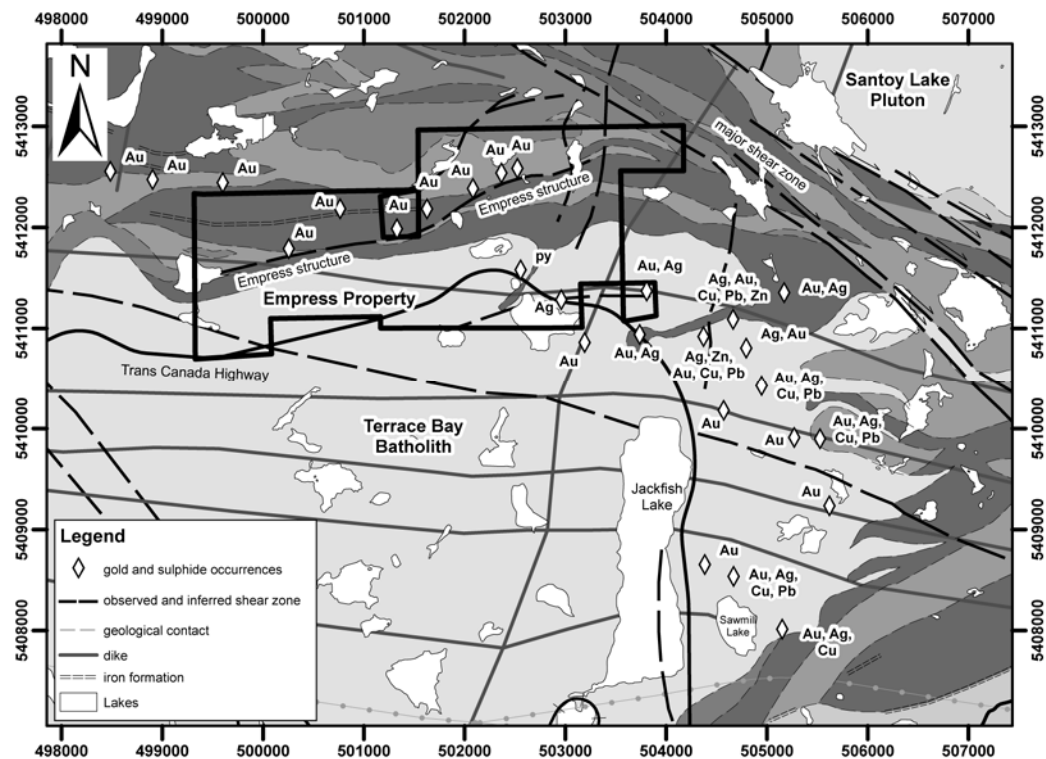


Figure 1. Gold and sulphide occurrences of the Jackfish Lake area (geology from Walker 1967 and Magnus and Walker 2015). All co-ordinates provided in NAD83 Zone 16.

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Setting of volcanogenic massive sulfide deposits of the Paleoproterozoic Penokean volcanic belt

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The Paleoproterozoic (ca. 1875 Ma) Penokean volcanic belt represents one of the world's principal orogens hosting volcanogenic massive sulfide (VMS) deposits (Franklin et al., 2005). Sporadic exploration from 1970-1995 has identified a large number of VMS deposits and prospects throughout the belt, including the world-class Crandon deposit that comprises an estimated 61 million tonnes of polymetallic massive sulfide ore (Lambe and Rowe, 1987). Despite successful exploration and the significant economic potential in the Penokean volcanic belt, only limited academic research has been conducted focusing on constraining the tectonic, structural, and volcanic setting of the VMS deposits. Many key aspects of the regional geology are not well understood, which is mostly due to extensive glacial cover of the Paleoproterozoic bedrock.

The present study aimed to use whole rock major and trace element geochemistry and U-Pb geochronology to investigate the geologic framework and tectonic setting of the belt and to constrain the timing of massive sulfide formation. Regional geochemical samples were taken from geophysically defined geologic domains. The high-precision chemical abrasion ID-TIMS U-Pb dating technique was used on zircon grains from seven felsic volcanic samples from the host rock successions of some of the major VMS deposits within the Penokean volcanic belt.

The results of the geochemical analyses reveal subtle differences between the geophysical domains. The majority of the volcanic rocks sampled have a tholeiitic affinity with fewer calc alkaline and transitional rocks. Geochemical evidence points to an island arc subduction environment with either intra-arc or back-arc extension.

Results of the ID-TIMS U-Pb geochronological analyses revealed that four of the deposits, namely Bend, Horseshoe, Lynne, and Pelican River were all formed at about 1874 Ma. This is evidence of a major period of volcanism and related VMS deposition that likely occurred in an extensional setting at this time.

The Back Forty massive sulfide deposit occurs on the east end of the Penokean volcanic belt. High-precision ID-TIMS U-Pb zircon geochronology of the host rhyolite yielded an age of about 1833 Ma, which is approximately 50 million years younger than the host rock successions of the other deposits of the Penokean volcanic belt. There are two possible explanations for this apparent age. The first explanation is that this represents a crystallization age and the host rocks to the Back Forty are part of a distinctly younger volcanic succession. Alternatively, a thermal event at 1833 Ma may have reset the U-Pb age.

The rhyolite sampled from the host rock successions of the Lynne and Back Forty deposits contain rare Archean-aged zircon grains. These zircon grains yielded U-Pb ages of approximately 2700 Ma and are presumably inherited from an Archean basement. These data

support the model that the Superior craton extends beneath the Pembine-Wausau terrane south of the Niagara Fault.

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Expanding the historical exploration document collection at the Minnesota Department of Natural Resources: the Polaris Joint Venture exploration program

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The Polaris Joint Venture was a large-scale five year-long exploration program targeting copper-zinc prospects in the greenstone belts of northern Minnesota during the early 1980s. Ernest K. Lehmann & Associates, in partnership with Getty and Billiton, completed airborne and ground geophysical surveys, geologic mapping, geochemical sampling, and 50 drill holes within a 13,000 square mile study area that stretched roughly from Bemidji to Ely.

In December 2014, the Lehmann Family Foundation donated the Venture's results and \$10,000 to the Minnesota Department of Natural Resources (DNR). Due to the large areal extent of the donation and quantity of work conducted in previously unexplored areas, the DNR decided to make the data digitally available to the public as soon as possible. Due to the manageable size of this donation, it also gave the DNR the perfect opportunity to experiment with new ways of managing its historical exploration document collection. The full historical exploration document collection can be found online at <http://minarchive.dnr.state.mn.us/information.html> (Fig. 1).

Resulting from the experimentation process with the Polaris Joint Venture data is the website: http://www.dnr.state.mn.us/lands_minerals/polaris/index.html (Fig. 2). From this site, the user should be able to smoothly navigate through and find the wanted data using the DNR's downloadable Microsoft Excel catalog, downloadable GIS shapefile and PDF links to the data, as well as being able to spatially search online through the web map application.

Updates to the Polaris Joint Venture collection are planned and the DNR will be accepting input from outside users. Once the Polaris Joint Venture collection portal is finalized, the DNR's next steps will be to adapt the new historical document management system to accommodate the other collections.



Fig. 1. The old historical document collection system.



Fig. 2. A new historical document collection and organization system.

Characterizing deformation of Gunflint Formation in contact with Archean basement rocks east of Thunder Bay, Ontario

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New expansion along Highway 11/17 east of Thunder Bay, Ontario exposes faults and damage zones that cut through and displace the Gunflint Formation of the Animikie Group, the underlying Archean basement rock, and the basal unconformity between them. Observations and stereographic projections were used to characterize outcrop-scale deformation along a curved road-cut on a hill approximately 1km long and covering an increase in elevation from west to east (where the unconformity is exposed) of about 65m. The Highway 11/17 road cut exposes a fault zone network that has accommodated a minimum of 60m of vertical displacement and unknown horizontal displacement. Two sets of well-preserved slickenlines record normal oblique sense movement on the fault zone. A void-filling calcite vein system is exposed in conjunction with the fault systems and is associated with brecciation.

Calcite crystals reach up to 10cm in diameter where larger voids are filled. At least two major fault zones with damage zones at least 1m wide are exposed at the study site and are seen at the far east and far west ends of the road-cut. The Eastern Fault Zone (EFZ) has an average strike and dip of $071^{\circ}/72^{\circ}$ cutting through both Archean basement rock and Gunflint Formation. The Western Fault Zone (WFZ) average strike and dip is $067^{\circ}/65^{\circ}$ and cuts through Gunflint Formation rocks. Two relatively minor reverse faults striking 345° and dipping 48° to 58° cut through the Gunflint Formation about 80m southwest of where the WFZ first appears. The relationship between the EFZ and WFZ is obscured by an oblique fault cutting through Archean rock between them with an average strike and dip of 040° and 60° .

The site is a potentially important study location for understanding fault/fluid interactions and how extensional faulting can accommodate fluid transportation. All major extensional features in the study area have a roughly northeast strike which aligns well with the orientation of the Mid-Continent Rift to the southeast suggesting that this fault zone is associated with extension ca. 1Ga.

The building blocks of stromatolites: Comparisons across time and environment

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Approximately one billion years separate the stromatolites of the Shakopee (Ordovician, Minnesota) and Rosspport (Mesoproterozoic Sibley Group, Ontario) formations, yet they may share similar carbonate building blocks, despite stark differences in age, large-scale morphology, and depositional environment.

The Shakopee Formation (Ordovician) was deposited in a shallow epeiric sea that covered much of the upper Midwest. Stromatolites in the Shakopee are diagnostic of the carbonate-rich, nearshore facies of the Shakopee (Davis, 1966; Johnson and Simo, 2002), perhaps marking the presence of restricted, warm, shallow marine environments. Stromatolites range in macroscopic form from low-relief, nearly stratiform morphotypes through low-relief columnar forms to internally complex domal structures.

In contrast, the Rosspport Formation (Mesoproterozoic) accumulated in an inland lacustrine environment that was at least intermittently hypersaline (Rogala et al., 2007). Robust stromatolite development is restricted to the Middlebrun Bay Member of the Rosspport and represents an interval dominated by carbonates within an otherwise mainly siliciclastic succession. In macroscopic form, the Rosspport stromatolites are stratiform to columnar, with low inheritance and low synoptic relief.

Despite these differences in environment and macroscopic outcrop expression, the two stromatolite occurrences share similar mesoscale to microscale textures – the structural building blocks of stromatolites. Although post-depositional processes, including recrystallization, silicification, and dolomitization, have affected the present-day preservation of these stromatolites, primary textures can be inferred in both units, permitting interpretation of the original carbonate building blocks of these ancient structures. At the mesoscale (visible in hand sample) level, stromatolites show isopachous lamination, oversteepened lamina, and complex internal textures that are characteristic of typical Proterozoic stromatolites formed by *in situ* precipitation of carbonate during stromatolite growth. At the microscale (visible under a microscope), stromatolites from both localities preserve (1) evidence of a primary micritic texture, with peloidal or clotted form, commonly associated with microbially-influenced carbonate precipitation, and (2) syndepositional cement growth coating stromatolites and forming the mesoscale isopachous laminae. Both stromatolite occurrences lack evidence of trapping-and-binding as a mechanism for stromatolite growth. when.

Similarities in stromatolite structural components across time and space suggest that the mechanisms of microbialite construction are broadly comparable in many settings, including ancient marine as well as both ancient and modern lacustrine environments. Modern marine stromatolites, such as those in the Bahamas and building blocks and are likely the outliers in microbialite construction across time and space.

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Evaluating H/V analysis of passive seismic data as a means to map sediment thickness in the Duluth-Superior harbor

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Drilling during the construction of the Interstate High Bridge between Duluth, MN and Superior, WI documented:

- 1) significant variations in depth to bedrock, showing that the thickness of the sediment cover increases towards Duluth;
- 2) that there are significant amounts of anthropogenic material (dredge spoil, waste material linked to historical sawmill activity in the harbor) in the areas surrounding the modern day harbor.

The seismic velocity structure of near-surface sediments can be determined from H/V analysis of passive seismic data collected with a 3-component geophone (ie the instrument measures ground motion in three orthogonal directions). This technique utilizes the ambient background seismic noise generated by nearby human activities (such as traffic or heavy machinery), winds and other atmospheric phenomena, and ocean waves. The response of the near-surface to excitation by ambient seismic noise varies with its' seismic velocity structure. Specifically, it exhibits unique seismic resonance frequencies that are linked to the structure of the near-surface.

The H/V spectral ratio method was originally introduced by Nogoshi and Igarashi (1971) with further development by Nakamura (1989). At each recording site, amplitude spectra are calculated for each of the three-component records of the ambient seismic noise. The ratio between the amplitude spectra of the horizontal (H) to vertical (V) frequency components identifies the resonance frequencies within the near-surface sediment package (SESAME, 2005). The lowest (fundamental) resonance frequency can be used to determine the thickness of the surface sediment layer.

H/V analyses of passive seismic observations made at multiple sites in the Duluth-Superior harbor area, are used to create a map depicting the spatial variation in seismic resonance frequency in the area. A map of sediment thickness in the harbor area is derived from this map by applying an empirical calibration function that links seismic resonance frequency to sediment thickness. This relationship is derived by making resonance measurements at sites with well control.

A more detailed interpretation of the near-surface shear-wave velocity structure is undertaken at selected sites. At these sites, the recorded data is used to construct a model of the near-surface velocity structure by iteratively perturbing a trial model, so that its calculated response matches the recorded data. This profile can yield valuable geotechnical information (specifically stiffness) about the near surface sediments (Lai and Rix, 1998; Xia et al., 1999).

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Geochemical and Petrological Comparisons of Peridotite Units in Marquette County, Michigan

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This study characterizes the following rock units in Marquette County, Michigan in terms of geochemistry and petrology: (1) Presque Isle Peridotite, (2) Deer Lake Peridotite, and (3) Yellowdog Peridotite. Analyses were conducted to determine if any petrological or geochemical relationships exist between these units, and to assess the potential of these units to host magmatic sulfide deposits. Based on the findings, these units have been separated into the two groups presented below.

Deer Lake Peridotite

Mineralogical compositions and textural characteristics of Deer Lake Peridotite are similar to those observed in the Presque Isle Peridotite and Yellowdog Peridotite. Prior to alteration, the unit's mineralogical composition was dominated by olivine and pyroxene. This rock type displays a cumulate texture. In some cases a poikilitic texture in which pyroxene oikocrysts enclose olivine chadacrysts is also present. However, these similarities are not sufficient to conclude that this unit shares a common origin with either of the other peridotite units. Also, it is noteworthy that the degree of serpentinization and hydrothermal alteration observed in the Deer Lake Peridotite is different, being far greater than that observed in either of Marquette County's other peridotite units.

Geochemical comparison of Deer Lake Peridotite with the other three units addressed in this study reveals obvious differences in chemical composition. Geochemical analysis also reveals that the Deer Lake Peridotite crystallized from a magma which formed as a result of shallow melting; whereas, the parent magmas of Presque Isle Peridotite and Yellowdog Peridotite formed as a result of deep melting.

Truncation of the Deer Lake Peridotite along its south-western margin by the Great Lakes Tectonic Zone suggests that the unit must have been formed either during, or prior to the formation of the GLTZ (2.7-1.85 Ga). This window of time for this formational event proves that the Deer Lake Peridotite predates the Yellowdog Peridotite's age (1.1 Ga) by no less than 750 Ma.

Trace element, and petrographic and geochemical analysis also suggest that Deer Lake Peridotite may actually represent two separate peridotite units emplaced during two separate events. Type 2 Deer Lake Peridotite displays foliation which is not present in Type 1 Deer Lake Peridotite. Possibly, Type 2 Deer Lake Peridotite was emplaced early in the formation of the GLTZ, and later deformed during the Penokean Orogeny (1.86-1.83 Ga), with Type 1 crystallizing during this later compressive phase. Bornhorst et al. (1993) postulated that the Deer Lake Peridotite may represent the subvolcanic base of the Mona Formation. Deer Lake Peridotite also appears to be associated with the metavolcanics of the Kitchi Formation. It is possible that these successive metavolcanic units may correspond to the two ultramafic units of Deer Lake Peridotite.

Based on geochemical and petrographic analysis, in conjunction with the geologic setting of the Deer Lake Peridotite, it is reasonable to conclude that the Deer Lake Peridotite was formed independently, and substantially earlier, than Presque Isle Peridotite and Yellowdog Peridotite. It is likely that this unit crystallized from a parent magma which resulted from shallow melting during the formation of the Great Lakes Tectonic Zone.

Presque Isle Peridotite and Yellowdog Peridotite

Presque Isle Peridotite and Yellowdog Peridotite, upon first examination, appear to be very different units. Presque Isle Peridotite is more finely grained, and lacks visible plagioclase feldspar crystals, such as those observed in the Yellowdog Peridotite. Presque Isle Peridotite has also undergone a notably higher degree of serpentinization, as is evidenced by a greater density of hydrothermal veins.

Additional examination also reveals that primary mineral assemblages in both units include a large fraction of olivine. Pyroxene, mostly in the form of augite, with a much smaller fraction of enstatite, also constitutes a substantial fraction of both units. They both display a cumulate texture. Additionally, a poikilitic texture in which rounded olivine chadacrysts are partially, or fully enclosed by pyroxene oikocrysts can be observed in both the Presque Isle Peridotite and Yellowdog Peridotite. Petrographic analysis of both units also reveals olivine hosted sulfide inclusions. Such inclusions may indicate the presence of an immiscible sulfide liquid at the time of crystallization.

Geochemical comparison of the Presque Isle Peridotite and Yellowdog Peridotite indicates that both formed from a parent melt of mantle origin, and became contaminated by crustal material prior to crystallization. Minor trace element analysis of the two units, reveals that they share a very similar geochemical composition.

Limited outcrop exposure of the Yellowdog Peridotite, and the lack of accessibility to host rock contacts at the Presque Isle Peridotite, make it difficult to draw conclusions based strictly on geologic setting relationships at both sites. However, Yellowdog Peridotite has intruded through the Late-Archean granite basement of the “Northern Complex”, and Paleoproterozoic sediments of the Baraga Basin (as confirmed by the exploration teams of both Kennecott and Lundin Mining). Ding et al. (2010), by the use of U-Pb baddeleyite dating, has confirmed that this unit crystallized at 1107.2 ± 5.7 Ma. This date allows for the reasonable conclusion that the Yellowdog Peridotite formed during the Midcontinent Rift event. The only unit which has been observed in direct contact with the Presque Isle Peridotite is the uppermost member of the Keweenaw series, the Jacobsville Sandstone. Here, it is clear that Presque Isle Peridotite is nonconformably overlain. Radiometric dating of zircons from Jacobsville Sandstone confirms that the unit is no younger than 960 Ma (Malone et al., 2015). Observation of the peridotite’s contacts with other units is not possible because they are concealed beneath Lake Superior. However, it can be safely assumed that the Presque Isle Peridotite has also intruded through the Archean granite basement of the “Northern Complex”. No geochronological dates have ever been obtained for the Presque Isle Peridotite.

The findings suggest the possibility that the Presque Isle Peridotite may also date to the Mesoproterozoic, at which time, it may have been formed contemporaneously with the Yellowdog Peridotite, during the early stages of the Midcontinent Rift event (1.1 Ga). Geochemical similarities between these units also suggest the likelihood that the plume induced, parent melts of both units were very similar, and may have been directly related.

Presque Isle Peridotite is shown to display the following: (1) High nickel content, comparable to that of the Yellowdog Peridotite (as shown by XRF analysis). (2) Sulfide inclusions within olivine. (3) Primary magmatic sulfide assemblages of chalcopyrite and pentlandite. (4) Incompatible element enrichment. Comparison of Ni content with Fo molar percentage, also yields results similar to those observed in both the “Eagle” and “Eagle East” intrusions of Yellowdog Peridotite. All these factors make Presque Isle Peridotite a prime target for future exploration, as they suggest the possibility that the unit has the potential to host magmatic sulfide deposit similar to those hosted by both intrusions of the Yellowdog Peridotite. It can be concluded from the available data, that peridotite units of Keweenaw age, located in the Lake Superior region should be considered high priority targets for magmatic sulfide exploration.

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Metal isotopic signatures in the Duluth Complex associated with magmatic Cu-Ni-PGE mineralization

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Magmatic Cu-Ni-PGE sulfide mineralization occurs in a series of deposits along the western margin of the Duluth Complex in northeastern Minnesota. While the mineralogy, geochemistry, and formation of these deposits has been investigated in some detail, there is little information available on the metal isotopic signatures (Ni, Cu) of these deposits and if this information allows to I) gain more insight into the genesis and evolution of these deposits and II) holds potential as an exploration tool. Recent studies have demonstrated that Ni isotopic fractionation exists in both high and low-temperature terrestrial material with a range of 2.1 ‰ [1-3]. Fractionation of Cu isotopes in magmatic systems has been established and significant differences between primary and secondary sulfides are noted [4,5]. For the Duluth Complex, recently reported Cu isotopic values range from -0.85 to 0.45 ‰ [6]. Sulfide-bearing drill core samples (massive, disseminated) and sulfide-barren material from all major deposits in the Duluth Complex were collected and analyzed, along with weathered surface material from mineralized outcrops and till samples. $\delta^{60/58}\text{Ni}$ values in olivine (ave: -0.03 ‰), sulfides (ave: -0.36 ‰), and secondary oxides (ave: -0.50 ‰) are comparable to previous work [1-2] and indicate i) high temperature fractionation of Ni into olivine with bulk silicate earth signature (BSE) during initial crystallization, ii) increasing lighter Ni isotope incorporation as a function of sulfide content, and iii) preferred ^{58}Ni incorporation into secondary oxides and silicates due to weathering processes. ^{60}Ni is presumed to enter solution during weathering, supported by isotopic signatures of garnierite (1.5 ‰) from a magmatic sulfide deposit in Germany.

$\delta^{65/63}\text{Cu}$ values for the Duluth Complex deposits range from -1.28 ‰ to 0.36 ‰ (Figure 1), comparable to published data [6]. Other magmatic Cu-Ni-PGE deposits in the area (Eagle, Tamarack; massive sulfides) show a distinctly heavier isotopic signature (> 0.69 ‰) while disseminated ore material from Eagle is much lighter (-0.16). While both massive and disseminated sulfides from all deposits in the Duluth Complex show similar Cu isotopic values (ave: -0.32 to -0.35 ‰), individual deposits differ in their isotopic signature and are quite distinct from each other. Surface material generally shows variable negative enrichment of ^{63}Cu , attributed to the weathering process and the preferential enrichment of lighter Cu isotopes into the weathering products.

Due to the difference in Ni isotopic values between unmineralized material (ave: -0.05) and sulfide-bearing samples (up to -0.97 with increasing sulfide content), Ni isotopes may be useful to distinguish barren magmatic systems (BSE signature) from mineralized systems because of the preferential incorporation of isotopically light Ni into sulfide-bearing rocks. The significance and use of Cu isotopes in the Duluth Complex is less clear since a variety of processes (Cu source, sulfide fractionation) likely influenced the overall Cu isotopic signature. However, if a mantle signature of ~ 0 ‰ is assumed, the relative contribution of sedimentary Cu in the Duluth Complex (ave: 0.97 ‰) and magmatic Cu may be determined and differences in the formation of individual deposits in the Duluth Complex assessed.

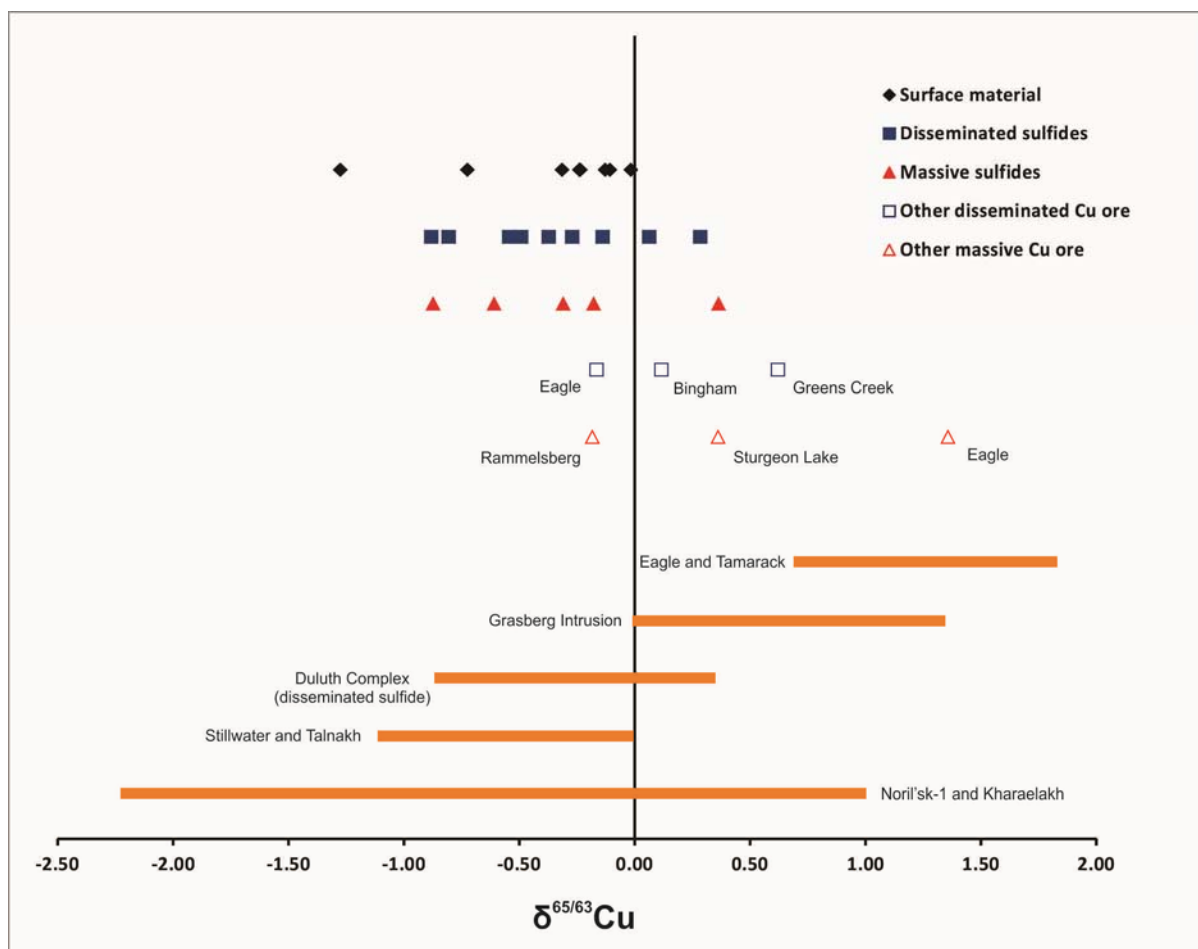


Figure 1: Cu isotopic values of primary and secondary sulfide material from Duluth Complex Cu-Ni-PGE ore deposits compared to other magmatic sulfide deposits and selected VMS deposits. Data for orange bars are taken from [6].

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Acid-Generating and Acid-Neutralizing Potential of Silicate Rocks from the Basal Mineralized Zone of the Duluth Complex, Minnesota

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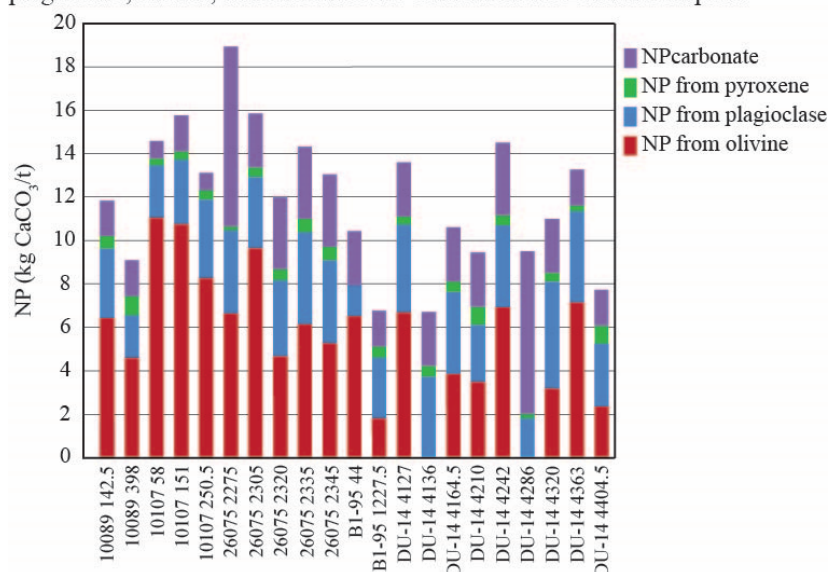
The acid-generating potential (AP) and acid-neutralizing potential (NP) of the basal zone of the Mesoproterozoic Duluth Complex are atypical of most mafic hosted copper-nickel-platinum-group-metal (Cu-Ni-PGM) ore deposits because: 1) the sulfide ores are typically disseminated, and 2) the gangue assemblages generally lack carbonate minerals; thus, any acid-neutralizing potential must be derived from more slowly reacting silicate minerals. Recent technological advances in mineral processing have improved the viability of developing these low grade, large tonnage Cu-Ni-PGM, which represent some of the largest undeveloped deposits of their type on earth (Eckstrand and Hulbert, 2007; Miller and Nicholson, 2013). The potential development of these resources necessitates an understanding of their environmental behavior including assessment of the AP and NP of future mine waste.

The 1.1 Ga Duluth Complex is a large (> 5,000 km²) composite body of troctolitic, gabbroic and anorthositic intrusions located in northeastern Minnesota. The complex is part of the Midcontinent Rift system that occurs in the Lake Superior region. The intrusions were emplaced into footwall rocks of Archean granite and greenstone terranes, Proterozoic metasedimentary rocks (Biwabik Iron Formation and Virginia Formation) and penecontemporaneous North Shore Volcanic Group basalts.

In order to evaluate the AP and NP of potential mine waste from the Duluth Complex, five drill cores were sampled at the Minnesota Department of Natural Resources Core Library in Hibbing, Minnesota. Drill core in the vicinity of the NorthMet (26075), Local Boy (10089 and 10107), Mesaba (B1-95), and Maturi (DU-14) Cu-Ni-PGM deposits was included in this study. Mineralogical, petrographic, and geochemical analyses were undertaken to evaluate NP contained in carbonate and silicate minerals and AP contained in sulfides. For most of the drill cores, the main analytical focus was on samples in the basal zone hosting disseminated sulfide mineralization, although representative samples from above and below the mineralized zones were also assessed to evaluate variations in AP and NP based on rock type and stratigraphic position. If the Cu-Ni-PGM deposits are developed, mine waste will consist of processed rock from the mineralized zones as well as material adjacent to those zones.

The ability of mine waste to generate or neutralize acid is commonly estimated using AP and NP values. In general, if the acid consumption or neutralization value (NP) exceeds the acid producing value (AP), the material will likely not be a source of acidity; whereas, if AP exceeds NP, the material may generate acid. The AP is based on the sulfide content and is typically estimated from total sulfur (S) content and calculated assuming all S occurs as the acid-generating mineral pyrite (Sobek et al., 1978). The NP of mine waste is typically based on direct or, more commonly, indirect measurement of its carbonate content. Carbonate minerals are considered the most effective neutralizing agents to mitigate the acid generated by sulfide oxidation in solid mine waste. However, this is problematic in deposits without significant amounts of carbonate minerals, such as those in the Duluth Complex. For these cores, we examined the potential for other minerals, particularly silicates, to contribute to the NP; if these deposits are developed, silicate minerals would constitute the bulk majority of the mine and milling waste. The main silicate minerals identified in drill cores from the Duluth Complex include plagioclase feldspar, olivine, pyroxene, mica, amphibole, and secondary minerals, such as serpentine

Figure 1. Acid-neutralizing potential (NP) contributions from pyroxene, plagioclase, olivine, and carbonate for cores from the Duluth Complex.



and chlorite. The NP contribution from the silicate minerals was calculated based on NP values of monomineralic samples from Jambor et al. (2002; 2007) and weighted by their abundances in the drill core samples from powder X-ray diffraction (XRD) analyses. Olivine contributes the most NP of the silicate minerals, at 38 kilograms of calcium carbonate equivalent per ton (kg CaCO₃/t) (Jambor et al., 2007). The NP of plagioclase feldspar depends on the anorthite content and ranges from less than 1 up to about 14 kg CaCO₃/t (Jambor et al. 2007). The NP of pyroxene is 4.6 kg CaCO₃/t (Jambor et al. 2007). As shown in Figure 1, calculated NP values from these cores range from 6.7 to 19 kg CaCO₃/t. Because the carbonate content is low in the Duluth Complex core samples, the NP contribution from the silicate minerals is significantly greater than NP from carbonate (Fig. 1).

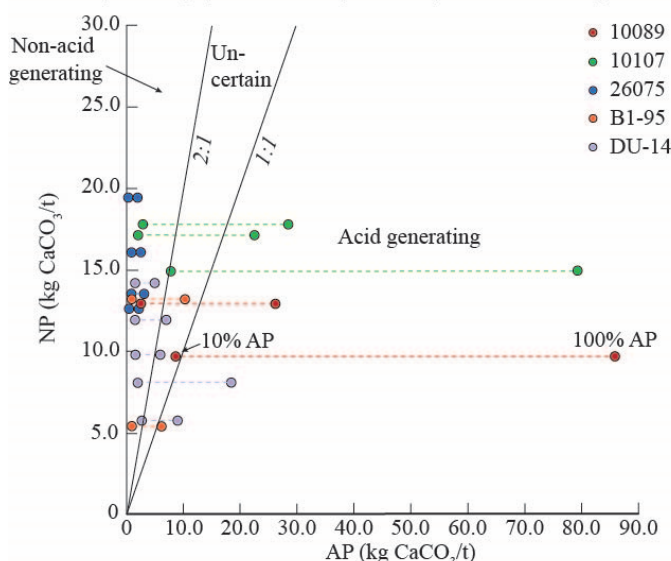
It is important to note that not all of the drill cores are predicted to be acid generating (Fig. 2). Specifically, all drill core samples from 26075 (NorthMet deposit) and most from DU-14 (Maturi deposit) have AP values that are less than their NP values. As a result, the NP in these cores may be sufficient to neutralize acid generated by sulfides. Furthermore, if we assume that 90 percent of sulfides will be recovered during mineral processing, the AP values of mill tailings decrease dramatically; thus, bulk samples previously predicted to generate acid no longer fall into the acid-generating category because most of the sulfides have been removed (Fig. 2). This is particularly important in drill core samples with significant sulfide contents, such as the Local Boy ore zone (drill cores 10089 and 10107).

NP and AP also can be discussed in terms of a neutralization potential ratio (NPR), where $NPR = NP/AP$. For these cores, NPR values vary from 0.1 to 14.2 assuming no sulfide has been recovered during mineral processing. Generally, NPR ratios less than 1 are considered acid producing and ratios greater than 2 are non-acid producing (Price 2009). NPR ratios between 1 and 2 are capable of producing acid rock drainage. Based on these benchmark values, some samples from the Duluth Complex Cu-Ni-PGM deposits could contribute to the production of acid mine drainage (Fig. 2). However, at 10 percent of the AP (assuming 90% sulfide recovery), the neutralization potential ratios are all above 1, with an average NPR value of 49, suggesting the mine waste generated after recovering sulfides from the ores may not be a source of acidity. Although silicates weather more slowly than carbonates, the NP of the silicates can facilitate the neutralization of acids generated in mine waste. Neutralization from silicate minerals is likely to have the greatest impact in tailings storage facilities where groundwater should have longer residence times due to the significantly finer grain size of the material compared to that of typical waste rock.

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Figure 2. Plot of acid-generating potential (AP) versus neutralizing potential (NP) for drill core samples from the Duluth Complex. Dashed lines represent the difference in 100% AP (on the right) and 10% AP (on the left) for the same sample.



The Geochemistry of the Siemens Creek Formation and the Nature of Early Midcontinent Rift Basaltic Magmatism in the Western Lake Superior Region

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The Siemens Creek Formation is the lower member of the Powder Mill Group and represents the earliest (>1108 Ma) exposed lava flows of the Midcontinent Rift in northern Michigan and Wisconsin (Hubbard, 1975). It extends from Sturgeon Falls in Michigan to as far west as at least Atkins Lake in Wisconsin, although it is disrupted by the intrusion of the Mellen Complex near Mellen, Wisconsin (Cannon and others, 2006). It is best exposed in a prominent east-west belt of knobby hills north of U.S. Route 2 between Bessemer, Michigan and Upson, Wisconsin. Near Ironwood, Michigan the Siemens Creek Formation is about 1,340 m thick (Hubbard, 1975).

The Siemens Creek Formation lies conformably upon the Bessemer Quartzite; rare quartzite interbeds also occur in the lower 30 m. The basal flows, 35 to 50 m thick, are typically pillowed, strongly chloritized, and at least locally contain hyaloclastite breccia. Basal flows west of a point about midway between Upson and Hurley, Wisconsin typically have olivine and pyroxene phenocrysts and range from picrite to basalt. In contrast, to the east of that point the basal flows mostly lack olivine-pyroxene phenocrysts and range from basalt to andesite. The western basal pillowed flows are locally overlain by a stromatolitic carbonate layer that divides the Siemens Creek into lower and upper members (basalt Types I and II, respectively of Nicholson and others, 1997). The upper lava flows are generally thinner (3 to 14 m) than the lower flows and were subaerially erupted with pahoehoe and sparsely vesicular flow tops. The upper flows range from basalt to andesite with more evolved andesites containing small plagioclase phenocrysts.

The western basal flows (Type I olivine-pyroxene-phyric picrites and related basalts) are geochemically distinct from the upper Siemens Creek Formation (Type II basalts). The basal Type I flows are characterized by high MgO (~8 to 17%), FeO (~13 to 16%), and TiO₂ (~2-3%), and low Al₂O₃ (~8 to 10%). Those samples that are chloritized have high water contents (2 to 3%), and also appear to have lost Na₂O (have high K₂O/(K₂O+Na₂O)). Based on the major element characteristics, the Type I flows would be classed as ferropicrites and ferrobasalts (Gibson and others, 2000). Their trace element characteristics also are distinctive with steep, strongly light REE enriched REE patterns, high high-field-strength element and V contents, and primitive mantle normalized patterns that peak at Ta, have a saddle at Zr-Hf, and positive V anomalies (Fig. 1A). Isotopically these rocks have an initial ϵ_{Nd} of ~0. The trace element characteristics are similar to some ocean island basalts (OIB), particularly alkaline HIMU OIB, and alkaline meymechites (low Al, high Mg rocks) in the Siberian Traps of Russia (Fig. 1A). They are also similar to the basal Keweenaw lava flows at Ely's Peak near Duluth, in the Grand Portage area, and at the base of the Osler Group in Ontario (Fig. 1B).

The eastern basal flows, although also pillowed, are Upper Siemens Creek Type II basalts in composition. Type II basalts are broadly similar in overall composition, although in detail three compositional types can be distinguished that appear to have distinct stratigraphic and lateral distribution (Type IIA, B, C in Fig 1C). The basal flows (Type IIA) extend from about the midpoint between Upson and Hurley eastward to Sturgeon Falls. They have high SiO₂ ~50 to 58%, MgO ~5 to 10% (one picrite with 17%), FeO ~10 to 13%, Al₂O₃ ~10 to 15%, and TiO₂ ~1.5 to 2.5% with low Al₂O₃/TiO₂ ratios (5-8). They show light REE enrichment with positive Th and mostly large negative Nb-Ta anomalies when normalized to primitive mantle (IIA in Fig. 1C). The Type IIB flows are directly above the basal flows and extend from east of Mellen to just east of Lake Gogebic. They show a smaller compositional range with SiO₂ ~50 to 55%, MgO ~5 to 8%, FeO ~10 to 12%, Al₂O₃ ~14 to 16%, and TiO₂ ~1.4 to 2% with Al₂O₃/TiO₂ ratios of 8 to 10. They are more enriched in light REE than the Type IIA basalts and most do not show negative Nb-Ta anomalies when normalized to primitive mantle (IIB in Fig. 1C). The last type (Type IIC) occurs as the uppermost Upper Siemens Creek flows in the area between just west of Hurley to Silver Mountain. They overlap in composition with the basalts below but mostly have lower TiO₂ contents (~1 to 1.8%) and higher Al₂O₃/TiO₂ ratios (9 to 14). Their trace elements are similar to those of

Type IIA basalts but they extend to more enriched Th and also have negative Nb-Ta anomalies when normalized to primitive mantle (IIC in Fig. 1C). The high SiO₂ contents, enriched Th, negative Nb-Ta anomalies, and negative initial ϵ_{Nd} values (-2 to -7) suggest significant, probably lower crustal contamination of the Type II Upper Siemens Creek basalts.

The lava flows of the Siemens Creek Formation and correlative units around western Lake Superior appear to record the initial decompressive melting of an enriched mantle plume (Fig. 1D). The first picritic to basaltic flows represent low degree partial melts (~1-3%) derived from considerable depth well in the garnet stability field (>120km) (Fig. 1D). Progressive lithospheric extension, however, appears to have relatively quickly given rise to basaltic melts derived at higher degrees of melting at intermediate to relatively shallow depths (spinel stability field), and that ponded and interacted with the lower crust (Fig. 1D).

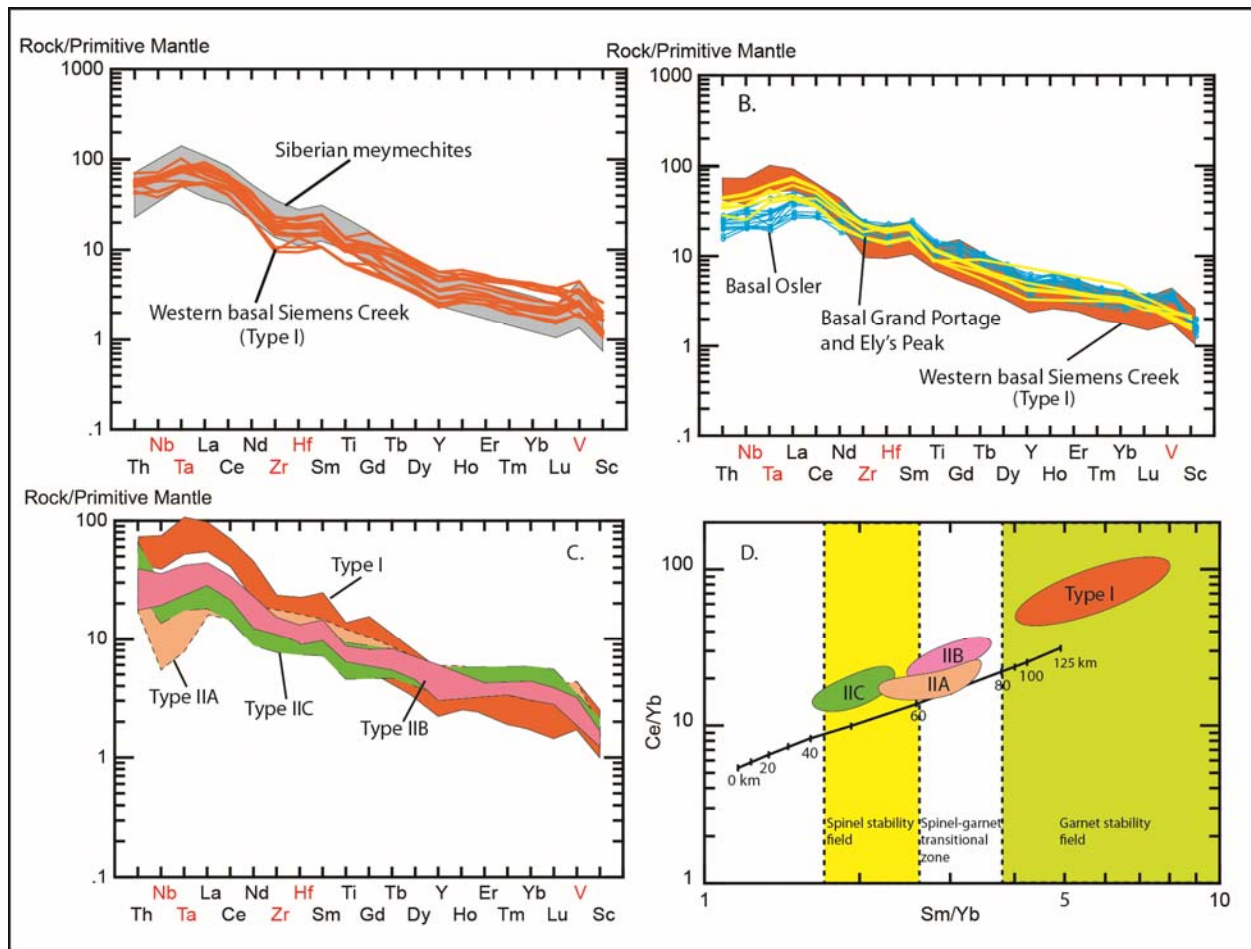


Figure 1. A. Primitive mantle normalized trace element plot for the western basal Type I Siemens Creek lava flows and field for Siberian meymechites; B. Primitive mantle normalized trace element plot for basal Keweenaw lava flows in western Lake Superior; C. Primitive mantle normalized trace element plot for lower Type I and upper Type II Siemens Creek basalts; D. Ce/Yb vs Sm/Yb plot comparing Siemens Creek basalts with model melts generated by progressive lithospheric extension. Tick marks on model melt curve indicate depth of final melt segregation in km (after Ellam, 1992).

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Potential value of pre-mining baseline oxygen, hydrogen, and sulfur isotopic data from surface waters for proposed large mining projects in northern Minnesota

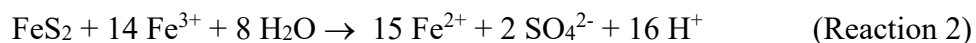
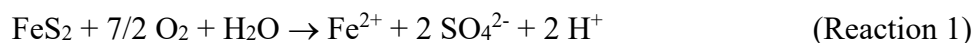
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Large mining projects, such as those proposed for the disseminated Cu-Ni-platinum group metal ores of the basal zone of the Duluth Complex, face a number of long-term challenges regarding environmental management due to their large size and the duration of mine lives. Leachates from mine waste may reach groundwater and eventually surface water from sources difficult to identify because they may be concealed by extensive piles of waste material. Acid drainage, even from low-sulfide mine waste, is one type of leachate that can be especially problematic to the environment by contributing acid, sulfate, and trace metals to the surrounding watershed. Large mines can have mine lives that span multiple decades. Under such long time spans, climate change, particularly drought, may have unanticipated effects on water quality and quantity in mine settings presently dominated by wetlands, such as those in northern Minnesota. Bacterial sulfate reduction is a common process acting in wetlands that consumes sulfate and organic matter to produce sulfide and alkalinity. The resulting sulfide can combine with iron or other metals to form authigenic sulfide minerals that sequester sulfur under the water-saturated anoxic conditions within wetlands. If these wetlands become unsaturated due to drought conditions, these authigenic sulfide minerals may oxidize and release sulfate to the watershed as surface-water levels decline, which can confound attempts to identify sources of dissolved sulfate and trace elements in regional watersheds.

Pre-mining baseline characterization of the oxygen and hydrogen isotopic composition of water and the sulfur and oxygen isotopic composition of dissolved sulfate provides a potential means of identifying the future influx of both acid drainage leached from mine-waste piles and sulfate derived from oxidation of naturally occurring authigenic sulfide minerals from drying wetlands. Three watersheds, Filson Creek, Keeley Creek, and the Saint Louis River, all of which transect the basal zone of the Duluth Complex, were sampled for baseline water-quality and stable isotope geochemistry over the course of a year focusing on peak-flow (June 2013) and base-flow (September 2012, 2013) conditions. The oxygen and hydrogen isotopic compositions of surface waters reflect the varying amount of evaporation that these waters have experienced. Isotopic analyses from samples from base-flow conditions reflect the influence of significant evaporation ($\delta^{18}\text{O} = -9.4 - -4.1 \text{ ‰}$; $\delta\text{D} = -65.5 - -38.8$), whereas samples taken during peak flow show minimal deviation from the meteoric water line and imply little or no evaporation. Comparison of the oxygen isotope composition of water and dissolved sulfate reflects the relative importance two pyrite oxidation reactions that primarily differ in terms of their oxidants:



Reaction 1 with molecular oxygen as the oxidant is most important at pH values above 4 – conditions of incipient sulfide oxidation. In contrast, Reaction 2 with ferric iron as the oxidant is most important below pH 4 – classic acid-mine drainage conditions. The oxygen isotopic composition of the water and dissolved sulfate can be used to estimate the relative importance of these two reactions in the generation of dissolved sulfate. The oxygen isotopic composition of

dissolved sulfate in surface waters around the basal zone of the Duluth Complex ($\delta^{18}\text{O} = -0.2 - 4.3 \text{ ‰}$) is consistent with greater than 70 percent of its derivation from Reaction 1 (Figure 1). Any future input of acid-mine drainage would be expected to produce sulfate with a distinctly lower oxygen isotopic composition.

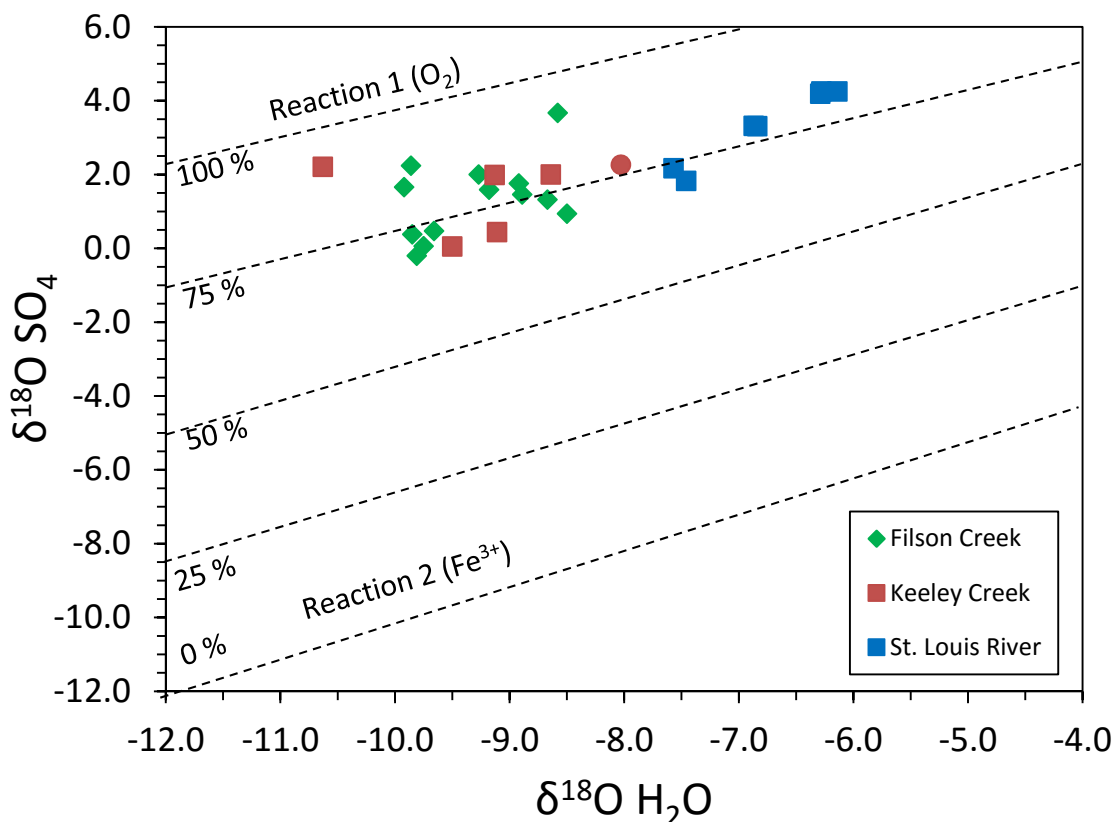


Figure 1. Oxygen isotope composition of dissolved sulfate and water from surface waters samples in the Filson Creek, Keeley Creek, and Saint Louis River watersheds near the basal zone of the Duluth Complex. The dashed lines correspond to the relative proportions of Reaction 1 and Reaction 2 contributing to the dissolved sulfate through sulfide oxidation.

The sulfur isotopic composition of dissolved sulfate has potential for being a sensitive indicator of sulfate derived from future emergence and drying of wetlands due to drought conditions. The sulfate-sulfur isotopic composition of dissolved sulfate ($\delta^{34}\text{S} = 5.6 - 8.6 \text{ ‰}$) overlaps known variations for ore and country rocks sulfides, suggesting that the current dissolved sulfate is derived from near surface oxidation of sulfide minerals from the basal zone of the Duluth Complex and the Virginia Formation. In contrast, the sulfur isotope fractionation caused by bacterial sulfate reduction can produce sulfide with isotopic compositions that can be between 15 and 70 ‰ lower than the corresponding sulfate. The sulfur isotope composition of sulfate derived from emergent wetland sulfide minerals in the future may be markedly different from the current sulfate in the watersheds.

Baseline isotopic data for waters and dissolved sulfate can potentially be the basis for sensitive indicators of the future onset of acid-mine drainage, or the release of sulfate from wetlands that emerge due to prolonged droughts. The recognition of either of these processes near their earliest inception will facilitate appropriate responses for environmental protection during mining and after closure.

The Mineralogy, Petrography and Geochemistry of the Anderson Lake Pegmatite Occurrence

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Anderson Lake Pegmatite is a S-type granitic pegmatite derived from the Hilma Lake Granite within the Quetico Terrane of the Southern Superior Province. The Anderson Lake pegmatite mineralogy consists of potassium feldspar, muscovite, quartz, beryl, and molybdenite. The pegmatite is crosscut by later quartz veins which occasionally host amethyst. The molybdenite within the pegmatite is syngenetic and occurs directly within quartz rich areas of the pegmatite, as well as within late stage dark gray quartz veins which crosscut the pegmatite.

The molybdenite is occurring as coarse-grained euhedral florets, as well as pod-like aggregates. Of the three main trenches within the property, the molybdenite is more abundant in trench A, with minor occurrences in B and C. Within trench C, ferrimolybdenite is present within fractures alongside the molybdenite. Re-Os dating of the molybdenite within the pegmatite produced an age of 2689 $\pm$ 12 Ma, which predates much of the plutonism, metamorphism and subsequent pegmatite injections within the Quetico Terrane (Percival and Sullivan, 1986). The pegmatite is roughly N-S trending along the contact between the host metasedimentary rocks and the Hilma Lake Granite.

The associated Hilma Lake granite is classified within this study as a equigranular, coarse-grained monzogranite to syenogranite. The Hilma Lake granite contains plagioclase – potassium feldspar – quartz – biotite – muscovite – titanite – garnet – apatite and the biotite is heavily altered to chlorite with magnetite inclusions between the sheets of the biotite. When plotted on a tectonic discrimination diagram (Rb vs. Y + Nb) (Pearce et al., 1984), the Hilma Lake Granite and the Anderson Lake Pegmatite plot as volcanic arc granites. This would be expected had they formed during the subduction and transpression of the Wabigoon Terrane to the north and the Wawa Terrane to the south, when the Quetico was an accretionary complex composed of sediments derived from the volcanic arcs to the north and south (Percival and Williams, 1989).

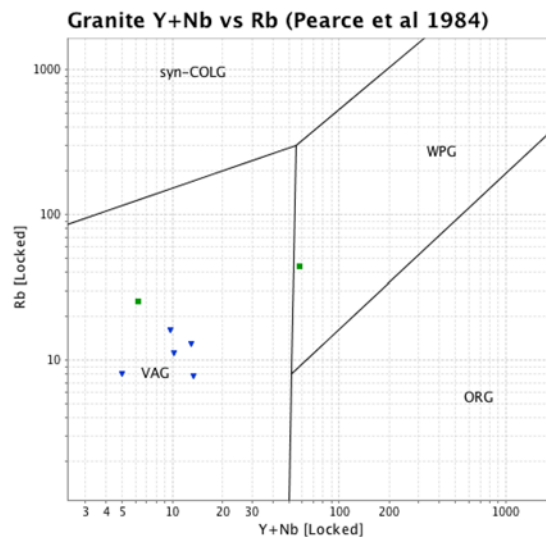


Figure 2: Tectonic discrimination diagram of the Hilma Lake Granite and the Anderson Lake Pegmatite based on (Pearce et al., 1984).



Figure 3: A) Pegmatitic Beryl crystal found in trench A. B) Amethyst within a quartz vein in trench C. C) Hand sample from trench A showing a large molybdenite crystal.

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A Preliminary Investigation of Enigmatic Igneous Rocks on Big Powder Island, Northern Lake Superior: A Possible Mesoproterozoic Magmatic Event

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A previously undescribed package of igneous rocks was investigated in 2015 on the southern shore of Big Powder Island (aka Anguros Island) in northern Lake Superior near Rossport. These relatively flat-lying rocks apparently overlie Paleoproterozoic Animikie Group sedimentary rocks of the Rove Formation (ca. 1835 Ma) and appear to be overlain by Mesoproterozoic clastic sedimentary rocks of the Pass Lake Formation, the lowermost formation of the ca. 1.4 Ga Sibley Group. All local rocks are intruded by ca. 1.1 Ga Nipigon diabase sills and dykes of the Midcontinent Rift (MCR).

This package of igneous rocks, originally ascribed to the MCR by Giguere (1975) comprise a variety of fragmental units with aphanitic to phaneritic groundmasses. Locally displaying columnar joints, these rocks contain features that suggest that they may have been alternatively emplaced as shallow intrusions, flows and/or pyroclastic units. Three broad varieties of fragmental rocks have been identified:

- Polymictic rocks with $\leq 50\%$ fragments;
- Monomictic rocks with $\leq 30\%$ black, fine-grained fragments; and
- Fragment-poor, aphanitic rocks with possible vesicles/amygdules.

The majority of fragments are sub-angular to sub-rounded and resemble chemical and clastic Animikie Group sedimentary rocks. Baked margins are visible on some fragments, while others show evidence of partial resorption, flow alignment and/or flow-induced folding.

The entire recovered zircon population appears to consist of detrital grains that exhibit metamorphic rounding but apparently lack metamorphic overgrowths. U-Pb data are concordant, yield typical Archean greenstone belt (2718-2720 Ma) and granitoid (2678 Ma) ages, and have normal igneous Th/U. These xenocrysts may have come from a xenolith that had been assimilated and heated sufficiently to cause resorption on the zircon surfaces, but not enough to produce melted rims (S. Kamo, personal communication, 2016). Or, alternatively, they represent a detrital zircon population that was abraded during transport and incorporated into a magma prior to overgrowth formation.

Unlike nearby Nipigon sills, the primary mineralogy of these rocks has been extensively altered. Plagioclase and microcline have been sausseritized and sericitized, respectively. Primary ferromagnesian minerals have been altered to amphibole and chlorite. Small, irregular patches of quartz are suggestive of partial melting or resorption.

Whole rock geochemistry of relatively fragment-free rocks is consistent with andesites to dacites ($\text{SiO}_2 = 57\text{-}70\text{ wt\%}$), with generally elevated K_2O contents of 1.8 to 6.1 wt%, placing them in the calc-alkaline field on an AFM diagram. Very low $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios for most of the samples strongly suggests removal of Na during near-surface weathering, though the significant amount of K in the samples indicates the weathering was not extensive. The Big Powder Island (BPI) rocks are characterized by enriched LREE ($\text{La}/\text{Sm}_n = 2.3\text{-}3.9$), weakly fractionated HREE ($\text{Gd}/\text{Yb}_n = 1.2\text{-}1.7$) and strong negative Nb anomalies.

When compared to MCR-related magmatic suites, the BPI rocks have similar La/Sm_n and Gd/Yb_n characteristics to both the Nipigon sills and the Osler volcanic rocks. Two thin dikes that cut a nearby Nipigon sill are geochemically similar to the BPI rocks rather than the sills, suggesting that they could be co-magmatic. However, the BPI fragmental rocks have lower TiO₂ contents at a given Mg# than the majority of MCR rocks, suggesting a distinct source region. Interestingly, the only other MCR suite that shows similar TiO₂ systematics is from the Moss Lake Intrusion. On a regional scale, the ~1590 Ma Badwater intrusive rocks show similar trends to the BPI with variable Mg#s at broadly constant TiO₂ contents (Hinz 2015) whereas the ~1540 Ma English Bay granites (Hollings et al. 2007) do not.

Lacking unequivocal primary zircon age data and based on apparent field relationships with other local Proterozoic rocks, it is suggested that the BPI rocks may represent magmatism that occurred between 1.4 and 1.8 Ga. Detrital zircon data from the overlying Sibley Group rocks contain populations that cluster between 1.9 to 1.8 Ga and 1.6 to 1.4 Ga (Rogala et al. 2007). Very few igneous rocks of those ages occur in this part of northwestern Ontario, suggesting that perhaps the BPI rocks could be a possible source of some of these zircons.

Further work is required to establish and constrain field relationships and determine the nature and age of these enigmatic igneous rocks.

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SEQUENCE STRATIGRAPHY AND BASIN EVOLUTION OF THE MESOPROTEROZOIC NONESUCH FORMATION, ASHLAND SYNCLINE, NORTHERN WISCONSIN

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The late Mesoproterozoic Oronto Group consists of the Copper Harbor Conglomerate, successively overlain by the Nonesuch Formation and the Freda Sandstone. These sediments were deposited within the Midcontinent Rift above about 20 km of mostly volcanic rocks. The Nonesuch Formation is a significant host for copper and silver, a potential unconventional hydrocarbon resource, and a potential seal for carbon sequestration (Thorleifson, 2011, Bornhorst and Williams, 2013). In addition, the formation is the focus of fundamental research into environmental controls on the expansion of terrestrial life (Cumming et al., 2013). Despite its significance to applied and fundamental geologic questions, the Nonesuch Formation's detailed sedimentology and stratigraphy remain relatively unstudied, and the formation has never been interpreted within a genetic, sequence stratigraphic framework.

We present a sequence stratigraphic framework for the Nonesuch Formation within the Ashland Syncline, northern Wisconsin, based on core description and geochemistry. Because the Midcontinent Rift developed as a series of relatively enclosed basins, we use lacustrine facies associations to interpret a sequence stratigraphic framework (Carroll and Bohacs, 1999). This does not exclude the probability of episodic marine incursions, and lacustrine environments described and discussed herein may be partly to fully marine (Hieshima and Pratt, 1991). This framework ties geologic variability to geologic processes, thus improving predictability of the distribution of physical, geochemical, and biologic characteristics of the Formation. We observe ten lithofacies which we group into fluvial-alluvial, fluctuating-profundal, and fluvial-lacustrine facies associations. Handheld XRF analyses provide geochemical data that help classify these lithofacies. We observe three regional stratigraphic surfaces: two flooding surfaces, and one progradational surface that is a potential sequence boundary.

The lithofacies succession we observe records a progression from a fluvial and alluvial depositional environment recorded by the upper Copper Harbor Conglomerate, to a balance-filled and then overfilled lacustrine environment within the Nonesuch Formation, and finally returning to a fluvial and alluvial environment within the uppermost Nonesuch Formation and lower Freda Sandstone. This interpreted evolution of depositional environments suggests that the primary control on sediment deposition and preservation was tectonic rather than climatic. The fluvial-alluvial facies association of the upper Copper Harbor Conglomerate was deposited when tectonic subsidence was relatively low. The basal Nonesuch contact records renewed tectonic subsidence, and the facies associations and stacking within the overlying Nonesuch Formation and lower Freda Sandstone record an evolution of sedimentary environments that developed in response to waning tectonic subsidence. The relative thicknesses and distribution of proximal and distal depositional environments, interpreted from lithofacies, show interpreted isopachs with arcuate shapes that thicken to the east. This indicates greater subsidence to the east. From this, we interpret deposition within an asymmetric half-graben bounded by one or more west-dipping normal faults to the east. Growth faults like these resulted in a series of relatively isolated sub-basins within the Midcontinent Rift basin structure. Distinct stratigraphic architecture and basin-bounding faults of these sub-basins may have acted as barriers to

mineralizing fluids and likely explain the difference between the unmineralized Nonesuch Formation in the Ashland Syncline and the ore-grade Cu mineralization in the Western Syncline and White Pine areas.

We demonstrate that a modern, sequence stratigraphic approach may be applied to fine-grained Precambrian sediments by using traditional rock description techniques and supporting lithogeochemistry. Our identification of a characteristic succession of lithofacies in Mesoproterozoic sediments demonstrates fundamental controls that are commonly interpreted for Phanerozoic lake systems may be extended into the Precambrian; these fundamental controls result in a predictable association of lithofacies, with distinct physical, biological, and geochemical properties.

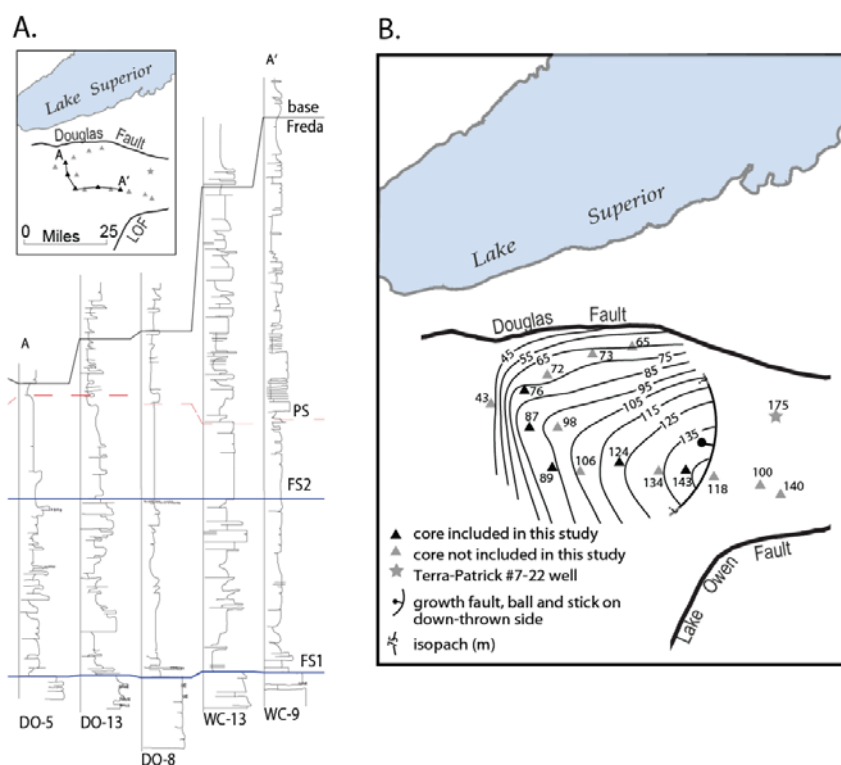


Figure 1: A. Fence diagram showing cores described for this study. Grain size increases to the right in each column. B. Nonesuch Fm. isopach map showing location of inferred basin-bounding fault(s).

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DISCOVERING HIDDEN FOLDS AND FAULTS IN THE PRECAMBRIAN: NEW INSIGHTS INTO BARABOO-INTERVAL STRATIGRAPHY AND DEFORMATION IN SOUTHERN WISCONSIN

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Laurentia records a complex history of continental collision and construction, accretion, stabilization, and reactivation of continental lithosphere. In the Southern Lake Superior Region, the Baraboo-interval sediments, including the Baraboo Quartzite, Seeley Slate, the iron-rich Freedom Formation (Sauk County) and the Waterloo Quartzite (Dodge and Jefferson Counties), were deposited after ca. 1.71 Ga and then deformed during ca. 1.65- 1.63 Ga Mazatzal accretion (Holm et al., 1998; Medaris et al., 2003). Ca. 1.4 Ga intrusion of the Wolf River Batholith and 1.0 Ga failed Midcontinent rifting subsequently affected the region. Since then, the Southern Lake Superior region has remained tectonically stable for the past billion years and thus uniquely preserves the complex history of Laurentian assembly but also results in subdued topography and a thick cover of Phanerozoic sediments that obscures direct observation of these rocks. We present preliminary results from geologic mapping of the buried Precambrian basement for a ~9000 km² area in southern Wisconsin that is based on integration of data from new bedrock drill core, sparse outcrops, and existing geophysical and subsurface data sets. Our mapping revises the stratigraphy of the Baraboo interval quartzites and allows us to interpret the deformation history of the area. We describe a two-stage deformation history, beginning with regional folding and ending with thick-skinned thrusting.

We integrate regional aeromagnetic data (Snyder and Daniels, 2002) with data from outcrops, existing bedrock geologic maps (Dalziel and Dott, 1970), drill cuttings, and new and existing bedrock drill cores (e.g. Weidman, 1904; Schmidt, 1951) and associated geophysical logs in a manner analogous to the NICE Working Group (2007). Aeromagnetic anomalies reflect the distribution of magnetic minerals in the upper crust and can be used to locate buried faults and characterize the distribution and structure of magnetic rocks. In the Lake Superior Region, Pleistocene glacial deposits and Paleozoic sedimentary rocks are magnetically transparent, so the aeromagnetic map reflects changes in the composition and geometry of the buried Precambrian crust. Importantly, a new drill core collected by the Wisconsin Geological and Natural History Survey in Dodge County recovered Precambrian iron-formation over a strata-bound aeromagnetic high present in the aeromagnetic anomaly map of Snyder and Daniels (2002). We correlate this iron formation to the Freedom Formation (Lamb and Stewart, this volume), allowing the strata-bound aeromagnetic high to be used as a marker unit in the aeromagnetic anomaly map, even in areas of southern Wisconsin with no surface exposure of Precambrian rocks.

Patterns observed in the aeromagnetic data suggest the development of broad-scale doubly plunging folds within Baraboo-interval sediments and underlying post-Penokean granites and rhyolites. These folds occur across >9000 km² of southern Wisconsin. The Baraboo syncline in Sauk County represents the western edge of regional folding. In Dodge County, the Waterloo Quartzite occurs in a broad basin stratigraphically above the aeromagnetic high marker unit interpreted as the Freedom Formation, indicating the Waterloo quartzite is a distinct quartzite unit stratigraphically above the Baraboo quartzite, the Seeley Slate and the Freedom Formation.

Aeromagnetic map patterns further suggest that regional folds were truncated by at least two basement-involved thrust faults. The well-known Baraboo Syncline lies in the hanging wall of one of these thrusts, which placed folded post-Penokean granites and rhyolites, as well as the lower portion of the Baraboo-interval stratigraphy, over stratigraphically higher folded Baraboo-interval sediments. Mazatzal-age accretion is interpreted to have caused this two-stage (i.e. folding followed by faulting) deformation history.

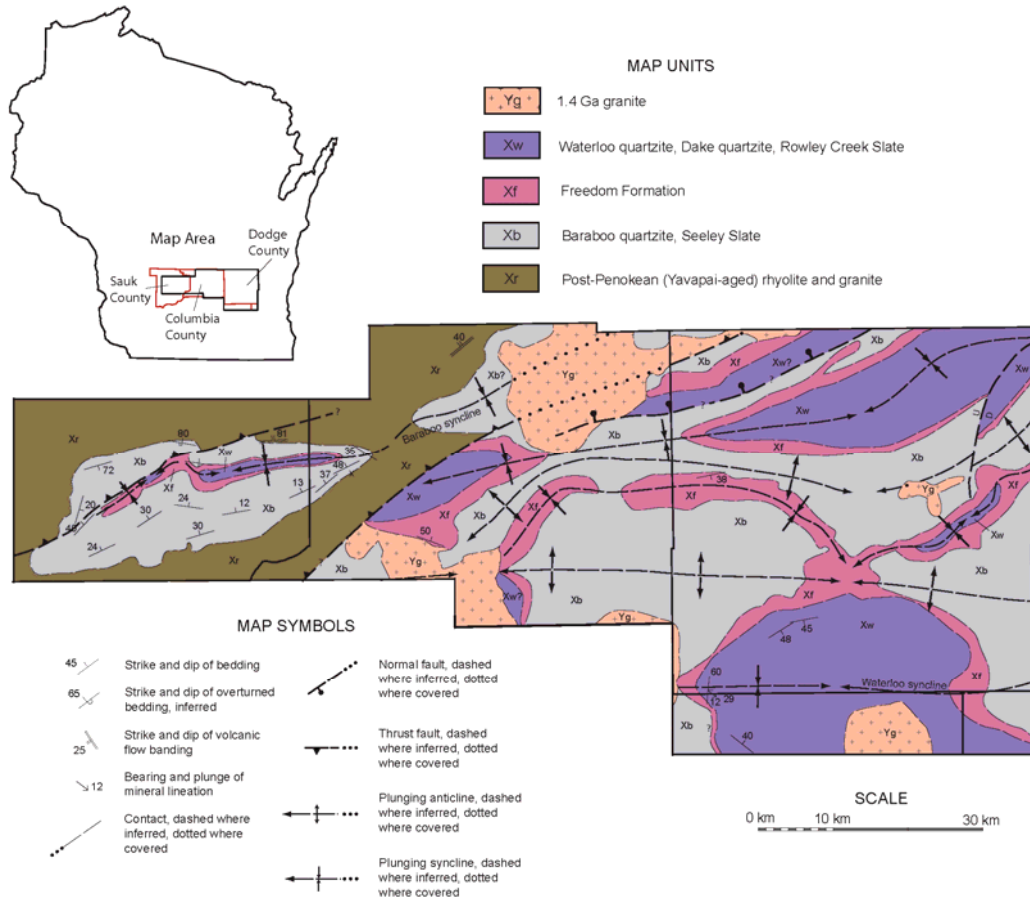


Figure 1. Preliminary Precambrian basement map.

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A RE-EXAMINATION OF THE KAPUKASING STRUCTURAL ZONE

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The Kapukasing Structural Zone in the Wawa-Abitibi terrane crosscuts the Superior province and exposes amphibolites, granulites, and migmatites of the middle and lower crust. The Wawa Gneiss Domain west of the Kapukasing Structural Zone is composed of various types of felsic intrusive bodies that crosscut diatexite migmatites. The diatexite migmatites transition to metatexites into the Kapukasing Structural Zone and are migmatized amphibolites, granulites, and metaconglomerate.

The transition from the Wawa Gneiss Domain into the western Kapukasing Structural Zone is gradational and is defined by a systematic pattern of regional to microscopic pinch and swell and boudinage structures. The boudin necks are defined by penetrative, tightly-spaced schistosity and gneissosity, dominantly east-west to northeast-southwest striking, steeply to moderately dipping south to southeast or north to northwest, steeply to moderately plunging dominantly east or west mylonites in dextral ductile to brittle-ductile shear zones. The rheologically competent boudins, acting as regional to microscopic lithons, display varying types of boudinage structures, and have wider-spaced gneissosity, strike east-west to northeast-southwest, are horizontal to gently dipping north or south, and horizontal to gently plunging east or west.

The formation of the Kapukasing Structural Zone can be explained by continental collision to dextral transpression between the Minnesota River Valley and the Wawa-Abitibi terranes in the Neoarchean to Paleoproterozoic. The oblique continental collision produced lithospheric-scale boudinage, creating and exposing the Kapukasing Structural Zone and metamorphic core complex of the Wawa Gneiss Domain, which were subsequently brittlely deformed throughout the Proterozoic.

Source of Native Iron in Canadian Arctic Artifacts

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A collection of fourteen samples of metal made from iron artifacts recovered from the Canadian Arctic Archipelago was received from the Canadian Conservation Institute, Department of Canadian Heritage in order to examine the origin of the materials. In Greenland, three sources of iron in artifacts have been determined: terrestrial native iron, manmade iron of European origin and meteoritic iron. The present study was undertaken in order to determine the origin of the metal in the Canadian artifacts.

Observation of polished surfaces made from the samples by reflected light microscopy revealed the presence of the Widmanstätten structure deformed in all cases by cold working, clearly indicating the meteoritic origin of all of the artifacts. The Widmanstätten structure is an oriented intergrowth of kamacite (α -Fe) lamellae in taenite (γ -Fe). This structure forms as the result of the exsolution of kamacite during the diffusion of the Ni into the taenite phase in octahedrites. The Ni distribution and concentration of the Ni in the kamacite phase can be used as an indicator of the equilibrium state of the specimen and in the classification of the meteorite. The results of a step scan across the entire bandwidth of the kamacite lamellae can yield an M-shaped profile indicating the diffusion of Ni. Although kamacite and taenite can be found in terrestrial iron sources, the Widmanstätten texture is unique to meteoritic iron and is commonly found in octahedrites such as the Cape York meteorite.

The Cape York meteorite landed close to Thule and Dorset territory in southern Greenland. It is reasonable to hypothesize that the Cape York meteorite is the source of iron for these artifacts because of its close proximity to Thule and Dorset territory. A comparison was done of the Ni-content and the bandwidth of the kamacite lamellae in the artifacts with that of the Cape York meteorite in order to precisely test this hypothesis. Here, we report the results of the mineral chemistry and compare these results to those reported for the Cape York meteorite in order to draw conclusions.

Only 0.5 to 2.0mm sized samples were taken for use in SEM-EDX analysis in order to preserve as much of the artifacts as possible. A step-scan and line scan were performed roughly perpendicular to the kamacite taenite interface to acquire a representative sample of the artifact's whole composition. The standard used for this analysis was the Filomena meteorite. Filomena is comprised almost entirely of kamacite, making it an excellent standard for the analysis of the kamacite lamellae. Both the deformation of the kamacite lamellae caused by the cold forging of the artifacts, and the small sample size prevent direct observation of the full bandwidth of the kamacite lamellae. The bandwidth of the kamacite lamellae may be calculated through the use of Goldstein's (1965) plot of average half-width of kamacite vs the average Ni-content in the kamacite, which also related mean kamacite bandwidth to Ni-content in the meteorite.

The M-profiles in this study are nearly flat, reflecting the approach to equilibrium in diffusion of Ni from kamacite lamellae. The kamacite bandwidth as measured in SEM images and by determination from Goldstein's (1965) figure 9 yield a range of widths of 0.042 to 0.0196mm. These bandwidths are significantly smaller than Buchwald (1975) reported for Cape York at 1.20 ± 0.2 mm. However, Buchwald's measurements were made on the Savik I mass of Cape York, which has the lowest reported Ni-content of the Cape York masses as reported by Esbensen et al. (1982). The Thule mass (table 1) has a much higher Ni-content and therefore a

narrower kamacite bandwidth. However, the bandwidths for other than Savik I have not been reported, and kamacite bandwidths can vary widely in a given meteorite.

We conclude that this study reveals that the Canadian Arctic metal artifacts are made from meteoritic iron and further, that the likely source is the Cape York meteorite.

Table 1: Ni-content of Cape York Meteorite Masses

Fragment	Ni (wt %)
Savik I	7.46
Savik II	7.54
Ahnighito East	7.46
Ahnighito West	7.63
Woman	7.65
Dog	7.89
Agpalilik	8.25
Thule	8.52

Data from Esbensen et al. (1982)

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The Badwater gabbro as an analogue for the weathering of Martian basalts

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The best way to study the surficial processes of other planets apart from indirect observation through rovers and orbiters is through the use of analogues. Studying the surface of Mars has become a popular topic as more sophisticated direct measurements are undertaken using instruments such as those on board the Curiosity rover. It is known from the study of Martian meteorites that the crust is entirely basaltic with no evidence of felsic igneous rocks. Through weathering, the basaltic crust was broken down and now comprises the material analyzed by Curiosity. Therefore, investigating the possible effects of weathering of basalts in a low oxygen atmosphere is important in order to better understand data retrieved from rovers such as Curiosity.

Here, we analyze the petrography, mineral chemistry and whole-rock geochemistry of the Badwater gabbro with a focus on the effects of weathering. The results were interpreted in order to assess the viability of the uppermost weathered zone of the Badwater gabbro as an analogue for the planet Mars. The Badwater gabbro is a 1598 ± 1.1 Ma, coarse-grained, intrusive unit that is disconformably overlain by the pillowed Pillar Lake volcanics. The gabbro has a striking paleoweathering profile developed in its upper five meters. The age of this weathering profile is poorly constrained, but it is Mesoproterozoic, constrained between the age of the Badwater gabbro and an 1100 Ma Midcontinent Rift related sill, which cuts the Pillar Lake volcanics. Sandstones present interbedded with the volcanics are similar to those of the ~1400 Ma Sibley group, which outcrops to the south. Data was collected from drill core samples obtained by East West Resources Corporation in 2004 during their search for PGE mineralization, near Armstrong, Ontario.

Trends in the whole rock geochemistry are some of the most telling features of the Badwater gabbro. Potassium was found to increase from 0.482%, 1612cm below the contact with the Pillar Lake volcanics to 2.508%-3.573% towards the Pillar Lake volcanics contact (Figure 1a). Similarly, the magnesium was found to increase from 7.319% to 14.602% towards the contact (Figure 1b). These are thought to be the influence of weathering due to the presence of a saline lake such as those for which the neighboring Sibley group is known.

Aluminum and sodium were found to show little variance near the contact. An average aluminum composition of $13.341 \pm 1.889\%$ (Figure 2a), and an average sodium concentration of $4.325 \pm 1.502\%$ (Figure 2b) were found. The aluminum data reflects the lack of overall loss or gain in the major elements. Therefore it can be concluded that the trends in magnesium and potassium do not reflect mass loss in the system. Similarly, sodium follows the same trend as Al, but is a much more mobile element and is therefore usually lost during weathering in subaerial or freshwater environments. This suggests that weathering took place in a saline lake environment thus restricting the mobility of Na.

The upward increase in K and Mg is unusual as these elements, in particular K, are commonly depleted during weathering. The upward enrichment without similar enrichment in Al means they were being added from above during weathering. This implies the presence of a saline water mass or groundwater system near a saline waterbody. The overlying pillowed basalts reinforce the probability of an overlying saline lacustrine system, which had abundant K and Mg that was incorporated into the loose sediment of the weathering profile. The saline

lacustrine sediments of the Sibley group attest to the development of the appropriate climatic conditions in the Mesoproterozoic for the formation of saline systems.

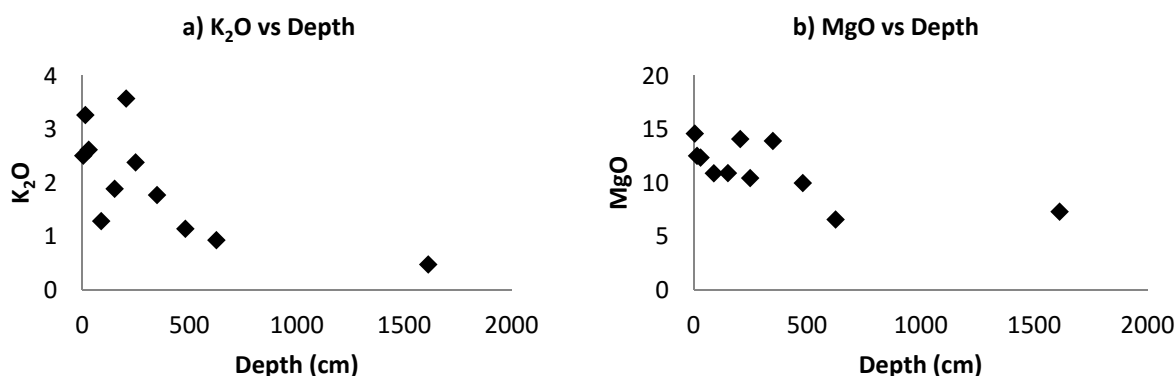


Figure 1: 1a) K₂O vs depth. 1b) MgO vs depth. Both these oxides increase significantly in concentration through the weathered zone towards the contact.

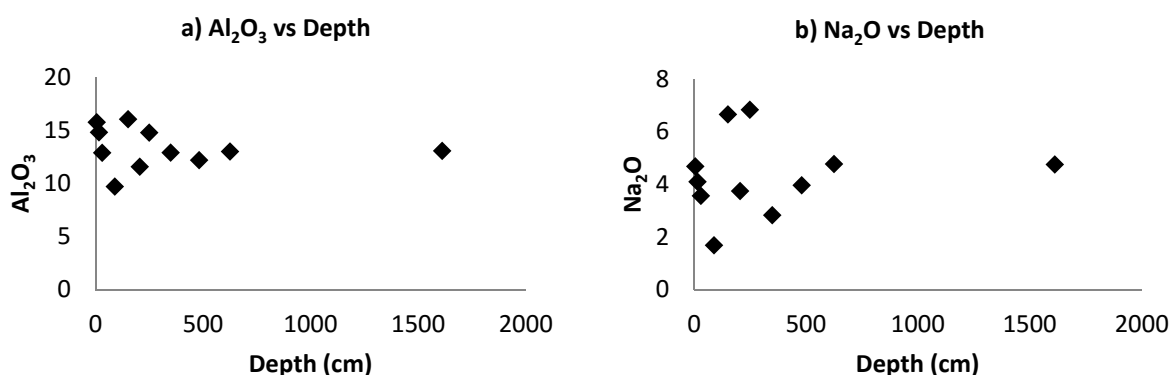


Figure 2: 2a) Al₂O₃ vs depth. 2b) Na₂O vs depth. Neither of these oxides show any significant increase or decrease in concentration towards the contact.

Saline lakes would have low amounts of sulfur thus invoking less of a restriction on dolomite production. The magnesium derived from the dolomite is the likely source of the anomalous magnesium values. These conclusions are consistent with the widely accepted magnesium concentrations and dolomitic evaporites in the Sibley lakes.

Given that weathering is dominated by the presence of saline water in a low oxygen environment it has these in common with weathering on the red planet as its water mass decreased. However, during this period on Mars the water became acidic resulting in iron being transported and iron sulfates commonly forming, whereas the non-acidic waters studied were capable of forming potassic clays and magnesium evaporites. It is reasonable to suggest that the Badwater gabbro may be as close to an analogue for Mars that can be studied on Earth, but would not make a totally appropriate analogue.

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Geologic mapping of Neoproterozoic and Proterozoic rocks near Kekekabic Lake, northeastern Minnesota, by students of the Precambrian Research Center's 2015 field camp

Abstract refers to poster entitled: "Bedrock geologic map of the Knife Lake Group and related intrusions near Kekekabic Lake, Lake County, Minnesota." First author: "[Christenson](#)"

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The University of Minnesota-Duluth's Precambrian Research Center conducted its ninth annual field camp in 2015, and this presentation shows results of one of several "capstone" mapping projects. The projects test student skills by creating new geologic maps in areas of poorly known geology. This benefits both

students and mentor organizations, and contributes to our collective understanding of Minnesota geology. The capstone project described here involved mapping an area of ~12 mi² in the Boundary Waters Canoe Area Wilderness (BWCAW), centered on the western part of Kekekabic Lake, but included all or parts of Spoon, Dix, Skoota, Missionary, Pickle, Kek, Strup, and Wisini Lakes (Fig. 1). The resulting map provides details about the complex depositional, magmatic, and tectonic history of a Neoproterozoic metavolcanic and metasedimentary terrane that is part of the Wawa subprovince of Superior Province, the basal Mesoproterozoic Duluth Complex and diabase dikes. Compared with the other 8 capstones mentored by Jirsa (2007-2014), this one presented the greatest lithologic diversity and logistical challenges.

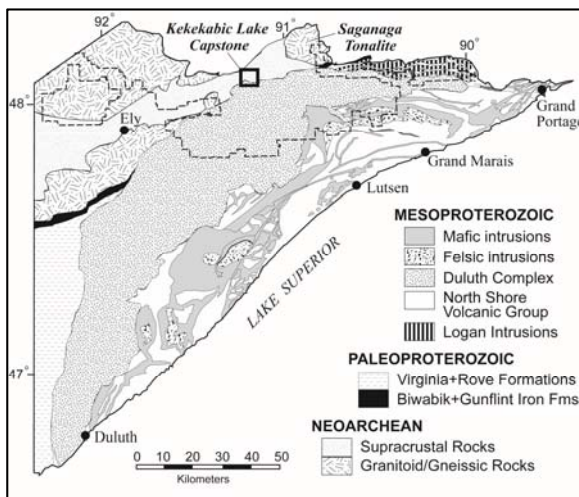


Figure 1. Generalized bedrock geologic map of NE Minnesota showing the Kekekabic Lake capstone area (solid black polygon). The Neoproterozoic unit labeled "Supracrustal Rocks" encloses both older volcanic sequences and younger, largely sedimentary ones. Outline of Boundary Waters Canoe Area Wilderness is dashed.

The Neoproterozoic rocks in the central BWCAW comprise a Timiskaming-type extensional basin deposit that consists of a broad array of sedimentary (terrestrial and shallow marine), volcanic, and intrusive rocks in close proximity. The Kekekabic Lake map area (Fig. 2) provides a window into this complex terrane.

Highlights of the mapping include the following:

- Tightly folded graywacke and mudstone (Fig. 2, unit **Aks**), locally containing thin lenses and layers of iron-formation. The latter implies deposition in marine or restricted basin settings.
- A unique sequence of unsorted oligomictic conglomerate composed of hornblende-, pyroxene-, and plagioclase-phyric trachyandesite clasts that grades up stratigraphic section to sandstone and gritstone containing abundant mafic minerals and chlorite presumably derived from them (unit **Akg**). Ripple marks and trough cross-bedding in sandy portions indicate fluvial transport (Fig.3).
- Both units are cut by a large, lithologically diverse intrusion (unit **Akp**) composed of porphyritic rocks that vary from monzonite to hornblende-, pyroxene- and biotite-bearing lamprophyre.

- Heterogeneous gabbro and troctolite of the basal **Duluth Complex** intruded the Knife Lake rocks, creating a **Hornfels** contact aureole that displays metamorphic recrystallization, thermally augmented deformation features, and magmatic brecciation of the host Neoproterozoic rocks.

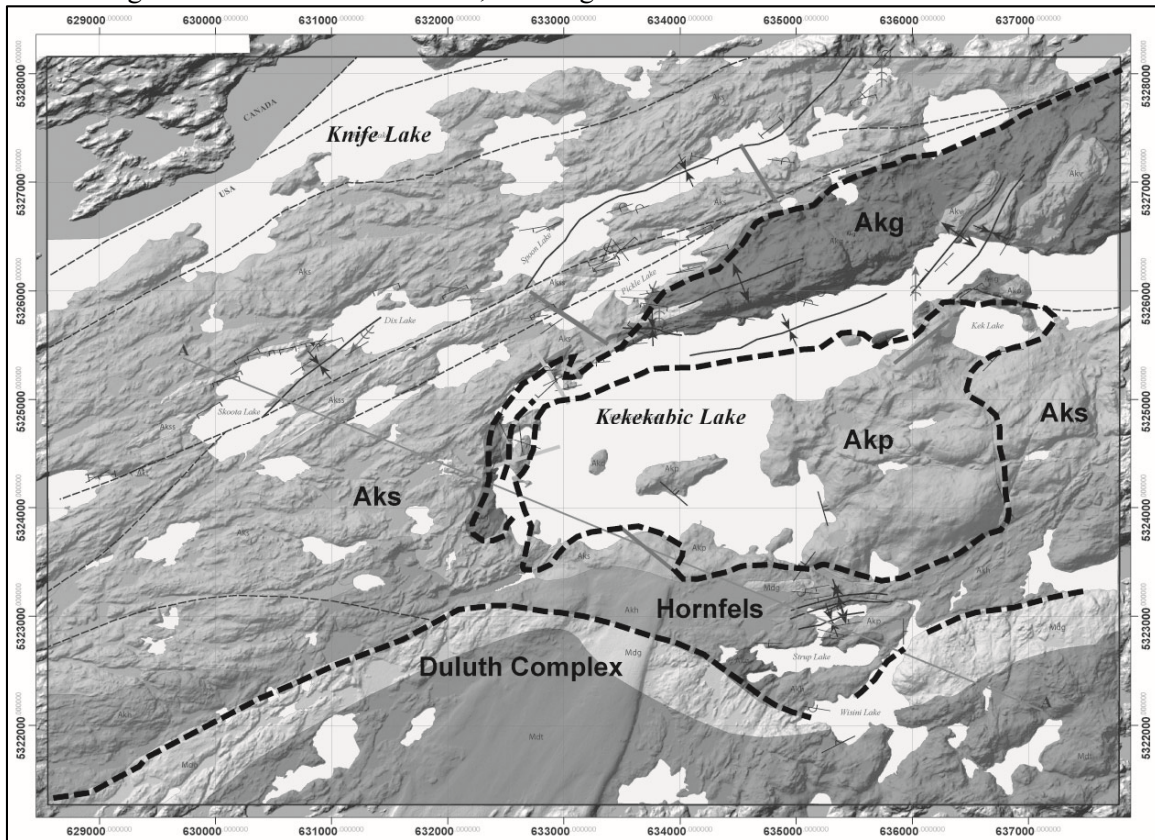


Figure 2. Gray-scale version of the 14-map unit Kekekabic Lake geologic map highlighting pertinent units discussed above. NAD83, Zone 15 UTM coordinates.



Figure 3. Field photographs of unit **Akg**. Left: unsorted volcanic conglomerate; Right: ripple-marked volcanic sandstone. See discussion above. North shore of Kekekabic Lake.

The results of this and other capstone mapping projects can be viewed at www.d.umn.edu/prc.

Influence of mineral liberation on metal leaching and dissolution rates in ore material and associated host rock

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Current methods of sulfide ore comminution produce harmful waste in the form of leached metals and acidic runoff. Conventional ore processing techniques leave some ore minerals with the tailings, the efficiency of which depends on many factors. In the case of sulfide mining, these ore minerals oxidize to form sulfate and free H^+ ions, lowering the pH of the system and accelerating sulfide oxidation and the release of metals, a phenomenon known as “acid rock drainage” (Nicholson et al., 1990; Lapakko et. al, 2013). A technology that has recently become commercially available, electric pulse disaggregation (EPD), breaks apart rock at mineral grain boundaries, void spaces, and other cavities within the rock. A given sample is submerged in water and variable amounts of electricity (200 kV in this experiment) are pulsed through the water, generating plasma streamers which break apart the rock by shockwaves formed by rapid heating and expansion (Cabri et al., 2008). By breaking the rock apart into individual mineral grains, the surface area of both sulfides and silicates is drastically increased, improving the recovery of ore minerals and increasing the buffering capacity of silicates, thereby limiting the potential production of acidic runoff. EPD should increase ore recovery efficiency while simultaneously decreasing the amount of waste released into the environment by separating ore minerals from the gangue at grain boundaries.

An ongoing experiment utilizing Cu-Ni-PGE sulfide ore material from Minnesota’s Duluth Complex is currently testing this hypothesis. Six different experiments, three with material processed via EPD (material stored in water at room temperature, at 50°C, in a solution with a starting pH of 4) and three with conventionally crushed material (same conditions as above) were set up and run over the course of 8+ weeks. Temperature, pH, conductivity, and mass measurements are being taken on a weekly basis. Samples of the aqueous solution will be taken twice over the course of the experiment and will be subjected to geochemical analysis. The reaction product will eventually be analyzed via x-ray diffraction to determine the final composition of the rock. Preliminary data indicate a slight increase in free ions in the material processed via EPD compared to the mechanically treated material but other parameters are similar. All experiments exhibit a decrease in mass to the current date and the pH of 4 experiment quickly reached neutral conditions (within five weeks) as expected, while the other experiments showed no signs of significant change.

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Small-Scale Petrographic Variations in a Nipigon Diabase Sill

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In this study, we report ongoing results describing the petrographic characteristics of a Nipigon diabase sill, part of the 1.1 Ga Midcontinent rift magmatic suite of ultramafic to mafic sills located in the Lake Superior region (Hollings et al., 2007). A ~250 m continuous core (BSE-07-01) drilled by RPT Uranium Inc. (2007) in the vicinity of Black Sturgeon Lake, southwest of Lake Nipigon has been archived in the geology department at Slippery Rock University (SRU). Previous research by SRU students and faculty has identified several reinjection horizons where new magma has intruded older, partially solidified magma within a crystal mush zone (e.g., Zieg, 2014). This investigation focused on a detailed petrographic and textural analysis of a 20-meter section (65-85 m above lower contact) to provide a better understanding of petrographic signatures of the reinjection process within this interval.

The primary data for this study were variations in modal mineralogy (obtained by point counting) and plagioclase mean length (determined by manually tracing crystals in photomicrographs). Using this data, we have identified a zone where plagioclase sizes deviate from a normal coarsening-inward trend. This deviation is accompanied by variations in modal olivine: anomalous decreases in plagioclase mean length are associated with sudden increases in olivine abundance. The decreases in mean plagioclase size are thought to represent soft internal chills. The olivine accumulations are interpreted as suspended crystals that settled out of the reinjected magma soon after emplacement, collecting on top of the more viscous crystal mush at the base of the freshly injected magma (Hayes et al. 2015; Zieg, 2014).

In addition to grain size we also examined plagioclase orientation. In the section with anomalous textures, we also found plagioclase grains with a preferred orientation, possibly induced by shear stresses related to the inflowing magma, parallel to reinjection margins (perpendicular to the core axis). The combination of plagioclase alignment, finer-grained textures, and the sudden increase in olivine abundance supports the hypothesis that magma was emplaced into the existing mush at this location as an olivine-rich slurry (Fig. 1, Fig. 2; Zieg, 2014).

The results of this project will contribute to a larger study (Zieg, this volume) that evaluates the processes of emplacement and identifies diagnostic criteria for recognizing reinjection horizons within sills. This data will then be used to refine model parameters for magma chamber evolution within the Earth's crust. Future work will focus on further defining the petrologic characteristics of reinjection horizons using textures and modal mineralogy, and eventually geochemical analysis, to further constrain the physical and chemical consequences of reinjection in sills.

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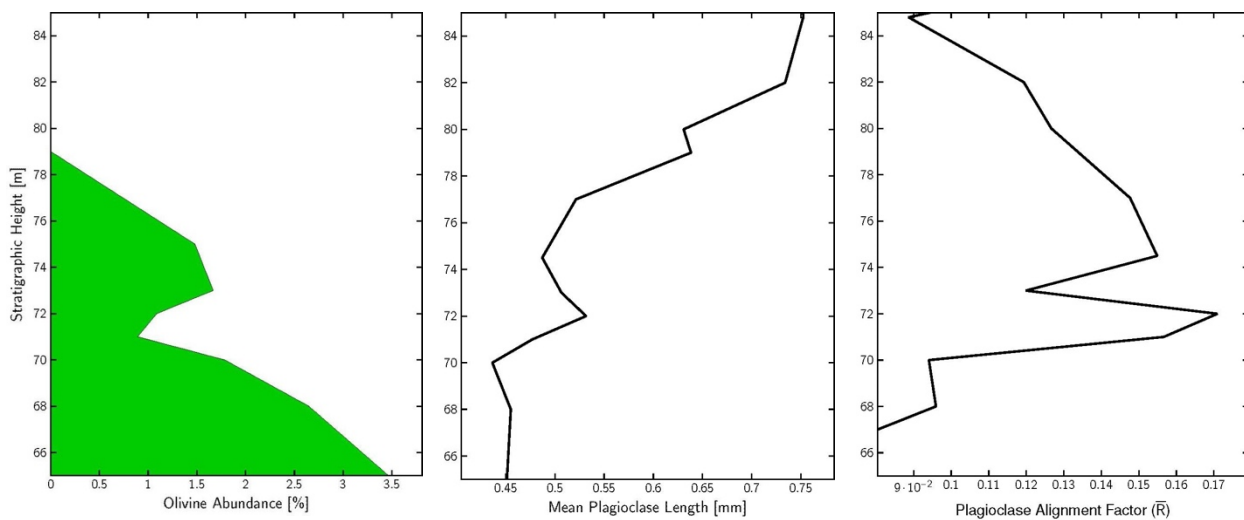


Figure 1(left to right): Variations in modal olivine, mean plagioclase length, and plagioclase alignment factor ($\bar{R}$)

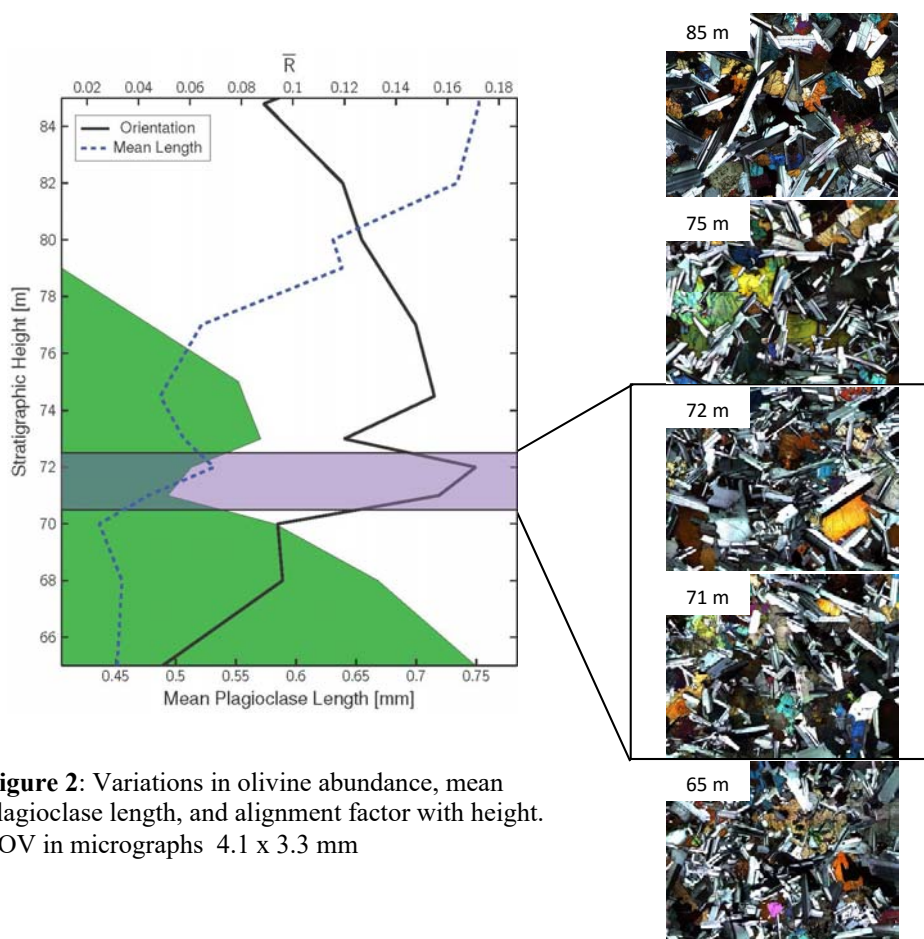


Figure 2: Variations in olivine abundance, mean plagioclase length, and alignment factor with height. FOV in micrographs 4.1 x 3.3 mm

Assessment of Undiscovered Nickel-Copper-Platinum Group Element (Ni-Cu-PGE) Resources Related to Conduit-Type Mineralization in the Midcontinent Rift System, Michigan, Minnesota, Ontario, and Wisconsin

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The U.S. Geological Survey (USGS) uses a geology-based three-part mineral resource assessment approach. The three parts for a specific deposit type are: 1) delineation of areas permissive for undiscovered mineral resources permitted by the geology; 2) estimation of the number of undiscovered deposits within each delineated area; and 3) estimation of the amount of resources contained in the undiscovered deposits, using appropriate ore characteristics and metal contents defined by worldwide grade and tonnage models. The USGS is completing such an assessment for conduit-type Ni-Cu-PGE sulfide deposits (defined as magmatic sulfide mineralization restricted to small- to medium-sized mafic and ultramafic dikes and sills derived from picritic and tholeiitic basaltic magma; Schulz and others, 2014) in rocks related to the Midcontinent Rift System (MRS) in Michigan, Minnesota, Ontario, and Wisconsin.

The name of this deposit type, conduit-type, emphasizes the relation of these Ni-Cu-PGE sulfide-rich deposits to small- to medium-sized mafic and ultramafic dikes and sills that served as pathways for the flow-through of picritic and tholeiitic basaltic magmas. These intrusions are orders of magnitude smaller than many layered intrusions that host contact-type Ni-Cu±PGE sulfide (e.g., Duluth Complex) or reef-type PGE deposits (e.g., Stillwater Complex, Montana).

Critical processes of conduit-type deposit ore formation are used to identify essential criteria appropriate for a regional-scale assessment and to define proxies for these system components. For this assessment, we emphasized a metal source (MRS-related mafic and ultramafic magmas), magma pathways (mafic and ultramafic dike swarms and small intrusions emplaced during development of the MRS), and a source of sulfur in country rocks that, if assimilated, could result in sulfur saturation of MRS magmas (in this setting, sulfide-bearing Paleoproterozoic metasedimentary and metavolcanic rocks).

It is difficult to predict, however, if a particular mafic or ultramafic intrusion emplaced into favorable country rock served as a high-flux magma pathway and thus, could contain a magmatic conduit-type sulfide deposit. Also, at the regional scale of an assessment, there are no proxies for predicting if and where sulfide minerals might accumulate in sills and dikes. As a result, all areas where MRS-related mafic and ultramafic dikes or sills are inferred to be present in sulfur-rich Paleoproterozoic rocks are considered to be permissive for the occurrence of conduit-type magmatic Ni-Cu-PGE sulfide mineralization. Thus, for this assessment, five permissive tracts are identified:

- 1) **Animikie tract** – strata of the Proterozoic Animikie Group in northern Minnesota (one known deposit (Tamarack) but no other known occurrences)
- 2) **Little Falls tract** – metamorphosed and deformed metasedimentary and volcanic rocks that are part of the Penokean-age fold and thrust belt in Minnesota (no known deposits or occurrences)
- 3) **Michigamme tract** – the known and inferred distribution of the Michigamme Formation, Michigan and Wisconsin (one known deposit (Eagle mine) and multiple occurrences (e.g., BIC, Roland Lake, Eagle East))
- 4) **Pigeon Point tract** – strata of the Animikie Group in northeast Minnesota and southern Ontario (one known deposit (Great Lakes Nickel deposit) and several occurrences)
- 5) **Pembine-Wausau tract** – volcanic and sedimentary rocks of the Pembine-Wausau magmatic terrane, Wisconsin (no known deposits or occurrences)

After a discussion of conduit-type deposit requirements and the favorable (or unfavorable) geology of the each tract, assessment team members made separate estimates of the numbers of undiscovered deposits. Estimators were asked for the least number of deposits of a given type that they believed could be present at three specified levels of certainty (90 percent, 50 percent, and 10 percent). Each person made initial estimates without sharing their results until everyone was finished; and then the results were compiled and discussed. Following the discussion, individual scores were adjusted and a single mean estimate of the number undiscovered deposits in each tract down to 2 km depth was determined. This final estimate reflects both uncertainties in what could exist and in the favorability of a tract.

As might be expected from the number of known deposits and occurrences, the Michigamme tract was assessed to have the highest number of possible undiscovered deposits, with a mean estimate of five undiscovered deposits. The Animikie, Pigeon Point, and Pembine-Wausau tracts each had mean estimates of two undiscovered deposits, whereas the Little Falls tract had a mean estimate of one undiscovered deposit.

New grade and tonnage models for conduit-type sulfide deposits were used in Monte Carlo simulations to obtain estimated probability distributions of undiscovered metals in each tract. The current known and, here estimated, undiscovered resources represented by MRS-related conduit-type deposits are significantly less than the known Ni-Cu±PGE resources in the undeveloped contact-type deposits along the western margin of the Duluth Complex; conduit-type deposits, however, are typically much higher grade, and therefore remain very attractive exploration targets.

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Geochemistry and Petrography of the Volcanic Strata Hosting the Flambeau Cu-Zn-Au Deposit in Rusk County, WI: A Re-examination of Wisconsin's Only Past-Producing Volcanogenic Massive Sulfide Mine.

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Volcanogenic massive sulfide (VMS) deposits are polymetallic mineral deposits and are the source of many important base (e.g., Cu, Zn, Pb) and precious metals (e.g., Au, Ag, Ga) (LaBerge, 1996; DeMatties, 1994). The Flambeau Cu-Zn-Au Mine and other VMS deposits are hosted within the Paleoproterozoic juvenile and continental volcanic arc sequences of the Wisconsin Magmatic Terrane of the Penokean Orogeny (Schulz and Cannon, 2007). Despite the Flambeau Mine being the only partially extracted VMS deposit in the Penokean orogeny (only the supergene-enriched zone was mined), the volcanic and tectonic setting of the rocks hosting the deposit are poorly constrained. Research on the deposit essentially ceased after the mine closure in 1997. The mine site has since been successfully reclaimed and all bedrock exposures were covered. This study revisits the volcanic strata hosting the Flambeau VMS deposit through examination of historic drill cores to describe the geologic, geochemical and alteration characteristics of the deposit in light of almost 20 years of advances in the fields of geochemistry, economic geology, and the tectonic evolution of the region.

Due to the absence of outcrop in the area surrounding the past-producing mine, Flambeau Mine drill cores were obtained and re-logged at the Wisconsin Geological and Natural History Survey core repository, in Mount Horeb, Wisconsin. Core samples were analyzed using X-ray Fluorescence and Inductively Coupled Plasma Mass Spectrometry at the Materials Science Center at UW-Eau Claire. This new geochemical data was compiled with historic mine maps and cross sections to develop a coherent scientific model describing the nature and evolution of the volcanic and hydrothermal system that hosts and formed the deposit.

The metamorphosed and recrystallized altered strata hinder the interpretation of the intensity of hydrothermal alteration. Presently, the altered rocks of the Flambeau consist of biotite-andalusite±sericite schists and quartz-sericite-pyrite stringer zones. There is little visual correlation between porphyroblast abundance/size and the degree of alteration. However, major element mobility and geochemical alteration indices emphasize the variable intensities that are present throughout the stratigraphy and potentially highlight several fluid pathways and new ore horizons (Figure 1). Trace elements reveal that the protoliths of the hanging wall strata consist of primarily dacites with interlayered mafic units. The protoliths of the foot wall consist of thick dacite and rhyolite units with local thin mafic units increasing up section.

Based on these preliminary geochemical characteristics of the stratigraphy, the Flambeau deposit is likely a series of stacked ore lenses in a rifting arc geodynamic setting where a submarine volcanic arc was undergoing extension and likely developing a back-arc rift (Zens et al., 2015). This is evidenced by the dacite-dominated volcanic pile with increasing abundance of mafic protoliths toward the ore horizon and stratigraphic hanging wall. This data provides invaluable constraints on the petrogenesis of the volcanic assemblages in this part of the Penokean Orogeny.

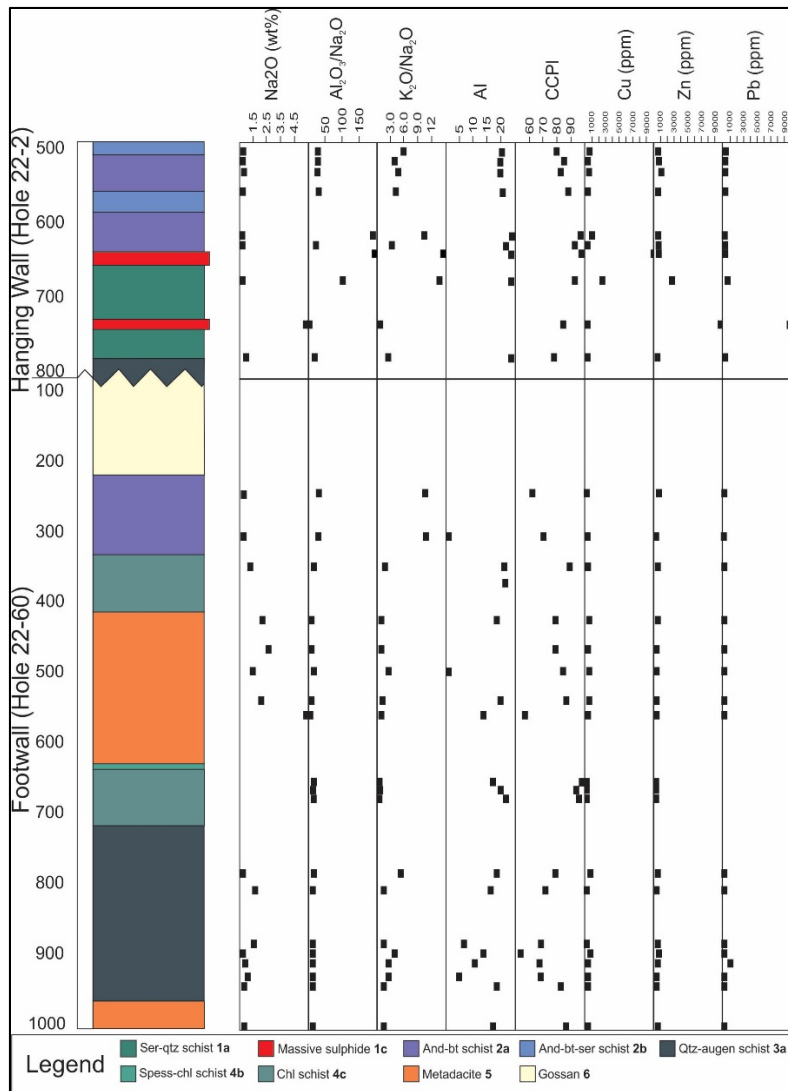


Figure 1: Downhole profiles of several hydrothermal alteration indices for the volcanic strata hosting the Flambeau Mine compiled using representative holes of the hanging wall (hole 22-2) and foot wall (hole 22-60). AI – Ishikawa Alteration Index (Ishikawa et al., 1976); CCPI – Chlorite-carbonate-pyrite index (Large et al., 2001).

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Evidence for Episodic Emplacement History of a Nipigon Diabase Sill

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The emplacement of magma into a magma chamber is one of the least-understood parts of the igneous cycle. Melting, crystallization, and differentiation can all be simulated experimentally as well as modeled theoretically. Emplacement, however, is an inherently large-scale, dynamic, and complex process that doesn't easily lend itself to experimental simulation or straightforward modeling. By the time an intrusive body is exposed at the surface, emplacement effects are commonly masked by subsequent processes including differentiation and textural re-equilibration, making it more difficult yet to recognize and reconstruct emplacement conditions.

Despite this difficulty, research on the timing and consequences of magma reinjections into an existing chamber is a dynamic topic of ongoing research. It is now well-accepted that magma chambers grow through incremental inflation (e.g., Menand et al., 2015, and references therein). By supplying new material, including more primitive liquids with or without suspended crystals, they can reset differentiation trends, and potentially deposit cumulate layers (Brandriss et al., 2014). Through a combination of thermal and compositional effects, reinjections into existing magma chambers have also been shown to be crucial in establishing conditions for the formation of magmatic ore bodies (e.g., Charlier et al., 2010; Maier et al., 2013).

We are attempting to develop a better understanding of the nature and consequences of these reinjection events using a continuous drill core profile through a ~250 m thick diabase sill from Nipigon, Ontario. A moderately thick sill was chosen for this study because it is large enough to have experienced a complex emplacement history, while also cooling quickly enough to avoid the pervasive textural re-equilibration effects associated with larger intrusions.

Using petrographic (plagioclase grain sizes, alignment factors, modal mineralogy, Fig. 1) and compositional (modal mineralogy and bulk-rock geochemistry, Fig. 2) trends in this sill, we have identified multiple horizons that can be tentatively identified as reinjection sites. The intervals interpreted as reinjection horizons are marked by an association between a sudden increase in olivine content and a decrease in plagioclase grain size. Additional characteristics include reversals in fractionation trends and changes in the composition of olivine populations.

These horizons are believed to represent the influx of a new pulse of magma that arrives bearing a suspended load of olivine phenocrysts. These phenocrysts settle toward the base of the newly-injected liquid layer, producing an olivine accumulation. Meanwhile, the older, partially-crystalline mush undergoes textural coarsening due to the heat from the fresh magma, enhancing the textural contrast between rocks crystallized from the old and new magma pulses.

Future work will focus on three key questions: 1) what exactly are the diagnostic petrographic and geochemical characteristics of a reinjection horizon? 2) what processes control the development of these signatures? and 3) what can these reinjection horizons tell us about the thermal evolution of mafic sills in general, and this sill in particular?

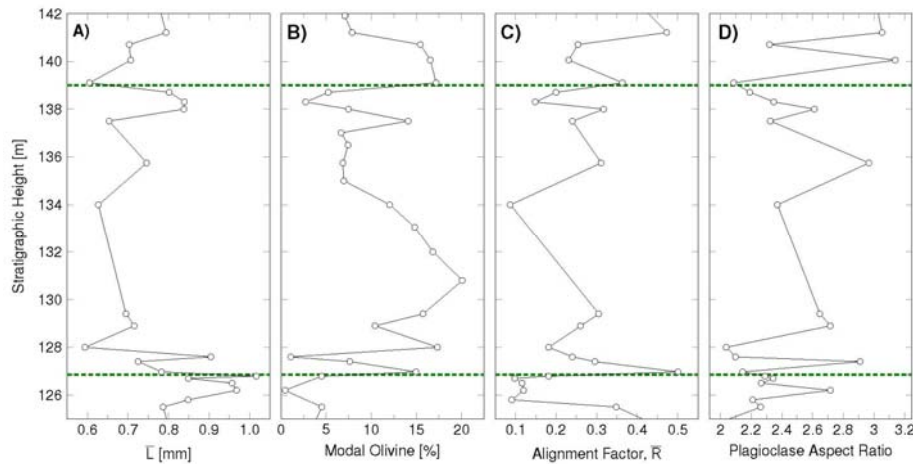


Figure 1. Petrographic data. Dashed lines represent the locations of inferred reinjection horizons.

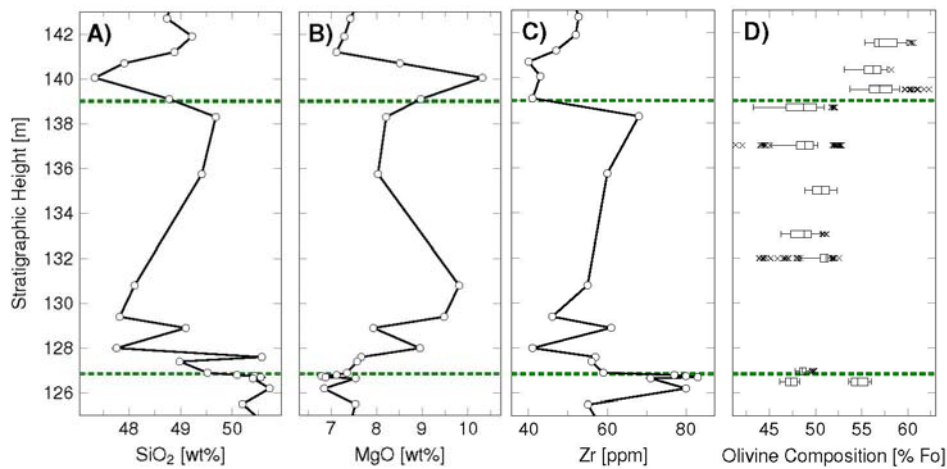


Figure 2. Compositional data. Dashed lines are the same proposed reinjection horizons, which were identified based on petrographic (primarily textural) variations.

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