



Institute on Lake Superior Geology

64th ANNUAL MEETING

May 15-18, 2018

Iron Mountain, Michigan

Hosted by:

LAUREL G. WOODRUFF, WILLIAM F. CANNON AND ESTHER K. STEWART

CO-CHAIRS

U.S. GEOLOGICAL SURVEY

WISCONSIN GEOLOGICAL & NATURAL HISTORY SURVEY

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Part 1 – Program and Abstracts

Edited by Esther K. Stewart

64th INSTITUTE ON LAKE SUPERIOR GEOLOGY

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PART 1: PROGRAM AND ABSTRACTS

PART 2: FIELD TRIP GUIDEBOOK

TRIP 1: ARCHEAN AND PALEOPROTEROZOIC GEOLOGY OF THE FELCH DISTRICT,
CENTRAL DICKINSON COUNTY, MICHIGAN

TRIP 2: GEOLOGY OF THE HEMLOCK FORMATION

TRIP 3: GEOLOGY AND IRON ORES OF THE MENOMINEE IRON RANGE, DICKINSON
COUNTY, MICHIGAN

TRIP 4: GRANITOID ROCKS OF THE PEMBINE-WAUSAU TERRANE IN NORTHEASTERN
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Peter Hollings
Department of Geology
Lakehead University
Thunder Bay, ON P7B 5E1
CANADA
peter.hollings@lakeheadu.ca

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<http://www.lakesuperiorgeology.org>

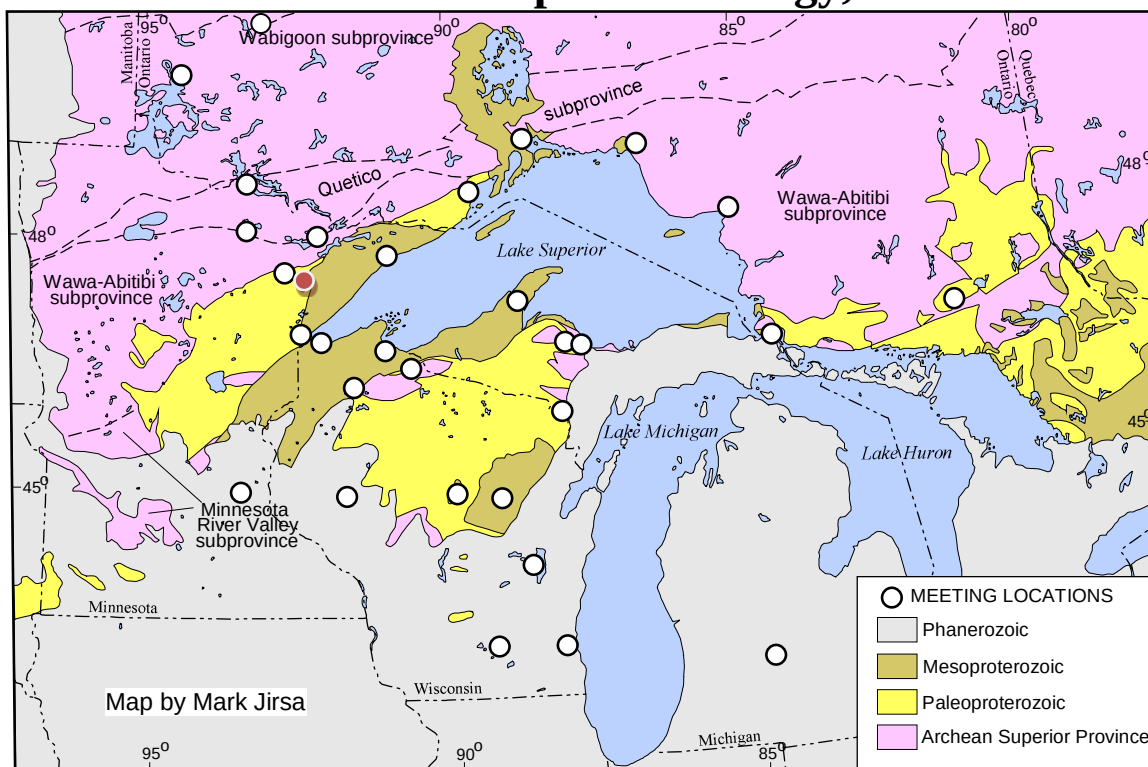
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Part 1: Program and Abstracts

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Institutes on Lake Superior Geology, 1955-2018



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

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

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

2018 GOLDICH MEDAL RECIPIENT

Val Chandler

Goldich Medal Committee

Serving through the meeting year shown in parentheses.

Shannon Zurevinski (2015-2018) Lakehead University

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

Dan England (2017-2020) Eveleth Fee Office

Citation for the Goldich Medal Recipient to **Val W. Chandler**

Val W. Chandler, geophysicist extraordinaire, has been my friend and professional colleague for almost forty years. We have worked together on projects too numerous to mention, beginning in 1979 only a few weeks after Val escaped to the blissful cool of Minnesota after a brief stint at Amoco, Inc. in the heat and humidity of Houston, Texas. His personal accomplishments and contributions to diverse joint projects at the Minnesota Geological Survey, and beyond, are remarkable in their scientific breadth. It is a privilege for me to be Val's citationist for the 2018 Goldich Medal.

Val was born and raised in Indianapolis, Indiana. After graduating from high school in 1967, having excelled academically and also athletically in track and field, he entered Indiana University. There he majored in geology and continued his athletic career as a "weight-man" on the IU varsity track team. In 1970 he won the Big Ten Conference championship in discus and placed second in shot-put. Fortunately for us, he declined the overtures of professional football scouts attracted by his impressive size and strength and instead decided to pursue a graduate education in the earth sciences at Indiana, where he obtained an M.S. in geophysics, and at Purdue, where he acquired a Ph.D. in geophysics in 1978 under the tutelage of Prof. Bill Hinze. His graduate work in both universities involved extensive practical applications of magnetic and gravity methods.

Val's professional contributions to understanding the geological framework of Minnesota and the greater Lake Superior region can be subdivided into three main parts. His first challenge was to plan and then supervise the production of a state-wide, high-definition aeromagnetic map of Minnesota. That project, spread over roughly 12 years, involved negotiating contracts with private-sector geophysical mapping firms, performing quality-control tests of the data, writing progress reports to university and governmental administrators, and securing funding for successive segments of the project from the Minnesota legislature. More or less coincident with all of this, Val oversaw a parallel effort to complete a high-quality gravity survey of the state that involved faculty and students from the University of Minnesota and Northern Illinois University and included important contributions of data from private-sector sources. The net result of these efforts was a set of digital potential-field geophysical maps of the state that were widely acknowledged to be among the very best in North America.

After the geophysical mapping of Minnesota was essentially finished, about 1992, Val devoted more and more of his time to geological interpretation of the geophysical data. In this work he collaborated in various ways with geologists in the MGS, such as myself, Mark Jirsa, Jim Miller, and Terry Boerboom, and with many geologists in adjacent states and provinces. Furthermore, he contributed to important national and international geophysical projects such as the development of the gravity anomaly map of North America (1988) and the magnetic anomaly map of North America (2002). All along, Val was assiduous in applying the latest technological advancements to the presentation and interpretation of geophysical data. Among the techniques he perfected is the so-called "SMOG" presentation in which gravity and magnetic anomalies are combined. The SMOG acronym means Superimposed Magnetics On Gravity. A SMOG map shows the first vertical derivative of the magnetic signature (typically in grayscale) draped over the second vertical derivative of the gravity signature (typically shown in bright colors). The value of modern computing power in producing

these maps and other analytical tools cannot be overemphasized, and Val's efforts in developing and improving computational applications, such as SMOG maps and various digital modeling methods, have proven to be powerful aids to the geologic mapping of Precambrian terranes beneath glacial cover in Minnesota and the rest of the Lake Superior region.

As we all know, the Precambrian rocks of the Lake Superior region host a wealth of metallic mineral resources, and the potential for discovering and developing future economically viable Precambrian mineral deposits in covered areas has long been an attractive possibility to exploration companies and politicians. Indeed, that possibility was emphatically presented to Minnesota policy makers in the late 1970s, during a deep recession in the Minnesota iron-mining industry. It gave rise to a push for "minerals diversification" and created a political environment in which the importance of geophysics to the diversification effort could be successfully argued. That set of conditions brought Val to us, and his presence has produced dividends. Today we can make much better geologic maps of Precambrian terranes than we could before digital aeromagnetic and gravity maps became a reality, and consequently can make more credible assessments of mineral potential.

In recent years, however, the sense of urgency expressed in the public and political sectors has changed. Clean water, especially clean groundwater, has supplanted metals as the political "ore of choice". This is reality. Val, in the third chapter of his career, has pivoted from the geophysical interpretation of Precambrian rocks to the pursuit of techniques that aid three-dimensional hydrogeologic mapping of Quaternary glacial deposits. He has applied passive seismic methods to the estimation of sediment thickness above sub-Quaternary bedrock, an important parameter in aquifer delineation and groundwater management. He continues to perfect passive seismic techniques and works in close cooperation with soft-rock stratigraphers and hydrogeologists at MGS and affiliated state agencies.

Last but not least, Val is a teacher. He is an adjunct professor of geophysics in the school of earth sciences at the University of Minnesota. He has taught various undergraduate-level geophysics courses over the years and advised or co-advised several graduate students pursuing M.S. or Ph.D. degrees. He has long been an advocate for advancing the understanding and sensible application of science in the public sphere.

Val continues to be fascinated by the geology and geological resources of the Lake Superior region, both solid and liquid. His enthusiasm and his professional contributions to our collective understanding of this area unquestionably qualify him to join the ranks of Goldich Medal recipients. It is my distinct pleasure, therefore, to present Val W. Chandler to the Institute as its 2018 recipient of the Samuel S. Goldich Medal for "Outstanding contributions to the geology of the Lake Superior region".

*Submitted by David Southwick
Director Emeritus
Minnesota Geological Survey*

Honoring the Pioneers of Lake Superior Geology

(Adopted by the Board of Directors, 2016)

Preamble

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

Award Guidelines

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

The Board will review this award every five years.

Pioneers of Lake Superior Geology

2017 Douglass Houghton (1809-1845)

2018 *not presented*

In Memoriam

William D. Addison



October 25, 2017- a day of great loss for The Institute on Lake Superior Geology, its members, and countless others whose professional and personal lives were deeply influenced by Bill Addison. Bill's many and varied accomplishments are impossible to fully enumerate in a short remembrance. Bill, born in Toronto, lived much of his younger years in Thunder Bay before earning his B.Sc. in Forestry and M.Sc. in Fisheries Biology from the University of Toronto, where he met Wendy Livingston, who would become his wife. Bill and Wendy settled in Thunder Bay, where Bill worked as a fisheries biologist before joining Wendy in a teaching career at Westgate High School, where he taught Biology, Chemistry, and Geology for nearly 30 years. The Institute, and the broader geological community, know Bill for the discovery, made with long-time colleague and co-investigator Greg Brumpton, of the layer of

meteor impact debris that was spread across the Lake Superior region because of the great Sudbury impact. Bill first presented the documentation of the impact layer near Thunder Bay in 2005, at the 51st Annual Meeting of the Institute. Papers in the journal "Geology" and a Geological Society of America Special Paper soon followed and led others to discover the debris layer at many other localities around Lake Superior. Bill and Greg received world-wide recognition for their discovery, which spurred a flurry of research by an international group of Earth scientists that continues today. Bill's search for the Sudbury layer was, remarkably, only one of his many interests in the natural world, although one that he and Greg pursued with great patience and diligence for more than a decade before their final success. Bill is one of a select few to receive both the Goldich Medal and Homer Award from the Institute-- the Goldich shared with Greg Brumpton, recognizing their work on the Sudbury impact-- the Homer entirely a recognition of Bill's own (mis)deeds.

Future generations, to their loss, will know Bill as a name and author of groundbreaking geologic research. But the man-- larger-than-life, congenial, gregarious, and generous, that so many of us had the pleasure of knowing, if for only too short a time, should be remembered and celebrated as well. You could not know Bill for long without feeling that you had made a great new friend—and you would be right. He had seemingly unlimited space in his life and heart for friendship and kindness. He loved sharing his many unique experiences through his raconteurial skills, and had a seemingly limitless trove of fascinating tales of his adventures. Bill was a true lover of nature and supporter of its preservation. He and Wendy traveled the back roads and trails of the world celebrating both its natural beauty and cultural history. A fortunate group of friends received his "Epistles" from the road, an authoritative diary of daily discoveries, beautifully illustrated by his exceptional photography.

A life well-lived to the fullest, two loving, accomplished daughters, Michelle and Kirsten who blessed him with four grandchildren, lasting scientific contributions, and a host of friends and colleagues who were fortunate to have known him--this is the legacy of William D. Addison

Eisenbrey Student Travel Awards

The 1986 Board of Directors established the ILSG Student Travel Awards to support student participation at the annual meeting of the Institute. The name “Eisenbrey” was added to the award in 1998 to honor Edward H. Eisenbrey (1926-1985) and utilize substantial contributions made to the 1996 Institute meeting in his name. “Ned” Eisenbrey is credited with discovery of significant volcanogenic massive sulfide deposits in Wisconsin, but his scope was much broader—he has been described as having unique talents as an ore finder, geologist, and teacher. These awards are intended to help defray some of the direct travel costs of attending Institute meetings, and include a waiver of registration fees, but exclude expenses for meals, lodging, and field trip registration. The number of awards and value are determined by the annual Chair in consultation with the Secretary and Treasurer. Recipients will be announced at the annual banquet.

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

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

Successful applicants will receive their awards during the meeting.

Joe Mancuso Student Research Awards

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

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

The 2012 Board of Directors approved modification of the fund's name, adding "Mancuso" to reflect the many contributions of Joseph Mancuso to the organization and sizeable donations made in his name. "Doc Joe," as he was known by his students, taught geology for 36 years at Bowling Green State University, Ohio. He advised many graduate students in field-oriented research, and frequently brought them to Institute meetings. Joe was the 2007 Goldich Medalist.

In fall 2018, the ILSG Board of Directors selected four students to be granted research funding of \$500.00 each from the Joe Mancuso Student Research Fund. The awardees were:

Chanelle Boucher

Lakehead University, MsC, Dept. Geology,
cbouche2@lakeheadu.ca

TOPIC: *Komatiitic units within the Lake of the Woods Greenstone Belt*

Jacqueline L. Drazan

University of Minnesota-Duluth, MsC, Dept.
Earth and Environmental Sciences,
draza004@d.umn.edu

TOPIC: *Can silicon isotopes of quartz be used to determine chert petrogenesis in VMS-hosting systems in the ~2.7 Ga Abitibi Greenstone Belt, Canada?*

Dustin Andrew Liikane

University of Toronto, PhD, Dept. Earth
Sciences, dustin.liikane@mail.utoronto.ca

TOPIC: *Controls on the timing and localization of mineralized intrusions within the Midcontinent Rift*

Margaret Upton

University of Minnesota-Duluth, MsC, Dept.
Earth and Environmental Sciences,
upton040@d.umn.edu

TOPIC: *Alteration mineral zonation and geochemical characteristics of the Back Forty Deposit, MI—A replacement-style zinc- and gold-rich volcanogenic massive sulfide deposit*

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.

2018 Student Paper Awards Committee

Latisha Brengman – University of Minnesota-Duluth

Robert Cundari – Ontario Geological Survey

Esther Stewart – Wisconsin Geological & Natural History Survey

Board of Directors

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

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

Anthony Pace (2017-2020) – Ontario Geological Survey

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

Rob Cundari (2015-2018) – Ontario Geological Survey

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

Mark Jirsa – Treasurer (2015-2020) – Minnesota Geological Survey

Local Committee

Tom Mroz- BSGE, MSPG, CPG

Session Chairs

Marcia Bjørnerud - Lawrence University

Ben Drenth - U.S. Geological Survey

John Esch - Michigan Department of Environmental Quality

Daniel Holm - Kent State University

Suzanne Nicholson - U.S. Geological Survey

Dean Peterson - Natural Resources Research Institute

Amy Radakovich - Minnesota Geological Survey

Shannon Zurevinski - Lakehead University

Field Trip Leaders

Field trips have been the mainstay of the ILSG since its inception 64 years ago. We want to give a special thanks to the field trip leaders who volunteered their time and talent in carrying that tradition forward.

1) Archean and Paleoproterozoic Geology of the Felch District, Central Dickinson County, Michigan

Bill Cannon, Klaus Schulz, Robert Ayuso – U.S. Geological Survey

Tom Mroz – BSGE, MSPG, CPG

2) Geology of the Hemlock Formation

Tom Waggoner – Consulting Geologist

3) Geology and Iron Ores of the Menominee Iron Range, Dickinson County, Michigan

Tom Mroz – BSGE, MSPG, CPG

Bill Cannon – U.S. Geological Survey

4) Granitoid rocks of the Pembine-Wausau Terrane in northeastern Wisconsin

Klaus Schulz – U.S. Geological Survey

Marcia Bjørnerud – Lawrence University

Sponsors

The following organizations and individuals made general contributions to the 64th Annual Meeting. We thank them for their commitment to the Institute on Lake Superior Geology. All of the funds contributed this year go toward supporting student travel and registration.

lundin mining



INDIVIDUAL CONTRIBUTORS TO STUDENT TRAVEL SCHOLARSHIP

MARY KAY ARTHUR

STEVEN BAUMANN

L. GORDON MEDARIS, JR.

With an especially generous donation provided by

RON SEAVOY

REPORT OF THE CHAIRS OF THE 63rd ANNUAL MEETING INSTITUTE ON LAKE SUPERIOR GEOLOGY WAWA, ONTARIO

The 63rd Institute on Lake Superior Geology (ILSG) was held in Wawa, Ontario, Canada on May 8-12, 2017 with headquarters at the Michipicoten Memorial Community Centre. This was only the second time in the 63 year history of ILSG that the annual meeting has been held in Wawa, the first time in 1987. The meeting was held completely during regular work days (M-F) with technical sessions on Wednesday and Thursday breaking with past tradition of technical sessions being on Thursday and Friday with post-meeting field trips on Saturday. The meeting was co-chaired by Anthony Pace (Ontario Geological Survey, Ministry of Northern Development and Mines, Sault Ste Marie, Ontario), Ann Wilson (Ontario Geological Survey, Ministry of Northern Development and Mines, Timmins, Ontario) and Ted Bornhorst (A. E. Seaman Mineral Museum, Michigan Technological University, Houghton, Michigan). Margaret Hanson (A. E. Seaman Mineral Museum, Michigan Technological University, Houghton, Michigan) was registrar for the meeting and co-editor and co-compiler of the two parts of the Proceedings Volume.

The meeting was attended by a total of 135 registrants, which exceeded our expected 100 registrants. This included 37 students which is near 30 %, similar to but slightly less than student participation in recent past meetings. The technical sessions and field trips are equally important components of the annual ILSG meeting. The two days of technical sessions included a total of 28 oral presentations (15 by students) and 22 poster presentations (11 by students). The oral presentations included a wide variety of geologic topics from across the Lake Superior region. They were organized to provide a mix of professional and student presentations rather than by themes. There were no student oral presentations scheduled on the afternoon of the second day to facilitate the decision making for the Doug Duskin Student Paper Awards. A separate block of time was set aside during the technical sessions for poster presentations rather than the past practice of poster sessions being held during the social and coffee breaks. The best student oral presentation was by Ross Salerno (University of Minnesota, Duluth) who presented on the Vermilion Granitic Complex of northern Minnesota; the best student poster presentation was by Morgan Sanger (University of Wisconsin, Madison) who presented on seismic interpretation of the Midcontinent rift. We are especially grateful to the members of the Student Paper Awards Committee who must attend each and every talk and truly listen to them! Each year overall presentations by students are improving and this makes the task of identifying the best among them more and more difficult. We thank Mark Puumala (Ontario Geological Survey), Amy Radakovich (Minnesota Geological Survey), and Laurel Woodruff (U. S. Geological Survey) for being willing to judge the student papers.

Field trips are an essential and important part of the ILSG annual meeting. All of the field trips were filled to capacity with 85 participating in at least one field trip. There were six field trips for the Wawa meeting, three pre-meeting and three post-meeting. The pre-meeting field trip #1 was a two day trip on May 8 and 9, 2017 that was based in Marathon, Ontario, about 190 km driving distance northwest of Wawa: *Archean and Proterozoic geology of the Marathon-Hemlo area* led by Allan MacTavish (Panoramic PGMs Canada Ltd), Mark Puumala, Mark Symk, and Tom Muir (Ontario Geological Survey), David Good (University of Western Ontario), and John McBride (Stillwater Canada Inc.). The other two pre-meeting field trips, #2 and #3, were one day

on May 9, 2017 based out of Wawa: *More unusual diamond-bearing rocks of the Wawa area* led by Ann C. Wilson (Ontario Geological Survey) and *Geology of the Wawa gold project* led by Jean-Francois Montrueuil, Quentin Yarie, and Conrad Dix (Red Pine Exploration Ltd.). Two of the three post-meeting field trips (#4 and #5) were one day on May 12, 2017 based out of Wawa: *Geology of the Island Gold Mine* led by Doug MacMillan, S. Comtois-Urban, and Harold Tracanelli (Richmont Gold Mines Ltd.) and *Geology of the Renabie area* led by Lise Robichaud (Ontario Geological Survey) and Jordan McDivitt (Laurentian University). The other post-meeting field trip (#6) was for one day on May 12, 2017 but relocated late afternoon for overnight in Chapleau, Ontario: *Kapuskasing structural zone and Borden Lake Gold deposit* led by Pierre Bousquet (Ontario Geological Survey) and Jason Rickard (Goldcorp Inc.).

The annual ILSG banquet was held at the Michipicoten Memorial Community Centre on Wednesday evening, May 10 and was attended by 81 individuals. The attendees were treated to a home cooked banquet meal followed by awarding of the the 2017 Goldich Medal to Philip Fralick of Lakehead University. Mark Smyk (Ontario Geological Survey) presented a summary of Phil's contributions to the understanding of Lake Superior geology to banquet attendees prior to awarding him the Goldich Medal. Phil has made significant contributions to the ILSG since 1985; he co-chaired the annual meeting in 2000 and has contributed to more the 75 ILSG abstracts and field trip guidebooks. The banquet presentation was by Johanna Rowe (historian and author from Wawa) who enlightened us on people involved in the long mining history of the Michipicoten area. Several in the local community came to the talk including Mickey Clement who was the first person to bring a sample of diamonds to the Wawa field office; the attendees gave him a round of applause.

At the 2016 Board of Directors meeting in Duluth the board adopted a new award, Pioneer of Lake Superior Geology, at the suggestion of Gene LaBerge, 1995 Goldich Medalist and Chair of the 1984 ILSG. The co-chairs selected Douglass Houghton (1809-1845) as the first ILSG "Pioneer of Lake Superior Geology." As the first formal presentation, Ted Bornhorst introduced the new award program and encouraged nominations to be sent to the 2017 co-chairs and followed his introduction of the award by a biographical sketch of honoree Douglass Houghton focused on the attributes that led to his success at such a young age. Pioneers of Lake Superior Geology have contributed to the understanding of geology in the Lake Superior region primarily before the inception of the ILSG in 1955.

The Eisenbrey Student Travel Awards are supported by the Institute on Lake Superior Geology and by generous donations by corporations, societies, and individuals. A total of \$2,500 US was awarded to students with varying amounts based on distance from Wawa, being senior author on a presentation, traveling with another senior author student presenter, and/or traveling with another student. Only students who applied by the deadline were given an award. This year we thank Argonaut Gold, Geological Society of Minnesota, Mary Kay Arthur, Gordon Medaris, and Ron Seavoy for providing funds, in addition to ILSG, to help us support student participation in the annual meeting of ILSG. The following students were provided financial assistance to attend the meeting in Wawa: Stephen Hanson, Ann Hunt, Ross Salerno, Margaret Upton (University of Minnesota, Duluth), Munira Afroz, Kira Arnold, Brittany Ramsay (Lakehead University), Morgan Sanger, Luke Schranz (University of Wisconsin, Madison), Juliana Olsen-Valdez, and David Wilkes (Lawrence University).

The Institute's Board of Directors met on Thursday May 5th to discuss the business of the Institute. The meeting was attended by meeting co-chairs Anthony Pace, Ann Wilson, Theodore Bornhorst, Rob Cundari (2018), Jim Miller (2017), Treasurer Mark Jirsa, Secretary Peter Hollings and guests Esther Stewart, Laurel Woodruff, and Bill Cannon. Secretary Hollings took the minutes of the Board meeting that are as follows:

1. Accepted report of the Chairs for the 62nd ILSG, Duluth, Minnesota; as printed in the Proceeding Volume (Miller), and minutes of last Board meeting, May 5, 2016 (Hollings)
2. Received, discussed, and accepted 2015-2016 ILSG Financial Summary (Jirsa).
3. Received, discussed, and accepted 2015-2016 report of the Secretary (Hollings).
4. Approved Anthony Pace as on-going ILSG Board member.
5. Discussed and approved renewal of Mark Jirsa as Institute Treasurer (end of term 2020). This was later approved by a vote of the membership.
6. Approved Iron Mountain as the site for the 64th annual ILSG meeting. The meeting will be hosted by Esther Stewart, Laurel Woodruff and Bill Cannon.
7. There was discussion as to future meeting locations in Wisconsin with suggested possibilities of Wisconsin Dells and Terrace Bay. Discussion of other locations included mention of Sudbury.
8. Discussed and approved replacing Helene Lukey as the "member from industry" on Goldich Committee (end of term 2017) with Dan England
9. Discussed the possibility of co-hosting ILSG 2020 with the NCGSA meeting – item was tabled pending further discussion with NCGSA organisers.
10. It was agreed that Amy Radakovich (MGS) would be the second signatory on the ILSG accounts.
11. It was agreed that the local chairs would have the final decision as to whether or not to allow silent auctions in support of the ILSG or affiliated student groups.
12. The topic of the A. E. Seaman Mineral Museum serving as registrar (by electronic and check payment) instead of the meeting Chairs running registration through an outside paid service such as Eventbrite was introduced for discussion by Ted Bornhorst. It was agreed that Ted would provide an estimate of the costs involved.
13. It was agreed that the hosting of the ILSG volumes would be relocated from the PRC server to Hollings' account on Lakehead University servers. Hollings to complete the move ASAP.

The dedication and perseverance of the local businesses played an important role in the success of the 2017 ILSG meeting. The co-chairs thanked the community of Wawa through a letter to the Mayor of Wawa, Ron Rody: The staff of the Wawa Economic Development Corporation for providing us with a list of motel accommodations, community contacts and providing all participants with a bag Wawa souvenirs. The staff of the Michipicoten Community Centre, who provided us with the venue to host this event and the staff that worked the bar during our evening social and banquet. We express our sincere gratitude towards Judy Moore and her staff, who catered the event. Many who attended complimented on the food and service she provided. A job well done! The staff of the local Subway shop, who provided the lunches for 5 of the 6 geological field trips during the week. Larry Lacroix of Lloyd's of Wawa who provided the school bus transportation that was needed for the geological field trips throughout the Wawa and Chapleau areas. Matt Larrett from Michipicoten High School, who provided us with the speaker system for the two days of technical sessions. We thanked the local motels and lastly, Johanna Rowe, who was our guest speaker at the banquet.

We the 2017 co-chairs would like to again thank all those who continue to make ILSG one of the best regional geoscience meetings in North America: participants, presenters, field trip leaders, session chairs, best student paper committee members, Goldich committee members, ILSG Board members and the incoming 2018 chairs. We appreciated all of support and positive comments about the Wawa meeting and look forward to seeing many of you at the 2018 ILSG in Iron Mountain.

Respectfully submitted,
Theodore J. Bornhorst, Anthony Pace, and Ann C. Wilson
Co-chairs, 63rd Institute on Lake Superior Geology

TECHNICAL PROGRAM

TUESDAY MAY 15, 2018

Field trips 1 and 2 begin and end at the Pine Mountain Lodge, Iron Mountain, Michigan

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

1) Archean and Paleoproterozoic Geology of the Felch District, Central Dickinson County, Michigan

Bill Cannon, Klaus Schulz, Robert Ayuso - U.S. Geological Survey

Tom Mroz – BSGE, MSPG, CPG

2) Geology of the Hemlock Formation

Tom Waggoner – Consulting Geologist

4:00 pm - 10:00 pm **Registration** (Pine Mountain Lodge)

7:00 pm - 10:00 pm **Welcoming Reception** (Pine Mountain Lodge)

Poster Session (Pine Mountain Lodge)

WEDNESDAY MAY 16, 2018

7:30 am – 11:30 am **Registration** (Pine Mountain Lodge)

8:00 **OPENING REMARKS** (Pine Mountain Lodge)

Laurel Woodruff, Bill Cannon, Esther K. Stewart, Co-Chairs, 2018 ILSG

TECHNICAL SESSION I

Session Chairs:

Shannon Zurevinski – Lakehead University

Ben Drenth – U.S. Geological Survey

8:10 **Christian Schardt and Mady David**

High-technology metal behavior in ore-forming environments and its implication for the Vermilion District, northern Minnesota

8:30 **Andrea Reed**

Pilot study results for potential lithium mineralization on state-managed mineral rights in Minnesota

- 8:50 ***Matthew W. Matko and Christian Schardt**
Microanalysis of rock and mineral textures and its relationship to mineralization and ore comminution
- 9:10 **Jeffrey L. Mauk**
Geochemical signatures of hydrothermal alteration in clastic sedimentary rocks: theory, recognition, and application
- 9:30 **COFFEE BREAK**
- 9:50 **Robert Cundari, Mark Smyk, Dorothy Campbell, and Mark Puumala**
Possible emplacement controls on diamond-bearing rocks north of Lake Superior
- 10:10 ***Joseph Rasmussen, Esther Kingsbury Stewart, John Skalbeck, and Madeline Gotkowitz**
Modeling the Precambrian topography of Columbia County, Wisconsin using two-dimensional models of gravity and aeromagnetic data and well construction reports
- 10:30 **David Southwick, Val Chandler, and Mark Jirsa**
Geophysical, structural, and tectonic interpretation of the Yellow Medicine and Appleton shear zones, SW Minnesota and SE South Dakota: A work in progress
- 10:50 **Val Chandler, David Southwick, and Mark Jirsa**
Recent gravity and magnetic investigations of the Minnesota River Valley Subprovince: New insights into ancient problems
- 11:10 **Benjamin J. Drenth, Laurel G. Woodruff, Klaus J. Schulz, William F. Cannon, and Robert A. Ayuso**
On the source(s) of the Felch-Arnold gravity anomaly, Upper Peninsula, Michigan
- 11:30 **End of Technical Session I**
- 11:30 **LUNCH BREAK**
ILSG BOARD OF DIRECTORS MEETING

TECHNICAL SESSION II

Session Chairs:

Dean Peterson – Natural Resources Research Institute

Suzanne Nicholson – U.S. Geological Survey

- 1:00 ***Kira Arnold, Pete Hollings, Seamus Magnus, Shannon Zurevinski, and Robert Creaser**
Geology and geochemistry of the Terrace Bay Batholith, N. Ontario

- 1:20 ***Simon Dolega and Philip Fralick**
Geochemistry of shallow and deep water Archean meta-iron formations and their post depositional alteration in Western Superior Province, Canada
- 1:40 ***Victoria Stinson and Y. Pan**
Neoarchean to Paleoproterozoic reconstructions using metamorphic core complexes as evidence of continental transform plate motion and their implications in Archean tectonics
- 2:00 **Wouter Bleeker**
Archean BIF clasts vs. Paleoproterozoic jasper clasts? The proof is in the pudding (stone)
- 2:20 **COFFEE BREAK**
- 2:40 **Paul Eger, Courtney Bot, Dave Meineke, and Dave Adams**
What to do after the bull has left the china shop- Picking up the community relation pieces
- 3:00 ***Vittoria Smith and Shannon Zurevinski**
Petrology and 11B composition of tourmaline within the 2685 Ma Ghost Lake Batholith and Mavis Lake Pegmatites
- 3:20 **Klaus J. Schulz, William F. Cannon, and Laurel G. Woodruff**
Geochemistry of mafic rocks in Dickinson County, Michigan: Evidence for ~2.1 Ga Rifting
- 3:40 **Thomas W. Buchholz, Alexander U. Falster, and Wm. B. Simmons**
Possible aluminantite from the Nine Mile pluton, Wausau Complex, Marathon County, WI.
- 4:00 **POSTER VIEWING- AUTHORS WILL BE PRESENT AT THEIR POSTERS**
- 5:00 **END OF TECHNICAL SESSION II**

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- 6:00 **RECEPTION AND CASH BAR** (Pine Mountain Lodge)
- 7:00 **ANNUAL BANQUET** (Pine Mountain Lodge)
- Announcement of 65th Annual Meeting Location
 - **2018 Goldich Award Presentation to Val Chandler**
 - Banquet Presentation - **Nancy Langston** (Michigan Technological University)
Presentation title: *Sustaining Lake Superior*

THURSDAY MAY 17, 2018

- 8:00 **OPENING REMARKS, UPDATES** (Pine Mountain Lodge)
Laurel Woodruff, Bill Cannon, Esther K. Stewart, Co-Chairs, 2018 ILSG

TECHNICAL SESSION III

Session Chairs:

Amy Radakovich – Minnesota Geological Survey

Daniel Holm – Kent State University

- 8:10 **Daniel Holm, Terrence J. Boerboom, and Scott Scheiner**
Reinterpretation of the ages of deposition and folding of Animikie Basin metasedimentary units in east-central Minnesota
- 8:30 **Joshua J. Schwartz, Esther Kingsbury Stewart, and L. Gordon Medaris Jr.⁺**
Detrital zircons in the Waterloo Quartzite, Wisconsin: Implications for the ages of deposition and folding of supermature quartzites in the Southern Lake Superior Region
- 8:50 **Brad Gottschalk, Caroline Rose, and M. Carol McCartney**
Geologic history meets the web – online data of the Lake Superior Division of USGS
- 9:10 **William J. Hinze**
Mapping the Midcontinent Rift System
- 9:30 **COFFEE BREAK**
- 9:50 **Jennifer Smith, Wouter Bleeker, Dean Rossell, and Justin Laberge**
Compositional and geochemical characteristics of the Crystal Lake intrusion, Ontario
- 10:10 **Sean O'Brien, Pete Hollings⁺, and Jim Miller**
Geology of the Crystal Lake Gabbro and the Mount Mollie Dyke, Midcontinent Rift, Northwest Ontario
- 10:30 ***Dustin A. Liikane, Wouter Bleeker, Mike Hamilton, Sandra Kamo, Jennifer Smith, Peter Hollings, Robert Cundari, and Michael Easton**
Controls on the localization and timing of mineralized intrusions within the ca. 1.1 Ga Midcontinent Rift system
- 10:50 **David Good**
Petrogenesis of mafic magmatism in the Coldwell Complex Part 1. Geochemical model to explain origin of metabasalt by partial melting in the SCLM

11:10 **Evgeniy Kulakov, Theodore J. Bornhorst⁺, Chad Deering, and James B. Moore**
The youngest magmatic activity of the Midcontinent Rift at Bear Lake, Keweenaw Peninsula, Michigan

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

11:30 **LUNCH BREAK**

TECHNICAL SESSION IV

Session Chairs:

Marcia Bjørnerud – Lawrence University

John Esch – Michigan Department of Environmental Quality

1:00 **Kelli McCormick, Kevin Chamberlain, and Colin Paterson**
An 1149 Ma U-Pb baddeleyite crystallization age and geochemistry of gabbroic intrusions at the southwestern margin of the Superior Craton, southeastern South Dakota

1:20 **Jim DeGraff and B.T. Carter**
Thrust Kinematics of the Keweenaw Fault North of Portage Lake, Michigan

1:40 **John A. Yellich**
Michigan Geological Survey six years after assignment to Western Michigan University, where are we today?

2:00 **John M. Esch**
LiDAR Revolutionizing Geological Mapping

2:20 **COFFEE BREAK**

2:40 **Dean M. Peterson**
Assembling Minnesota: Integration of 140 years of government, academic, and industry geologic studies into a seamless statewide GIS database

3:00 **Mark A. Jirsa and others**
On-going geologic mapping in Minnesota's Arrowhead Region by the Minnesota Geological Survey

3:20 **John M. Esch, Alan Kehew, Sebastian Huot, and John Yellich**
Surficial geology of the Iron Mountain 7.5 Minute Quadrangle, Dickinson County, Michigan, Florence & Marinette Counties, Wisconsin

3:40 **Phil Larson, George Hudak, Al Mactavish, Peter Hinz, Amy Radakovich, Juk Bhattacharyya, Paula Engelhardt, Steve Engelhardt, Brigitte Gelnias, David Good, Emily Gorner, Sheree Hinz, Peter Jongewaard, Deb Kroch, Matt Svensson, and Andrew Tims**

Land of fire and ice: Summary of the 2017 ILSG field trip to Iceland

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

4:40 **END OF TECHNICAL SESSIONS**

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

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

FRIDAY MAY 18, 2018

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

Field trips 2 and 3 begin and end at the Pine Mountain Lodge, Iron Mountain, Michigan

3) Geology and Iron Ores of the Menominee Iron Range, Dickinson County, Michigan

Tom Mroz – BSGE, MSPG, CPG

Bill Cannon – U.S. Geological Survey

4) Granitoid rocks of the Pembine-Wausau Terrane in northeastern Wisconsin

Klaus Schulz – U.S. Geological Survey

Marcia Bjørnerud – Lawrence University

POSTER PRESENTATIONS

ANDERSON, Eric, SCHULZ, Klaus, DRENTH, Benjamin, CANNON, William, and QUIGLEY, Thomas

New gravity and high-resolution aeromagnetic data provide insights into Precambrian geology in the eastern Pembine-Wausau terrane

***ASHAUER, Zachary, CURRIER, Ryan, NORFLEET, Mark**

Textural analyses of rapakivi mantles: Evidence for semi-selective replacement in Proterozoic rapakivi granites

AYUSO, R.A., SCHULZ, K.J., CANNON, W.F., WOODRUFF, L.G., VAZQUEZ, J.A., FOLEY, N.K., and JACKSON, J.

New U-Pb zircon ages for rocks from the Granite-Gneiss Terrane in Northern Michigan: Evidence for events at ~3750, 2750, and 1850 Ma

***BLOTZ, Kaelyn E., LODGE, Robert W.D.**

Ore petrography of the Flambeau volcanogenic massive sulfide deposit, northwestern Wisconsin: Implications for hydrothermal fluid composition

BOERBOOM, Terrence J.

Fault-controlled dike emplacement in the Grand Marais, Minnesota area

***DRAZAN, Jacqueline, BRENGMAN, Latisha, FEDO, Christopher**

Preliminary petrographic and geochemical investigation of silicified volcanic rocks and silica-rich exhalative rocks from the ~2.7 Ga Abitibi Greenstone Belt, Canada

EASTON, Robert M.

GEON 12 to 11 history of the Lake Superior Region and speculation about the relationships between the Midcontinent Rift and the Grenville Orogen

ESCH, John M, KEHEW, Alan, HUOT, Sebastien, YELLICH, John

Surficial geology of the Iron Mountain 7.5 Minute Quadrangle, Dickinson County, Michigan, Florence & Marinette Counties, Wisconsin

***FITZPATRICK, William, HOOPER, Robert, and LODGE, Robert, Gélinas, Brigitte**

Mineral chemistries of the Tower Mountain Intrusive Complex Au-deposit, Ontario

GRAUCH, V.J.S., BEDROSIAN, Paul A., STEWART, Esther Kingsbury, and HELLER, Samuel

Inferences on the subsurface distribution of Oronto and Bayfield Groups north and west of the Douglas Fault, Northwestern Wisconsin

GREEN, Carlin J., SEAL, Robert, R., II, CANNON, William F., PIATAK, Nadine, and MCALEER, Ryan J.

Origin, distribution, morphology, and chemistry of amphiboles in the Ironwood Iron-Formation, Gogebic Iron Range, Wisconsin, U.S.A.

***HAFFTEN, Doug and RADWANY, Molly**

Geothermobarometry of a Precambrian amphibolite from Cornell WI

***HANNACK, Gina, and RADWANY, Molly**

Hornblende-plagioclase thermometry of the Eau Claire River Complex, western Wisconsin

***HONE, Samuel V. and ZIEG, Michael J.**

Olivine crystal size distribution in the Black Sturgeon Sill, Nipigon, Ontario

***JACOBSON, Regan E., LODGE, Robert W.D**

Reconstructing Paleoproterozoic volcanism in northwestern Wisconsin: Geochemistry of the Flambeau Cu-Zn-Au Mine

JIRSA, Mark A., STARNES, Edward C., and SCHMITZ, Mark D.

Geology and geochronology of the 2006 Cavity Lake forest fire area, Boundary Waters Canoe Area Wilderness, NE Minnesota

KINGSBURY STEWART, Esther, STEWART, Eric D., and ROUSHAR, Kathy

New bedrock geologic mapping of Dodge County, Wisconsin provides evidence for Paleozoic reactivation of Precambrian structures

***LIKANE, Dustin A., BLEEKER, Wouter, HAMILTON, Mike, KAMO, Sandra, SMITH, Jennifer, HOLLINGS, Peter, CUNDARI, Robert, and EASTON, Michael**

Controls on the localization and timing of mineralized intrusions within the ca. 1.1 Ga Midcontinent Rift system

MATTOX, Stephen, BOLHUIS, Chris, and SOBOLAK, Christina

Using credit-by-exam to connect advanced high school geology courses to university geology departments: Current status of a state-wide program in Michigan

***OLSEN-VALDEZ, Juliana and BJØRNERUD, Marcia**

The Brussels Hill Structure, Door County, Wisconsin: Impact crater, diatreme or other?

***OLSON, Maile J., LODGE, Robert W. D.**

Komatiite-hosted nickel-copper mineralization potential in the eastern Shebandowan Greenstone Belt, Ontario, Canada

*** ROSE, Katharine; ESSIG, Esprey, and THAKURTA, Joyashish**

Variation trends in sulfur isotope ratios at the Eagle and East Eagle intrusions and the surrounding country and basement rocks of the Baraga Basin, Upper Peninsula, Michigan

***RUPP, Kevin, THAKURTA, Joyashish, and MAHIN, Robert**

Preliminary investigation of the East Eagle Intrusion Gabbro in Marquette County, Michigan.

*** TYRRELL, C.W., HUBBELL, G.E., and DEGRAFF, J.M.**

Keweenaw Fault geometry and kinematics along Bête Grise Bay, Michigan

***UPTON, Margaret, SCHARDT, Christian, HUDAK, George, QUIGLEY, Eric**

Alteration mineral zonation and geochemical characteristics of the Back Forty Deposit, MI; a replacement-style zinc- and gold-rich volcanogenic massive sulfide deposit

*** VALL, Kathryn G., STEINMAN, Byron A., POMPEANI, David P., SCHREINER, Kathryn M., DEPASQUAL, Seth**

Reconstruction of paleoenvironmental conditions and temporal patterns of ancient mining on Isle Royale using biogeochemical analyses of lake sediment

YELLICH, John A.

Michigan Geological Survey Six years after assignment to Western Michigan University, Where are we today?

ZIEG, Michael J. and HONE, Samuel V.

The Origin of Layering in the Olivine Zone, Black Sturgeon Sill, Nipigon, Ontario

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

ABSTRACTS

New gravity and high-resolution aeromagnetic data provide insights into Precambrian geology in the eastern Pembine-Wausau terrane

ANDERSON, Eric¹, SCHULZ, Klaus², DRENTH, Benjamin¹, CANNON, William², and QUIGLEY, Thomas³

¹US Geological Survey, MS 964, PO Box 25046, Denver, CO 80225 USA

²US Geological Survey, 12201 Sunrise Valley Dr., MS 954, Reston, VA 20192 USA

³Great Lakes Exploration Inc., Menominee, MI 49858 USA

The Pembine-Wausau terrane represents a major Paleoproterozoic belt of metavolcanic and intrusive rocks that formed in an island-arc setting at the southern limit of the Archean Superior Craton (Schulz and Cannon, 2007). The island-arc complex was accreted to the continental margin along the Niagara fault zone during the Penokean orogeny and subsequently intruded by syn- to post-tectonic granitoids. The terrane is known to host a number of significant volcanogenic massive sulfide deposits including the Back Forty deposit. Limited outcrop makes bedrock mapping difficult. In 2016, the USGS contracted a high-resolution aeromagnetic survey over parts of the Pembine-Wausau terrane. The data were collected along north-south flight lines spaced 150 m at a nominal height of 80 m. These data, along with existing and in-fill gravity stations and physical property measurements, are helping improve Precambrian bedrock maps (Figure 1; Sims, 1990; Sims and Schulz, 1993).

The complete (terrain-corrected) Bouguer gravity anomaly map shows strong gradients, indicating significant lateral variations in bedrock density. A west-northwest trending linear high with ~5 mGal amplitude occurs along splays of the Niagara fault and correlates with mapped mafic-ultramafic rocks having measured density of ~2.90 g/cm³. South of the Niagara fault zone, a strong gravity gradient trends east-west along the southern mapped extent of the McAllister Formation that consists of basaltic and andesitic rocks with a density of ~2.91 g/cm³. South of the gradient is a linear low that expands to the south and east beneath Phanerozoic cover. A broad high with amplitude of ~15 mGal occurs over the southern extent of the Athelstane and Amberg granites. However, the anomaly differs from geologic map patterns and aeromagnetic magnetic anomalies and so the source is not well understood.

A standard reduction-to-pole (RTP) transformation was applied to the aeromagnetic data to better align anomalies with causative sources. The RTP map shows broad positive anomalies with amplitude around 2000 nT north of the Niagara fault. Between fault splays is a series of west-northwest trending linear highs with amplitude around 1000 nT. The linear features are 1.5 to 3 km-long and 500 m-wide; some of these correlate with mapped mafic-ultramafic rocks. The Pembine ophiolite rocks are well imaged by ~2000 nT anomaly high; several additional high amplitude anomalies occur within the Quinnesec Formation. A west-northwest trending aeromagnetic gradient is observed at the southern extent of the McAllister Formation that broadly parallels the strong gravity gradient. To the south are linear north-south to north-northeast trending magnetic highs that extend for more than 10 km. These linear features have

amplitudes between 5 and 60 nT. Near Amberg, they are associated with diabase dikes (magnetic susceptibilities of about $15 \times 10^{-3} \text{SI}$) that cut the late tectonic Athelstane Quartz Monzonite. At the southern end of the mapped Athelstane and Amberg granites is an oval magnetic high that trends northeastward contradictory to geologic map patterns. The amplitude ($\sim 325 \text{ nT}$) is significantly less than the anomalies observed over the mafic-ultramafic rocks to the north, suggesting a different source rock composition.

The tilt and first vertical derivative maps were derived from the RTP data to accentuate near surface and subtle magnetic features. Both maps show linear trends that change orientations proximal to gravity gradients. The prominent north-south to northeast trending magnetic lineaments do not appear to extend much beyond the gravity gradient into the McAllister Formation. In addition, these lineaments appear to have several subparallel northeast trending discontinuities. Magnetic lineaments in the Pemene Formation parallel mapped trends in the volcanic rocks. Near the Niagara fault the extent of the west-northwest trending magnetic lineaments is much better resolved in the derivative maps than in the RTP maps.

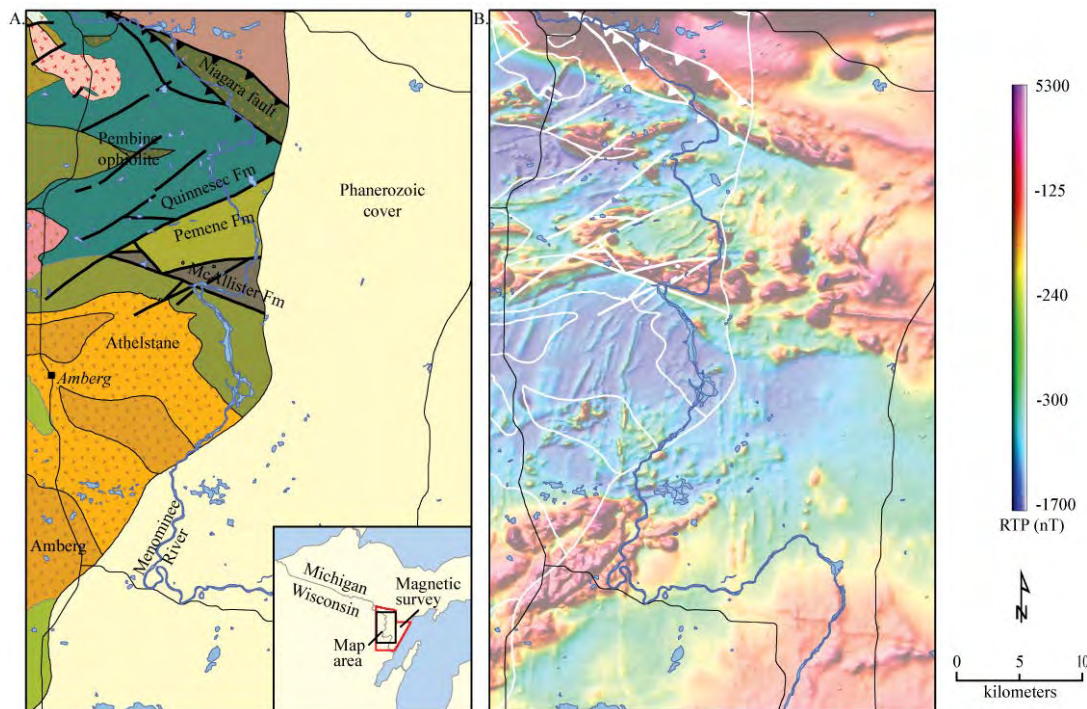


Figure 1: Geologic map (A) and reduced-to-pole (RTP) anomaly map (B) of the study area.

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

ARNOLD, Kira¹, HOLLINGS, Pete¹, MAGNUS, Seamus², ZUREVINSKI, Shannon¹, CREASER, Robert³

¹*Department of Geology, Lakehead University, Thunder Bay, Ontario P7B5E1*

²*Ontario Geological Survey, Ministry of Northern Development and Mines, Earth Resources and Geoscience Mapping Section, 933 Ramsey Lake Road, Sudbury, ON, P3E 6B5, Canada*

³*Department of Earth & Atmospheric Sciences, University of Alberta, 126 ESB Edmonton, Alberta, T6G2R3, Canada*

The Terrace Bay Batholith is a 25 km long oval shaped granitoid intrusion located in the western portion of the Schreiber-Hemlo greenstone belt, part of the larger Wawa-Abitibi terrane. The pluton, emplaced at 2689 $\pm$ 1.1 Ma (Kamo, 2016) intrudes *circa* 2720 Ma metavolcanic rocks, and a nearby pluton of equivalent age intrudes *circa* 2698-2693 Ma clastic metasedimentary rocks (Kamo, 2016; Davis and Sutcliffe, 2017). Younger plutonism in the region occurred between 2673 and 2667 Ma (Kamo, 2016, Kamo and Hamilton, 2017). This study describes and classifies the Terrace Bay batholith in order to investigate its petrogenesis and related gold and base metal mineralization.

The core of the Terrace Bay Batholith is a massive, homogeneous equigranular and locally quartz porphyritic granodiorite. The granodiorite typically consists of medium- to coarse-grained quartz and feldspar phenocrysts with a groundmass of fine-grained feldspars, quartz, amphibole, biotite and disseminated magnetite and sulphide minerals. Multiple outcrops in the center of the batholith host very coarse-grained phenocrysts of feldspar, ranging in size from 1 to 3 cm. An outcrop of diorite was found in the center of the pluton, composed of medium-grained amphibole and plagioclase, with very few quartz crystals. Some areas of the diorite outcrop are monzodioritic, with over 5% potassium feldspar. Thick overburden which covers the contacts with the granodiorite making their relationship uncertain, but the diorite likely represents either a more mafic phase of the granitic magma or possibly an autolith.

Geochemically the granodiorite is classified as I-type granite. It has a calc-alkaline signature, characteristic of rocks formed above a subduction zone. On a primitive mantle-normalized trace element profile the samples are LREE enriched with unfractionated HREE and prominent negative Nb-Ti anomalies. The diorite shows a similar trend to the granodiorite suggesting that it was formed from a similar if not the same source.

Two distinct alteration styles have been observed in the pluton; a common pervasive potassium-hematite alteration and a less common chlorite and epidote alteration. The chlorite-epidote variety is an intense alteration but is restricted to veins and dykes. The potassium-hematite alteration has been observed across the batholith. In most cases, the groundmass is obliterated and composed of fine- to very fine-grained hematite and potassium feldspars. Phenocrysts of quartz are typically unaltered but relict feldspars have been sericite altered. The chlorite-epidote alteration is generally composed of fine-grained chlorite and epidote in the groundmass with quartz phenocrysts and relict sericite-altered feldspars.

The pluton is crosscut by quartz carbonate veins, which locally contains black tourmaline along the vein contacts. Mineralization in the quartz veins includes pyrite, chalcopyrite, galena, molybdenite and arsenopyrite. In contrast, the pluton typically hosts only pyrite and molybdenite. Generally the molybdenite present in the granite is disseminated, but has been

found to occur in coarse pods up to 3 cm wide. Occurrences of molybdenum mineralization are spatially correlative with the gold mineralized occurrences, which are most commonly located in quartz-veined and altered zones near the contacts of the pluton. A molybdenite sample yielded a mineralization age of 2671 $\pm$ 12 Ma.

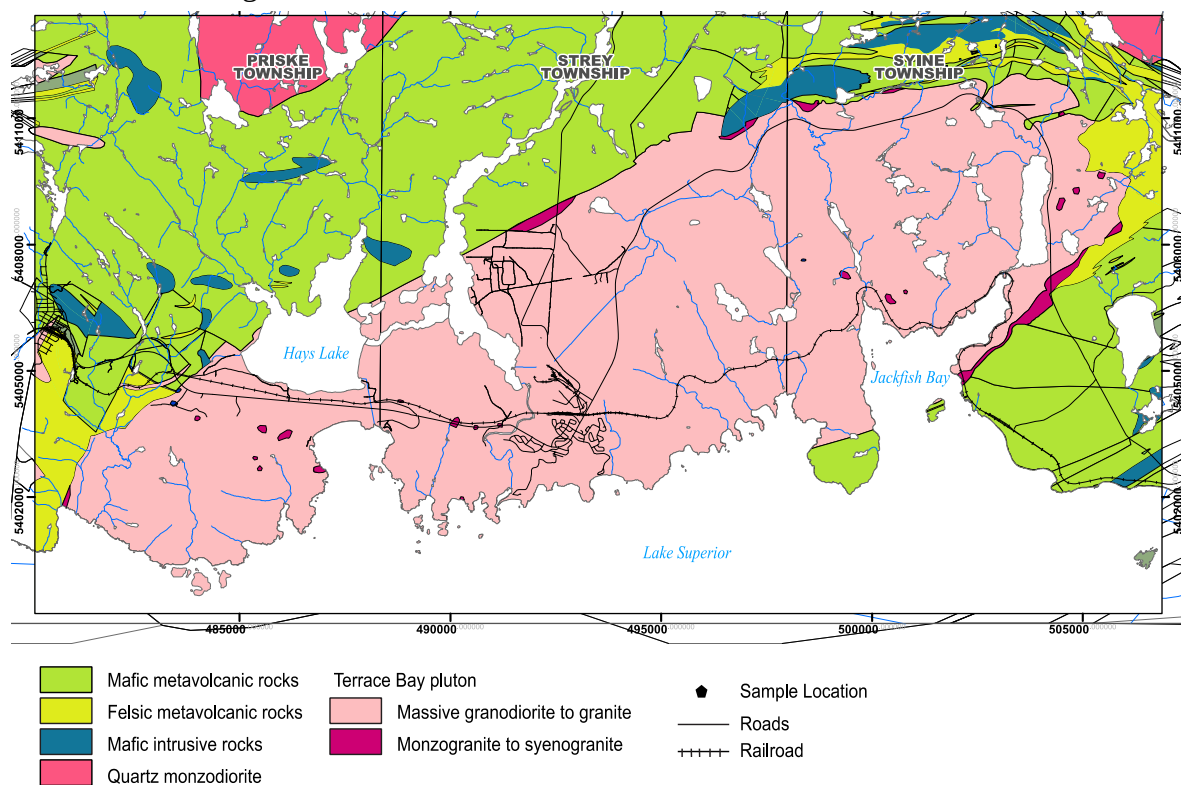


Figure 1. Simplified bedrock geology map of the Terrace Bay batholith and surrounding greenstone belt in Priske, Strey and Syine townships. Modified from Arnold et al. (2017).

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Textural Analyses of Rapakivi Mantles: Evidence for Semi-Selective Replacement in Proterozoic Rapakivi Granites

ASHAUER, Zachary¹, CURRIER, Ryan¹, NORFLEET, Mark¹

¹Natural and Applied Sciences, University of Wisconsin Green Bay, 2420 Nicolet Dr. Green Bay, Wisconsin 54311

Rapakivi granite complexes are commonly associated with caldera forming eruptions (Karell et al., 2014). Characteristic of these granites is the rapakivi texture, the mantling of plagioclase on K-feldspar megacrysts. First described in scientific literature by Sederholm in 1891, consensus on a model for rapakivi texture formation remains elusive. Textural analyses that help constrain the mechanism of formation are presented here. The textural analysis consists of a systematic survey of mantle thicknesses in relation to the mantled feldspar radius, and was conducted on two classical rapakivi systems: the Wolf River Batholith (1.48-1.46 Ga; Dewane and Van Schmus, 2007) Wisconsin and the Wiborg Batholith (1.65-1.62 Ga; Rämö, 1991) southeastern Finland. Mantle analysis samples were obtained from dimension stone slabs of the *Waupaca Wiborgite* in the Wisconsin Capitol Rotunda and of *Ylämaa Wiborgite* (Baltic Brown) slabs from five Green Bay area businesses.

The Wolf River and Wiborg batholiths are A-type intrusive bodies underlying areas >9,000 km², containing wiborgite variety of rapakivi granite, *Waupaca Wiborgite* and *Ylämaa Wiborgite*, respectively. Wiborgite is a porphyritic granite containing ovoidal megacrysts of K-feldspar ranging upwards of 6 cm in diameter, with over 50% of megacrysts mantled by 1-4 mm of plagioclase. The *Waupaca Wiborgite* contains a greater population of euhedral K-feldspars than the *Ylämaa Wiborgite* where nearly all crystals are ovoidal in shape.

Mantled feldspar cores and mantles were outlined by hand from high-resolution pictures of slabs. Mantle and core area dimensions were calculated using image analysis software Image J (Schneider et al., 2012) and converted to respective radii for comparison. Results illustrate a trend of thickest mantles developing on the middle size class of crystals, which is consistent across all samples and the two separate systems (Figure 1). Data density plots stretch out along the x-axis; implying larger radius crystals generally have smaller thickness mantles.

To properly interpret results, a model was produced replicating variable mantle and crystal radii size scenarios observed from a 2D slice of mantled spheres. The model evaluates three scenarios of mantle thickness in relation to increasing mantled feldspar radius: (1) mantle thickness is variable with crystal radius, (2) mantle thickness is a consistent proportion of crystal radius, and (3) mantle thickness decreases with increasing crystal radius. Scenarios 1 and 2 overestimate mantle thicknesses and display data distributions inconsistent with mantle analysis results (Figure 2). Scenario 3 closely resembles mantle analysis results showing thickest mantles occur on the middle size class of crystals and concentrate closest to the x-axis.

Mantle analysis coupled with theoretical modeling suggests mantle thickness has dependence on mantled feldspar size. This is interpreted as forming within a contact melt zone, driven by underplating of hot magma, which resulted in vigorous stirring once a tipping point is reached through buoyant instability. This model thus suggests dissolution-controlled replacement mantle growth in an up-temperature regime, consistent with caldera volcanism.

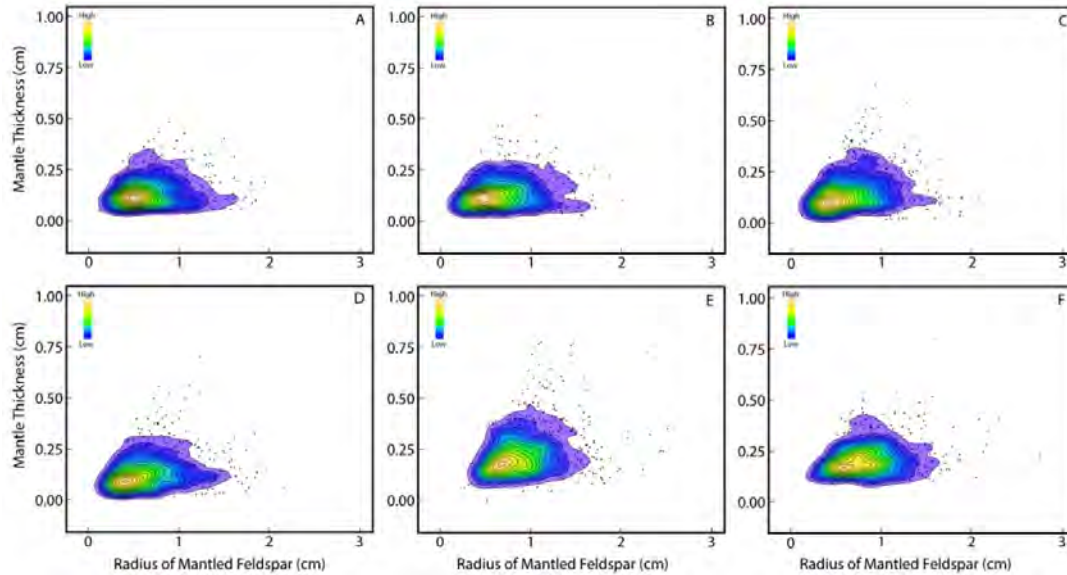


Figure 1. Mantle thickness (radius of mantled feldspar – radius of core feldspar) plotted against radius of mantled feldspar. A-E independent slabs of *Ylämaa Wiborgite*, F compiled slabs of *Waupaca Wiborgite*. Notice middle size class of crystals generally have thickest mantles.

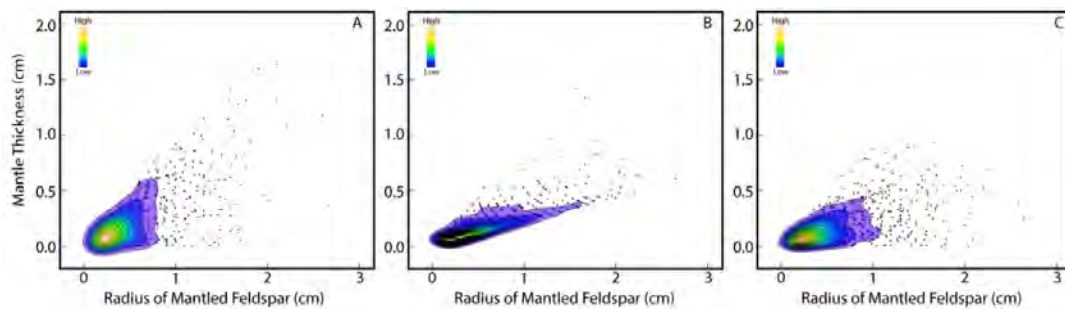


Figure 2. Mantle thickness (radius of mantled feldspar – radius of core feldspar) plotted against radius of mantled feldspar. (A) Random thickness mantle scenario, (B) consistent proportion of mantle thickness to mantled feldspar size, and (C) mantle thickness decreases with increasing mantled feldspar size. Notice y-axis scale is double that of mantle analysis results.

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New U-Pb Zircon Ages for Rocks from the Granite-Gneiss Terrane in Northern Michigan: Evidence for Events at ~3750, 2750, and 1850 Ma

AYUSO, R.A.¹, SCHULZ, K.J.¹, CANNON, W.F.¹, WOODRUFF, L.G.², VAZQUEZ, J.A.³, FOLEY, N.K.¹, and JACKSON, J.¹

¹ U.S. Geological Survey, Reston, VA 20192, ² U.S. Geological Survey, Mounds View, MN 55112, ³ U.S. Geological Survey, Menlo Park, CA 94025

Early Archean rocks are part of the granite-gneiss terrane along the southern margin of the Superior craton [1]. Recently, we reported preliminary zircon age data from the Carney Lake gneiss in the granite-gneiss terrane of northern Michigan that indicated an Eoarchean component ca. 3750 Ma [2]. Here we report additional sensitive high-resolution ion microprobe (SHRIMP) U-Pb zircon ages for the Carney Lake gneiss that further document the Eoarchean component. We also report new U-Pb zircon ages for the Hardwood gneiss complex, the Peavy Pond complex, and a porphyritic red granite from northern Michigan. Two samples were collected from the Carney Lake gneiss. Zircons were obtained from a granitic K-feldspar-bearing gneiss that is locally pegmatitic; the zircons range from anhedral to subhedral, contain complex irregular growth zoning, and display multiple growth rims. Zircons also were obtained from a banded and folded gray to red granitic gneiss; the zircons are slightly rounded to subhedral. One sample each was collected from the Hardwood gneiss complex, Peavy Pond complex, and porphyritic red granite. The Hardwood gneiss sample is a fine-grained, layered garnet-pyroxene-quartz-magnetite gneiss (granulite grade) that contains brown and mostly anhedral zircons. The Peavy Pond sample is a medium-grained granite with honey-colored euhedral to subhedral zircons characterized by doubly terminated prisms. The porphyritic red granite is foliated, contains K-feldspar augen, and has clear to pale brown subhedral zircons that commonly display igneous oscillatory bands. SHRIMP U-Pb data were obtained on handpicked zircons. All peaks, including U, Th, Pb, REE, Hf, Ti, and Y, were measured sequentially. Raw data were reduced using the Squid 2 and Isoplot programs [3, 4].

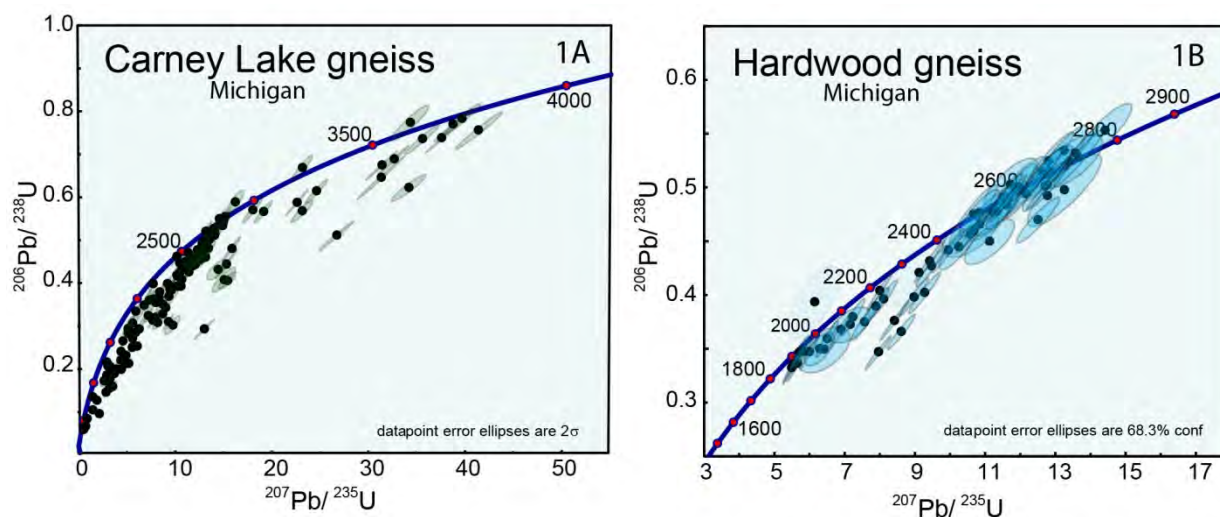


Figure 1: A. Concordia diagram for 129 spot analyses from zircons in the Carney Lake gneiss. B. Concordia diagram for 56 spot analyses from zircons in the Hardwood gneiss.

On a Concordia diagram, U-Pb data for Carney Lake show clusters with points ranging from concordant to discordant (Fig. 1A). The predominant data cluster of nearly concordant points has an intercept ca. 2750 Ma; a smaller concentration of nearly concordant analyses occurs at ca. 3750 Ma. One possible data

alignment spans from an upper intercept age of ca. 3750 Ma to the lower intercept age of ca. 2750 Ma; a second possible alignment spans a range from 2750 Ma toward an imprecisely defined intercept around 1000 Ma (Fig. 1A).

The ca. 3750 Ma age on zircon cores from the Carney Lake gneiss is evidence of an Eoarchean component in the granite-gneiss terrane (Fig. 1A). The gneiss was affected by igneous and thermal events at ca. 2750 (and younger), which resulted in new zircon crystallization, recrystallization, and formation of overgrowths. U-Pb zircon dates for the Hardwood gneiss yielded evidence of a Neoarchean component (concordant spot analyses) ca. 2750-2500 Ma as well as younger dates ca. 1900 Ma (Fig. 1B). U-Pb data for the Peavy Pond complex range from concordant to discordant and plot along a trend intercepting Concordia at ca. 1850 Ma (a small data cluster plots at ca. 2600 Ma) (Fig. 2A). The majority of spots for the red granite is concordant or plots adjacent to Concordia at ca. 2099 Ma (age of crystallization) (Fig. 2B).

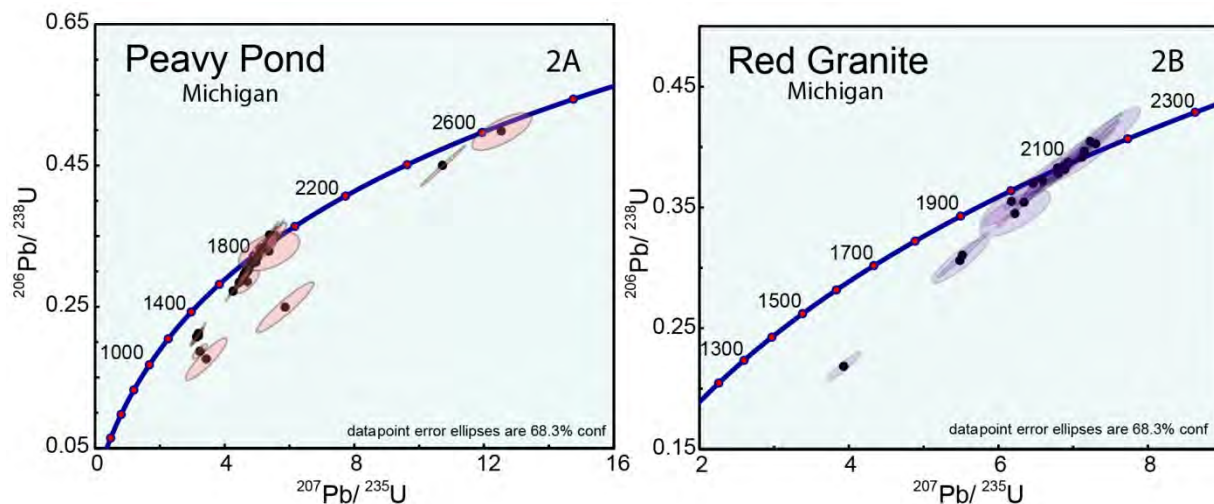


Figure 2: A. Concordia diagram for 32 spot analyses of zircons from the Peavy Pond complex. B. Concordia diagram for 18 spot analyses of zircons from the porphyritic Red Granite.

The zircons show typical REE chondrite-normalized patterns (LREE-depleted, HREE-enriched), negative Eu anomalies, and positive Ce anomalies. The Carney Lake gneiss zircons have the most diverse REE patterns and widely variable Eu and Ce anomalies. The Hardwood gneiss also has diverse REE patterns. Trace element ratio plots (e.g., U/Yb vs. Hf) [5] suggest a continental magmatic origin for zircons from the Carney Lake gneiss, Hardwood gneiss, and Peavy Pond complex. A continental arc (or enriched mantle?) is implicated for zircons from the red granite.

The ca. 3750 Ma age of the Carney Lake gneiss documents the presence of an Eoarchean component in northern Michigan. The ca. 2750 Ma of the Hardwood gneiss indicates the contribution of a Neoarchean component in the region. Igneous intrusive events occurred ca. 2750, 2099, and 1850 Ma. There is no evidence for an older Archean component in the porphyritic red granite.

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Archean BIF clasts vs. Paleoproterozoic jasper clasts? The proof is in the pudding (stone)

BLEEKER, Wouter

Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, K1A 0E8

Email: wouter.bleeker@canada.ca

The *ca.* 2.50-2.25 Ga Huronian Supergroup (Bennett et al., 1991; Young et al., 2001), a largely intra-cratonic rift and regional cover sequence overlying the southern Superior craton (Bleeker and Ernst, 2006), contains one of the more important records of Paleoproterozoic Earth evolution. Among other things, it contains a superb volcanic rift sequence including subaerial and subaqueous basalt flows, and the Copper Cliff Rhyolite and its subvolcanic pluton, the Creighton Granite, now precisely dated at 2459 ± 7 Ma (Bleeker et al., 2015). This lower rift sequence is terminated by conglomerate/sandstone and greywacke turbidites of the Matinenda and McKim formations, the former hosting important detrital pyrite and uraninite concentrations that have been mined for uranium in the Elliott Lake area (Roscoe, 1969).

Overlying this lower rift sequence are several cycles of conglomerate, sandstone and silt- to mudstone, and back to sandstones, three of which start out with glacial diamictites. Minor erosional disconformities or unconformities are present at the base of these cycles. Diamictites of the second cycle are overlain by carbonates of the Espanola Formation, which may represent cap carbonates and, thus, may constitute a globally important marker horizon. The third and aerially most extensive of these cycles starts with the Gowganda Formation, which consists of glacial diamictites at its base and hosts the first red-bed sandstones of the Huronian toward its top. The Gowganda Formation is overlain by white to red sandstones and conglomerates of the Lorrain Formation, which hosts a conspicuous member of red jasper clast conglomerate, locally known as “puddingstone” (Fig. 1). The red jasper clasts, typically 0.5-5.0 cm in size, in a white to off-white quartz-dominated matrix, make for an attractive rock type that is sought after as a decorative stone.

For the last century, these jasper clasts have been interpreted as being derived from Archean basement to the north, particularly the *ca.* 2720-2725 Ma, black to sometimes red, banded iron formations (BIFs) of the Abitibi greenstone belt. Good exposures

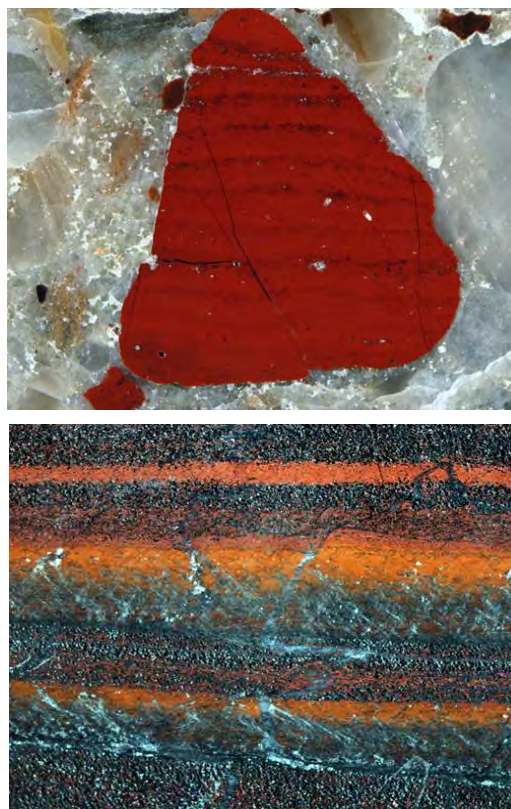


Figure 1: Top, red jasper clast in “puddingstone”, very fine-grained and with delicate lamination and textures, and no metamorphic minerals (no magnetite). Bottom, typical recrystallized Abitibi BIF, at about the same scale, with recrystallized texture, a fabric, and metamorphic magnetite.

of such BIFs occur in the Timmins area, around Temagami, and in Wawa. They have been mined for iron ore at a number of localities including Temagami (Sherman Mine), south of Kirkland Lake (Adams Mine), and Wawa (Helen Mine). All of these BIFs have seen pervasive deformation and low grade metamorphism, and contain abundant magnetite. Several observations lead me to question this interpretation: the jasper clasts of the Huronian puddingstone are often angular, i.e. more or less proximal; in typical puddingstone they suddenly become a dominant clast type, again suggesting a proximal source; there are few if any real BIF clasts; the jasper clasts are extremely fine-grained and delicately textured (Fig. 1) and do not contain magnetite, unlike BIF samples from the Abitibi which are noticeably more recrystallized (an order of magnitude coarser in grain size) and invariably contain metamorphic magnetite (Fig. 1).

I conclude that the conspicuous jasper clasts of Lorrain puddingstone are not of Archean derivation, but rather represent penecontemporaneous reworking of otherwise poorly preserved Huronian jasper deposits, possibly associated with a minor volcanic or hydrothermal centre that has not yet been identified. Given that the occurrence of puddingstone is strongly concentrated in, if not unique to, the area around Bruce Mines, the source jasper beds were likely local deposits restricted to that part of the Huronian basin, possibly the fine-grained siliceous siltstone and associated layers that have been referred to in some of the early papers on the Huronian as “Bruce Mines Jasper” (Collins, 1925). The jasper clasts constitute a range from dark red to pure white chert, all of which show delicate textures and layering. Among the white chert-like clasts some resemble unrecrystallized agate, also suggesting deep weathering and reworking of Paleoproterozoic volcanic units containing agate nodules. Rare accompanying clasts of quartz porphyry may allow dating of this part of the Huronian succession. If indeed Lorrain-age jasper, these clasts could host important information about the ambient environment at *ca.* 2.35 Ga.

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Ore Petrography of the Flambeau volcanogenic massive sulfide deposit, northwestern Wisconsin: Implications for hydrothermal fluid composition

BLOTZ, Kaelyn E., LODGE, Robert W.D.

Department of Geology, University of Wisconsin-Eau Claire, Eau Claire, WI 54701

The Paleoproterozoic Flambeau Cu-Zn-Au volcanogenic massive sulfide (VMS) deposit is located near the town of Ladysmith, Wisconsin within the Pembine-Wausau Terrane of the Penokean Orogeny (Schulz and Cannon, 2007) and is one of at least 13 other VMS deposits that have been identified in the state (DeMatties, 1994). The Flambeau is the only deposit to have been mined in Wisconsin after it was discovered by Kennecott Minerals Company in 1968 and was exploited due to the unusual grade of the orebody in the supergene enriched cap (May and Dinkowitz 1996). Mining began in 1993 and lasted until 1997 when extraction of the supergene enriched cap was completed. The high-grade copper ore body produced nearly 1.8 million tons of ore with an average of 10% copper and 0.18 ounces of gold per ton before the open pit was completely refilled and the site was reclaimed (Jones and Jones, 1999). The hypogene geology of the Flambeau deposit is characterized by massive to semi-massive Cu-Zn-Pb sulfides hosted in altered intermediate-felsic rocks that were metamorphosed into chlorite-andalusite-biotite schists. Before metamorphism occurred, these rocks were formed in a submarine hydrothermal system and their compositions can provide insight into the mechanisms of gold enrichment at the Flambeau mine.

This study focuses on the identification of trace minerals and mineralogical variations within the ore zone at the Flambeau deposit. Samples were collected from drill core stored at the Wisconsin Geologic and Natural History Survey core repository and were then processed into polished thin sections. There are two main types of primary ore: a massive pyrite-chalcopyrite dominated assemblage and a weakly banded sphalerite-pyrite-galena dominated assemblage (May and Dinkowitz, 1996). Using scanning electron microscopy-energy dispersive spectroscopy, trace ore minerals identified in the ore zone include tellurides (hessite, altaite, tsumoite, bismuth), electrum, arsenopyrite, acanthite, bismuthinite, cassiterite, monazite, and an unnamed tungsten mineral. The presence of these minerals is important in determining the physical and chemical characteristics of the hydrothermal fluids since these trace minerals form under specific hydrothermal conditions. The relative abundance of the trace minerals, coupled with the anomalous Cu-enrichment in the Flambeau felsic-intermediate dominated strata, may indicate that this is not a traditional VMS deposit. Preliminary data suggests that there may have been magmatic fluids present in the seawater-dominated hydrothermal system. This interpretation is supported by geochemical characteristics of the alteration assemblages (Blotz et al. 2018). Mass balance calculations suggest a sericite-silica dominated assemblage consistent with argillic alteration. Based on these observations, the Flambeau deposit is possibly an example of a hybrid VMS-epithermal system.

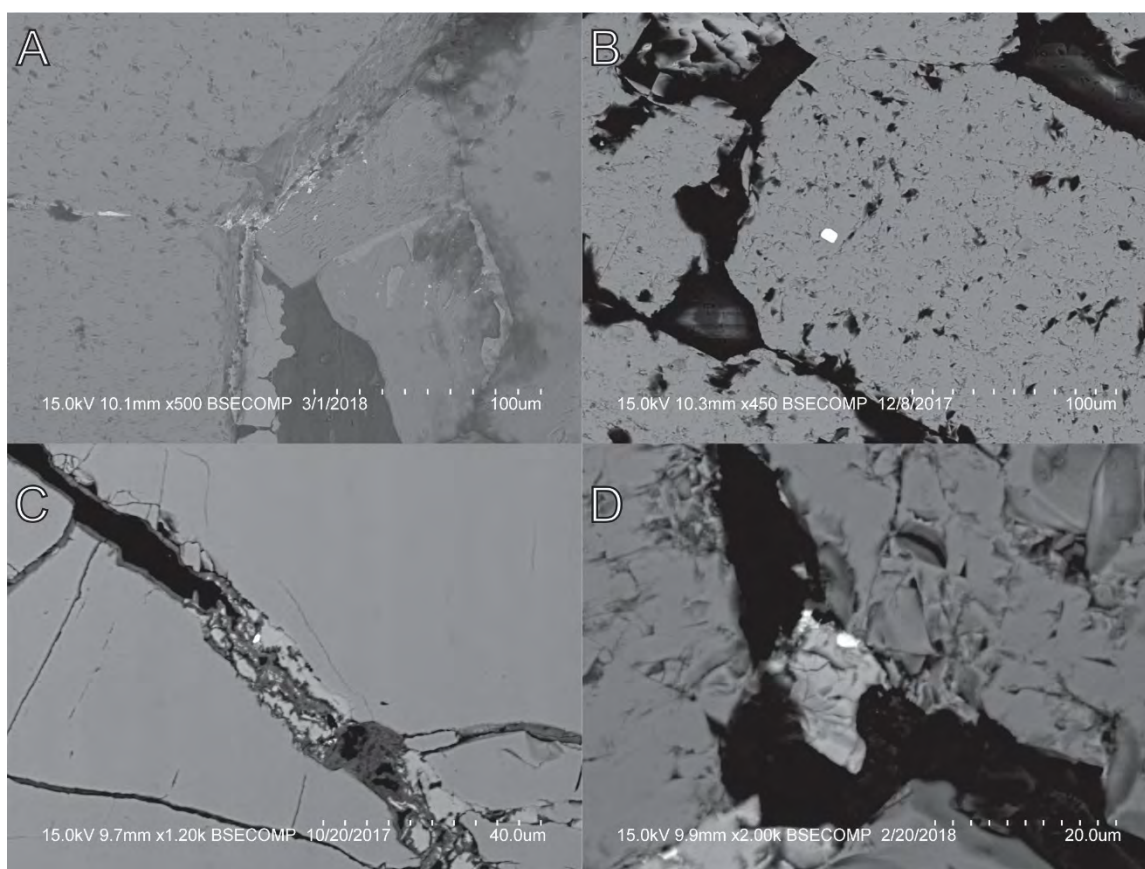


Figure 1: A) Silver telluride throughout pyrite grains and grain boundaries. B) Bismuth telluride within pyrite grain. C) Gold electrum within chalcopyrite. D) Acanthite within sphalerite.

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Fault-controlled dike emplacement in the Grand Marais, Minnesota area

BOERBOOM, Terrence J., *Minnesota Geological Survey*

Over the past few years bedrock field mapping projects have been undertaken in the area around Grand Marais, northeastern Minnesota; these were funded in part by the USGS Statemap mapping program. The most recent round of field work, completed in 2017, was in the Mark Lake 7.5' quadrangle (Fig.1), near the southern margin of the ca. 1,099 Ma Eagle Mountain granophyre (EMG). This work has delineated a network of diabase dikes and sills, some of which were apparently intruded along faults, as evidenced by disruption of a distinctive quartz- and feldspar-phyric rhyolite (QFPR) unit, which in one block has been folded into a southwest-plunging syncline (Figs. 1 and 2). The correlation of the QFPR between the blocks is strengthened by an underlying thin unit of a distinct sparsely but coarsely porphyritic andesite flow along most of its length (Fig. 2).

The extent of the QFPR is much greater than previously recognized; it may correlate with the Devil's Kettle Rhyolite to the east, but correlation of this as well as other interlayered mafic to intermediate volcanic rocks is difficult owing to gaps in outcrop, structural complications, and intervening intrusions. The mafic volcanic rocks within several km of the EMG are typically quite metamorphosed/altered, particularly the more primitive ophitic basalt varieties, and the amygdules contain epidote, local fine fibrous amphiboles, and rarely garnet along with the usual mixtures of chlorite, calcite, and quartz.

The diabase dike/sill complex is continuous with the Lake Clara diabase, as previously mapped by the author to varying degrees to the west and southwest of the Mark Lake quadrangle. The Lake Clara complex generally forms an arc from northeast to east-west that mimics the synformal shape of the Sawbill Lake intrusion (Brooker and Miller, 2012), which is part of the Brule-Hovland complex (Fig. 1), and also the general curvature of the volcanic pile. However, several northwest-trending diabase offshoots imply that emplacement was locally controlled by preexisting faults, as the QFPR is clearly offset across these northwest dikes. The margins of the dikes, particularly those of northwest orientation, are flanked by thin zones of intermediate intrusive rocks that commonly show quench textures, and the central part of one of the thickest northwest dikes contains a zoned pod that ranges from ferromonzodiorite at the edge to granophyre in the center (Fig. 2). All of the intermediate to felsic phases associated with the diabase, including the granophyre pod, contain small glassy 'quartz eyes' interpreted to be xenocrystic grains derived from melted QFPR implying that melting of rhyolite may have also taken place at some depth.

Another small, northwest-trending hybrid dike (NE corner of Figure 2) consists of red fine-grained felsite that contains comagmatic cm-to m-sized, scallop-edged intermediate to mostly mafic enclaves, in nearly equal proportions of felsic to mafic material. The red felsite matrix contains abundant quartz and feldspar phenocrysts, and is essentially identical to the nearby QFPR. This hybrid dike is adjacent to another 'felsite' dike that is enclave free, and has only small feldspar phenocrysts. Both are oriented to the northwest, nearly perpendicular to the strike of the hosting volcanic rocks, and are believed to be related to the main Lake Clara diabase dike set (Figure 2). These are outside of the main diabase swarm, but are consistent with melting of the rhyolite at depth and commingling with mafic magma prior to upward movement along fault zones, along smaller incipient faults outside of the main swarm.

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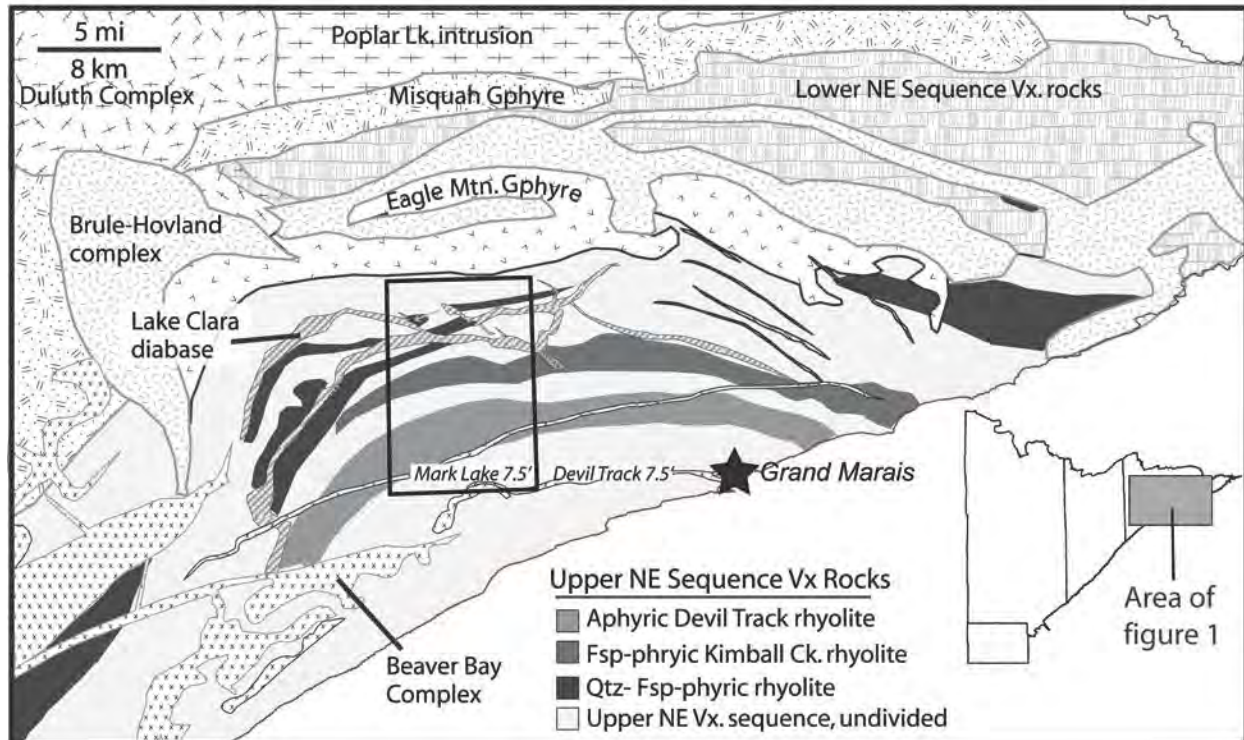


Figure 1. Regional geologic context of the Lake Clara diabase complex. Unlabeled areas – Keweenawan volcanic rocks, undivided. Outline of Mark Lake quadrangle shown; geology of the south half of this map from varied 1:24,000 scale maps by Boerboom and others; north half from MGS map S-21.

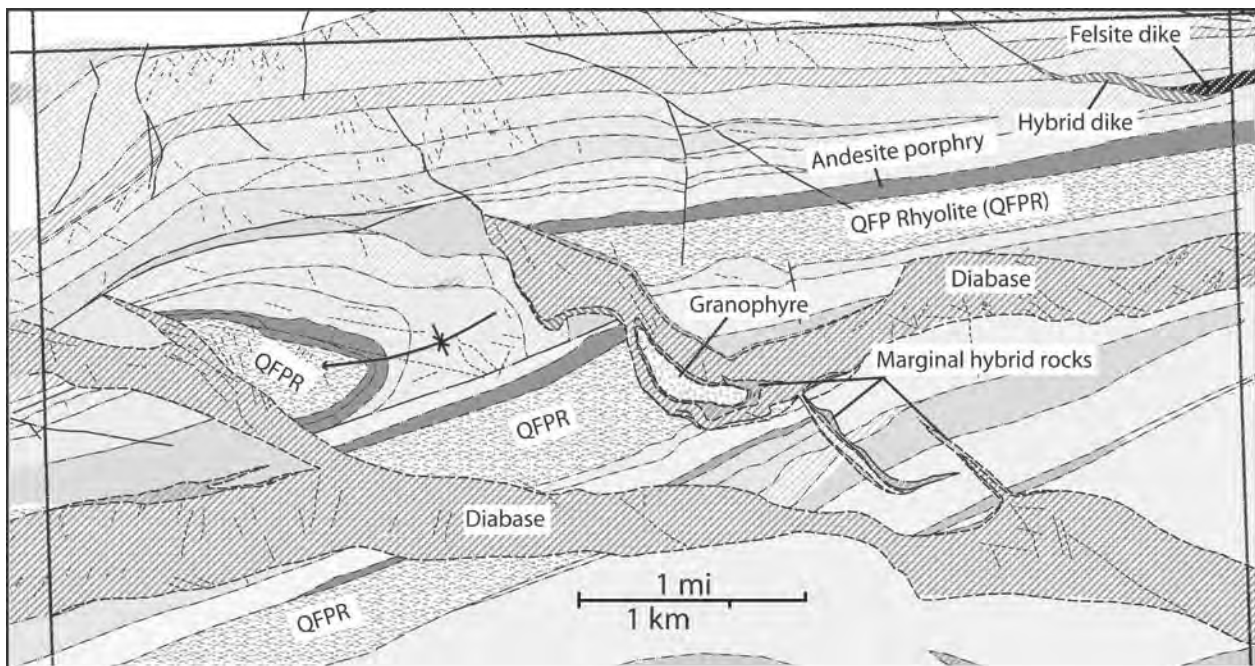


Figure 2. Northern third of the Mark Lake quadrangle showing offset of QFPR across NW trending diabase dike offshoots, marginal intermediate hybrid rocks, and central felsic granophyre pod.

Possible Almotantite from the Nine Mile pluton, Wausau Complex, Marathon County, WI.

BUCHHOLZ, Thomas W.¹, FALSTER, Alexander U.², and SIMMONS², Wm. B.

¹1140 12th Street North, Wisconsin Rapids, Wisconsin 54494; ²Maine Mineral and Gem Museum, PO Box 500, 99 Main Street, Bethel, Maine 04217.

The Nine Mile granite and quartz monzonite pluton is the youngest (≈ 1505 Ma, Dewane & Van Schmus, 2007) and most silicic of the four intrusions comprising the Wausau Syenite Complex. The Red Rock Granite northeast gravel pit is located in the south-western portion of the Nine Mile Pluton.

Pegmatites and aplites are uncommon in this portion of the pluton, but in 2015 a small aplite-pegmatite was exposed in the western working face of the northern portion of the pit, and samples were recovered from the talus below the exposure. The arch-shaped dike was approximately 20 cm thick, with a thin pegmatitic zone measuring approximately 5-6 cm thick near a margin of the dike. The center of the pegmatite in several samples had a thin (<0.5 cm) discontinuous band of fine-grained albite. Occurring adjacent to and within the albite band were small zircons, small crystals of columbite-group minerals, and very small (300-400 μm) brownish grains of an unusual non-fluorescent niobium-bearing almotantalate mineral. Associated minor minerals include: almandine-spessartine, columbite-(Fe), tapiolite-(Fe), zircon, hafnian zircon, zoned microlite-pyrochlore and U-rich pyrochlore, betafite, xenotime-(Y), ilmenite, monazite-(Ce), and thorite.

Chemical analysis of this almotantalate yields a formula of

$(\text{Al}_{0.986}\text{Fe}^{2+}_{0.021}\text{Mn}^{2+}_{0.001})_{\Sigma 1.008}(\text{Ta}_{0.803}\text{Nb}_{0.147}\text{Ti}_{0.062})_{\Sigma 1.012}\text{O}_{4.000}$ which is essentially identical to almotantite (AlTaO_4). The stoichiometry of simpsonite, $\text{Al}_4\text{Ta}_3\text{O}_{18}(\text{OH})$, effectively rules this species out, and there are no other known almotantalates. X-ray diffractometry is needed to further confirm the presence of almotantite, but paucity of material precludes this. Pegmatites of the Nine Mile Pluton are anorogenic in origin; and typically such pegmatites lack Ta-dominant phases. However, as we have previously reported, Nine Mile pluton pegmatites often contain late-stage Ta-enrichment, resulting in the formation of various Ta-dominant phases, including tantalite-(Mn), tapiolite-(Fe), and microlite. The occurrence of 'almotantite' is noteworthy considering the overall metaluminous nature of the NYF pluton. It seems likely this occurrence resulted from a process of very late-stage fractionation similar to the processes that produced the high-Ta species in other pegmatites in the pluton. The lack of dark mica (annite or siderophyllite) in these dike samples suggests availability of Fe was probably somewhat limited, and the small amount of Fe available for interaction with late-stage fluids was likely consumed in the formation of columbite-(Fe), tapiolite-(Fe), almandine-spessartine and ilmenite, while crystallization of almandine-spessartine suggests development of a peraluminous environment. Pyrochlore, microlite, monazite and albite crystallization probably also reduced concentrations of

Ca, Na, U and other elements. Lacking other cations, remaining Al combined with residual Ta and Nb to crystallize small amounts of probable alumotantite. Another possibility for increased Al availability may be a greisenization trend such as has been observed in one location in the pluton where abundant topaz was found.

In an attempt to recover additional material, the site was revisited in June 2017. Little dike material was accessible in the pit wall due to slumping, but aplite-pegmatite samples were recovered from the adjacent floor of the pit. Due to the virtual absence of aplites and pegmatites in this area of the pluton, it is very probable that the samples originated from the same dike as those hosting the probable alumotantite. None of the samples exhibited the thin aplite band noted previously. However, examination of heavy mineral separates from the samples revealed a somewhat similar mineral assemblage partially reflecting the above association. The 2017 samples contained small crystals of dark mica (annite or siderophyllite, unlike the 2015 material with the thin albite band), along with Nb-bearing ilmenite, a Nb-bearing TiO₂ phase, pyrochlore, betafite, monazite, Hf-enriched zircon and columbite-(Fe). Notable is the lack of microlite, tapiolite-(Fe), almandine-spessartine, and probable alumotantite, suggesting the extreme fractionation that produced the unusual phases recovered in 2015 was restricted to a small portion of the dike.

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Recent gravity and magnetic investigations of the Minnesota River Valley Subprovince: New insights into ancient problems

CHANDLER, V.W., SOUTHWICK, D. L., and JIRSA, M. A.

Minnesota Geological Survey, University of Minnesota, 2609 Territorial Rd, St. Paul, MN 55114 U.S.A.

Geophysical studies have been a long-standing companion to geologic investigations of the gneissic Minnesota River Valley (MRV) subprovince, due in part to limited outcrops and drill cores. Over the last decade various geophysical investigations conducted as part of state and academic programs have provided new insights into the crustal structure and evolution of this ancient and somewhat enigmatic component of the Archean Superior Province.

Gravity and magnetic methods have continued to dominate geophysical studies of the MRV subprovince. Recent compilations of regional-scale gravity and magnetic grids and maps have assisted in extending MRV geology into eastern South Dakota (McCormick 2010 a, b; Southwick and others, 2018). At higher resolution, derivative-enhanced grids of gravity and magnetic data have been used extensively for bedrock mapping, which is being conducted in support of the County Geologic Atlas (CGA) Program of the Minnesota Geological Survey. These studies have added considerable detail regarding the internal geology of the blocks comprising the MRV subprovince — which from north to south are the Benson, Montevideo, Morton, and Jeffers. The enhanced gravity and magnetic data have been especially useful in 1:100,000-scale mapping of compositional variations and fold patterns within the gneissic blocks. The enhanced gravity and magnetic grids have also been very helpful in detailed mapping of the structural discontinuities that bound the blocks, including the Great Lake Tectonic Zone, the Appleton Shear zone, the Yellow Medicine shear zone, the Brown County lineament, and the Spirit Lake tectonic zone (SLTZ).

Model studies of gravity and magnetic data along selected profiles have been useful in compiling geologic cross-sections for CGA mapping. Similar to earlier modeling at lower resolution, the newer models indicate that the three northernmost structural discontinuities of the MRV subprovince can be suitably approximated by slab-like sources that dip moderately to steeply northwards. Modeling of the interior of the MRV blocks is considerably more challenging; complex fold patterns and strong anomaly interference make interpretation difficult, especially with regard to determining the subsurface geometry of individual anomaly sources. In addition, outcrop evidence in the Minnesota River Valley indicates shallow structural dips of lithologic units locally that may obfuscate geophysical modeling. Nonetheless, model studies in these areas can still be useful for estimating the general range and spatial distribution of density and magnetization values for upper crustal rocks, resulting in improved lithologic identification and mapping.

Gravity and magnetic modeling reveals significant differences between the SLTZ and the other structural discontinuities of the MRV subprovince. Firstly, the SLTZ, which forms the southern terminus of the MRV subprovince, is interpreted to dip southwards not northwards. Secondly, using values that are consistent with existing rock property data, most anomaly

signatures of the MRV subprovince can be accommodated by sources within the shallow crust (<10 km. depth), but a prominent magnetic minimum that extends along SLTZ may involve much of the crustal section. Physical property data are not available for lower crustal rocks in Minnesota, but studies elsewhere of long-wavelength magnetic anomalies, crustal xenoliths, and crustal thicknesses indicate that the lower crust of cratonic areas typically is strongly magnetic, most likely reflecting enrichment of magnetite in granulite facies rocks (Langel and Hinze, 1998). Assuming reasonable levels of magnetization for the lower MRV crust (~3.5 SI), much of crustal section to the southeast of the SLTZ is interpreted to be non-magnetic. This apparent loss of crustal magnetization might reflect the deep emplacement of non-magnetic rocks, such as Paleoproterozoic metasedimentary rocks along the tectonic zone, or destruction of magnetic oxides via fluids moving along and above the tectonic zone. Evidence for the former possibility is available from recent magnetotelluric studies, where a conductive zone has been imaged along the southeastern edge of the SLTZ at mid- to deep- crustal levels (Bedrosian, 2016; Yang and others, 2015). Bedrosian suggested that the conductive zone might reflect Paleoproterozoic metasediments, which are known to be associated with prominent conductivity anomalies further north, where these rocks lie at or near the surface.

Given the success so far for gravity and magnetic studies of the MRV subprovince, it seems likely that these data will continue to be useful for geologic studies for many years to come.

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Possible Emplacement Controls on Diamond-Bearing Rocks North of Lake Superior

CUNDARI, Robert¹, SMYK, Mark¹, CAMPBELL, Dorothy¹ and PUUMALA, Mark¹

¹Resident Geologist Program, Ontario Geological Survey, Ministry of Northern Development and Mines, 435 James St. S., Suite B002, Thunder Bay, ON, P7E 6S7 Canada

The recent discoveries of a number of diamond-bearing, ultramafic rocks, including kimberlite, in Archean country rocks of the Superior Province, north of Lake Superior, has provided insights into lithotectonic controls on their emplacement and suggest potential for further discoveries.

The Permian to Triassic Pagwachuan kimberlites, 100 km north of Marathon, were discovered by De Beers Canada Inc. in 2015-16 within Neoproterozoic metasedimentary rocks of the Quetico Subprovince. Five separate kimberlites range in size from 0.5 to 2.5 ha and are reportedly multi-phase, complex pipes (Delgaty et al. 2017).

The Paleoproterozoic Rabbit Foot kimberlite, 50 km east-southeast of Marathon, has been explored in recent years by Rio Tinto Canada Diamonds Exploration Inc. It intrudes Neoproterozoic granitoids of the Pukaskwa batholithic complex and deformed metasedimentary rocks that are probably related to rocks of the Schreiber-Hemlo greenstone belt (Brett and Russell 2016).

A number of diamondiferous ultramafic rocks of unknown age have been discovered within the Trans-Superior Tectonic Zone (TSTZ) west of Marathon. In 2007, the Madonna alnöite ultramafic lamprophyre dyke was discovered 35 km northwest of Marathon by Rudy Wahl, who also discovered the nearby Prairie Lake paralamproite. Although hosted by Neoproterozoic rocks, these ultramafic intrusive rocks are spatially associated with Midcontinent Rift (MCR)-related and TSTZ-hosted intrusions, such as the Coldwell and Killala Lake alkalic complexes, the Prairie Lake carbonatite. The Chipman Lake fenites and carbonatites also occur within the northern extension of the TSTZ (Sage 1991), north of the Pagwachuan kimberlites. The Ripple Lake diatreme and associated lamprophyre dykes occur immediately west of the Coldwell complex and are likely associated with the TSTZ. They have also been the focus of diamond exploration.

The TSTZ is a north-northeast-trending fault zone that extends for at least 600 km and is locally referred to as the Thiel fault (Sage 1991). The major MCR-related alkalic intrusions emplaced along the TSTZ cluster around 1.0 Ga, although Sage (1983) identified lamprophyre dikes on the Slate Islands emplaced at approximately 300 Ma. The Gravel River fault, traced for over 200 km, is a northeast- to east-northeast-striking regional fault system that displays an oblique sinistral sense of transcurrent motion (Williams 1989). Several structures related to the TSTZ, the Gravel River fault and a number of northwest-trending faults intersect in the vicinity of the Pagwachuan kimberlite pipes.

The discovery of five new kimberlite pipes in the Pagwachuan Lake area highlights the potential for further discovery in the region. In the Geraldton area, a number of discrete magnetic anomalies resemble anomalies related to known kimberlite pipes. The confluence of major, intersecting structures (e.g. TSTZ and Gravel River fault) are proven to be effective pathways for deep-seated magmas, tapping melts well within the diamond stability field. These fault systems are shown to have been activated for extended periods of time (i.e. MCR-related alkalic intrusive rocks ca. 1.1 Ga and the Pagwachuan kimberlite swarm ca. 220 to 252.9 Ma). The occurrence of the Paleoproterozoic Rabbit Foot kimberlite (ca. 1945 Ma; Brett and Russell 2016) suggests that large, crustal-scale faulting and magmatism is long-lived in this part of

the Superior Province, although obvious lithotectonic controls are not as yet identified. Recent discoveries of diamondiferous rocks north of Lake Superior demonstrate its potential and suggest that further discoveries will be made.

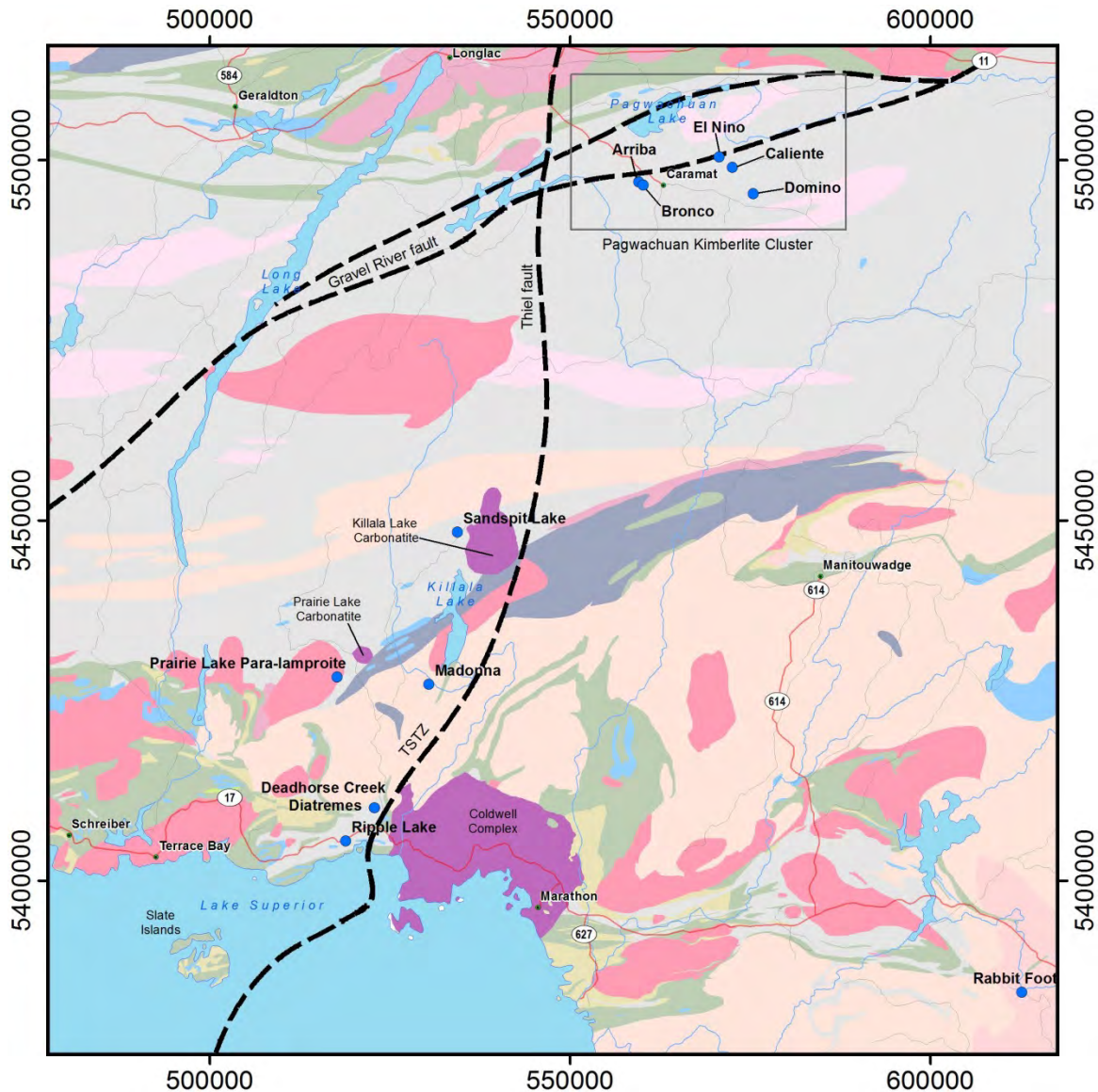


Figure 1. Geological map showing the location of the Pagwachuan kimberlite cluster and other kimberlitic and ultramafic rocks mentioned in the abstract. Approximate traces of the Gravel River fault *after* Williams (1989). The abbreviation “TSTZ” indicates the approximate location of the Trans-Superior Tectonic Zone. All UTM co-ordinates provided in NAD83, Zone 16. Bedrock geology *from* Ontario Geological Survey (2011).

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Thrust Kinematics of the Keweenaw Fault North of Portage Lake, Michigan

DeGraff, J.M.¹ and Carter, B.T.²

¹Michigan Technological University, Houghton, MI 49931

²Consultant, Houston, TX 77027

The Keweenaw Fault (KF) is the most significant fault of the Midcontinent Rift System (MRS) based on its length of 350 km (1), postulated net slip of 9 km (2), and thrusting of copper-bearing Portage Lake Volcanics (PLV, 1.1 Ga) over younger Jacobsville Sandstone (JS) (Fig. 1). This large fault and others figure prominently in ideas about MRS development (3-4) and copper deposits mined until recently along the Keweenaw Peninsula (5). Ideas about the KF (6-7, USGS 1950s maps) largely date to before modern concepts about thrust faults and before advances in cross-section modeling. As a result, many aspects of the fault's geometry, kinematics, and timing remain unclear or are simply outdated.

The prevailing view (3-5) is that the KF began as a steep, rift-bounding, normal fault during crustal extension and later was inverted during compression. This scenario would produce a fault dipping $> 45^\circ$ NW, however published maps and cross-sections show the KF dipping $\leq 45^\circ$ NW for much of its length and often $< 30^\circ$ (6, USGS 1950s maps). PLV layers locally exhibit slip along their boundaries (6, 8) and near the fault they generally parallel its surface. These observations suggest a thrust fault system detached along PLV layers (Fig. 1b), which is inconsistent with direct inheritance from a rift-bounding normal fault.

North of Portage Lake (Fig. 2) good fault exposures occur along crosscutting valleys (5-7), and mining drill holes and workings provide good local control on PLV stratigraphy and structure. One transect northeast of Houghton (Fig. 2, Loc. 1) crosses the Keweenaw and Hancock faults, which bound an anomalous area of gently dipping to horizontal PLV layers (2). USGS geologists interpreted the KF as dipping 22° NW at the surface and possibly connecting to a steeper Hancock Fault. Our data compilation and kinematic modeling show that this geometry can be replicated by thrust motion of a detached master fault, the Hancock Fault being an imbricate thrust with increased dip in its hanging wall.

A second transect west of Lake Gratiot (Fig. 2, Loc. 2) crosses the KF and another one to the northwest, possibly analogous to the Hancock Fault but less well defined. USGS geologists described horizontal to shallow dipping PLV layers between these faults based on surface and drill hole data (2). Furthermore, USGS maps show that the KF trace has a prominent reentrant of JS into the area of overthrust PLV layers, which implies a nearly horizontal fault surface based on our 3-point calculations. Forward kinematic modeling of these relationships suggests that the KF propagated upward from a deep detachment and reached a shallow detachment near the top of the JS. The northwest fault may represent an out-of-sequence cutoff of the leading edge of the thrust sheet near the top of a major ramp.

We suggest that the KF began as a thrust fault during a post-rift compressional event, its initiation point possibly controlled by deeper, precursor, normal faults. This ongoing research raises many questions answerable with further work. Objectives are to determine layer and fault geometry at the onset of faulting, to infer deformation history of layers displaced by fault motion, and to define subsurface relationships between the Keweenaw and nearby faults. The ultimate goal is to define tectonic conditions leading to origin and evolution of the KF and other major faults in the region.

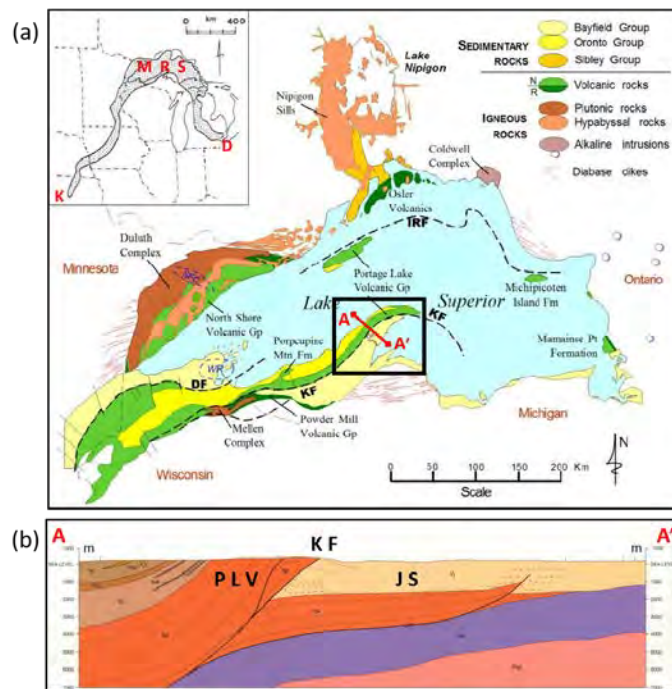


Figure 1: (a) Major rock units and faults in the Lake Superior area; KF = Keweenaw Fault, DF = Douglas Fault, IRF = Isle Royale Fault (1). Inset map shows extent of Midcontinent Rift System (MRS) from Lake Superior southwest to Kansas (K) and southeast to Detroit (D). Black rectangle is focus area of Figure 2. (b) Cross-section along A-A' in map showing PLV (red-orange) offset about 9 km by the Keweenaw Fault, and JS (tan) locally deformed in the footwall (2).

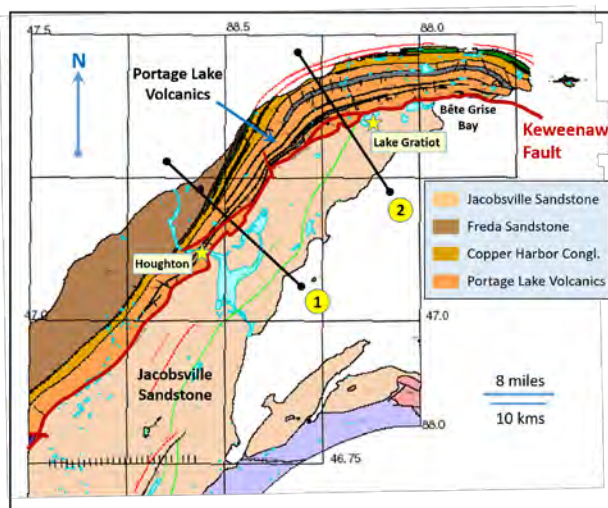


Figure 2: Focus area north of Portage Lake (adapted from 2). Major faults shown as dark red traces. 1) Dover Creek transect with smaller Hancock Fault northwest of the Keweenaw Fault. 2) Bruneau Creek transect with unnamed fault northwest of the Keweenaw Fault.

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Geochemistry of Shallow and Deep Water Archean Meta-Iron Formations and their Post Depositional Alteration in Western Superior Province, Canada

DOLEGA, Simon¹ and FRALICK, Philip¹

¹*Department of Geology, Lakehead University, 955 Oliver Road, Thunder Bay, Ontario P7B 5E1 Canada (sdolega@lakeheadu.ca)*

One purpose of studying banded meta-iron formations is to determine the chemical composition of seawater in the Archean ocean and the oxygen content of the Archean oceanic-atmospheric system. Geologists use the geochemistry of meta-iron formations to make interpretations on the chemical conditions in the Archean. However, most scientists neglect the possibility of post-depositional alteration affecting the element geochemistry preserved in the meta-iron formations. This thesis explores the role of post-depositional mechanisms on the geochemistry of four banded meta-iron formations.

The four different locations hosting Archean meta-iron formations chosen for this study include: meta-iron formations from the Beardmore/Geraldton greenstone belt of the Eastern Wabigoon Domain, Lake St. Joseph greenstone belt of the Uchi Domain, North Caribou greenstone belt of the North Caribou Terrane and Shebandowan greenstone belt of the Wawa Subprovince. The meta-iron formations from the Beardmore/Geraldton and Lake St. Joseph greenstone belts are interpreted to be deposited in a shallow water setting, while meta-iron formations from the North Caribou and Shebandowan greenstone belts are interpreted to be deposited in deeper water environments. This thesis also investigated ocean stratification by comparing the geochemistry of shallow and deep meta-iron formations.

The main source iron and silica to the oceans was hydrothermal venting fluids. Iron and silica precipitated out of seawater as iron oxyhydroxides and amorphous silica, which deposited through cyclical processes. Elements dissolved in the Archean ocean were adsorbed onto iron oxyhydroxides and silica during deposition. Crystallization of quartz, magnetite and hematite occurred during diagenesis and magnetite continued to grow during progressive metamorphism.

The lack of cerium anomalies, significant Y/Ho ratio values greater than average shales and the non-significant amount of authigenic chromium preserved in the meta-iron formations suggests that the oceans were anoxic. Therefore, in the Archean there was no significant oxygen stratification between the shallow and deeper water environments.

Significantly most of the elements were derived from multiple sources, including the siliciclastic phase, seawater or hydrothermal venting fluids, at various proportions. Al_2O_3 , TiO_2 , Th, V, Nb, U, REEs and Y were determined to be immobile during post-depositional alteration. The rest of the elements may have been isochemical during post-depositional alteration or may have been mobilized during post depositional alteration.

Mobility during diagenesis is clearly exhibited by sodium and potassium in the meta-iron formation samples from the Beardmore/Geraldton, Lake St. Joseph and North Caribou greenstone belts. Sodium was relatively immobile, and potassium was mobilized in the magnetite- and magnetite/grunerite-dominated meta-iron formations during diagenesis. Potassium was relatively immobile, and sodium was mobilized in the hematite-, jasper- and chert-dominated meta-iron formations during diagenesis.

If most of the elements remained relatively immobile during post-depositional alteration, then the ocean compositions in the Archean were heterogeneous. Shallow waters were more enriched in K_2O , Rb and LREEs, while the deeper waters were more enriched in Cs, Na_2O , CaO, MnO and HREEs. However, if the assumption that these elements were immobile is false, then the meta-iron formation does not preserve the ocean chemistry of the ancient ocean.

Preliminary petrographic and geochemical investigation of silicified volcanic rocks and silica-rich exhalative rocks from the ~2.7 Ga Abitibi Greenstone Belt, Canada

DRAZAN, Jacqueline¹, BRENGMAN, Latisha¹, FEDO, Christopher²

¹*Department of Earth and Environmental Sciences, University of Minnesota-Duluth, 1114 Kirby Dr., Duluth, MN, 55812;* ²*Department of Earth and Planetary Sciences, University of Tennessee, 1621 Cumberland Avenue, 602 Strong Hall, Knoxville, TN 37996 USA.*

The ~2.7 Ga Abitibi greenstone belt (AGB) is a well-preserved volcanic arc terrane dominated by mafic and felsic volcanic lithologies interstratified with siliceous chemical sedimentary rocks (namely chert and iron formations) and less prevalent clastic rocks (Mueller et al., 2009; Thurston et al., 2008; Gibson et al., 1983). Regionally, the terrane is characterized by sub-greenschist facies metamorphism and locally high SiO₂ concentrations due to silicification (post-depositional addition of silica phases; Brengman and Fedo, 2018; Gibson et al., 1983). Typically, silica-rich fluids permeate porous ash, tuffaceous material, or individual volcanic flow units during hydrothermalism to produce silicified rocks of varying composition and SiO₂ content. Under conditions of minor replacement, primary textures preserve (ie- phenocrysts, glass shards, amygdules, pumice fragments, volcanoclastic features), allowing field identification of silicified rocks. However, in volcanogenic massive sulfide producing systems, hydrothermal replacement leads to mineralogical and geochemical changes of protolith volcanic rocks, often obscuring primary volcanic textures in the process. This leaves behind a rock with excess SiO₂ lacking features indicative of the rocks' initial genesis. Within these geologic settings, silicified rocks can be difficult to distinguish from other siliceous chemical sedimentary rocks, which precipitate directly from seawater and/or mixed hydrothermal fluids forming discrete units (e.g. Brengman and Fedo, 2018; Thurston et al., 2008). Results from preliminary studies show that the silicon isotope composition of quartz differs between the two siliceous rocks (Brengman et al., 2016). Here we present initial results from a preliminary geochemical investigation of well-preserved silicified volcanic rocks and an associated exhalite from the Amulet Rhyolite locality near Rouyn-Noranda, QC. We aim to provide a geochemical framework for interpreting preliminary silicon isotope isotopic data of the same rocks used as a tool to differentiate siliceous volcanic rocks from siliceous chemical sedimentary rocks.

Composition and texture of the Amulet Rhyolite samples were determined using scanning electron microscopy, transmitted and reflected light microscopy, inductively coupled plasma optical emission spectrometry, and inductively coupled plasma mass spectrometry. The primary volcanic mineral assemblage consists of feldspar, chlorite, and amphiboles, with prevalent zones of epidote and quartz alteration. Based on geochemistry (SiO₂ = 55.08–73.1 wt.%; Al₂O₃ = 12.11–15.36 wt.%; CaO = 0.79–7.67 wt.%; Na₂O = 0.18–5.11 wt.%; K₂O = 0.2–5.36 wt.%; Fe₂O₃(t) = 4.13–18.53 wt.%; MgO = 0.8–5.47 wt.%), mineralogy (amphibole and feldspar micro-phenocrysts, glassy groundmass replaced by chlorite), and texture (quartz-filled amygdules, aphanitic matrix), samples classify as basalts and andesites, with an overabundance of quartz (Figure 1a, b). Mineralogically, samples show alteration features similar to other localities within the AGB: abundant mega- and micro-quartz alteration and patchy epidote alteration with minor dispersed carbonates (Figure 1a,b; Brengman and Fedo, 2018). Overlying one of the amygdaloidal pillowed basalt units is the marker “A” exhalite unit, thought to represent exhalative precipitation (Gibson et al., 1983; Figure 1c,d). The exhalite unit is

characterized by fine banding (Figure 1d) and is principally composed of microcrystalline quartz with minor aluminous mineral phases (Figure 1d). Geochemically this unit is distinct from local volcanic rocks, with higher SiO₂ (78.03 wt.%) and K₂O content (5.36 wt.%), lower Al₂O₃ (10.64 wt.%), CaO (0.37 wt.%), and Na₂O content (2.33 wt.%) content, and significantly lower Fe₂O₃(t) and MgO content (1.69 and 0.04 wt.% respectively). Due to the level of preservation, the exhalite unit and underlying silicified volcanic rocks can be differentiated based on petrography and geochemistry making them a good test locality for studying the silicon isotope variability between the two siliceous rock types. These initial geochemical results provide the framework for future silicon isotope analyses on the same sample suite.

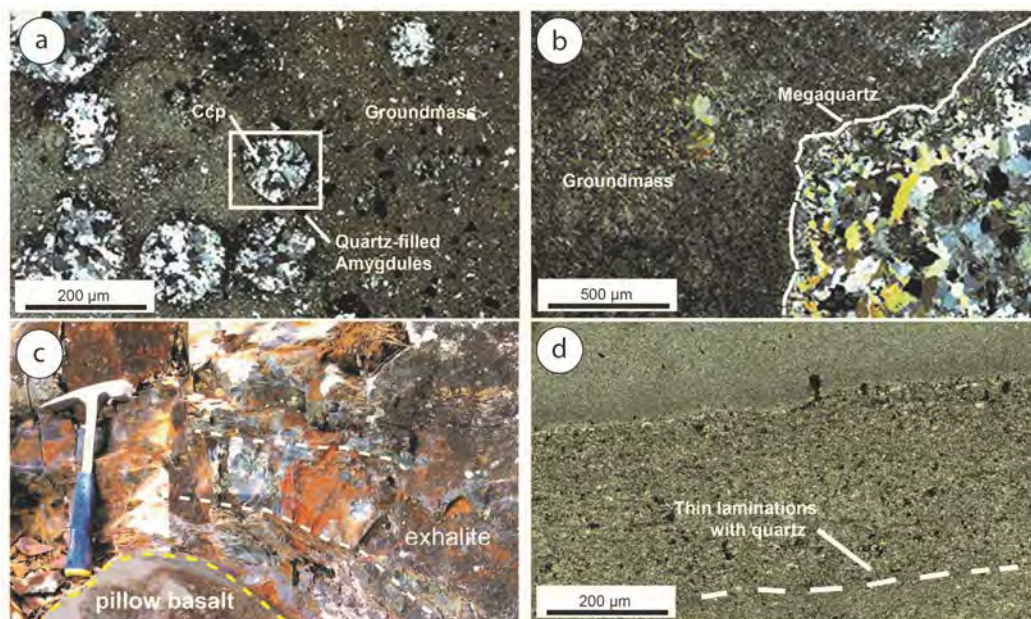


Figure 1. Representative samples photographs (field and photomicrographs) from samples of the Amulet Rhyolite. (a) Cross-polarized light photomicrograph of amygdaloidal basalt (quartz-filled with chalcopyrite centers). (b) Cross-polarized light photomicrograph of quartz altered andesitic volcanic rock with megaquartz alteration patch. (c) Field photograph of exhalite contact with underlying pillowed basalt unit. (d) Cross-polarized light image of finely banded exhalite unit.

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On the source(s) of the Felch-Arnold gravity anomaly, Upper Peninsula, Michigan

DRENTH, Benjamin J.¹, WOODRUFF, Laurel G.², SCHULZ, Klaus J.³, CANNON, William F.³, and AYUSO, Robert A.³

¹*U.S. Geological Survey, PO Box 25046, MS 964, Denver, CO, 80225*

²*U.S. Geological Survey, 2280 Woodale Drive, St. Paul, MN, 55112*

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

Away from the Midcontinent Rift, gravity highs in the Upper Peninsula of Michigan are normally attributed to rocks of the Paleoproterozoic Marquette Range Supergroup. In particular, dense iron formations and mafic volcanic rocks of the Menominee Group produce gravity highs where they reach significant thicknesses, and are juxtaposed against lower-density Archean rocks and sedimentary rocks of the Marquette Range Supergroup (e.g., Klasner et al., 1985).

A 13 mGal, E-W trending gravity high lies over Archean and Paleoproterozoic rocks in the eastern part of the Felch trough area near the town of Felch, and extends ~25 km eastward over Paleozoic sedimentary rocks to the vicinity of the town of Arnold (Fig. 1). Bacon (1956) suggested the source is dense units of the Paleoproterozoic Marquette Range Supergroup. However, subsequent mapping (James et al., 1961) in the Felch trough area showed that Archean, not Paleoproterozoic, rocks dominate the area of Precambrian exposures that coincide spatially with the gravity high (Fig. 1).

New ground gravity data and density measurements, as well as inspection of spatial relations between gravity anomalies and geologic mapping, show that the most likely candidates for the source of the Felch-Arnold gravity anomaly are the Six-Mile Lake Amphibolite and the Hardwood Gneiss (both long assumed to be Archean). Archean granites and gneisses form most of the surrounding rocks and have mean density of 2700 kg/m³. The Six-Mile Lake Amphibolite (mean density 3020 kg/m³) and the Hardwood Gneiss (mean density 2880 kg/m³) present the best spatial correspondence with the anomaly, and each could have a plausibly large subsurface volume to account for the eastward extension of the anomaly over Paleozoic sedimentary rocks. Other units in the area lack either the density, volume, or spatial distribution required to be candidates for the source.

Geochemical similarities between the Hardwood Gneiss and Six Mile Lake Amphibolite suggest that those two units may be related (Schulz et al., this volume). Further, a new radiometric date on the Hardwood Gneiss of ~2.75 Ga (Ayuso et al., this volume) confirms the long-assumed Archean age for that unit.

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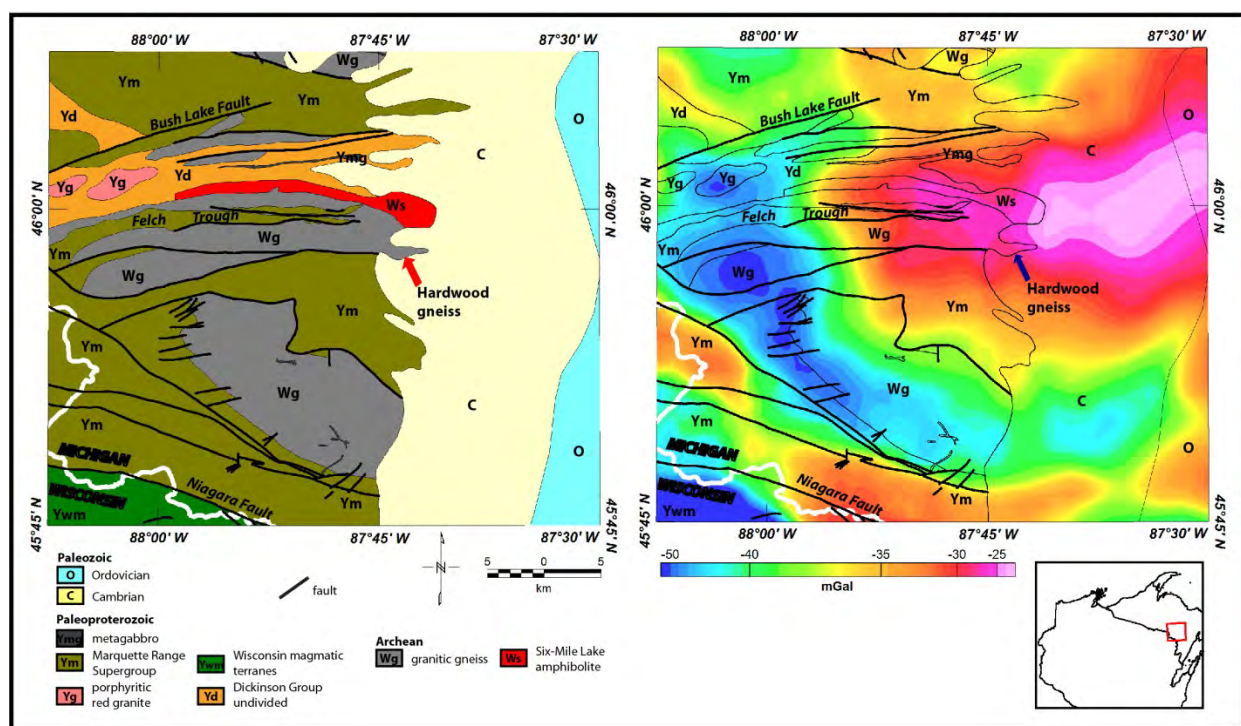


Figure 1: Left: Bedrock geology, after James et al. (1961), Bayley et al. (1966), Cannon and Ottke (1999), Ayuso et al. (this volume), and Cannon et al. (this meeting). Right: Complete Bouguer gravity anomalies. Inset (lower right) shows location of study area.

GEON 12 to 11 history of the Lake Superior Region and speculation about the relationships between the Midcontinent Rift and the Grenville Orogen

EASTON, Robert Michael¹

¹*Earth Resources and Geoscience Mapping Section, Ontario Geological Survey, 933 Ramsey Lake Road, Sudbury, Ontario P3E 6B5 mike.easton@ontario.ca*

This presentation was inspired by some of the questions posed in the recent Geological Association of Canada Howard Street Robinson Lecture Tour presentation by Dr. P. Hollings on the “Metallogeny and Magmatism of the 1.1 Ga Midcontinent Rift”. It will focus on 3 specific topics related to the evolution of the Midcontinent Rift and whether or not the rift is the result of a typical mantle plume event. These are: 1) regional Geon 12 events that may have had an effect on localizing the rift, 2) the apparent time gap between major tectonic events in the Grenville Orogen in central North America during Geon 11 and the onset of magmatic activity in the Midcontinent rift, and 3) an alternative tectonic setting for generating a Large Igneous Province (LIP) without an active “hotspot” or mantle plume.

Regional Geon 12 Events

There were 2 attempted rifting events in North America that occurred to the northwest and the east of the Midcontinent Rift during Geon 12. Both produced large, radiating dike swarms, and near their centres, a variety of layered mafic intrusions. These are the *circa* 1267 Ma Mackenzie dike swarm (LeCheminant and Heaman 1989) and the *circa* 1238 Ma Sudbury dike swarm (Krogh et al. 1987). The centre of the latter swarm is now buried beneath the Grenville Orogen in western Quebec, approximately 1,800 km east of the centre of Lake Superior. The Midcontinent Rift developed in the area between these 2 earlier rifting attempts. Is its location between these 2 earlier “plumes” significant?

The Grenville Orogen (Ontario region) during Geon 11

The Grenville Orogen in Ontario is divided into 3 major segments (Carr et al. 2000): 1) the Laurentian margin (which consists of para-autochthonous and para-allochthonous rocks that developed on the margin of Laurentia during the Archean to Mesoproterozoic), 2) the Composite Arc Belt (CAB), which consists of a variety of arc fragments that developed somewhere outboard of North America between 1300 to 1220 Ma and which were stitched together between 1220 and 1190 Ma), and 3) the Frontenac-Adirondack belt (FAB), a continental platform to continental arc that was the site of voluminous anorthosite-mangerite-charnockite-granite (AMCG) magmatism between 1190 and 1140 Ma, and which was stitched to the southern margin of the Composite Arc Belt at *circa* 1160 Ma (Carr et al. 2000). It is unclear if the Laurentian Margin and the co-joined CAB and FAB were proximal to one another prior to *circa* 1080 Ma (see discussion in Carr et al. 2000). It is possible also that they were distal to Laurentia at the time the Midcontinent Rift was active.

The Ottawa (or “Grenville”) orogeny is the onset of Grenville-wide metamorphism and deformation across all 3 segments of the Grenville in Ontario and is the result of Himalayan-style continent-continent collisional event. Grenville-wide metamorphism and deformation occurs across all 3 segments of the Grenville in Ontario during the Ottawa orogeny. In Ontario, there are remarkably few U-Pb ages (Ontario Geochronology Inventory 2018), and certainly no major magmatic, metamorphic or pervasive deformational events, between the end of AMCG magmatism at *circa* 1140 Ma and the start of the Ottawa orogeny, a period of approximately 55 million years (1140-1085 Ma). This Ontario Grenville time gap almost exactly coincides with the magmatic time span encompassed by the Midcontinent Rift (Abitibi and other dikes at *circa* 1140 Ma to late felsic volcanism at *circa* 1085 Ma on Michipicoten Island). Interestingly, this time gap does not exist in the Grenville in West Texas, where the period 1130-1110 Ma was characterized by high-grade metamorphism, deformation, and thrusting (Moser et al. 2008), however this was occurring approximately 2,000 km south-southeast of the Midcontinent Rift.

Possible Tectonic Setting

An important aspect of the geology of the Lake Superior region is that from *circa* 1900 to 1350 Ma the southern margin of Laurentia was the loci for repeated arc development, similar to the west coast of North America during the Mesozoic to Cenozoic. The culmination of this arc activity was the formation of a large Andean-style arc, represented by the magmatic rocks of the Eastern Granite-Rhyolite Province and its equivalents (*circa* 1480-1350 Ma) in the Laurentian Margin of the Grenville Orogen in Ontario. This almost 500 million year period of subduction beneath Laurentia would have greatly modified the lithosphere beneath Laurentia, and left remnants of partly subducted slabs in the mantle beneath the margin of Laurentia. Consequently, the recent history of western North America may provide some insights into how the Midcontinent Rift have formed.

Fouch (2012) and Zhou et al. (2018) provide an alternative to the “hotspot” model for the development of the Columbia River basalts, the Snake River Plain, and Yellowstone; one that does not require a “hotspot” or classic mantle plume. Their model involves asthenosphere upwelling following slab-breakoff after subduction of the Farallon and Juan du Fuca plates beneath western North America. There are some similarities between this scenario and the development of the Midcontinent Rift. First, in both areas, there was a long period of arc magmatism prior to the onset of LIP magmatism. Second, magmatism in both areas occurred over a long time interval (more than 30 million years), was geographically widespread, and toward the waning stages became localized with a greater abundance of felsic magmas. Third, the model does not result in radiating dike swarms characteristic of many mantle plumes. Finally, in the case of Yellowstone, this upwelling may eventually lead to a pseudo-plume — something which would explain the latter stages of the Midcontinent Rift and the plume-like geochemistry of the magmas.

What is not known is if a transform fault setting is needed after the end of subduction for the down-going slab to break-off and result in asthenosphere upwelling. This was the case for western North America, but presently cannot be confirmed to have occurred in the Ontario Grenville. Nonetheless, a transform would be one means whereby events in the Grenville realm could be isolated from events in Laurentia for a protracted period of time.

Even if the tectonic setting envisioned by Fouch (2012) and Zhou et al. (2018) is a viable model for explaining the development of the Midcontinent Rift, there is a key difference. Unlike western North America, in the Mesoproterozoic a continent-continent collision occurred not long after the LIP event was initiated, effectively shutting the system down, likely prematurely. However, this extensive pre-heating of the lower crust in the Lake Superior region may have well been responsible for the ductile and long-lived metamorphism present in the Ontario Grenville, as suggested by Carr et al. (2000).

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What to do after the bull has left the china shop- Picking up the community relation pieces

EGER, Paul¹, BOT, Courtney¹, MEINEKE, Dave¹ and ADAMS, Dave²

¹*Global Minerals Engineering*

²*LaPointe Iron Company*

Today successful mining projects must meet the “triple bottom line”; economic, environmental and social. In 2010 Gogebic Taconite (GTac) acquired a lease option to develop an open pit taconite mine in northwestern Wisconsin. Although the company had mining experience, it was limited to coal near existing mines with minimal opposition.

GTac’s proposed development was viewed as either an economic boon or an environmental disaster. GTac’s decision to focus on lobbying at the state level mobilized opposition from the local, environmental and tribal communities. After spending millions of dollars in additional resource evaluation and environmental studies, GTac decided to abandon the project in 2015.

When the option to lease was terminated in 2015, LaPointe decided it was important to rebuild local partnerships and begin to develop sound data so that future decisions could be based on science and not fear. These efforts include support for scientific studies, baseline regional water quality monitoring and periodic meetings with community leaders.

Surficial Geology of the Iron Mountain 7.5 Minute Quadrangle, Dickinson County, Michigan, Florence & Marinette Counties, Wisconsin

ESCH, John M¹, KEHEW, Alan², HUOT, Sebastien³, YELLICH, John⁴

¹*Michigan Dept. of Environmental Quality, Office of Oil, Gas, and Minerals, P.O. 30256, Lansing, MI 48909,*

²*Department of Geological and Environmental Sciences, Western Michigan University, Kalamazoo, MI 49008,*

³*Illinois State Geological Survey, Prairie Research Institute, University of Illinois at Urbana-Champaign, Champaign, IL 61820,*

⁴*Michigan Geological Survey, Western Michigan University, Kalamazoo, MI 49008*

The Iron Mountain 7.5 minute quadrangle lies within complex glacial deposits of the Green Bay Lobe of the Laurentide Ice Sheet. In 2017 the Michigan Geological Survey mapped the quad as part of a USGS STATEMAP project. Surficial mapping was greatly aided by the availability of LiDAR elevation data. This mapping has provided new, detailed information on the surficial landforms and deposits as well as relationships between the glacial deposits and the underlying bedrock. The complexity of the glacial deposits is in part due to high relief on the bedrock surface and complexity of underlying bedrock formations and structure. Three ice-margins were mapped across the quad. A deep bedrock trough mapped as part of an earlier environmental investigation was further defined as well as the bedrock topography and drift thickness mapped across the quad. In addition, the mapping identified ice-walled lake plains, eskers, drumlins and terraces that were not previously mapped. A new OSL age date was obtained for an outwash deposit. The sediments include diamicton (till), sand and gravel, boulders and interbedded silt and clay. The glacial deposits are late Wisconsinan (about 14,500 cal yr BP to 12,500 cal yr BP) in age.

Within the Iron Mountain Quad, the west-northwesterly ice flow direction is reflected in the numerous drumlins on the uplands and streamlined bedrock hills. Rock drumlins occur within the quad and others are exposed in the bottom of some sand and gravel pits. The elevation across the map ranges from 919 feet above mean sea level (AMSL) along the Menominee River to 1572 feet AMSL at the top of Millie Hill. Three distinct bedrock-controlled uplands occur north of the Menominee River: Pine Mountain, Millie Hill and Trader Hill. These uplands are mostly cored by diamicton and strewn with boulders. These boulders extend to depth into the subsurface based on the local water wells logs and the three borings drilled for this project. The diamicton is mostly reddish brown to brown. Although the larger foundation for these uplands is bedrock controlled, drift up to 140 feet thick occurs in places. Three ice margins are interpreted within the map. From west to east they are the Winegar-Sagola-Early Athelstane Moraine (about 14,500 cal yr BP), the Middle Athelstane ice margin and the Marenisco-Late Athelstane ice margin (about 13,000 cal yr BP).

Under the City of Kingsford lies an extensive pitted outwash plain with elevations ranging from 1140 to 1120 feet AMSL formed west and south of the Middle Athelstane ice margin. An OSL age $12,600 \pm 1,000$ cal yr was obtained from a sample taken from the edge of this outwash plain. This outwash plain overlies a lacustrine sequence of mostly silts, clays, sands

and some gravels that is as much as 300 feet thick. This lacustrine sequence overlies a deep bedrock trough under the City of Kingsford. A later, short term fluvial event likely occurred over this outwash surface, as evidenced by the sharp, steep, wave cut or fluvially cut scarp at 1140 feet AMSL along the northern side of this surface. As the Green Bay Lobe ice retreated to the east, there must have been successive lowering of the outwash outlets to the south and southeast because of the step-like lowering of the outwash terraces to east along the Menominee River. The lowest of these terraces to the east is 180 feet lower than the large outwash plain to the west.

A passive seismic instrument using the Horizontal-Vertical Spectral Ratio (HVSr) method was used to gather additional bedrock control for data on bedrock topography and drift thickness. This technique uses the horizontal-to-vertical spectral ratio method to record ambient seismic noise with 3-component geophones. HVSr calibration readings were gathered at 15 wells and borings of known bedrock depth. These data were used to develop a local HVSr bedrock depth calibration curve. Exploration readings were taken at 44 locations within the map. Very good bedrock depth estimates were made in the outwash areas of the map. In the upland morainal area, however, the method yielded depth estimates that were much too shallow relative to the local bedrock elevation of the area. This disconnect is likely due to buried, over-consolidated dense glacial till which was encountered at depth in the three borings drilled for this project. The HVSr bedrock depth estimates at these three borings match well with the depths to the top of the dense till. A significant gamma-ray log kick was also seen in the borings at or near the top of this dense till.

Although the glacial deposits in the Iron Mountain Quadrangle average 40 feet thick, numerous bedrock outcrops exist. The drift is maximally 363 feet over the deep bedrock trough in Kingsford. In many places, the land surface topography is controlled not by the glacial deposits, but by the underlying bedrock and bedrock structure. One important exception is a pronounced buried deep bedrock trough that underlies the large pitted outwash plain in Kingsford. Another buried bedrock trough underlies the lowland along the Menominee River in the southeastern part of the map. A poorly defined bedrock low connects the two troughs north of the Menominee River. There is high relief on the bedrock surface ranging from 730 feet to 1530 feet AMSL across the map. Bedrock outcrops and mounds appear throughout the area, even where nearby borings show over 100 feet to bedrock.

The bedrock geology exposed at the surface and underlying the glacial deposits in the Iron Mountain Quadrangle is very complex and has had a significant and controlling effect on the overlying glacial deposits. Underlying the quad are Precambrian complexly faulted and folded Precambrian metasedimentary rocks and metavolcanics and granitic intrusions as well as much later Cambrian Sandstones.

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LiDAR Revolutionizing Geological Mapping

ESCH, John M

Michigan Department of Environmental Quality, Oil, Gas & Minerals Division, Constitution Hall 2nd Floor South, 525 West Allegan Street, Lansing, Michigan, 48933

LiDAR (Light Detection And Ranging) has fundamentally changed how we view and interpret the landscape and has revolutionized geological mapping. Often subtle features can be seen in the LiDAR topography data that are not visible on aerial photography, topographic maps, or digital elevation models (DEMs).

LiDAR is an optical remote sensing technology that emits intense, focused beams of Light at the ground and measures the time it takes for the reflections to be detected by a sensor. This results in a densely spaced (QL2): 2 points/meter network of highly accurate georeferenced elevation points called a point cloud. These elevation points are classified as to what the LiDAR pulse was reflected off (ground, vegetation, water, buildings or other objects). The ground elevation points are used to produce highly accurate Digital Elevation Models that can be used to generate three-dimensional representations of the Earth's surface and its features. Elevation accuracies are on the order of 10 centimeters. Airborne LiDAR is the most common, but there is also terrestrial LiDAR and bathymetric LiDAR. Terrestrial LiDAR can be used for mapping high cliff and quarry faces to create a virtual outcrop.

The most useful airborne LiDAR product is the bare earth digital elevation model (DEM). Other common deliverable LiDAR products are a classified point clouds and intensity Images. A LiDAR attribute that may be of value for geologists is the intensity of the returned pulse, which is the strength of the return or how strongly the laser pulse was reflected back to the sensor. This is usually presented a greyscale .tif image and may be useful for mapping soft ground (wetlands) vs hard ground (potentially bedrock outcrops). Common LiDAR derivative products include DEM hillshade, digital surface models, shaded relief, contours and automated building extraction.

The higher resolution topography advantage of 0.6 meter LiDAR DEMs over existing 30 and 10 meter DEMs is obvious. This very dense data coverage allows for seeing subtle geologic features, and cultural features like curbs, plow furrows, and two-tracks. It can also can be used to see what is under tree canopy. Bedrock outcrops often appear distinct from the surrounding topography in the LiDAR data. This is valuable for mapping in remote areas with little known exposure. Hydrologic features like streams, valleys and subtle erosional features are more accurately and easily seen using LiDAR. Many more karst feature like sinkholes, disappearing streams, and solution enhanced joint areas have been identified using LiDAR. Subtle glacial features like ice-walled lake plains are almost never seen on aerial photos or topographic maps

(except for large ones) and were rarely identified in Michigan prior to LiDAR. With LiDAR they are relatively easy to see. Other subtle glacial features seen using LiDAR, but sometimes too small to be seen on topographic maps include small eskers, drumlins, flutes, subtle terraces, fans, deltas, small sand dunes, paleo-shorelines, ice margins, bars, pendants, and erosional scarps. These previously undetected landforms may fundamentally change how one interprets the area geology. Pits and other excavations as well as scarps are easily seen using LiDAR and are helpful for places to investigate.

LiDAR allows geologists to be more efficient in the field by allowing them to see the landscape how it really is before going out in the field. It also helps in fine tuning and focusing field work in specific area, features and landforms. It also allows them to map subtle features that may not be accessible due to land ownership permissions. This presentation will show the widely varying applications of LiDAR for geological mapping across Michigan.

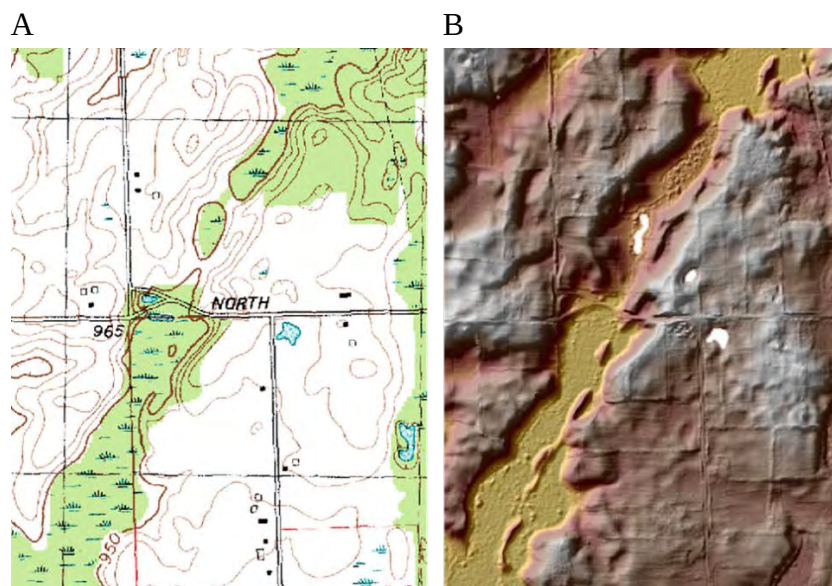


Figure 1 (A) Northwest Albion, Michigan, 7.5 Minute Topographic Map, USGS 1980. 10 Foot Contour Interval. (B) Northwest Albion Area, Calhoun County LIDAR Shaded Relief Map, clearly indicating esker trending SW-NE across map. From Carswell (2014) and Esch (2013).

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Mineral Chemistries of the Tower Mountain Intrusive Complex Au-Deposit, Ontario
FITZPATRICK, William¹, HOOPER, Robert¹, and LODGE, Robert¹, G  linas, Brigitte²

¹Dept. of Geology, University of Wisconsin Eau Claire, 105 Garfield Av., Eau Claire, WI 54701

²Dept. of Geology, Lakehead University, 955 Oliver Rd, Thunder Bay, ON, P7B5E1

Hydrothermal fluid systems driven by magmatic activity are some of the most important ore forming processes for many metallic minerals. This project involves characterization of hydrothermal alteration associated with the Archean Tower Mountain Intrusive Complex and its related Au deposit within the Shebandowan Greenstone Belt. The Tower Mountain Intrusive complex (TMIC) consists of a $\sim 1.5\text{km}^2$ monzonite stock cored by a later diorite intrusion. Cross cutting both units are small dikes of monzonite porphyry and meter-scale areas of hydrothermal brecciation. The TMIC intrudes Timiskaming-type assemblages of calc-alkaline volcanic rocks and conglomeritic alluvial-fluvial sedimentary. The main monzonite and syenite stocks have been U-Pb dated to 2690 ± 3 Ma while calc-alkaline volcanics elsewhere in the Shebandowan greenstone belt similar to TMIC host rocks were dated to 2690 Ma (Corfu and Scott, 1998). The contemporary U-Pb dates as well as the lack of a surrounding contact metamorphic zone implies that the Tower Mountain Intrusive complex was syn-volcanic and emplaced at relatively shallow depth (Carter, 1990). The hydrothermal alteration at TMIC requires at least a two stage process. The first alteration results in initial oxidation followed by a mineralizing event with lower $f\text{O}_2$.

Mineral chemistry data has been collected from numerous primary and alteration minerals using a SEM/EDS detector. The rocks have been heavily altered and few primary minerals remain except for scattered patches of Mg rich-hornblende, Mg-rich augites, magnetite-ilmenite intergrowths and minor monazite, zircon. All primary feldspars have been altered to end-member alkali feldspars (albite and k-spar).

The first hydrothermal alteration event resulted in oxidation of the magmatic Fe-Ti oxides with production of hematite and secondary rutile. Other minerals associated with this alteration event include: titanite, epidote, fluoro-apatite (e.g. $\text{Ca}_{4.5}\text{Mn}_{0.5}\text{Fe}_{0.5}(\text{PO}_4)_3\text{F}$), and Mg-rich phengite, Mg-chlorite which petrographically are seen as sericitization of magmatic alkali feldspars and mafic minerals. Some of the epidotes from this alteration episode have LREE enriched epidote rims and some of the phengites have fluorine in the hydroxyl-site $(\text{K}_{1.7}\text{Na}_{0.3})(\text{Al}_3\text{Mg}_{0.8}\text{Fe}_{0.2})(\text{AlSi}_7)(\text{OH}_{3.9}, \text{F}_{0.1})$. This first alteration episode resulted in pervasive pink hematite staining and green (epidote) alteration seen in outcrop (G  linas et al., 2016). Also related to this alteration episode are scattered, small ($\sim 3\mu\text{m}^2$) barite and celestine grains. The rocks were subsequently altered by a sulfidizing fluid which results in hematite replacement by pyrite, chalcopyrite, and pyrrhotite. Sulfidizing fluid alteration also results in observed Fe-rich chlorite, ferroan-dolomite and the gold mineralization. This model is consistent with Au being transported as an Au-bisulfide complex and precipitated along with the sulfide minerals.

Relating the fluid history described above to lithologies seen in the field, the first oxidizing phase of alteration is likely to have initiated with intrusion of the monzonite stocks. Fluids related to alkaline magmatism have long been known to have an association with oxidizing, hematitic alteration (e.g. Greenberg, 1986) and also carbonatizing, halide and LREE-rich metasomatism (e.g. Wooley, 2003). Evidence observed in thin section indicates that introduction of reducing, sulfidizing fluids and Au-mineralization is related to later intrusion of the monzonite porphyry

dikes. No magnetite is observed in the monzonite porphyry whereas all other samples contained magnetite in various states of decay along with pyrite. This indicates that sulfidizing fluids were more active in the monzonite porphyry, possibly because of closer spatial association to the intruding magmas.

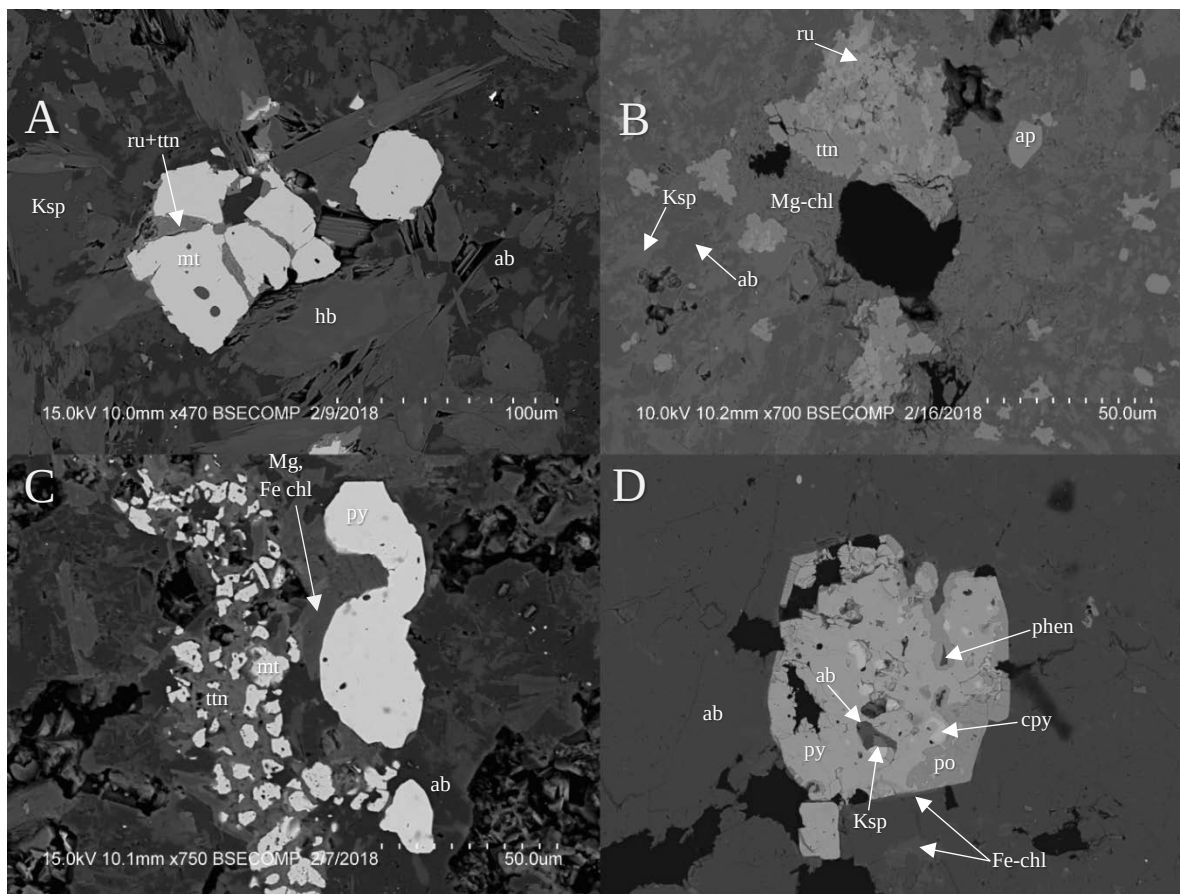


Figure 1: A: Magmatic hornblende and magnetite in matrix of Mg-chlorite, albite and k-spar. From monzonite. B: Rutile, titanite clusters with scattered apatite in mg-chlorite, phengite, albite, k-spar matrix. From monzonite. C: Highly corroded magnetite separated by Fe-chlorite from pyrite in equilibrium. From hydrothermal breccia. D: Zoned pyrite grain containing rim of pyrrhotite and inclusions of chalcopyrite. From monzonite porphyry. ru: rutile, mt: magnetite, Fe/Mg chl: Iron or Magnesium rich chlorite, py: pyrite, hb: hornblende, Ksp: k-spar, ttn: titanite, cpy: chalcopyrite, po: pyrrhotite

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Petrogenesis of mafic magmatism in the Coldwell Complex

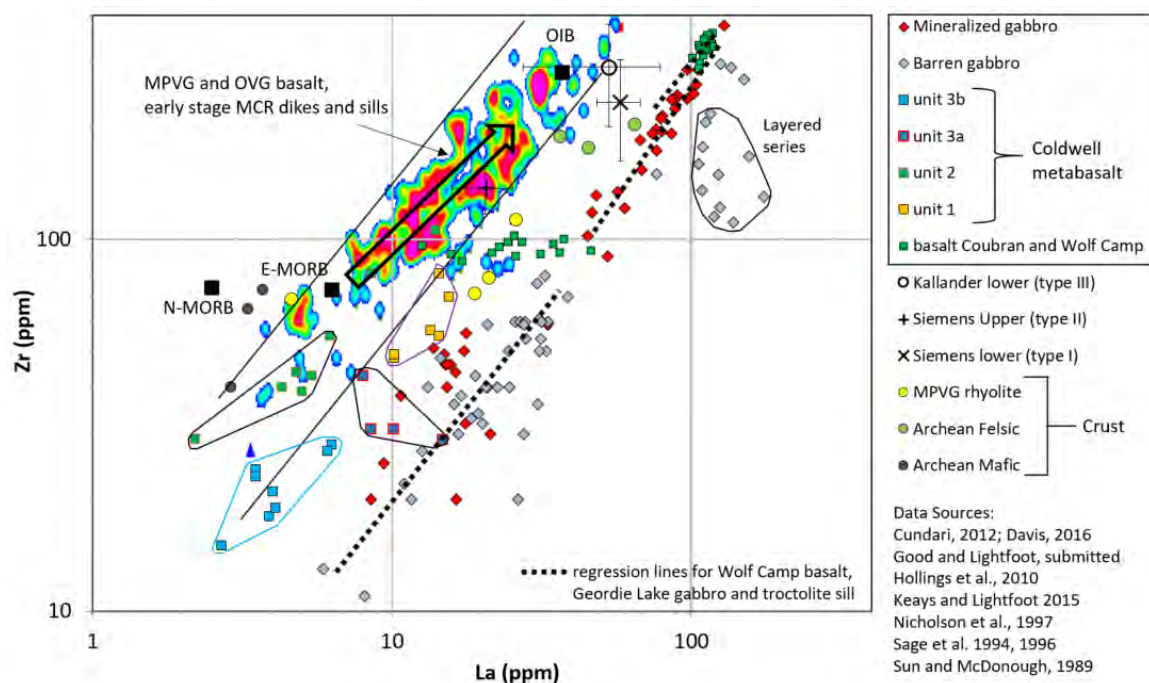
Part 1. Geochemical model to explain origin of metabasalt by partial melting in the SCLM

GOOD, Dave

Department of Earth Sciences, Western University, London, ON N6A 5B7 Canada

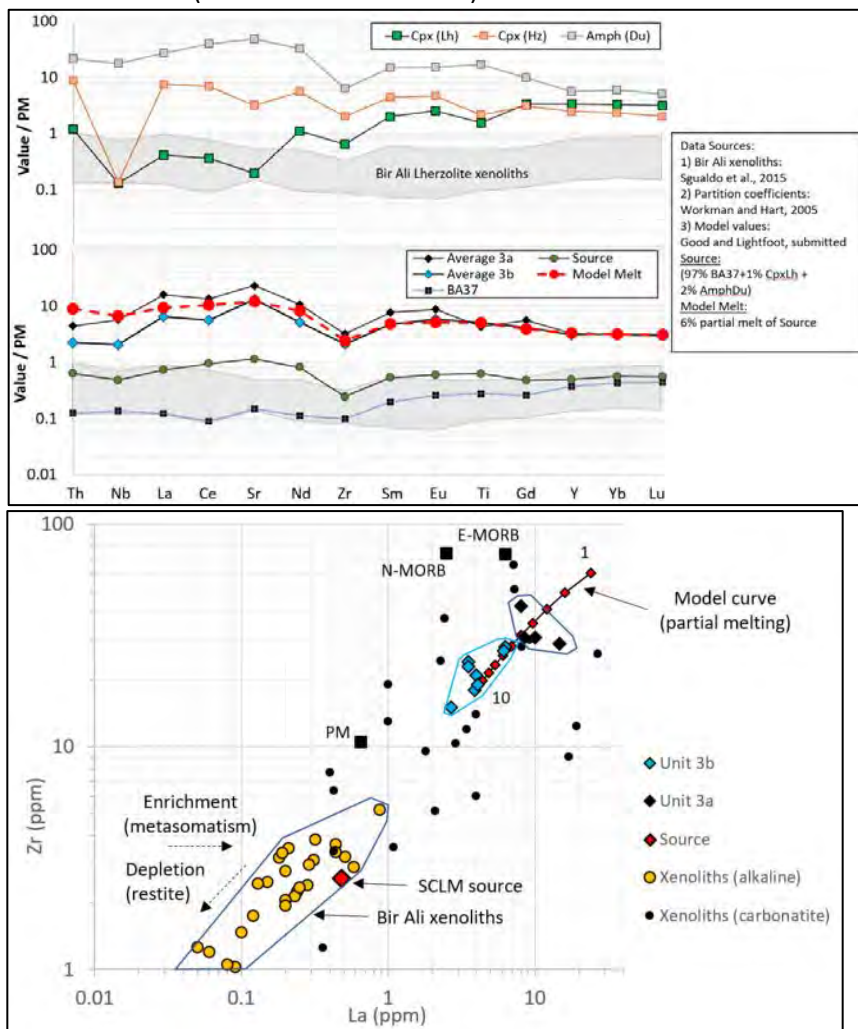
Data for basalt and intrusive mafic rocks from the early stage of evolution of the Midcontinent Rift show well-defined trends for trace element abundances that are consistent with variable degrees of partial melting in a mantle plume source and subsequent fractional crystallization. For example, in a plot of La vs. Zr, early MCR basalt data plot in a field that spans compositions from E-MORB to OIB. The La/Zr values increase from about 0.07 to 0.18 with increasing La, as expected given the relative incompatibility of these elements. Deviations from the E-MORB to OIB-like compositions are explained by interaction of the magma with either SCLM or continental crust during ascent, or by varying depths of partial melting.

A comparison of the early stage MCR rocks to the Coldwell mafic rocks shows significant differences between the two groups. First, the ranges of trace element concentrations for Coldwell rocks is one to two orders of magnitude greater than for the entire suite of MCR rocks. Second, Coldwell rocks show significant LREE enrichment relative to HFSE (example, very high La/Zr). Remarkably, Th/Nb for the Coldwell rocks are near mantle values (0.12) signifying enriched LREE is not a result of crustal contamination. It is difficult to explain these differences between Coldwell and MCR rocks by processes such as partial melting or crystal fractionation and some other explanation is required for the decoupling of these highly incompatible trace elements.



Trace element abundances for Coldwell metabasalt units 1 to 3b are some of the lowest values in the MCR. Spider diagram patterns for the metabasalt and gabbro units are characterized by strong negative Nb and Zr anomalies that resemble patterns observed for mantle xenoliths from the SCLM at numerous locations, including Bir Ali, Yemen.

A geochemical model that supports generation of Coldwell metabasalt by partial melting of a hypothetical SCLM source was proposed by Good and Lightfoot. The source composition is based on mantle xenolith data from Bir Ali, Yemen and was synthesized by mixing lherzolite with a very small fraction (1-2%) of secondary clinopyroxene or amphibole. This model can explain many features of the Coldwell metabasalt units, however, at this stage, trace element abundances are too low to predict the nature of metasomatism (carbonatite or alkaline) in the source.



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Geologic history meets the web – online data of the Lake Superior Division of USGS

GOTTSCHALK, Brad, ROSE, Caroline, and MCCARTNEY, M. Carol

Wisconsin Geological and Natural History Survey, University of Wisconsin – Extension,
caroline.rose@wgnhs.uwex.edu

Working out of their headquarters in Madison, Wisconsin from 1882 to 1922, USGS Lake Superior Division geologists laid the groundwork for all subsequent investigations of this region's Precambrian rocks. Nine monographs, four bulletins, and a professional paper describe the findings of those early geologists. The physical samples and paper records they collected and used to produce those publications comprise the Lake Superior Legacy Collection held by the Wisconsin Geological and Natural History Survey (WGNHS, the Survey).

The Survey began digitizing the Lake Superior collection in 2011, when the UW Digital Collection scanned field notes written by Charles Van Hise. The collection contains: more than 30,000 hand samples; over 13,000 thin sections (photographed in plane- and cross-polarized light); 467 field notebooks (321 of which have been scanned); 67 maps; and, 35 catalogs of specimens, lithological descriptions, and more. The web application links all of these components together, presents this image-rich dataset in a visual way, and also provides some historical context.

<http://data.wgnhs.uwex.edu/lake-superior-legacy/index.html>

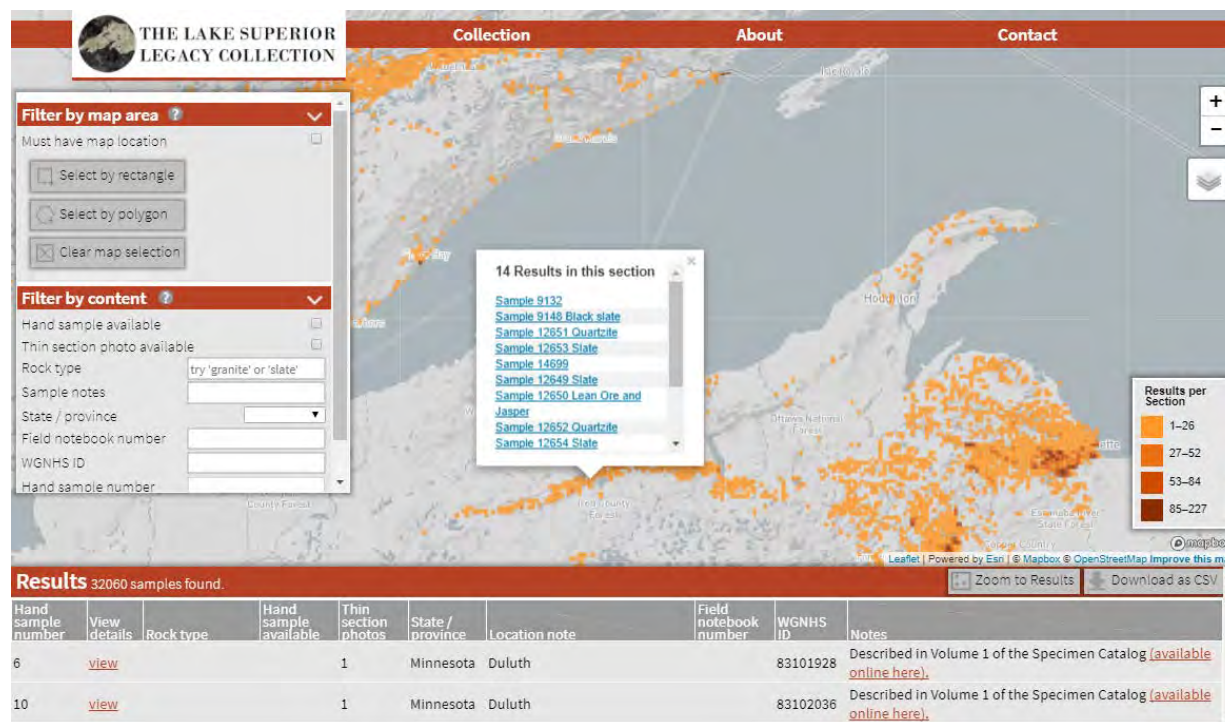


Figure 1: Through the interactive map, samples can be found by location, rock type, sample notes, sample number, field notebook number, and other attributes.

In the Lake Superior Legacy Collection application, researchers and historians can: search for hand sample locations on an interactive map; browse a gallery of thin sections and a list of field notebooks; view and zoom into high-resolution thin section photographs; examine hand-drawn topographic and geologic maps; and review the hand-written field notebooks and lithological descriptions of the pioneering geologists who collected these physical samples. More importantly, they can relate a hand sample to its thin sections and to its location. They will also find the notebook and page number where any specific sample is described – with a link to the online scanned version of those notes.

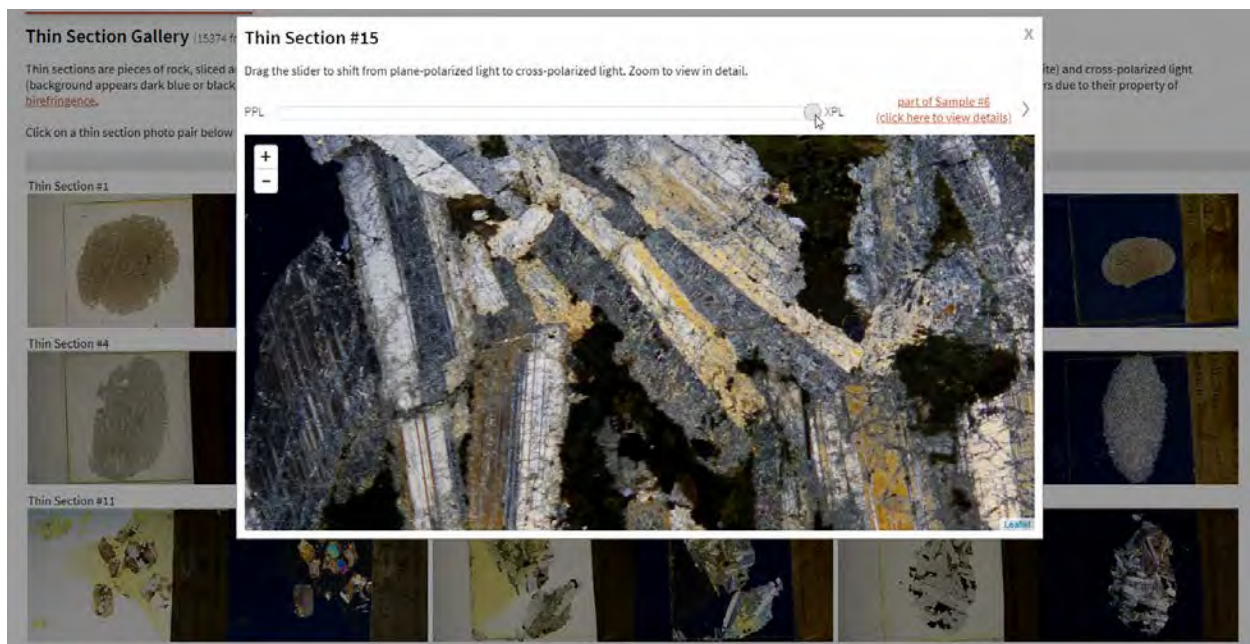


Figure 2: Browse thin section photographs in the gallery; use the viewer to zoom and to fade between plane- and cross-polarized light; follow the link to view details for the related hand section.

This long-term data preservation project, completed with the help of the USGS National Geological and Geophysical Data Preservation Program, is allowing today's geologists to gain access to the work of the early giants, Roland Irving and Charles Van Hise. Additionally, we have been able to present this collection of beautiful thin sections and hand-written notes in a visually appealing application that shares the beauty and history of Lake Superior geology online.

Inferences on the Subsurface Distribution of Oronto and Bayfield Groups North and West of the Douglas Fault, Northwestern Wisconsin

GRAUCH, V.J.S.¹, BEDROSIAN, Paul A.¹, STEWART, Esther Kingsbury³, and HELLER, Samuel²,

¹*U.S. Geological Survey, MS 964, Federal Center, Denver, CO, 80225*

²*U.S. Geological Survey, MS 939, Federal Center, Denver, CO, 80225*

³*Wisconsin Geological and Natural History Survey, 3817 Mineral Point Rd., Madison, WI 53705*

The period of extensive sedimentation that largely post-dated magmatic activity related to the 1.1 Ga Midcontinent rift is recorded by the Oronto and overlying Bayfield Groups in northwestern Wisconsin and correlative units in neighboring Minnesota (Fig. 1). The reverse-sense Douglas fault juxtaposes the two Groups: Oronto Group rocks form a syncline within the St. Croix Horst to the south and east, and the gently inclined Bayfield Group sandstones are to the north and west (Fig. 1). Previous subsurface interpretations north and west of the Douglas Fault have come from geophysical studies (e.g., Ocala and Meyer, 1973; Allen et al., 1997), which relied on recognizing characteristic densities and seismic velocities derived from modeling or sample measurements (Halls, 1969) to identify formation divisions within the Groups. Formations within the Bayfield and Oronto Groups have characteristic velocities and densities that both increase with older age.

We have reassessed the previous geophysical work in northwestern Wisconsin using recently obtained digital access to proprietary seismic-reflection data, preliminary results from new airborne electromagnetic (AEM) survey lines, and a reexamination of characteristic seismic velocities correlated to geologic units from legacy refraction data, borehole logs and drill core in the Ashland Syncline area (Fig. 1). Our findings are summarized as follows (refer to Fig. 1).

Data processing tests of LS-10 seismic line (westernmost Lake Superior) to find the velocity function that images the sharpest reflections suggest that the top ~2 km is composed of low-velocity (3.2 to 3.7 km/sec) rocks overlying igneous basement. This finding is in general agreement with previous refraction studies (e.g., Ocala and Meyer, 1973), who attribute the low velocities to the Bayfield Group (typical range 2.74-3.5 km/sec from Mooney et al., 1970). However, our geologic correlations from the well data indicate that the upper part of the Freda Sandstone (upper Oronto Group) has velocities from 3.2 to 3.9 km/sec, which overlap with the range expected for Bayfield Group. The low velocities here compared to Freda Sandstone elsewhere are likely caused by the greater volume of siltstones and shales (Halls, 1969).

Comparison of lithology and unit picks in drill core to resistivity sections from the AEM lines show consistent correlation of low resistivities (10-50 ohm-m) with siltstones and shales of the upper Freda Sandstone and of moderate to high resistivities (>200 ohm-m) with sandstones of the Bayfield Group. Using these results, we interpret the AEM resistivity sections to show a lakeward thinning wedge of Bayfield sandstones that appear to terminate near the northern shore of the Bayfield Peninsula. The wedge overlies low resistivities typical of the shales and siltstones of the Freda Sandstone.

The sequence of velocities found from a refraction site near onshore seismic-reflection line SEI-1 has a velocity-depth pattern generally compatible with overall variations in the velocities observed for Oronto Group units within the Terra-Patrick well (Dickas and Mudrey, 1999). We thus can roughly correlate the refraction velocity profile to reflection packages in

SEI-1 and extrapolate the interpretation to LS-10. Combined with low-resistivities observed below 500 m depth where an AEM line crosses SEI-1, we infer that about 500 m of Bayfield Group overlies about 3.5 km of Oronto Group along SEI-1. Thus, the ~2-km thick, low-velocity, low-resistivity sedimentary section under LS-10 indicates that lower Oronto (Copper Harbor and probably Nonesuch) units are missing in the westernmost part of Lake Superior and Freda strata directly overlie igneous basement. This conclusion is supported by Allen et al. (1997), who used a different line of reasoning from seismic reflection line LS-8. The results imply that lower Oronto strata were either not deposited or were eroded from the area under the westernmost lake up until upper Freda time, whereas the areas to the southeast were accumulating sediments throughout the entirety of Oronto and Bayfield times.

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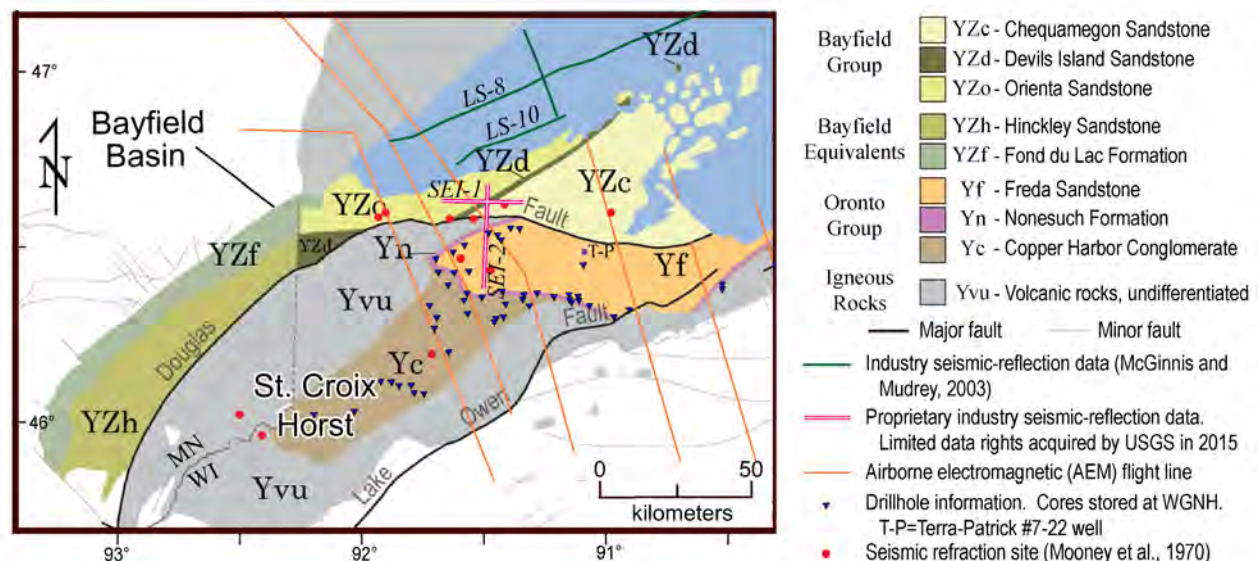


Figure 1: Regional geology and index map locating geophysical and drillhole information. Modified from Stewart and Mauk (2017). USGS – U.S. Geological Survey. WGNHS – Wisconsin Geological and Natural History Survey

Origin, distribution, morphology, and chemistry of amphiboles in the Ironwood Iron-Formation, Gogebic Iron Range, Wisconsin, U.S.A.

GREEN, Carlin J., SEAL, Robert, R., II, CANNON, William F., PIATAK, Nadine, and MCALEER, Ryan J.

U.S. Geological Survey, MS 954, Reston, VA 20192

The Ironwood Iron-Formation, located in the Gogebic Iron Range in Wisconsin, is one of the largest undeveloped taconite resources in the United States. Interest in the development of this resource is complicated by potential environmental and health effects related to the presence of amphibole minerals in the Ironwood Iron-Formation, a consequence of Mesoproterozoic contact metamorphism. The purpose of this study is to provide mineralogical information about these amphiboles to aid regulatory, medical, and mining entities in their evaluation of this potential resource. Optical microscopy, X-ray diffraction, scanning electron microscopy, and electron microprobe analysis techniques were utilized to study the origin, distribution, morphology, and chemistry of amphiboles in the Ironwood Iron-Formation. The development of amphiboles from Fe-carbonates and Fe-phyllosilicates at temperatures of approximately 300 -340° C has long been recognized as a result of regionally extensive contact metamorphism of the Ironwood Iron-Formation by the Mellen Intrusive Complex, however amphiboles related to the emplacement of diabase or gabbro dikes and sills in low-grade iron-formation were also recognized in this study area. Amphiboles in the Ironwood Iron-Formation most commonly developed in massive and prismatic habits, and locally assumed a fibrous habit. Fibrous amphiboles were locally recognized in the two potential ore zones of the Ironwood Iron-Formation, but were not observed in the portion considered to be waste rock. Massive and prismatic amphiboles show a wide range of Mg# values (0.06 to 0.87), whereas Mg# values of fibrous amphiboles are restricted from 0.14 to 0.35. Factors that influenced the compositional variability of amphiboles in the Ironwood Iron-Formation may have included temperature of formation, the presence of coexisting minerals, morphology, bulk chemistry of the iron-formation, and variations in prograde and retrograde metamorphism.

Geothermobarometry of a Precambrian amphibolite from Cornell WI

HAFFTEN, Doug and RADWANY, Molly

Department of Plant and Earth Sciences, University of Wisconsin – River Falls, 410 S 3rd Street,
River Falls, WI

Garnet amphibolite at Cornell, Wisconsin is part of the Chippewa amphibolite complex, a group of amphibolite-facies rocks with diverse protoliths, outcropping in the valley of the Chippewa River and its tributaries in western Wisconsin (Laberge and Myers, 1984). Metamorphism of the region occurred in Precambrian time, due to the Penokean orogeny (Schulz and Cannon, 2007). The Cornell amphibolite contains an ideal mineral assemblage for estimating both temperature and pressure of metamorphism, making it useful for understanding the effect of the Penokean Orogeny on the Marshfield Terrane.

We obtained whole-rock geochemical data for the sample using a Bruker S8 Tiger X-ray fluorescence spectrometer at University of Wisconsin – Eau Claire. Ratios of immobile trace elements ($Zr/Ti=0.02$ and $Nb/Y=0.14$) indicate a mafic-intermediate protolith for the amphibolite. Petrographic analysis of the Cornell amphibolite reveals an assemblage of 20% hornblende, 45% plagioclase, 20% quartz, and 15% garnet with accessory apatite and zircon.

We used a JEOL 8900 electron microprobe at the University of Minnesota to obtain mineral compositions. Which revealed ferro-tschermakitic hornblende, almandine-rich garnet and plagioclase An_{40-65} . To determine the temperature of metamorphism, we used the Holland and Blundy (1994) hornblende-plagioclase thermometer. The results of this method suggest temperatures between 606-646°C. To determine the pressure of metamorphism, we applied the Kohn and Spear (1990) garnet-hornblende-plagioclase-quartz geobarometer. The range of pressures determined using this method is 5.74-6.64 Kbar. These results reveal more specific information about the Chippewa amphibolite complex and the dynamic Precambrian past of Wisconsin.

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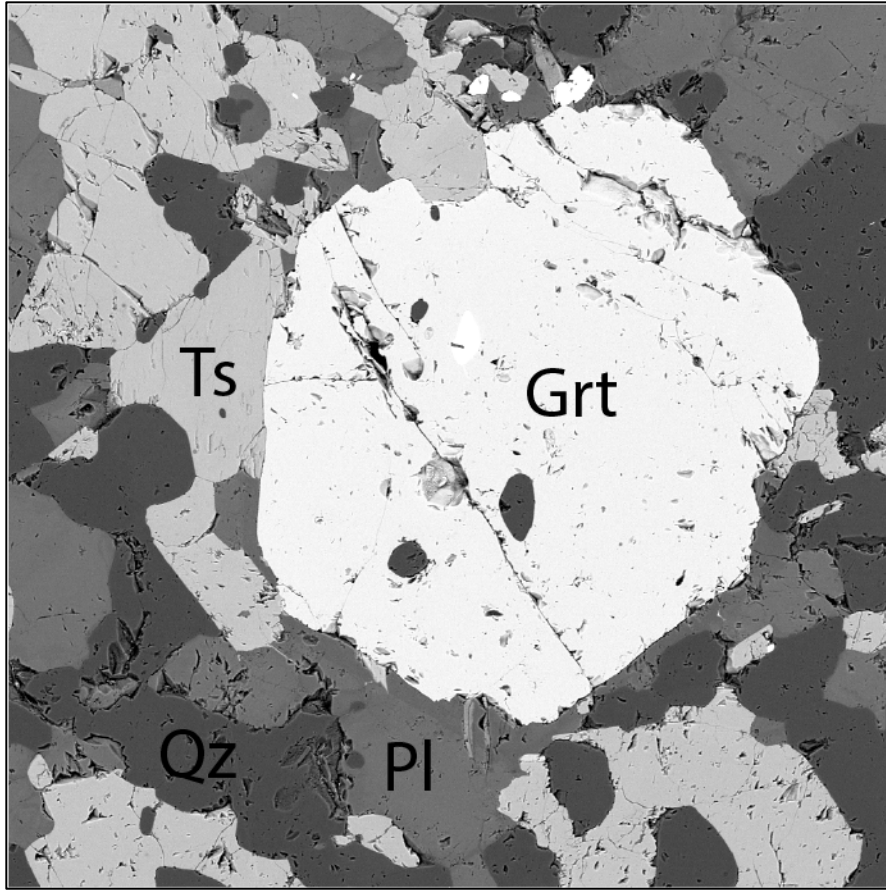


Figure 1: Backscatter electron image showing the main four phases in the Cornell amphibolite. Mineral compositions were used to determine pressure and temperature of metamorphism. Grt: garnet, Pl: plagioclase, Ts: tschermakite, Qz: quartz.

Hornblende-Plagioclase thermometry of the Eau Claire River Complex, western Wisconsin

HANNACK, Gina, and RADWANY, Molly

Department of Plant and Earth Sciences, University of Wisconsin River Falls, 410 S. 3rd Street
River Falls, WI

The Eau Claire River Complex is a metamorphosed and deformed layered mafic intrusion that outcrops in Big Falls County Park near Eau Claire, Wisconsin. The unit is part of the larger Chippewa amphibolite complex within the Precambrian Marshfield Terrane (Cummings, 1984). The unit is characterized by a compositional layering that alternates between mafic and feldspathic compositions. We distinguish two types of rock - mafic amphibolites, containing ~80% hornblende, and feldspar-rich amphibolites, containing ~15% hornblende. The vertical, north-south striking foliation is defined by compositional layers, likely inherited from primary, igneous layering. Lineations, defined by hornblende, are at a high angle to compositional layering (approximately east to west) and represent crystallization of hornblende during metamorphism of the complex.

Cummings (1984) established field evidence of a granulite facies metamorphic event represented by garnet porphyroblasts. Overprinting occurred during a second event at amphibolite facies and resulted in pseudomorphism of garnet by hornblende. The second event was pervasive and accompanied by dynamic recrystallization of plagioclase. Finally, there was a third, greenschist facies metamorphic event, resulting in crystallization of epidote, zoisite, biotite, and chlorite.

Mafic amphibolites consist of approximately 80% hornblende, 15% plagioclase and 5% accessory minerals ilmenite and apatite. The feldspar-rich amphibolites are comprised of 80 to 85% plagioclase, 10 to 15% hornblende and 5% ilmenite and apatite. Greenschist facies retrograde assemblage consists of minor epidote, zoisite, chlorite, and biotite. Pyrite also occurs in several samples, especially in association with epidote veins.

We determined mineral compositions for one mafic amphibolite using a JEOL 8900 electron microprobe at University of Minnesota. Plagioclase compositions range from An₄₂ to An₈₅. The amphibole present is magnesio-hornblende with Mg/(Mg+Fe) between 0.55 to 0.59. Microprobe data

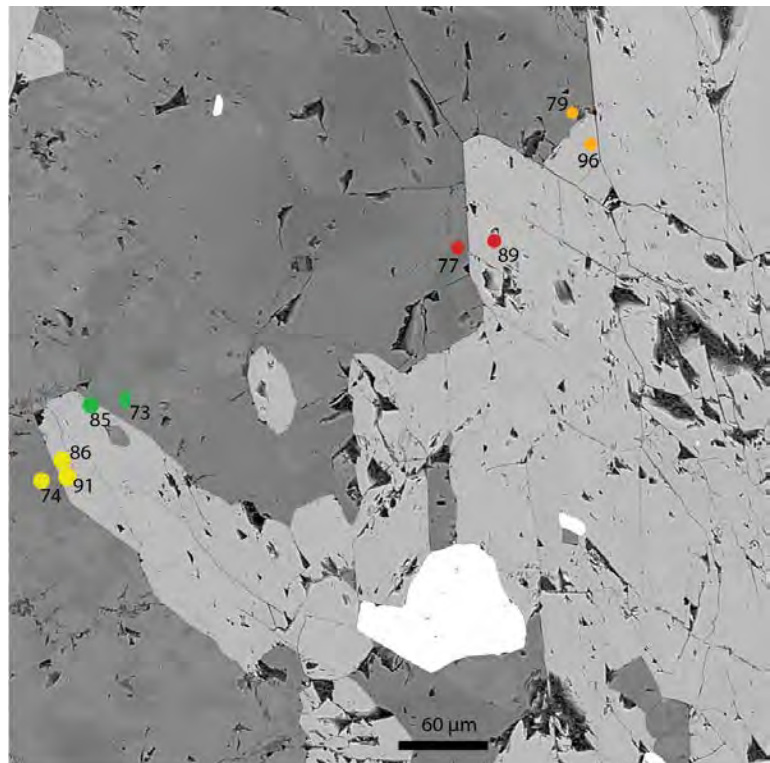


Figure 1: Microprobe image containing hornblende-plagioclase thermometer pairs

was utilized in the application of the Holland & Blundy (1994) edenite-richterite thermometer (Figure 1). We chose this thermometer based on the minor amount of quartz found in petrographic analysis. Results of this thermometer show that the Eau Claire Complex underwent upper amphibolite facies metamorphism at temperatures ranging from 719 °C to 769 °C (assuming P of 10 kb; Figure 2).

Our results provide insight into the mineralogic and structural effects of the Penokean Orogeny on the crystalline rocks of the Marshfield terrane and a quantitative estimate of thermal conditions during this collisional event.

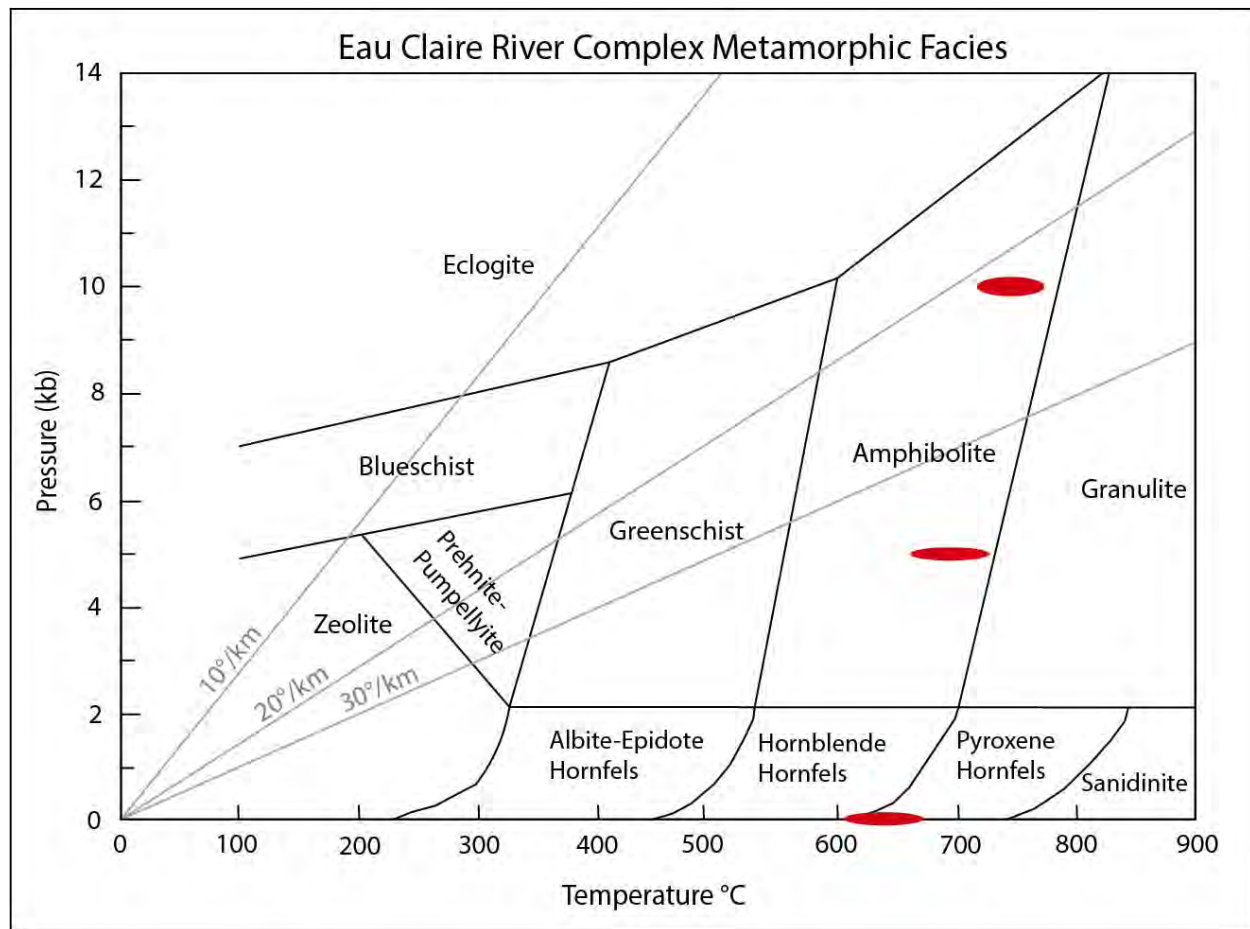


Figure 2: Temperatures of metamorphism of the Eau Claire River Complex, as determined by application of the Holland and Blundy (1994) edenite-richterite thermometer.

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Mapping the Midcontinent Rift System

Hinze, William J.

Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, IN 47906

Mapping the ca. 1100 Ma old Midcontinent Rift System (MRS) which is arguably the most significant non-orogenic structure of the North American midcontinent has been an important, but challenging objective for the past half century because it is hidden for most of its ~2500 km length by relatively flat-lying Phanerozoic sedimentary rocks. Even where it crops out in the Lake Superior region, it is largely covered by sedimentary rocks of late-stage Keweenaw rift basins and Pleistocene glaciation sediments. Mapping of the buried rift system is based on interpretation of gravity and magnetic anomaly data that are not definitive, poorly distributed deep seismic profiling, and limited basement drill holes. As a result, uncertainty exists in the geographic location, extent, and configuration of the buried MRS. Additional ambiguity is caused by confusion in defining the required characteristics of continental rifts.

A review of the available data on the MRS and Mesoproterozoic rocks of the North American midcontinent provides insight into the likely geographic location, configuration, and extent of the rift system and identifies portions of the rift's configuration that are most problematic. Generally, the MRS is shown extending in a southerly-open arc along several rift units from the western end of Lake Superior into Kansas and a shorter, eastern, branch of less intense rifting that continues south from the eastern end of the Lake into southeastern Michigan. Studies of basement rocks from Kansas southwestward indicate that magmatic activity similar in age to the MRS occurred in this region as it did broadly over the present-day midcontinent. However, no rift basins have been found or are indicated by geophysical and deep drilling data to the south of Kansas or elsewhere where magmatic activity occurred outside of the trend of the MRS. Perhaps this magmatic activity is evidence of *incipient* rifts, that is regions where intrusions have accompanied lithospheric extension which failed to reach an intensity where surface faulting and rift basins developed. The termination of the other branch of the rift in Michigan is complicated by its intersection with geologic structures resulting from the Grenville orogeny whose latest activity is slightly younger than the MRS. Gravity and magnetic anomalies suggest that the MRS terminates at the Grenville Front in southeastern Michigan, but originally it may have extended to approximately the border with Ontario. Late stage Grenvillian overthrusts may overlie the extreme terminus of the MRS in Michigan.

North/south striking gravity positive anomalies extending through Ohio along the eastern margin of the Grenville Front perhaps as far as Alabama have fostered the hypothesis that the rift system extends south from southeastern Michigan. The positive gravity anomalies have been purported to be the locus of rift basins of volcanic rocks. However, because rift basins do not occur at the basement surface coincident with the gravity highs, they have been interpreted as *relic* rifts that exist beneath Grenvillian overthrusts that post-date the MRS. Unfortunately, seismic reflection profiling does not confirm the presence of these rifts beneath the overthrusts observed

in the seismic reflection data. Alternatively, integrated interpretation of the Grenville Front Tectonic Zone gravity and magnetic anomalies, seismic reflection profiling, and basement drillhole samples indicate that the Grenville Front positive gravity anomalies are caused by up-thrusted high-grade metamorphic rocks from upper and mid-level crustal rocks of the Grenville orogen. According to the latter interpretation the lithic-arenites, the Middle Run formation, that occur unconformably below the Paleozoic sedimentary formations west of the Grenville Front in Ohio and adjacent states were deposited in a foreland basin primarily from erosion of the Grenville highlands to the east rather than in a marginal late-stage rift basin adjacent to a rift trough. This conclusion is supported by reported dating of detrital zircons from the Middle Run formation.

Especially problematic in mapping the MRS is the location of the eastern margin of the terminus of the rift in the Northern Peninsula of Michigan and the connection of the Lake Superior Rift with the Cross-Michigan Rift segment to the south. A “third branch” of the MRS remains elusive, but the most likely candidate is the Nipigon Embayment that did not develop into a rift basin such as found beneath Lake Superior and the eastern and western branches of the MRS.

Reinterpretation of the ages of deposition and folding of Animikie Basin metasedimentary units in east-central Minnesota

HOLM, Daniel¹, BOERBOOM, Terrence J.², and SCHEINER, Scott¹

¹Dept of Geology, Kent State University, Kent OH 44224 dholm@kent.edu

²Minnesota Geological Survey, boerbo001@umn.edu

Animikie Basin (AB) sedimentary rocks in Minnesota have historically been interpreted solely as Penokean (1875-1835 Ma) foredeep deposits. Yet detrital zircons as young as ca. 1770 Ma (Heaman and Easton, 2005) in the northern reaches of the AB (Rove Formation in Ontario) indicate that deposition in the upper part of the basin may have occurred during Yavapai orogenesis (1800-1700 Ma). Much of the AB sequence is only very weakly metamorphosed and mildly deformed. However, along its southern margin in east-central Minnesota, deformed AB sedimentary rocks show an increase in metamorphism and strain southward toward a mid-crustal plutonic-gneiss dome terrane largely exhumed during Yavapai orogenesis. Holst (1984) recognized two distinct structural zones; a northern once-deformed region characterized by upright folds and a single well-developed cleavage, and a southern twice deformed terrane characterized by refolded recumbent fold nappes and two cleavages. Holst interpreted the map trace separating these two deformation zones to be a Penokean thrust fault (Fig. 1A) and assumed all of the sedimentation and deformation to be Penokean. Given the wealth of geologic and geochronologic data which now document Yavapai-age magmatism, metamorphism, sedimentation and deformation overprinting the Penokean orogeny, we reinterpret Holst's Line as a possible Yavapai age angular unconformity that separates the once/twice-deformed units (Fig. 1B), implying that only the southern terrane sediments and the early recumbent nappes are Penokean. In this model, rapid exhumation of the entire Penokean/Yavapai internal zone resulted in rapid erosion rates and renewed Yavapai orogenic sedimentation into the Animikie Basin followed by folding of both sedimentary sequences. Bedrock mapping, geophysical data, and geochemical/isotopic analyses of the metasedimentary rocks along the southern margin of the AB in Carlton County Minnesota, briefly described below, are at least consistent with this new hypothesis.

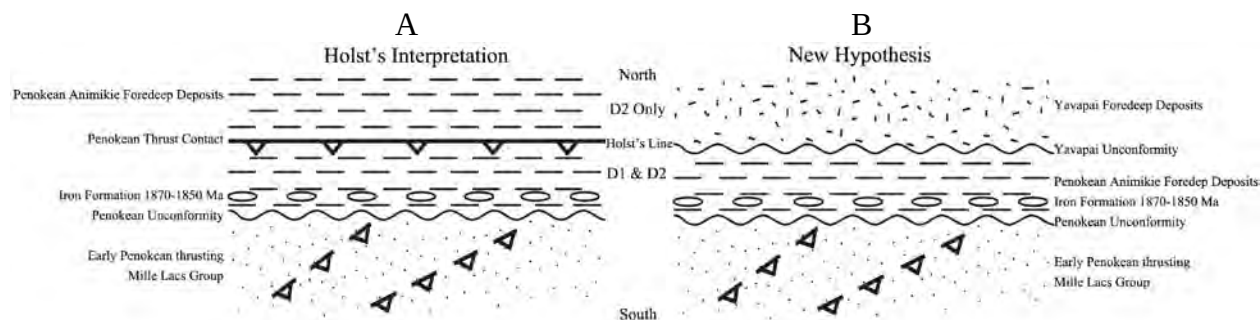


Fig. 1. Schematic synopsis of tectono-sedimentary interpretations along the southern margin of the Animikie Basin, east-central Minnesota. A: Late Penokean thrust fault cuts Penokean Animikie foredeep deposits (after Holst, 1984). B: Yavapai age unconformity separates Penokean (south) from Yavapai orogenic deposits (north).

Remapping and relogging of cores and cuttings (Boerboom, 2009) and aeromagnetic data reveals lithologic differences south and north of Holst's Line. The southern units are characterized by a moderate gravity high and a belt of discontinuous aeromagnetic anomalies interpreted as 'sulfidic horizons' with large cubic pyrite porphyroblasts. The sulfidic horizons may be similar to those at the base of the Baraga basin in Michigan (the Bijiki Iron Formation) and possibly to portions of the iron rich layers near in the Cuyuna South Range. The sulfidic horizons are absent north of Holst's Line.

Geochemical analyses of samples collected across the contact reveal a concentrated grouping of trace element data from the southern samples and a larger spread from the northern samples, suggesting a more variable source for the northern sedimentary sequence. More importantly, Nd isotopic data across the contact reveal a more juvenile source for rocks south of (i.e., below) the contact ($\epsilon\text{Nd}(T)^{1.77\text{Ga}} = 9.2$ and 1.2) and an older more enriched Archean source directly north of (i.e., above) the contact ($\epsilon\text{Nd}(T)^{1.85\text{Ga}} = -0.4$ and -3.9). We interpret the southerly sequence to be Penokean and derived from the newly accreted juvenile arc terrain. However we propose that the northerly sequence is Yavapai in age and derived from an older more enriched Archean or mixed source such as is presently exposed in the plutonic-gneiss dome corridor.

We propose a simplified model for tectono-sedimentary formation of the AB (Fig. 2). At the base of the basin the Penokean unconformity is shown as a nonconformity above Archean basement. To the south, the basal Penokean unconformity becomes an angular unconformity separating pre-Penokean sedimentary and volcanic rocks to the south from Penokean foredeep rocks to the north. Only the southern portion of the AB closest to the orogenic zone experienced Penokean deformation. During the Yavapai orogeny, the southern margin of the basin experienced uplift and erosion, followed by Yavapai orogenic deposition resulting in the formation of a disconformity in the north and a Yavapai angular unconformity in the south. Rapid Yavapai age exhumation of the plutonic-gneiss dome terrane led to copious amounts of sediment being shed into the basin. Near the end of the Yavapai orogeny, deformation resulted in folding of the Yavapai foredeep deposits and refolding of Penokean and pre-Penokean rocks in the south. Deformation waned to the north away from the orogenic zone. If correct, our reinterpretation has important ramifications for interpreting the inventory of structures in the upper Great Lakes region. For instance, the sedimentary rocks and the late open upright second-generation folds exposed at Thomson Dam, may both be manifestations of Yavapai orogenesis and not classic features of Penokean orogenesis.

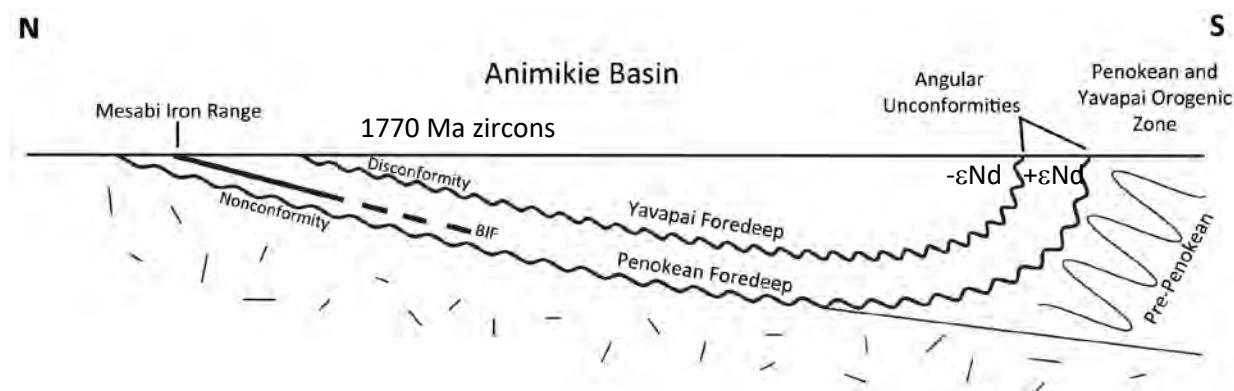


Fig. 2. Simplified schematic synopsis of tectono-sedimentary formation of the Animikie Basin in east-central Minnesota.

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Olivine Crystal Size Distribution in the Black Sturgeon Sill, Nipigon, Ontario

HONE, Samuel V. and ZIEG, Michael J.

Department of Geography, Geology, and the Environment, Slippery Rock University, Slippery Rock, PA 16057

Recent years have seen widespread acceptance of the idea that igneous intrusions are often emplaced in multiple phases or pulses (Miller et al., 2011). To test whether textural data could be used to distinguish between these pulses, we examined olivine from the Black Sturgeon sill, a 256 m thick diabase intrusion located southwest of Lake Nipigon in Ontario. We collected samples from a continuous drill core through the sill and subdivided it into several zones using modal mineralogy and textural data. The most primitive and olivine-rich zone is from 120-200 m above base. In this study, we investigated the use of crystal size distributions (CSDs) to discriminate between distinct populations of olivine in this olivine-rich zone.

CSDs are a well-established method of quantifying the textures of igneous rocks (Zieg and Marsh, 2002). We performed this analysis by collecting images from 42 samples throughout the olivine zone and stitching them together into large mosaics. We manually traced at least 200 olivine crystals from each sample, then entered the list of crystal sizes into the software package CSDCorrections 1.5 (Higgins, 2000) to calculate the CSDs. The slope and intercept of best-fit lines to the CSDs are used to quantify the texture (Zieg and Marsh, 2002). Two typical CSDs with best-fit lines are shown in Figure 1.

Cluster analysis of the slope-intercept data reveals four well-defined textural groups, which could correspond to distinct populations of olivine (Fig. 2). These groups are typically found in separate parts of the olivine zone (Fig. 3), with sharp boundaries between the different groups. As an example, the textures of samples 264 and 265.5 are clearly qualitatively and quantitatively distinct (Fig. 1), even though they are found within 1.5 m of each other.

Using the slope and intercept of CSDs, along with cluster analysis, we can identify separate populations of olivine in the olivine zone of the Black Sturgeon sill. While we have not found any consistent variation within groups, the breaks between the populations are sharp and coincide roughly with compositional changes (Zieg and Hone, this issue). We interpret these breaks as evidence of the episodic emplacement of the Black Sturgeon sill. CSDs have proved an effective complement to other methods in identifying discrete magma pulses in this sill. The episodic nature of magma emplacement in the Black Sturgeon sill also raises the possibility that other layered mafic intrusions formed by a similar process.

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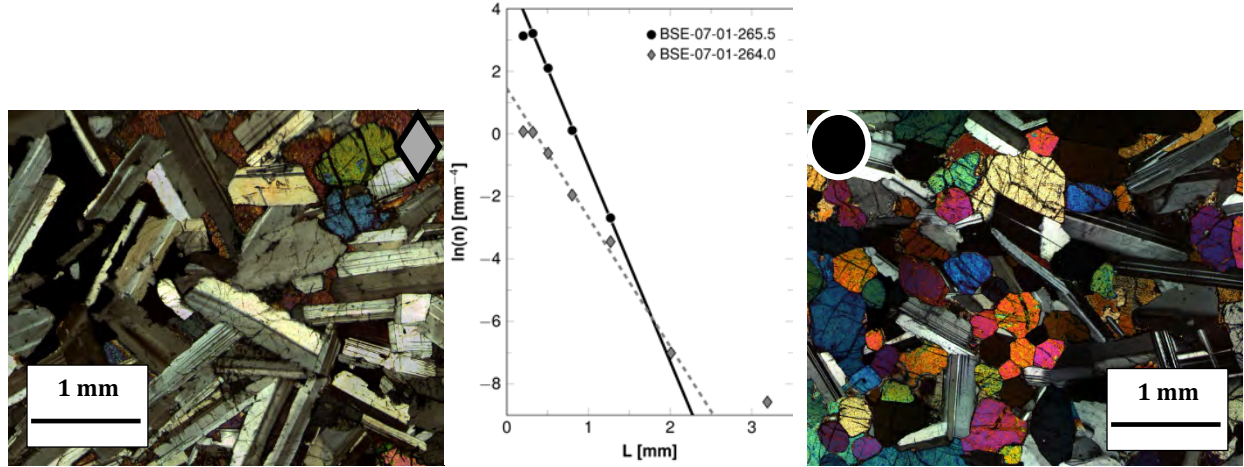


Figure 1. Representative textures. **a)** Photomicrograph of sample 264(5% olivine). **b)** CSDs of samples 264 and 265.5. **c)** Photomicrograph of sample 265.5 (26.5% olivine). The finer-grained texture (c) has a higher intercept and steeper slope.

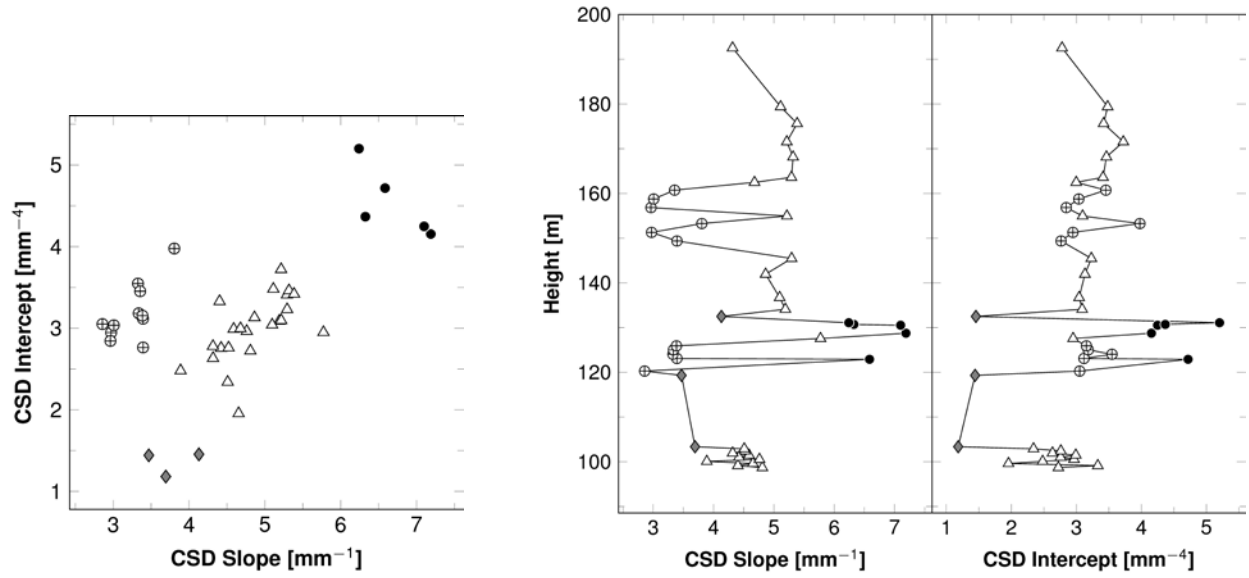


Figure 2. Identification of four textural groups based on the CSD slope and intercept.

Figure 3. CSD slope (a) and intercept (b) profiles through the olivine zone.

Reconstructing Paleoproterozoic volcanism in northwestern Wisconsin: Geochemistry of the Flambeau Cu-Zn-Au Mine

JACOBSON, Regan E., LODGE, Robert W.D.

Department of Geology, University of Wisconsin – Eau Claire: Eau Claire, WI 54702-4004

The Flambeau mine is located 1 mile southwest of the town of Ladysmith, located in Rusk County, WI. The mine is a part of the Wisconsin Magmatic Terrane and is a group of volcanic and plutonic rocks that formed during volcanism associated with the accretion of the Pembine-Wausau terrane onto the southern end of the Superior craton during the Paleoproterozoic Penokean orogeny (May and Dinkowitz, 1996). The Flambeau is one of a number of volcanogenic massive sulfide (VMS) deposits, but it is the only one that has been mined. The mined portion of Flambeau deposit is part of an enriched zone where relatively little is known about the original hypogene geology. The ore-hosting rocks consists of metamorphosed variably-altered volcanic rocks and cherty iron-formations that are now sericite to quartz-sericite schists, and biotite-andalusite-chlorite schists (DeMatties, 1994). The Flambeau was mined from 1993-1997 and produced 181,000 tons of copper, 334,000 ounces of gold, and 3.3 million ounces of silver contributing over a billion dollars in state revenue. Mining of the enriched orebody was completed in 1997 (Jones and Jones, 1999). Since then, the site has been reclaimed and revegetated. Therefore, the only remaining rock for the Flambeau site is preserved in drill core stored at the Wisconsin Geological & Natural History Survey core repository.

VMS ore deposits are formed in submarine environments where high temperature hydrothermal fluids react with cold sea water to cause the precipitation of sulfide minerals. Usually, the characteristics of the volcanic system influence the composition of ore and alteration mineral assemblages. However, ongoing studies of Flambeau ores and hydrothermal alteration do not align with previous interpretations for the Flambeau volcanic system (Blotz et al. 2018). Historic research focuses largely on the mined portions of the deposit as the remainder of the strata is covered by thick Quaternary glacial deposits. This study utilizes major and trace element geochemistry of least-altered host rocks to assess the magmatic and tectonic affinity of the rocks hosting the Flambeau deposit. This study is the first trace rare earth data set for the Flambeau deposit. Assessing the magmatic affinity of these rocks will provide insight to the petrogenesis of arc magmatism/collision and the magmatic/tectonic controls on VMS mineralization during ocean-continent collision. Previous stratigraphic interpretations of the hangingwall rocks indicate three units consisting of quartz-augen schist, metadacite, and chlorite schist (May and Dinkowitz, 1996). Geochemical data produced in this study indicates that the Flambeau deposit is primarily hosted by intermediate volcanics locally interleaved with quartz-phyric rhyolitic rocks (Fig. 1). Preliminary data reveal a bimodal distribution and all show arc-like characteristics on primitive-mantle normalized plots with light REE enrichment and negative Nb and Ti anomalies. Felsic rocks show FI to FII type (Leshner et al. 1986) trace element characteristics indicative of formation at moderate crystal depths. Ongoing trace element analysis will more clearly document the magmatic affinity of this volcanic suite.

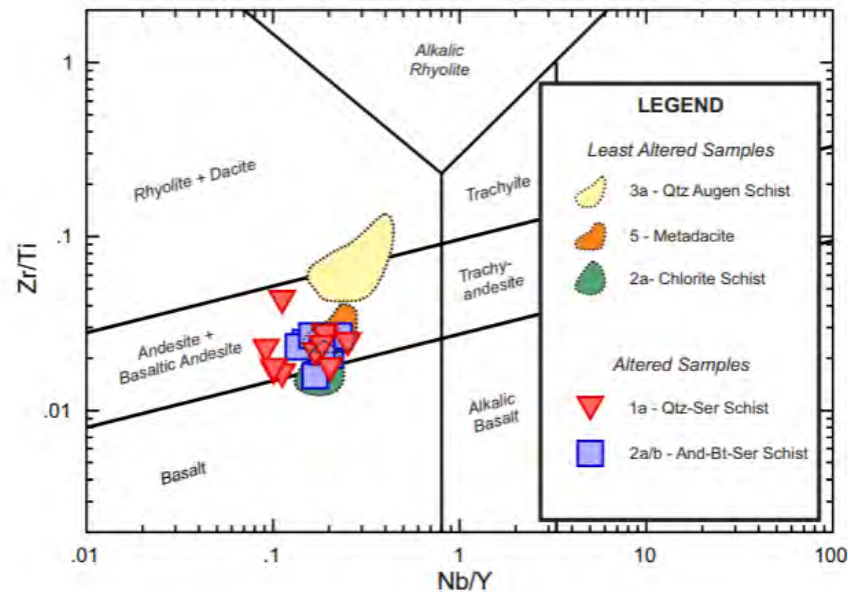


Figure 1 This shows Zr/Ti and Nb/Y ratios of units 3a, 5, and 2a. These ratios are representative of the host rocks in the Flambeau VMS deposit. Plot from Pearce (1996).

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On-going Geologic Mapping in Minnesota's Arrowhead Region by the Minnesota Geological Survey

JIRSA,* Mark A., Minnesota Geological Survey (MGS) (jirsa001@umn.edu)

**The large number of collaborators engaged in various components of this endeavor precludes complete acknowledgement here. Consult MGS Open-File Report OFR2016-04 for authorship details.*

This presentation describes geologic mapping by the MGS in northeastern Minnesota, with an emphasis on the bedrock geology. We are in year 3 of a 6-year process to create County Geologic Atlases for St. Louis and Lake Counties. The “Arrowhead Project” area includes parts of the Boundary Waters Canoe Area Wilderness, Voyageurs National Park, Superior National Forest, and several State forests. It also encloses the easternmost part of the Mesabi Iron Range, the “Cu-Ni District,” and the Duluth metropolitan area (the 4th largest in the state). County atlases contain maps and other imagery depicting bedrock geology, geophysical data, bedrock geochronology, bedrock topography, depth to bedrock, surficial sediments, and subsurface sediment layers; together with the extensive digital data sets used to construct them. The atlases are designed to provide regional 4-D geologic framework in digital and print formats to support ongoing and future studies related to land, water, and mineral resources.

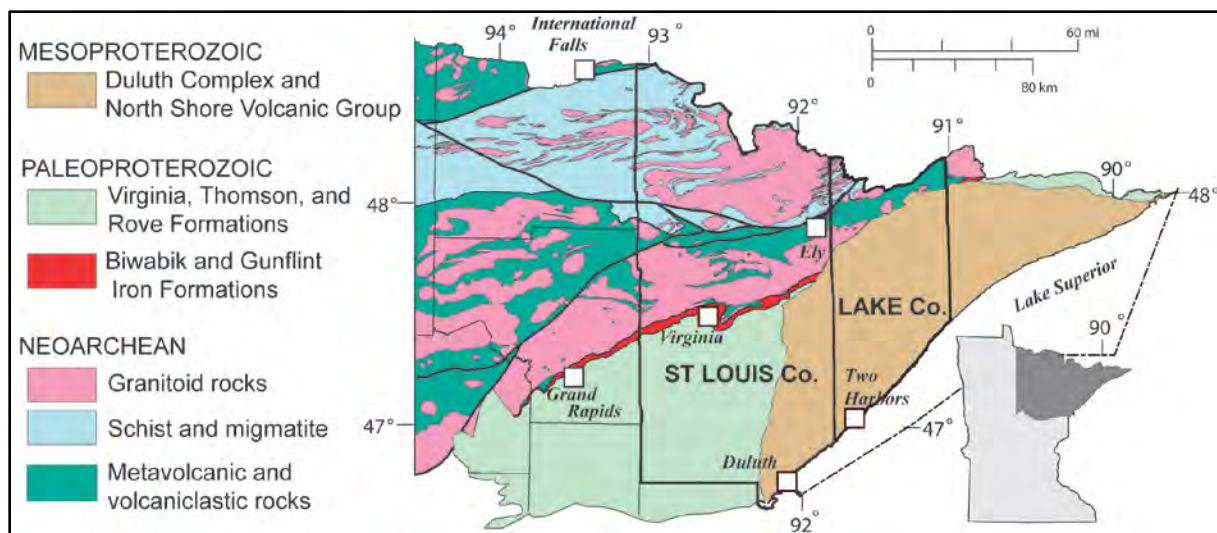


Figure 1. Generalized map of northeastern Minnesota showing the location and geologic setting of county-scale mapping (modified from MGS State Map Series S-21).

Because these are two of the largest counties in the state, we've divided them for mapping purposes into subareas referred to here as the Central, Southern, and Northern Arrowhead. Work in each subarea involves 1 or more seasons of field mapping by 5 geologists, rotary-sonic drilling, trenching, and acquisition of drill hole, petrographic, geochronologic, and geophysical data. Work in the Central Arrowhead subarea is complete (e.g., Jirsa and others, 2017), and components of the other subareas are in various stages of completion. Preliminary products for all subareas are published as they become available in *MGS Open-File Report OFR2016-04*. This open-file report will remain the primary repository for on-going mapping. Once preliminary work in all subareas is published, the data will be recombined into county geologic atlases. Creation of these products is a team effort, involving 14 staff members from MGS, and

several from partner agencies. Staff of the Minnesota Department of Natural Resources will use these maps and data sets to conduct regional groundwater studies, including assessments of flow systems, aquifers, groundwater chemistry, and an assessment of sensitivity to pollution, to produce Part B of the County Geologic Atlases. Support is provided by the U.S. Geological Survey National Cooperative Geologic Mapping Program, the Environment and Natural Resources Trust Fund (as recommended by Legislative-Citizens Commission on Minnesota Resources—LCCMR), and the Boards of Commissioners of St. Louis and Lake Counties.

The region's bedrock includes portions of three subprovinces of the Archean Superior Province, Paleoproterozoic strata including the Biwabik Iron Formation, and Mesoproterozoic volcanic and intrusive rocks of the North Shore Volcanic Group and Duluth Complex (Fig. 1). The latter hosts polymetallic mineral deposits under consideration for new mining. The bedrock in much of the region has been mapped to varied levels of detail in the past, driven in part by minerals exploration. Despite this, our current effort identified many areas that escaped previous mapping or were mapped in minimal detail, and it attempts to fill those voids and integrate the disparate sources of information. Mapping is conducted primarily at 1:24,000-scale, with printable products that are generalized from the companion digital data sets to scales of 1:100,000 to 1:200,000.

One of the more geologically interesting aspects of recent work is the recognition that chemical weathering of bedrock prior to glaciation played a fundamental role in shaping the region's topography, bathymetry, hydrogeology, and ecology. In this region where bedrock is at and close to the land surface, recently acquired empirical evidence indicates that differential erosion of saprolitic bedrock reflects both the compositional and structural attributes of the rock. Essentially, the bedrock surface in much of the area reflects the somewhat transitional boundary between fresh and weathered rock. In areas where outcrop, drill hole data, and access are limited, lidar imagery can be employed to infer both compositional and structural trends in bedrock. In addition, the presence of varied thicknesses and compositions of saprolite likely contributes to hydrogeologic characteristics, though further study is needed.

The most recent bedrock mapping (Northern Arrowhead subarea) includes a component of geochronologic analyses. Although the results are not yet published, all the samples submitted are inferred to be Neoarchean—an era of rocks in Minnesota historically lacking extensive high-resolution geochronologic data. Three main temporal objectives are attempted with these samples: 1) establish ages of successor basin deposits in the Wawa subprovince of the Superior Province; 2) establish ages of intrusions emplaced into several geologic settings; and 3) establish ages of major neosomatic components of migmatitic rocks that comprise the Quetico subprovince. If successful, these data will refine the temporal framework for deposition, magmatism, deformation, and metamorphism that will contribute to understanding the region's tectonic evolution. As with all products derived from the Arrowhead project, the geochronologic results will be published in the open-file report mentioned above.

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Geology and geochronology of the 2006 Cavity Lake forest fire area, Boundary Waters Canoe Area Wilderness, NE Minnesota

JIRSA¹, Mark A., STARNES², Edward C., and SCHMITZ³, Mark D.

¹Minnesota Geological Survey, 2609 W. Territorial Road, St. Paul, MN 55114-1009

²ConocoPhillips Alaska, Inc. 700 G St., Anchorage, AK 99501

³Department of Geosciences, Boise State University, 1910 University Drive, Boise, ID 83725-1535

The bedrock geology in this part of the Boundary Waters Canoe Area Wilderness (BWCAW) is incredibly diverse and remarkably well exposed. Parts of the area were mapped to varied levels of detail in the 1930's, and more recently in the 1970's and 1980's, with efforts focused primarily along waterways. A devastating wind storm in 1999 flattened trees in much of the region, and a delayed result in 2006 was the Cavity Lake forest fire. The fire exposed bedrock and allowed comparatively unencumbered access to interior parts of the map area, creating a unique and time-sensitive opportunity for mapping. Field work and compilation of prior mapping was conducted in 2007-2008 with funding from the USGS National Cooperative Geologic Mapping Program, and a preliminary map was produced (Jirsa and Starns, 2008). That map has been revised to incorporate subsequent geochronologic analyses and field work by the lead author and students of University of Minnesota, Duluth, Precambrian Research Center field camps (2007-2015). The map at scale 1:24,000, and companion data are published as *Minnesota Geological Survey Miscellaneous Map M-193 (Jirsa and others, 2017)*. One previously unpublished geochronologic date by coauthor Schmitz is presented on the map and discussed here.

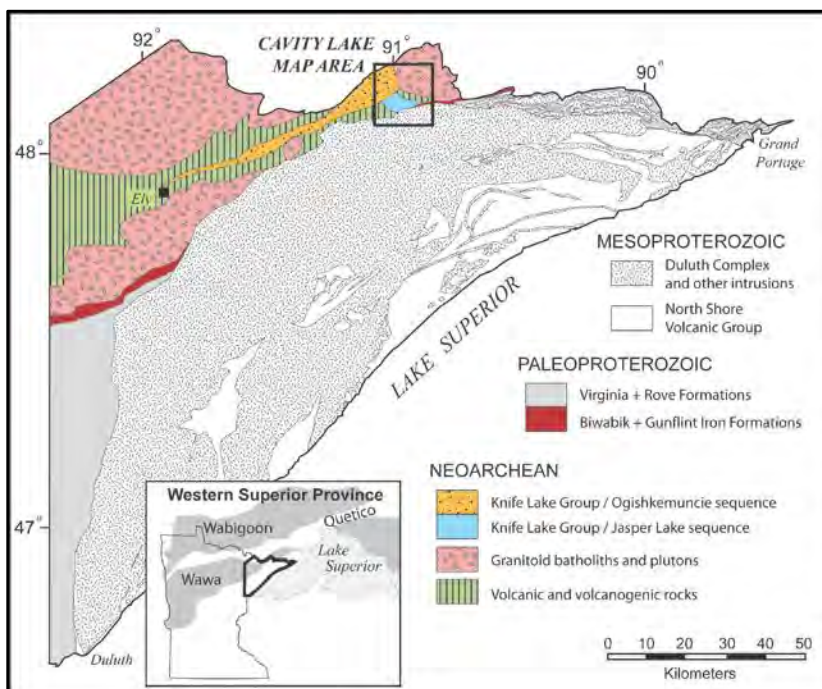


Figure 1. Generalized bedrock geology of northeastern Minnesota showing the location of Cavity Lake map area (bold black outline). Inset map shows location of Neoproterozoic rocks within the Wawa subprovince of the Superior Province.

M-193 portrays bedrock that represents crustal evolution spanning the Neoproterozoic to the Mesoproterozoic (Fig. 1), with an emphasis on structural and stratigraphic relationships in the Neoproterozoic portion. Neoproterozoic greenstone-granite terrane of the Wawa subprovince of Superior Province is represented by a succession of mostly mafic to ultramafic metavolcanic and hypabyssal intrusive rocks (ca 2700 Ma); unconformably overlain by hornblende-phyric, calc-alkalic volcanic and volcanoclastic rocks (ca 2690 Ma; *newly published age*), and intruded by the Saganaga Tonalite (also ca 2690 Ma). This succession was uplifted, chemically weathered (Driese and others, 2011), and subaerially

eroded to provide detritus to one or more successor basins. Based on correlation with Neoarchean terrane along strike in Canada (Corfu and Stott, 1998), the latter sequence of clastic strata is thought to have been deposited at about 2684-2682 Ma—after emplacement of the Saganaga Tonalite (2690 Ma), and before the primary regional deformation and metamorphic event at about 2680 Ma (Boerboom and Zartman, 1993). All of these rocks were cut by mafic dikes inferred from field relationships to be both Paleoproterozoic and Mesoproterozoic. The Neoarchean rocks and some dikes are unconformably overlain by Paleoproterozoic metasedimentary strata of the Animikie Group (ca 1880-1830 Ma), which includes the Gunflint Iron Formation. The uppermost layers of iron-formation are intensely deformed and overlain east of this map area by thin lenses of ejecta from a meteorite impact that occurred near Sudbury, Ontario, at ca 1850 Ma (Jirsa and others, 2011). Mesoproterozoic rifting is manifest in hypabyssal dikes and sills known collectively as the Logan intrusions (ca 1115 Ma), and several intrusive phases of the Duluth Complex (ca 1100 Ma) emplaced into both Neoarchean and Proterozoic rocks. One of the most notable geologic features in this region is the local preservation of 4 major unconformities; two within Neoarchean rocks, and two in and at the base of Paleoproterozoic strata.

The Neoarchean rocks in the central Boundary Waters Canoe Area Wilderness are inferred here to comprise a Timiskaming-type extensional basin and its apparent wall- and floor-rocks. The geologic units in the region were parceled by Gruner (1941) into eight structural segments separated by anastomosing shear and fault zones, and this map exposes parts of the eastern four of those segments. Although rock types are comparatively pristine within each segment, correlation of units from one fault-bounded block to another is challenging. Each block was uplifted, down-dropped and tilted differently, which results in different stratigraphic levels of exposure and repetition of strata locally. This map attempts to “unstrain” the rocks within each segment to reveal stratigraphic variations that may reflect fluctuations in basin geometry and progressive erosional dissection of basin wall rocks. This contributes to a regional tectonic model that involves basin development during late stages of terrane accretion.

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The youngest magmatic activity of the Midcontinent Rift at Bear Lake, Keweenaw Peninsula, Michigan

KULAKOV, Evgeniy¹, BORNHORST, Theodore J.², DEERING, Chad³, and MOORE, James B.⁴

¹Centre for Earth Evolution and Dynamics, University of Oslo, Oslo, Norway

²A. E. Seaman Mineral Museum, Michigan Tech, Houghton, MI 49931

³Department of Geological and Mining Engineering and Sciences, Michigan Tech, Houghton, MI 49931

⁴Moore Rock Farm, Keweenaw Peninsula, MI

The Bear Lake igneous body is located near Michigan's McLain State Park in the southwest side of the Keweenaw Peninsula (sections 24 and 25, T56N, R34W) and represents the youngest known magmatic activity of the Midcontinent Rift. Bear Lake was mapped as an intrusive rhyolite (Cornwall and Wright, 1956) cross-cutting the Freda Sandstone of the Oronto Group. It is a dark gray to red colored fine-grained igneous rock with micro-phenocrysts of K-feldspar, biotite, hornblende, quartz, apatite, and iron oxides and is flow-banded in many outcrops. Bear Lake is, however, not a rhyolite, but instead intermediate in composition with an average (N=6) of 59.1 wt. % SiO₂, 1.2 wt. % Na₂O and 6.6 wt. % K₂O. This composition falls in the trachyandesite field of LeMaitre for fresh rocks (2002 Cambridge University volcanic rock classification) and would be further subdivided as a latite. While altered, the alkaline tendency of the rock is confirmed by the high concentration of the immobile elements with 1273 ppm Zr, 270 ppm La, and 496 ppm Ce.

The grain size and flow banding texture is consistent with the igneous body having formed either as a shallow intrusive or an extrusive flow. The interpretation that this is an extrusive deposit is supported by the results of drilling within the body by Johnson et al. (1980). They described glacial overburden underlain by 9 m of highly altered fragmental rocks in turn underlain by 8 m of siltstone and coarse-grained arkose over the igneous rock body. The contact between the igneous body and beds of the Freda Sandstone is not exposed. Those beds nearest to the contact are altered with visible calcite. The igneous body is variably altered and contains veinlets of calcite, quartz, and heulandite, which are more prominent near an exploration shaft in the west central side of the body dug about 1917. Strong conductors and anomalous copper content of about 190 ppm (Snider and Parker, 1979) led to geophysical surveys and drilling (Johnson et al., 1980). Minor amounts of native copper were reported in the drill core (Johnson et al., 1980).

Importantly, establishing a geologically meaningful absolute age for the Bear Lake latite would constrain the rate of rift-centric sedimentation and the true end of known rift magmatism. Early attempts at establishing an age were discussed by Morey and Van Schmus (1988) who reported a Rb-Sr age of 1062+/-34 Ma compared to 1007+/-25 Ma by Chaudhuri (1975), but concluded the Rb-Sr isotopic system did not represent the emplacement age. Subsequent dating has shown that the 1060 Ma age is comparable to the 1060 to 1050 Ma age of widespread hydrothermal alteration associated with the native copper deposit (Bornhorst et al., 1988).

In 1984, Bornhorst and a student, D. Wall, completed field work along Seven Mile Creek which bisects the body near the contact with the dual objective of developing a better understanding of the age relationship with the Freda Sandstone, intrusive versus extrusive origin and selecting a

sample for zircon U-Pb dating. A sample was submitted to the Royal Ontario Museum for zircon separation and U-Pb dating. However, petrographic observations of the zircons revealed that they were likely xenocrysts and, therefore, no follow up analytical work was completed.

Recently, the University of Oslo was able to extract three small zircons that yielded a statistically consistent concordia age of 1091.4 ± 1.7 Ma by ID-TIMS. The Bear Lake body intersects the Freda Sandstone and is about 1,500 m above the base of the Nonesuch Shale (Fig. 1) dated at 1081 ± 9 Ma (Pb-Pb isochron; Ohr, 1993). Stratigraphically about 1,000 m under the Nonesuch is the Lake Shore Traps dated at 1087.2 ± 1.6 Ma (U-Pb age on zircons; Davis and Paces, 1990). Fairchild et al. (2017) reported a 1.6 Ma younger age for the Lake Shore Traps and also reported an age of about 1084 Ma for rocks of comparable stratigraphic position from Michipicoten Island. Thus, the 1091 Ma age on the Bear Lake igneous body is not consistent with other published radiometric ages and, therefore, is not geologically meaningful; i.e. the zircon grains are xenocrysts as suspected decades prior.

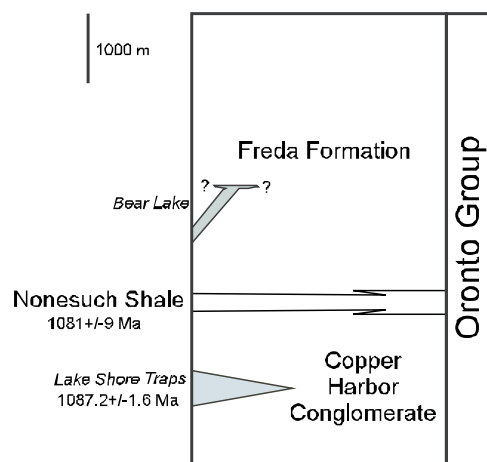


Figure 1: Stratigraphic column.

We have not yet exhausted our efforts to obtain a geologically meaningful radiometric age for Bear Lake and continue to search for primary igneous zircons.

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Land of Fire and Ice: Summary of the 2017 ILSG Field Trip to Iceland

LARSON¹, Phil; HUDAK², George; MACTAVISH³, Al; HINZ⁴, Peter; RADAKOVICH⁵, Amy; BHATTACHARYYA⁶, Juk; ENGELHARDT⁷, Paula; ENGELHARDT⁸, Steve; GELNIAS⁹, Brigitte; GOOD¹⁰, David; GORNER⁹, Emily; HINZ⁴, Sheree; JONGEWAARD¹¹, Peter; KROCH, Deb; SVENSSON¹⁰, Matt; TIMS¹², Andrew

¹Vesterheim Geoscience, PLC, Duluth, MN

²Natural Resources Research Institute, University of Minnesota - Duluth, MN

³Panoramic PGMs (Canada) Limited, Thunder Bay, ON

⁴Ontario Ministry of Northern Development and Mines, Thunder Bay, ON

⁵Minnesota Geological Survey (MGS), University of Minnesota-Twin Cities

⁶Department of Geography, Geology and Environmental Science, University of Wisconsin – Whitewater

⁷HydroGeo Solutions LLC, Green Bay, WI

⁸Green Bay, WI, independent photographer

⁹Department of Geology, Lakehead University, Thunder Bay, ON

¹⁰Department of Earth Sciences, Western University, London, ON N6A 5B7 Canada

¹¹Cliffs Natural Resources - Retired

¹²Northern Mineral Exploration Services, Thunder Bay, ON

ABSTRACT

The Institute on Lake Superior Geology recently conducted a field trip to Iceland between July 26 and August 5, 2017. The 11-day trip was led by Phil Larson, George Hudak, Al MacTavish, and Peter Hinz, and included 16 participants, including 10 professional geologists and 4 graduate students. The trip traversed roughly the south one-half of the island (Fig 1). Stops covered a wide variety of topics – from volcanology, igneous petrology, and magmatic-hydrothermal ore deposits to the glacial geology and geomorphology of Iceland.

Iceland is the subaerial expression of the crust that forms the floor of the Atlantic Ocean. Though all of its rocks are younger than about 25 Ma, the geology of Iceland bears many similarities to that of the 1.1 Ga Midcontinent Rift in North America. The Mid-Atlantic Ridge steps ~100 km east across the island and allowed us to see a modern-day expression of rift-related volcanic and hypabyssal intrusive mafic (to rarely felsic) rocks, which continue to form today. The onset of the most recent Ice Age in the Pleistocene created spectacular ice sheets, valley glaciers, and glacial sediment deposits, as well as the unique landforms reflecting the interaction of volcanism and glacial ice, all of which we observed on the trip (Thordarson & Hoskuldsson, 2014).



Figure 1. Shaded relief map (Google Images, 2017) of Iceland, showing glaciers in white. Colored lines show the 11-day trip route, starting and ending in Reykjavik.

This presentation summarizes highlights from our trip and draws comparisons of Iceland's geology to the Midcontinent Rift. Featured highlights of the bedrock geology will include both subaerial and subglacial volcanic deposits such as mafic tuffs, pillowed basalts, cinder cones, columnar basalts, peperites, pillowed dikes, pumice and ash deposits, moberg, tuyas, and spectacular aa and pahoehoe fields. We will discuss the surface expression of the Mid Atlantic Ridge at the Krafla Lava Fields, the Snaefellsnes Peninsula Volcanic Zone, and the historic Láki Flow. The presentation will also showcase vast outwash plains created by glacial jokulhaups, moraine deposits, proglacial lakes, and crevasse fields.

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Controls on the localization and timing of mineralized intrusions within the ca. 1.1 Ga Midcontinent Rift system

LIKANE, Dustin A.¹, BLEEKER, Wouter², HAMILTON, Mike³, KAMO, Sandra³, SMITH, Jennifer², HOLLINGS, Peter⁴, CUNDARI, Robert⁵, and EASTON, Michael⁶

¹*Department of Earth Sciences, University of Toronto, Toronto, Ontario; dustin.liikane@mail.utoronto.ca*

²*Geological Survey of Canada, Ottawa, Ontario*

³*Jack Satterly Geochronology Laboratory, Dept. of Earth Sciences, University of Toronto, 22 Russell St., Toronto, Ontario, Canada, M5S 3B1*

⁴*Department of Geology, Lakehead University, 955 Oliver Rd, Thunder Bay, Ontario, Canada, P7B 5E1*

⁵*Ontario Geological Survey, 435 James Street South, Thunder Bay, Ontario, P7E 6S7*

⁶*Ontario Geological Survey, 933 Ramsey Lake Road, Sudbury, Ontario, Canada, P3E 6B5*

The 1.1 Ga Mid-Continent Rift (MCR) represents one of the largest and best-preserved intra-continental rift systems of Precambrian age (Davis and Green, 1997; Miller and Nicholson, 2013; Swanson-Hysell et al., 2014; Bleeker et al., 2018). It is host to the Duluth Complex (second largest layered intrusion in the world), which contains significant low-grade mineralization of Ni-Cu-Co and platinum group elements (PGEs), and possibly reef-style PGE mineralization. Higher-grade Ni-Cu mineralization has also been identified within the rift, localized in smaller, conduit-type intrusions (e.g., Eagle deposit). Numerous mineralized intrusions are associated with the MCR on both sides of the border (e.g., Coldwell Complex near Marathon, Ontario; Tamarack near Duluth, Minnesota; Eagle near Marquette, Michigan), with many being actively explored by a number of companies.

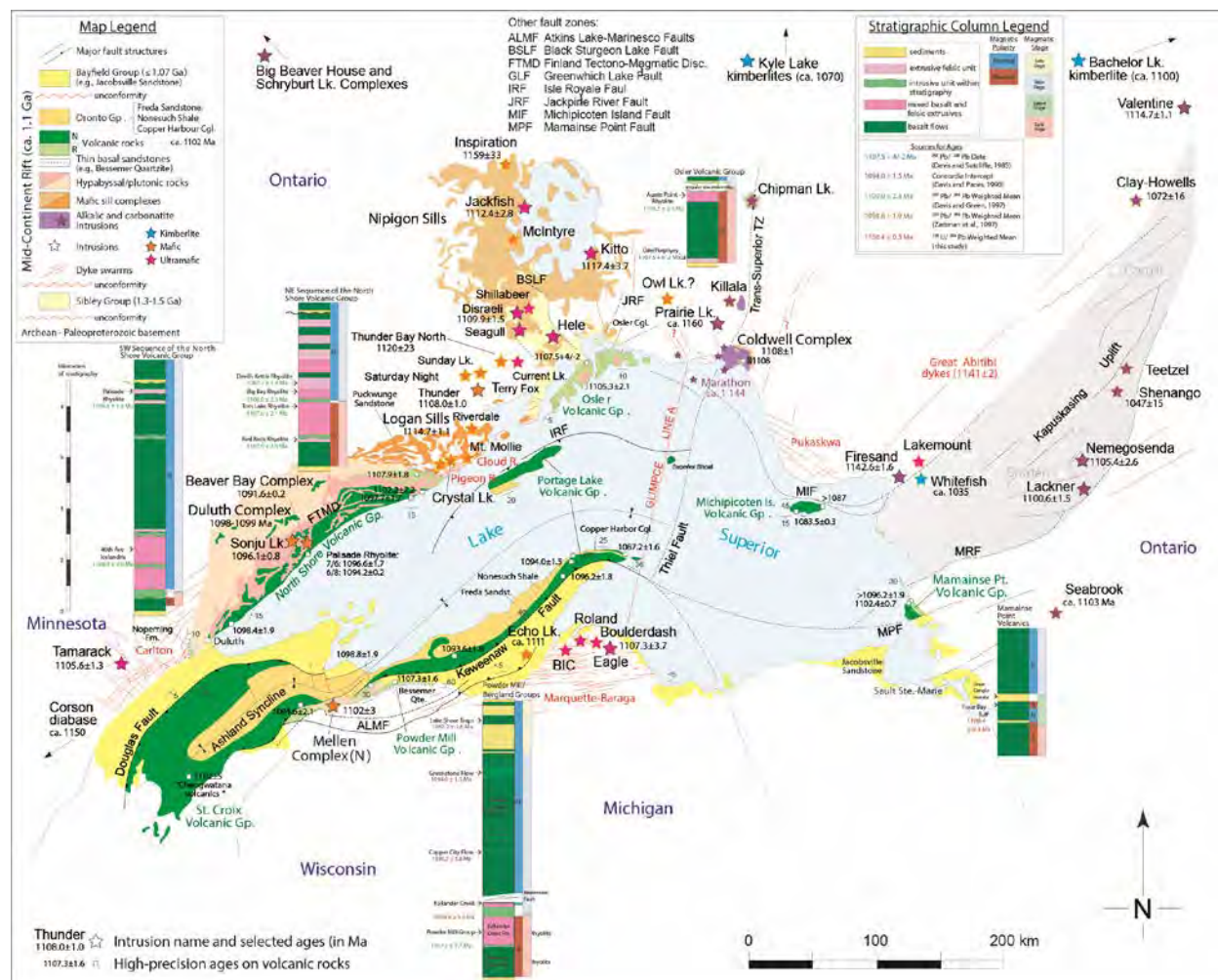
Many intrusions related to the MCR have been dated by U-Pb methods (Figure 1); however, many of the ages were obtained prior to the introduction of routine chemical abrasion techniques on single zircon grains. This improvement often leads to better precision and accuracy, allowing for sub-million-year age resolution. With this technique, we can better constrain (for the first time, in some cases) the age of emplacement of several MCR-related intrusions. This will allow us to understand the dynamics of the MCR's plumbing system, and how it evolved over time. At the deposit scale, the high-precision ages may allow us to recognize whether these intrusions are long-lived conduits or intrusions emplaced in one single magmatic pulse. Furthermore, high-precision ages, along with lithogeochemistry, will allow us to link these individual intrusions to distinct stages of the flood basalt sequence. It may also reveal temporal constraints on the formation of mineralized intrusions within the MCR.

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Microanalysis of rock and mineral textures and its relationship to mineralization and ore comminution

MATKO, Matthew W., and SCHARDT, Christian

Department of Earth and Environmental Sciences, University of Minnesota Duluth, 229 Heller Hall, 1114 Kirby Drive, Duluth, MN 55812

Research on ore bodies has typically focused on macro-scale processes, such as fluid migration, chemical and metal transfer, as well as physical and chemical changes (Cathles, 1981; Zientek, 2012). The results of this research are then typically been applied to large-scale features based on field observations, laboratory experiments, and theoretical assumptions to create models for ore deposits. However, it is not well understood how micro-scale properties such as: mineral grain size, grain shape, grain orientation, or fracture characteristics may influence various ore deposit formation. Mineralization styles such as: disseminated, next-texture, porphyry, vein-style may be partially controlled, if not dictated, by these features. It is therefore important to gain a better understanding of the role of these features in larger-scale processes.

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

Results show that XRCT data can be utilized to locate small-scale melt migration pathways such as micro-fractures (fig. 1a) in addition to mineral grain morphology and size distribution. Identification of these micro-scale features has the potential to greatly assist in our understanding of how ore textures and mineral deposits form. In addition to visual analysis of in-situ material, data can be exported to construct vector graphs, which enable the visualization of ore grain orientations to determine existing ore grains orientation patterns within the rock (fig. 1b). Results also indicate very good mineral separation of silicates from sulfides using EPD compared to traditional mechanical processing, especially at < 250-150 μm . Separation efficiency was confirmed by running MLA on the samples, where it was determined that the average liberation yield for ores present ranged from 70 % to 80 % (fig. 1c). There does appear to be some dependence on ore grain size and deposit type that can affect these values. EPD technology offers unique opportunities for ore processing such as the pre-weakening of material before being subjected to more traditional methods of crushing, or an initial ore-silicate separation phase to remove the bulk of the gangue material.

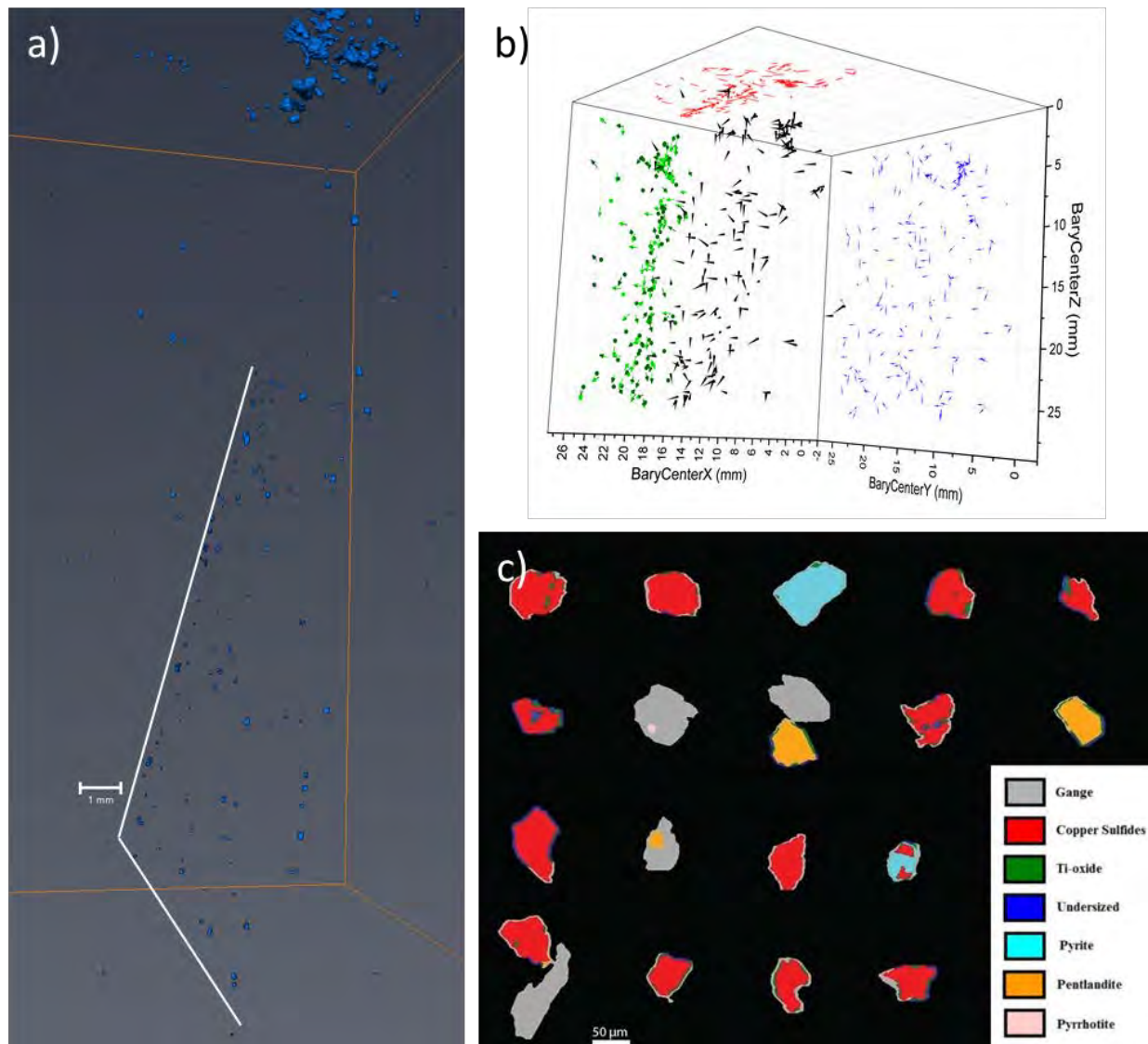


Figure 1 3D reconstruction of Cu-sulfide ore from a porphyry deposit that highlights a planar feature created by mineralization within a micro-fracture (a). Data for particles within the planar feature graphed to display long axis grain orientation (b). A composite image showing a representative sample of sulfide mineralization from disaggregated Eagle Mine material using MLA software. It highlights the high degree of Cu-sulfide liberation from silicates while also showing minor Cu-sulfides association with Ti-oxides (c).

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Using Credit-by-Exam to Connect Advanced High School Geology Courses to University Geology Departments: Current Status of a State-wide Program in Michigan

MATTOX, Stephen¹, BOLHUIS, Chris², and SOBOLAK, Christina³

¹*Department of Geology, Grand Valley State University, Allendale, MI,* ²*Hudsonville High School, Hudsonville, MI;* ³*St. Fabian Middle School, Farmington Hills, MI*

To address the national shortage of geologists and to diversify the geoscience workforce we are constructing a seamless path from rigorous high school geology classes taught by well-trained teachers to geoscience departments at state universities and colleges. This program is modeled on an existing high school – university collaboration that has added a significant number of students to the career pipeline.

Although geologists have vigorously lobbied for an AP course and exam in geology, the College Board has resisted because they perceive that demand will be low. The lack of an AP course has made it difficult for those high schools nationwide that offer advanced (i.e., college-level content) geology courses to obtain appropriate recognition for their students' accomplishments.

Mattox designed a test, with input from my GVSU peers (and reviewed by faculty at eight other university geology departments), that includes 70 multiple choice, 10 essay questions, a map test with skills and landforms, and a rock and mineral exam (essentially what we use in our introductory physical geology course). We give the exam over 5-6 hours on two different days.

The support of two NSF grants allowed us to build the network of universities and then extend the size of the program. NSF supported ended in 2016.

Universities awarding credit: Central Michigan, Eastern Michigan, Grand Valley, Lake Superior State, Michigan Tech, Northern Michigan, University of Michigan-Dearborn, Wayne State University, Western Michigan, and Hope College. Montana State has awarded credit to two students. Mattox has started new discussions with Ferris State University and nearby 2YCs: Muskegon Community College and Grand Rapids Community College. Additional colleges and universities are invited to join each year. Participating colleges sign a MOU to award credit.

Since 2001, 1334 students have taken a rigorous high school geology/Earth science course. Of these 777 students have passed, about 58%. With NSF support the program has grown and now about 250 students are tested each year at 9 or 10 high schools. Commonly, 20 students request credit and 5-7 start university as declared geology or Earth science majors, usually at CMU, GVSU, MTU, NMU, or WMU.

Insights from this project include:

- Administrators were surprisingly receptive to and supportive of a rigorous high school geology credit by exam course.
- Ideally teachers with a B.S. in Geology and additional course work or M.S. teach the course. However, motivated science teachers without an Earth Science B.S. can be successful.
- The high school course can be a single semester, two trimesters, or a full year.

- Pass rates tend to improve over 3-4 years and then stabilize. Some schools never had a student pass.
- About two new high schools join the program each year.
- Currently, high school teachers are working to align the Next Generation Science Standards to the content/skills of the college physical geology class.
- We have demonstrated the feasibility of establishing a statewide network of universities to award college credit for passing a credit by exam during a high school geology course.

	Year 1 -2012			Year 2 -2013			Year 3 - 2014			Year 4 - 2015			Final NSF Year 5 – 2016			2017		
School	Take	Pass	rate	Take	Pass	rate	Take	Pass	rate	Take	Pass	rate	Take	Pass	rate	Take	Pass	rate
HUD	34	31	91%	56	52	93%	48	46	96%	56	48	86%	55	44	80%	69	62	90
GH	18	6	33%	-	-	-	18	6	33%	19	8	42%						
GPS	15	11	73%	18	7	39%	16	7	44%	26	12	46%	12	5	42%	14	10	71
OK	17	0	0	13	1	8%	15	2	13%	19	2	10%	22	3	14%	18	1	5.5
BR	-	-	-	16	1	6%	18	5	28%	11	4	36%	15	0	0	15	7	46.6
DA	-	-	-	10	0	0	9	0	0	3	0	0						
DIT	-	-	-	-	-	-	17	0	0	7	0	0						
HF	-	-	-	-	-	-	5	0	0	-	-	-						
MA	-	-	-	4	0	0	-	-	-	-	-	-						
PHS										1	0	0	1	0	0			
HHS										9	0	0	3	0	0			
SHS										43	10	23				11	1	9
RHS													13	12	92%	4	3	75
WOHS													20	3	15%	27	11	40
FHC																54	22	41
KH=16																49	20	41
Total	84	48	57%	117	61	52%	146	66	45%	186	92	49%	141	67	47.5%	250	148	59.2
Total w/o HUD	50	17	34%	61	9	15%	98	20	20%	130	44	34%	86	23	26.7%	188	79	42
# schools	4			6			8			10			8			9		
Cumulative # schools	4			7			9			12			14			16		

Growth of credit-by-exam in Michigan over the last six years. High schools in the program: HUD (Hudsonville); GH (Grand Haven); GPS (Grosse Point South); OK (Okemos); BR (Black River); DA (Dream Academy); DIT (Detroit Institute of Technology); HF (Henry Ford Academy); MA (Multicultural Academy); PHS (Pioneer); HHS (Huron); SHS (Sturgis); RHS (Roscommon HS); WOHS (West Ottawa HS); FHC (Forest Hills Central); and KH (Kenowa Hills).

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Geochemical signatures of hydrothermal alteration in clastic sedimentary rocks: theory, recognition, and application

MAUK, Jeffrey L.

¹USGS, MS-973 Denver Federal Center, P O Box 25046, Denver, CO 80225-0046, USA

Much of the terminology to describe hydrothermal alteration came from classic studies of porphyry copper deposits, which popularized terminology such as potassic, argillic, advanced argillic, phyllic, and propylitic (e.g., Lowell and Guilbert, 1970; Sillitoe, 2010, and references therein). This terminology was developed for plutonic and volcanic igneous rocks that, when fresh, contain unaltered feldspar and mafic minerals. The main driver of hydrothermal alteration, hot water, promotes reactions that convert feldspar and mafic minerals to phyllosilicate minerals.

In contrast, clastic sedimentary rocks form from weathered material, and that weathering results in degradation or destruction of feldspar and mafic minerals to form clay minerals such as smectite. During diagenesis, these clay minerals transform to higher rank clay minerals, such as interstratified illite-smectite and illite. Diagenetic reactions can ultimately lead to formation of micas such as muscovite. Therefore, normal weathering and diagenetic reactions destroy many igneous minerals, and form minerals that are similar to those that occur in hydrothermally altered igneous rocks. This can make it difficult to recognize hydrothermal alteration in sedimentary rocks. This abstract describes some key styles of hydrothermal alteration, and evaluates geochemical methods that can help to identify these types of alteration in clastic sedimentary rocks. Chemical sedimentary rocks, such as limestone and dolomite, are not considered.

In igneous rocks, propylitic alteration commonly covers extensive areas; it is characterized by chlorite, epidote, and calcite, with minor pyrite. Chlorite, calcite, and pyrite are common diagenetic minerals, so propylitic alteration is an excellent example of a style of alteration that is readily identifiable in igneous rocks, but difficult to impossible to recognize in sedimentary rocks. Furthermore, geochemical studies of altered igneous rocks show that major elements are relatively immobile during propylitic alteration, and the main components that are gained are sulfur and carbonate. Again, because carbonate minerals and pyrite are common in sedimentary rocks, geochemical analyses are unlikely to provide diagnostic evidence of propylitic alteration.

In contrast, alkali metasomatism, which includes K and Na alteration, can produce diagnostic minerals and distinct whole rock geochemical compositions. These reactions can produce K-feldspar albite, illite, or Na-mica, or a combination of these minerals. Mass changes associated with K and Na metasomatism can be evaluated graphically using plots of molar $(2Ca + Na + K)/Al$ versus molar K/Al to evaluate K-metasomatism, and molar $(2Ca + Na + K)/Al$ versus molar Na/Al to evaluate Na-metasomatism. These plots allow identification of important hydrothermal minerals, and reflect alteration processes by showing trends from unaltered toward altered rocks. Sodium metasomatism is a hallmark of many sediment-hosted Cu deposits, but albite is also a common diagenetic mineral, so geochemical testing must include a sufficiently large suite of rocks to test how common and widespread albite is on a regional basis, and whether Na metasomatism stems from diagenesis or mineralization, or both.

Phyllic alteration is characterized by quartz, sericite, and pyrite. Where intensely and pervasively developed, this alteration produces white rocks that are rich in pyrite; the pyrite may form up to 10% of the volume of the rock. Phyllic alteration is accompanied by leaching of Mg, Na, and Ca, and enrichment of K and S, so it is readily characterized by major element and S data.

Argillic alteration can be texturally destructive, and produces clay minerals such as montmorillonite, illite, chlorite, and kaolinite. Advanced argillic alteration is very texturally destructive; it results from more aggressive acid leaching of rock that produces quartz or vuggy silica, plus alunite and kaolinite. In both argillic and advanced argillic alteration, Mg, Fe, Ca, Na, and K are leached from the rock. Silica may appear to be enriched, but that is due to loss of other elements rather than actual addition of SiO_2 .

Silicification is the addition of silica to the rock, typically as quartz in veins, or in pore-filling cement, or both. In some cases, quartz replaces precursor minerals in the rock. All styles of silicification may be well-developed in host rocks around hydrothermal veins. Recognition and quantification of veins is relatively easy, but identification of silicification by pore filling or mineral replacement is more difficult. This is best exemplified in sandstones and quartzites, where beds that are naturally coarser-grained and more well-sorted would be harder and may have a more vitreous luster, leading them to be classified as silicified. Alas, geochemistry offers little assistance here, because the natural variability of clastic sedimentary rocks ensures a wide range of SiO_2 concentrations, and it is exceptionally difficult to document Si gain except under extreme conditions.

Sulfidation is the addition of sulfide minerals—typically pyrite—to rock. This is common around many hydrothermal veins, and can be intense and pervasive around sediment-hosted massive sulfide deposits. Sulfur addition is readily characterized by whole rock geochemistry, provided that, as noted above, the addition of sulfur is sufficient to exceed background concentrations from diagenetic pyrite.

Bleaching is used where rock is a lighter color than normal, and has two main styles: (1) a general lightening in color, such as dark green to light green, and (2) changing of a red rock to a white rock. The former is common around some hydrothermal veins. The latter occurs in some sediment-hosted copper deposits, and is spectacularly displayed in redbeds in the four corners region of the U.S., where the bleached zones reflect pathways of oil and gas migration. Bleaching is a nearly isochemical process, although in some cases (2) results in Fe loss.

Carbonate alteration is common and widespread around many hydrothermal veins, and around many stratiform and stratabound orebodies. Some deposits show pronounced zonation of carbonate minerals, from Fe-rich near deposits, to Ca-rich in distal areas. The carbonate alteration can occur as veins and veinlets, particularly in the inner alteration zones, but disseminated carbonate is more common. Carbonate alteration can be quantified by geochemical analyses of carbonate C, provided that the addition of carbonate is sufficient to exceed background concentrations from diagenetic carbonate.

In summary, whole rock geochemistry can provide a means to evaluate and quantify many, but not all types of hydrothermal alteration. Major element analyses, plus total S, carbonate C, and organic C, are the most important for geochemical evaluation of clastic sedimentary rocks. The most significant sediment-hosted deposits in the Midcontinent Rift are sediment-hosted Cu deposits, and for those, alkali metasomatism is the most promising alteration indicator.

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An 1149 Ma U-Pb baddeleyite crystallization age and geochemistry of gabbroic intrusions at the southwestern margin of the Superior Craton, southeastern South Dakota

McCORMICK, Kelli¹, CHAMBERLAIN, Kevin², and PATERSON, Colin³

¹*Department of Mining Engineering and Management, South Dakota School of Mines and Technology, Rapid City South Dakota 57701;* ²*Department of Geology and Geophysics, University of Wyoming, Laramie, WY 82071, Faculty of Geology and Geography, Tomsk State University, Tomsk 634050 Russia;* ³*Department of Geology and Geological Engineering, South Dakota School of Mines and Technology, Rapid City South Dakota 57701*

Gabbroic intrusions have been intersected in drill holes in southeastern South Dakota along the southwestern margin of the Superior Craton (Fig. 1). In order to better constrain the ages of the basement terranes in this region, several samples from one set of intrusions, the Corson diabase, were analyzed for the presence of datable minerals. For this study, samples of one Corson intrusion analyzed by Meyers (2013) was sent for mineral separation. Approximately 40 baddeleyite grains were separated by U. Söderlund (Lund University). Dating of the baddeleyite was by U-Pb isotope dilution thermal ionization mass spectrometry at the University of Wyoming. A U-Pb baddeleyite crystallization age of 1149.4 ± 7.3 Ma from this Corson diabase sample (McCormick et al., 2017) is interpreted to represent an early stage of the Midcontinent Rift (MCR). McCormick et al. (2017) suggest that Corson diabase intrusions represent a failed rift arm (Fig. 1). The inferred NE trend of the Corson diabase, considered together with the trends of other possible MCR-related intrusions, are also consistent with the model of a mantle plume origin for the MCR (Hutchinson et al., 1990). Sampling of another Corson diabase core for U-Pb mineral dating is in progress.

Several samples from two cores (03-W-01 and 03-W-02) intersecting a large gabbroic intrusion(s) near the town of Wakonda (Fig. 1) were analyzed in this study for the presence of datable minerals. A sample from 03-W-01 sent for mineral separation yielded approximately 50 baddeleyite grains, some more than 100 μm . Dating of these minerals is in progress.

In conjunction with the dating, samples were taken from the Wakonda cores for geochemical analysis and compared with existing geochemistry of Corson diabase. The Wakonda and Corson samples are tholeiitic and generally olivine normative. A plot of TiO_2 vs $\text{Mg\#}$ (Fig. 2) shows the Wakonda gabbros to be somewhat geochemically distinct from the Corson diabase, but similar to MCR intrusions around the Thunder Bay region.

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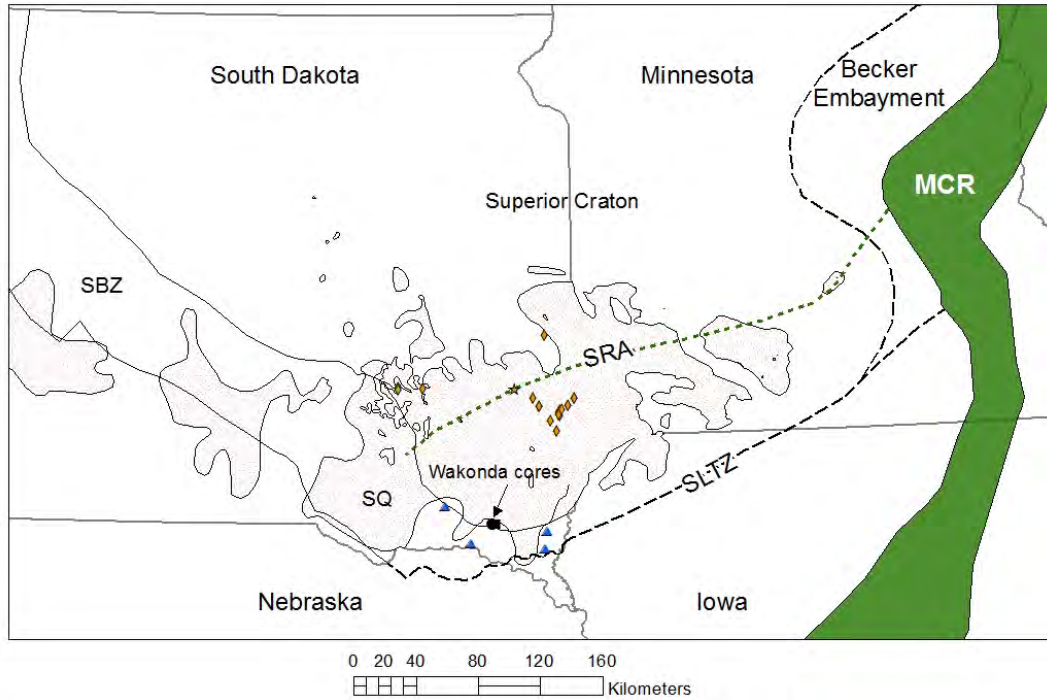


Figure 1: Map encompassing the intrusions discussed in this study. Diamonds are Corson diabase, triangles are other gabbros. MCR = Midcontinent Rift; SBZ = Superior boundary zone; SLTZ = Spirit Lake tectonic zone; SQ = Sioux Quartzite (subsurface extent); SRA = Superior rift arm (proposed). Becker embayment after the NICE working group.

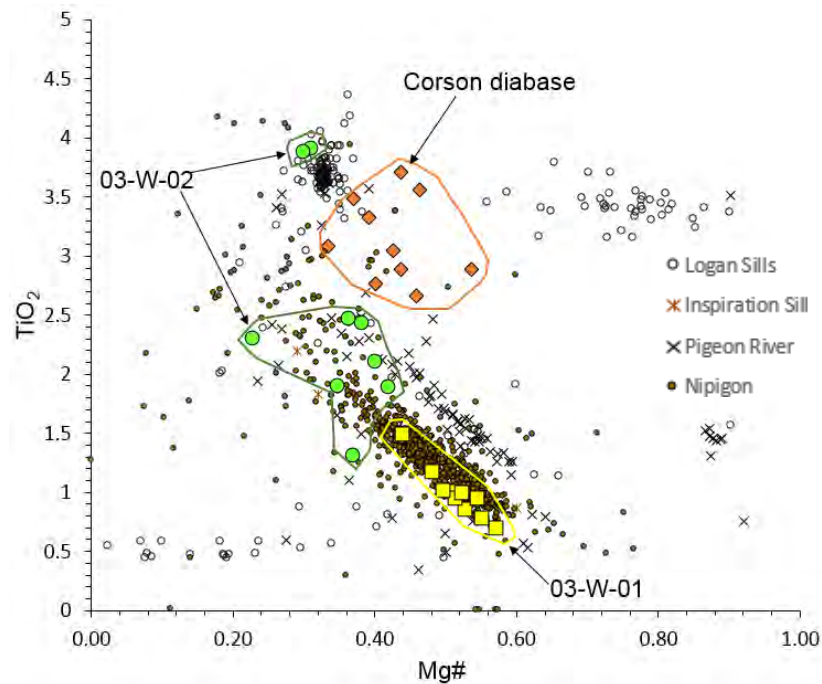


Figure 2: TiO_2 vs $\text{Mg\#}$ plot of southeastern South Dakota gabbroic intrusions and Thunder Bay area MCR intrusions from Cundari et al., 2013. Filled diamonds are Corson diabase, filled squares are Wakonda gabbro core 03-W-01, and large filled circles are Wakonda gabbro core 03-W-02.

Geology of the Crystal Lake Gabbro and the Mount Mollie Dyke, Midcontinent Rift, Northwest Ontario

O'BRIEN, Sean¹, HOLLINGS, Pete¹, and MILLER, Jim²

¹*Department of Geology, Lakehead University, 955 Oliver Road Thunder Bay, ON P7B 5E1 Canada;* ²*Department of Earth and Environmental Sciences, University of Minnesota - Duluth, 1114 Kirby Drive, 223 Heller Hall, Duluth, MN 55812.*

The Crystal Lake Gabbro (CLG) is a Y-shaped, up to 750 m wide, layered mafic intrusion with a 5 km long northern limb and a 2.75 km long southern limb, with localized Cu-Ni mineralization. The Mount Mollie Dyke (MMD) is an arcuate, 60 to 350 m wide, macrodyke that lies on trend east of the CLG and extends for 35 km toward Lake Superior. Both intrusions are part of the 1.1 Ga Midcontinent Rift (MCR) and were emplaced into the Paleoproterozoic Rove Formation of the Logan Basin, approximately 50 km south of Thunder Bay. Current U-Pb age determinations imply a ~10 m.y. age difference with CLG being formed at 1099.6 ± 1.2 Ma and the MMD being formed at $\sim 1109.3 \pm 6.3$ Ma (Heaman et al., 2007; Hollings et al., 2010). However, this age difference is at odds with both intrusions being normally polarized (an attribute of MCR rocks younger than 1102 Ma; Davis and Green, 1997) and their being on trend with each other.

The CLG profiled in a drill core from its southern limb can be broadly divided into Upper, Main, and Lower Zones with further subdivisions of the Main and Lower Zones based largely on geochemistry. The Lower Zone occurs between two xenoliths of an early MCR (~1115 Ma) plagioclase porphyritic Logan Sill diabase. The Lower Zone consists of subophitic to ophitic troctolite, augite troctolite, and olivine gabbro and can be subdivided into an upper and basal marginal subzone as well as an interior subzone. Both marginal subzones host disseminated sulphides. An overall bottom-up-directed fractional crystallization of the Lower Zone is suggested by the progressive decrease in Fo content of olivine, Mg# of clinopyroxene, and whole-rock MgO upsection. Above the upper Logan Sill xenolith, the Main Zone similarly consists of subophitic to ophitic troctolite, augite troctolite, olivine gabbro, and gabbro. Petrography, lithogeochemistry, and mineral composition was used to subdivide the Main Zone into five subzones: a basal marginal subzone, upper margin subzone, and three interior cycles that display cryptic variations indicative of fractional crystallization and magma recharge events. Like the margins of the Lower Zone, the Upper Zone as well and the basal marginal subzone of the Main Zone contain disseminated sulphides and are characterized by relatively high Fo content olivine and low incompatible trace element concentrations. These mineralized zones are interpreted to have crystallized from the same initial pulse of magma into the CLG, which was sulphur-saturated. Cyclical cryptic variations in the internal subzone of the Main Zone are interpreted to indicate upward directed fractional crystallization, interrupted by emplacement of additional magma pulses into the core of the intrusion. All rocks of the Main Zone are olivine and plagioclase orthocumulates indicating that fractional crystallization was not particularly efficient. Throughout the evolution of the CLG, the differentiation of the magma was limited as it did not result in clinopyroxene and Fe-Ti oxide becoming cumulus phases. This was likely due to magmatic recharge and inefficient fractional crystallization.

Texturally and geochemically, the MMD can be broadly divided into an Upper and Main Zones, with a subdivision of the Main Zone into an upper and lower sequence and a pegmatitic segregation subzone. The Upper Zone consists of ferrodiorite and likely represents the end product of extensive fractionation. The Main Zone is characterized by troctolite, augite troctolite, olivine gabbro, and gabbro with MgO, CaO, Al₂O₃, and Ni concentrations decreasing upwards and SiO₂, TiO₂, K₂O, Na₂O, P₂O₅, and incompatible trace element concentrations increasing, consistent with bottom-up fractional crystallization. Strong differentiation of the MMD magma is indicated by the habit change of clinopyroxene from ophitic (intercumulus) to granular (cumulus), which is the basis for the subdivision of the lower and upper sequences. The lower sequence of the Main Zone also hosts a 24 m thick interval containing 1 to 2 m wide gabbroic pegmatite layers. These pegmatites are interpreted to be the result of localized enrichment of magmatic volatiles.

The presence of an evolved core in the MMD surface expression, coupled with the mineral composition of olivine, plagioclase, and clinopyroxene, remaining at relatively constant Fo, An, and Mg# values, respectively, below the pegmatitic layers suggests that there was some degree of lateral crystal fractionation as well as bottom up fractionation. The well-defined fractionation sequence as well as an absence of abrupt geochemical changes suggests that the MMD fractionally crystallized from a single pulse.

Liberation of external sulphur from the surrounding Rove Formation, is suggested by the greater than mantle S/Se values as well as $\delta^{34}\text{S}$ values between +4.0 and +21.0‰ of the sulphides within the CLG. The addition of external sulphur evidently resulted in sulphur saturation during initial emplacement of the CLG magmas. Primitive mantle normalized multi-element diagrams and trace element ratios provide supporting evidence for a localized shallow level of crustal contamination, as well as a deeper more widespread contamination component of both the CLG and MMD magmas.

The estimated parental magma compositions and average primitive mantle normalized trace element concentrations of the CLG and MMD suggest that they shared similar, if not the same, magma source. The CLG parental magma was slightly more evolved than the MMD suggesting that the magmas were sourced from a fractionating staging chamber. The estimated parental magma compositions of the CLG and MMD closely resemble those of the Layered Series intrusions of the Duluth Complex, supporting previous speculation that the CLG may be a satellite intrusion of the Duluth Complex. Despite current geochronology data to the contrary, the results of this study strongly suggest that the CLG and the MMD are petrogenetically linked, if not parts of the same intrusive system.

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The Brussels Hill Structure, Door County, Wisconsin: Impact crater, diatreme or other?

OLSEN-VALDEZ, Juliana and BJØRNERUD, Marcia

Geology Department, Lawrence University 711 E Boldt Way, Appleton, WI 54911 USA

Brussels Hill (44.759°N, 87.593°W) is a localized area of intensely fractured and faulted bedrock in a region of otherwise undeformed lower Silurian dolostone. It was first identified as a geologic anomaly by Kluessendorf (2011), who suggested that the site was an impact crater. More recently, Lawrence University students have carried out geological and geophysical surveys of Brussels Hill (e.g., Zawacki & Bjørnerud, 2014), and in 2017 we obtained a ca.100 m core from the center of the structure. While some characteristics of the site are consistent with an eroded impact crater, others are at odds with this hypothesis.

The area of disturbed rock coincides with a distinctive, nearly circular, flat-topped topographic high, ca. 2 km in diameter, which stands 40 m above the surrounding landscape and is ringed by rugged, tree-covered slopes. Around the edges of the hill, most prominently on the north side of the structure, the Silurian bedrock dips gently (15-20°) inward. Glacial till lies above the dolostone at the top of the hill. A quarry near the central part of the disturbed area provides excellent three-dimensional exposures of the most intensely deformed bedrock. In the quarry, bedding orientations vary dramatically over distances of meters. Coherent structures are difficult to discern, and the rocks are fragmented at every scale. In places, primary layering can be traced for tens of meters, while elsewhere the rocks are pervasively brecciated to centimeter- or smaller-sized clasts. Some breccias are monomict but most are polymict, containing dolostone and chert clasts with a variety textures and hues. Both types of breccia commonly contain subspherical vugs 1-5 mm in diameter. The breccias lack any sort of internal stratigraphy and are thus unlikely to represent fall-back ejecta, as first suggested by Kluessendorf (2011). No shatter cones have been observed, even though the finely crystalline host dolostone would be favorable for their formation.

Silurian dolostone is the only bedrock normally exposed in this area, but meter-scale lenseoid and tabular bodies of fine-grained glauconite-bearing sandstone occur at Brussels Hill. These sandstones have a carbonate matrix with spherical, sub-mm-scale voids. Many also have fine laminae that parallel the edges of the bodies. Most of the grains in the sandstones are highly rounded, but about 15% have unusual shapes: shard-like, crescentic, and irregularly concavo-convex. No shock lamellae have been observed in the quartz grains. The mature, rounded grains and presence of glauconite suggest that these sands were derived from Cambrian or possibly Ordovician strata that normally lie 350 to 400 m in the subsurface in Door County, and their presence rules out a karstic collapse origin for the disturbance.

We conducted a gravity survey of Brussels Hill using a LaCoste-Romberg gravimeter and Trimble differential GPS system (Edwards, 2016). N-S and E-W transects with readings every 200 m were made across the hill, extending on the north and west into areas where bedrock is undisturbed. Using the GPS ‘base and rover’ system, station locations were sited to 1 cm precision. After free-air, terrain, and tidal corrections of the time-stamped and geo-located data, the resulting Bouguer anomaly map revealed a small but significant positive gravity anomaly of 0.85 mGal near the center of the hilltop. Because the brecciated rocks exposed at the surface have a lower density (ca. 2.5 g/cm³) than the surrounding pristine dolostone (2.8 g/cm³), the observation of a positive gravity indicates that there must be relatively dense rocks in the subsurface below the center of the Brussels Hill structure.

We have recently logged a 103-m drill core from the quarry, obtained in cooperation with the Wisconsin Geological and Natural History Survey. The rocks in the core are brecciated to varying degrees to a depth of about 70 m, and the core intercepted the Upper Ordovician Maquoketa Shale at about 66 m. The brecciated zones are similar to those exposed at the surface, with vug size broadly correlated with the size of clasts. Thin sections of apparently intrusive veins of brecciated material show crude size sorting. Chert clasts in the core have a wide range of colors – not only white and grey, common in the Silurian units -- but also beige, green, dark red and brown, perhaps from Ordovician strata. Some brown cherts are shattered dilatantly in a manner that suggests explosive decompression. Collectively, these observations point to the involvement of a gas phase that forcefully propelled broken rock upward from significant depth and into a complex network of fractures.

The biggest surprise from the drilling was that the lowest rocks in the core – about 30 m of the Maquoketa Shale -- are almost undeformed. This was unexpected, given that material from underlying Cambrian/Ordovician units is intermingled with the Silurian dolostones above; the exotic sandstones and cherts must have passed through the Maquoketa level *en route* to the surface. Our provisional interpretation is that the Maquoketa Shale, which acts as a regional aquitard in the modern groundwater system, behaved in a similar way in the face of the gas pressures during the explosive event at Brussels Hill. In an impact scenario, carbon dioxide released by shock-related devolatilization of carbonate rocks in the deep subsurface may have been trapped by the low-permeability Maquoketa Shale, which then failed locally, providing isolated conduits for deep-seated rocks to be brought to the surface by over-pressured gases. The drilling site was apparently not one of those spots.

However, recent experiments on carbonates in shock metamorphism (Bell, 2016) show that the pressures required for devolatilization of calcite and dolomite exceed 20 GPa – higher than the transient pressures needed to form shatter cones and planar deformation features in quartz (ca. 8 and 12 GPa, respectively), which are absent at Brussels Hill. Other inconsistencies with the impact hypothesis are 1) the inward dips of the beds around the disturbed zone and 2) the height of the hill, which at 40 m is about 10 times higher than the expected central uplift for a crater of 2-3 km diameter (Cintala & Grieve, 1992).

We therefore speculate that the disturbance was caused by an overpressured gas phase that came from below, perhaps from a kimberlite or similar intrusion. In this case, the gases that formed the vuggy rocks and carried rocks up from lower stratigraphic levels may have left a distinctive geochemical signature. Preliminary XRF and cathodoluminescence analyses do suggest that some of the carbonate material in the vuggiest breccias and intrusive sandstone bodies is chemically distinct, with elevated Sr values and blebby occurrences of calcite (in rocks that are otherwise entirely dolomitic). The Brussels Hill structure lies about 160 km south of the Jurassic Lake Ellen kimberlite in Iron County, MI (Cannon & Mudrey, 1981; Zartman et al., 2013).

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Komatiite-hosted nickel-copper mineralization potential in the eastern Shebandowan Greenstone Belt, Ontario, Canada

OLSON, Maile J¹., LODGE, Robert W. D¹., and HINZ, Sheree²

¹Department of Geology, University of Wisconsin-Eau Claire, Eau Claire, WI 54702-4004

²Ontario Geological Survey, Thunder Bay, ON, Canada, P7E 6S8

Komatiite-hosting strata in Archean greenstone belts are important exploration targets because of the potential for hosting nickel-copper (Ni-Cu) magmatic sulfides (e.g. Houlié 2011). The 2.72 Ga Shebandowan greenstone belt, which is part of the Wawa-Abitibi terrane (Stott et al. 2010), has known to host such deposits in the western part of the belt at the Shebandowan Nickel Mine (Morton 1982). Despite abundant komatiite deposits in the Eastern part of the belt, no other magmatic sulfide deposits have been discovered in this region to date. Our research continues to refine geochemical and textural data that provides evidence of assimilation and supports interactions between komatiites and silica- and sulfur-rich sedimentary rocks. This project explores the potential for Ni-Cu deposits in this region. Furthermore, petrographic and geochemical study of these rocks can improve our limited understanding of Archean tectonic processes.

Komatiites were formed during the Archean when young Earth had enough heat to produce large volumes of mantle-derived magmas. Because these komatiitic melts have such an extremely high temperature, they thermally mechanically erode the base of the flow deposit, carving out a channel for itself, giving the melt the ability to assimilate the host rock. When ultramafic magmas assimilate sulfur-bearing crustal sedimentary rocks, they can form Ni-Cu-PGE deposits.

Detailed field mapping of bedrock exposures was completed in the Bateman property exploration trenches, dug in 2008 by Linear Metals Corporation and expands on previous research by Hinz and Hollings (2015). These exploration trenches improved and expanded the available outcrop surface, giving the opportunity to observe the stratigraphy of komatiite flows and how they interact with the surrounding strata. Original textures have largely been preserved in this area due to minimal deformation and metamorphism so textural evidence can be used as a good indicator of komatiite-sediment interaction. Preliminary results from textural, petrographic, and geochemical analyses provide indication of komatiite-sediment intermingling and the presence of Ni-Cu-PGE sulfides.

Fig. 1.A-B shows komatiite-sediment contact textures in outcrop with the lighter colored chert being brecciated in contact with the ultramafic flow. The bedding in the chert are being truncated and the edges of the breccia fragments are rounded and potentially thermally eroded (Fig. 1.A). Transmitted-light petrography, and whole rock geochemical analyses were used on the collected samples. Fig. 1.B shows the chert and komatiite have a very chaotic contact zone with arms and irregular blobs of each rock type. In some areas, the contact is diffuse. Other textures include variolitic glassy margins, rounded sedimentary inclusions, and disruption of chert laminations, suggesting the two rock types had interactions prior to lithification. Fig. 1.C-D are petrographic photos of thin sections from the samples and have jigsaw brecciation as well as rounded edges of brecciated sediment clasts from komatiite assimilation. Fig. 1.D also has a diffuse contact that distinctly presents evidence for komatiite-sediment mingling and potential partial melting of the sedimentary rock. The irregularity of the contact and brecciation expresses that the fracture mechanism is not tectonic but is due to hot komatiites shattering colder

sediments. Geochemical diagrams show the compositional array of komatiites deflects towards the calc-alkalic part of the diagram which is unusual for these magmatic suites and is likely caused by contamination. Melt modeling diagrams showing komatiite-sediment interactions with potential melt compositions display geochemical ranges that cannot be explained by fractional crystallization but instead seems to have a mixing pattern with the sedimentary rock.

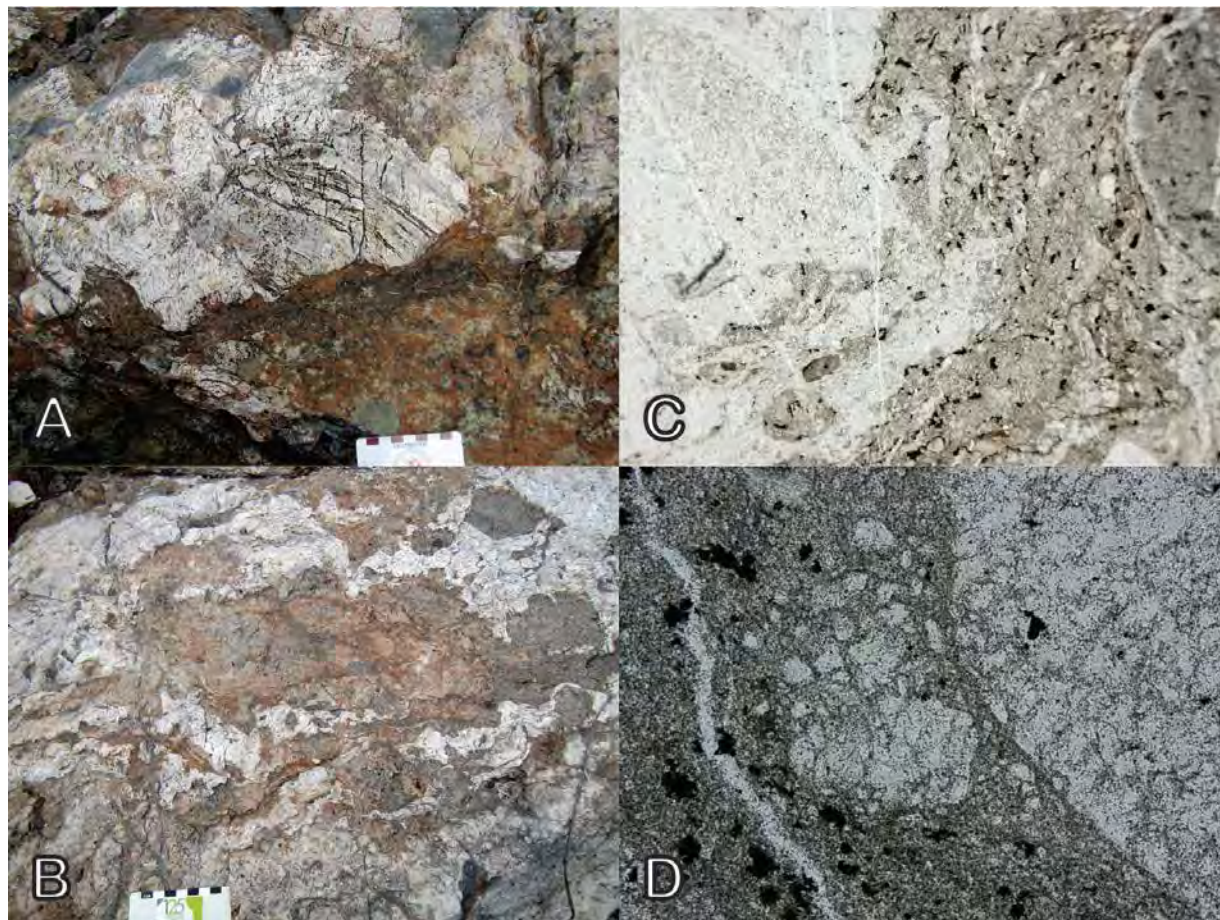


Figure 1: A-B) Outcrop photographs illustrating the various contact relationships between light colored metasedimentary and dark colored mafic to ultramafic units exposed in the Bateman Property trenches. **C-D)** Petrographic photographs illustrating the same contact relationships.

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Assembling Minnesota: Integration of 140 Years of Government, Academic, and Industry Geologic Studies into a Seamless Statewide GIS Database

PETERSON, DEAN M.¹

¹Natural Resources Research Institute, University of Minnesota Duluth, 5013 Miller Trunk Highway, Duluth, Minnesota 55811-1442. dmpeters@d.umn.edu

Over the last 140 years, the search for ores and the mining of mineral deposits has played a huge role in revealing the geology of Minnesota. Dozens of companies utilized classic exploration techniques (geological mapping, geophysical surveying, geochemical studies, test pitting, drilling, and shaft sinking) to target, develop, and mine ore deposits. The early successes (1880s) of these endeavors drove home to forward thinking individuals in government and at the University of Minnesota the need to understand and characterize the geology of the state in a broad context. These developments included regulations to manage lands and archive company data, long-lived programs in mineral processing and metallurgy research, and dedicated programs to map the bedrock geology of the state (Figure 1). All told, a vast amount of information exists on the geology of Minnesota in archives of state agencies, at colleges and universities, and within the United States (USGS) and Minnesota geological surveys (MGS).

However, much of this information is currently still archived in file cabinets in analog form (paper maps, documents, folios), though vast amounts of these data have been scanned and are accessible online. Although great strides have been made to integrate these historic datasets into ongoing digital geologic products, major gaps exist and the standardization of how to capture and digitally archive the geologic facts these data hold is by no means complete. To encourage the development of, and risk assessment tools for, an environmentally sound mining industry, government agencies need to put forth both attractive and competitive policies as well as **robust geological information**. This is particularly true for the mineral exploration component of the mining industry, for without exploration activities the eventual development and extraction of minerals will not take place.

Therefore, the University of Minnesota's Natural Resources Research Institute (NRRI) has begun a copyrighted internal initiative to create a seamless digital GIS compilation (Table 1) that preserves, integrates, and interprets all of the known and trusted bedrock geological data for the entire state of Minnesota, i.e., **Assembling Minnesota**. The completion of such a compilation in a format prepared for integrated modeling via spatial analysis is a formidable task, and in the end can take many years to complete. This geological compilation is designed to preserve the observed facts generated by geologists/geophysicists/ geochemists in the field over the last 140 years in a way that future geologists may use to make new geological interpretations long into the future.

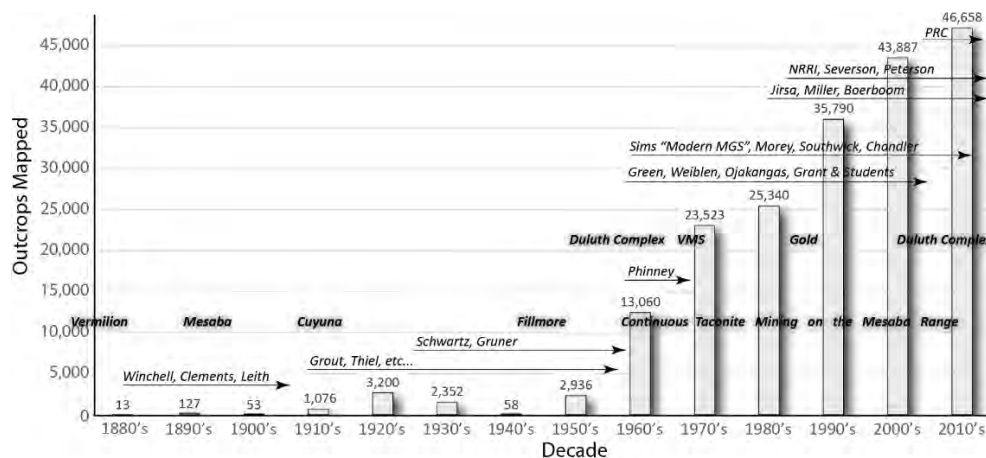


Figure 1. Timeline of outcrop mapping and mineral exploration/development in Minnesota.

Table 1. Listing of the current datasets in the Natural Resources Research Institute's, Assembling Minnesota geological GIS compilation, © 2018 Regents of the University of Minnesota. All rights reserved.

	Name	Type	Description	Entities
Geology	Precambrian Geology Map	Polygon	Seamless detailed Precambrian bedrock geology map of Minnesota. Utilizes all of the known and trusted geologic mapping data.	13,365
	Geolines	Polyline	Fully categorized and topologically correct line theme. Ready for all types of spatial analysis of mineral potential.	60,853
	Geosymbols	Point	Location of measured geologic feature/structure.	19,104
	Outcrops	Polygon	Fully described description of exposed bedrock outcrops and many vertical projections of rocks cut in drill holes.	198,083
	Drill Holes	Point	Collar Location of Drill Holes	98,000
	Geochemistry	Point	3D location of samples taken for geochemical analyses (rocks, drill core, till, soil, seeps, lake sediments).	193,000
	Depth to Bedrock	Image	Color image of depth to bedrock	1
Geophysics	State_Gravity.tif	Image	500 meter gridded color image	1
	State Magnetics	Image	Four 100 meter gridded shaded relief images with different illuminations	4
	Airborne_EM_Survey_Boundary	Polyline	Boundary of airborne geophysical surveys.	24
	Airborne_EM	Point	Point theme of airborne electromagnetic anomalies (EM). In other words, locations where the Earth conducts electricity.	9,139
	Airborne_EM_Interpretation	Polyline	Line theme digitized from airborne EM maps where the survey geophysicist thought point anomalies connect.	241
	Helicopter_EM_Points	Point	Point theme of airborne EM follow-up detailed helicopter EM survey.	530
	Helicopter_EM_Interpretation	Polyline	Line theme digitized from helicopter detailed EM maps where the survey geophysicist thought point anomalies connect.	253
	Ground_EM	Polyline	Line theme digitized from exploration company maps in the MNDNR archive.	230
Mineral Occurrences	NRRI_MinOccur_Minerals	Polygon	Rock-based mineral occurrences with data taken from various attribute table columns from the NRRI_MinOccur_(Rocks, DDH, and Prospect) datasets and fully attributed with individual minerals.	43,732
	NRRI_MinOccur_Rocks	Polygon	Mineral occurrences from surface exposures	14,161
	NRRI_MinOccur_DDHH	Polygon	Mineral occurrences from drill holes	29,332
	NRRI_MinOccur_Prospect	Polygon	Mineral occurrences from trenches, test pits, prospects	239
	NRRI_MinOccur_Underground	Polygon	Mined underground Iron/Iron-Manganese ores.	555
	NRRI_MinOccur_OpenPit	Polygon	Open pit iron mines, including Taconite, Natural Ores, and Bog Ores	449
	NRRI_MinOccur_GravelPit	Polygon	Gravel pits, not close to being complete	1282
	NRRI_MinOccur_Quarry	Polygon	Various types of quarries, including dimension stone and aggregate	230
Other Things	NRRI_Gold_Potential_Model	Polygon	Gold potential model based on proximity to, curvature of, and sense of shear of primary shear zones	971
	DC_Mineral_Resources	Polygon	Historic and NI 43-101 compliant mineral resources within the Duluth Complex	52
	NRRI_Mesabi_Tailings	Polygon	Tailings basins, Mesabi Iron Range	204
	NRRI_Mesabi_Stockpiles	Polygon	Stockpiles, Mesabi Iron Range	1,754
	NRRI_Mesabi_Mine_Features	Polygon	Mine features, Mesabi Iron Range	2,285

Modeling the Precambrian topography of Columbia County, Wisconsin using two-dimensional models of Gravity and Aeromagnetic data and Well Construction Reports

RASMUSSEN, Joseph¹, KINGSBURY STEWART, Esther², SKALBECK, John¹, and GOTKOWITZ, Madeline²

¹*University of Wisconsin-Parkside, 900 Wood Road, Kenosha, WI 53141*

²*Wisconsin Geologic and Natural History Survey, 3817 Mineral Point Road, Madison, WI 53705*

The Cambrian-Ordovician aquifer is the primary source of groundwater for high-capacity wells across much of Wisconsin. This prominent groundwater system is over 2000 feet thick in some areas and is impacted by the underlying crystalline Precambrian basement (Leaf et al., 2014), which includes many irregularities, the most prominent of which is the Baraboo Syncline of Columbia and Sauk Counties.

This project is a continuation of previous work done in Dodge and Fond du Lac Counties by the University of Wisconsin-Parkside and the Wisconsin Geological & Natural History Survey (MacAlister et al., 2016). The goal of this project is to produce an updated Precambrian topographic map of Southern Wisconsin by using gravity and aeromagnetic data to interpret Precambrian topography away from outcrop and boreholes. This will improve definition of the lower extent of the aquifer, aiding water supply management efforts.

Modeling of gravity and aeromagnetic data from the United States Geological Survey (Snyder and Daniels, 2002) was conducted using GM-SYS 3D modeling software in Geosoft Oasis Montaj. Grids of subsurface layers were created from the data and constrained by well and drilling records as well as outcrop maps that were digitized using ArcMAP (Dalziel and Dott, 1970). The Precambrian basement underlying Columbia County is comprised of ca 1.75 Ga granites and rhyolites that are non-conformably overlain by <1.71 Ga quartzite, slate, and iron-formation of the Baraboo interval (Medaris et al., 2003). The Baraboo interval metasedimentary rocks and underlying granite and rhyolite was subsequently folded and faulted (e.g. Dalziel and Dott, 1970). The folded layer of iron-formation provides a telltale signatures that aids construction of geophysical models because it has an average magnetic susceptibility of 53000 μcgs , compared to the average susceptibility of the rest of the bedrock of around 1500 μcgs . We use geologic mapping and cross-sections, drill core, magnetic susceptibility and density measurements, petrography and geochemistry, and well construction reports to refine physical modeling constraints. Preliminary results indicate (1) regional Precambrian geology may be interpreted from geophysical data and (2) Precambrian topography is controlled by Precambrian geology and is therefore somewhat predictable.

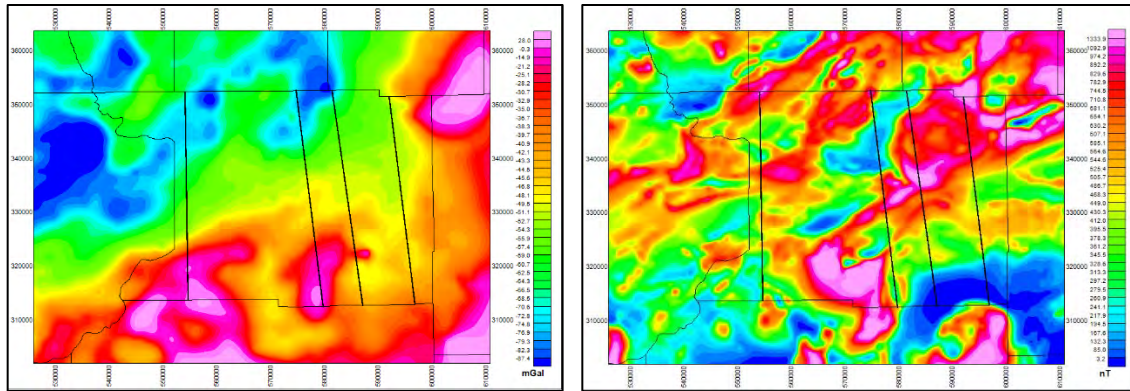


Figure 1 – Gravity (left) and Aeromagnetic (right) anomaly maps of Columbia County showing the location of 2D models.

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Pilot study results for potential lithium mineralization on State-managed mineral rights in Minnesota

REED, Andrea

Minnesota Department of Natural Resources, 1525 3rd Avenue East, Hibbing, MN 55746

The Minnesota Department of Natural Resources (DNR) manages mineral rights on approximately 12 million acres of land. The royalties and rentals generated from these lands help fund Minnesota's School and University Trusts, the state General Fund, and local governments. To improve the earnings for these entities, the DNR maintains and collects mineral exploration data. The DNR also seeks opportunities to diversify Minnesota's nonferrous mineral portfolio. With lithium recognized as an element critical for clean energy development (U.S. Department of Energy 2010) and an increasing demand for it, the DNR decided to conduct a pilot study on the potential for lithium occurrences in Minnesota.

Of the different lithium deposit types, granitic pegmatites seem to show the most promise of hosting lithium occurrences in Minnesota. Igneous and metamorphic rocks cover a significant portion of the state and are the host rocks for pegmatites (London 2008). Pegmatites host known lithium occurrences in the Quetico Subprovince (the Georgia Lake pegmatites) and Wabigoon Subprovince (Mavis Lake pegmatite group) in Ontario (Selway *et al.* 2005). A minor amount of lithium is known to occur in the abandoned Rader Mine near Lake of the Woods, on the Minnesota side of the Wabigoon Subprovince (Zamzow & Morey 1991).

The pilot study site is located in the Quetico Subprovince on Public School Trust Land northeast of Orr, MN. Little was initially known about the site other than it contained a large pegmatitic granite outcrop. Bulk samples (roughly 4 kg each) of rock were taken from a single pegmatite dike to determine the type of granite and identify the presence of lithium and other trace elements. Small chip samples of feldspar were taken from multiple places along the length of multiple dikes to assess overall fractionation trends. Similar methods are generally accepted for rare element-bearing granitic pegmatite exploration (*e.g.*, Černý 1991, Selway *et al.* 2005). In addition, nearby glacial till was sampled to see if Laser-Induced Breakdown Spectroscopy (LIBS) could be used to link sand fraction sediments to the pegmatite outcrop. The results for the pegmatite sampling are presented here.

Three pale pink monzogranite-pegmatite dikes were identified in the course of fieldwork. The dikes range from 1 to 15 meters in width in outcrop, strike slightly north of east, and have variable apparent dips to the south. Textures range from aplitic to pegmatitic (up to 10 × 20 cm crystals), with the most common grain size being medium- to coarse-grained granite. Mineralogy is principally composed of feldspars and quartz with trace amounts of magnetite, biotite, and apatite (in order of decreasing abundance).

Using the methods and descriptions of Frost *et al.* (2001), Whalen *et al.* (1987), London (2008), Černý (1991), whole rock analysis of the bulk samples indicate a mixed A- and I-type signature (tending more towards A-type) and a weakly peralkaline to metaluminous nature, suggesting the sampled dike should be categorized as an NYF granite. Trace element analysis revealed low lithium and REE content, slightly increasing fractionation to the west in the Rb/Sr, Rb/Ba, and La/Yb ratios, confirmation of the non-peraluminous nature of the dike in the Zr/Hf ratio, and confirmation of the A-type signature in the behavior of the REE pattern.

Electron microprobe analysis of k-feldspar in collected perthite chip samples reveals that the ratios of Rb/Ba, Rb/Sr, and K/Rb, as well as the distribution of P, (London 2008, London &

Černý 1990) show a strong increasing fractionation trend of this dike set to the northwest. It also shows a slight increasing fractionation trend to the west, confirming the trend pattern seen in the bulk samples. In general, the fractionation trend of these granitic dikes is oriented approximately perpendicular to their strike.

Overall, the results suggest that lithium is unlikely to be a significant component in any rocks related to this specific granitic system, even if the identified fractionation trend were to be followed beyond the bounds of the pilot site.

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Variation trends in sulfur isotope ratios at the Eagle and East Eagle intrusions and the surrounding country and basement rocks of the Baraga Basin, Upper Peninsula, Michigan

ROSE, Katharine¹; ESSIG, Espree² and THAKURTA, Joyashish¹

¹Department of Geological and Environmental Sciences, Western Michigan University,
1903 W. Michigan Ave. Kalamazoo, MI 49008

²Eagle Mine, Lundin Mining Corporation, 4547 County Road, Champion, MI 49814

The Eagle Ni-Cu sulfide deposit in Marquette County, Michigan is a magmatic sulfide deposit composed of massive, semi-massive and disseminated sulfide minerals hosted in conduit-shaped peridotitic intrusive rocks in the Baraga Basin (Ding et al., 2010). The intrusion has been dated at 1.1 Ga and has been interpreted to be a part of the magmatism associated with the Mesoproterozoic Midcontinent Rift event. Although the ore-grade Ni-Cu sulfide mineralization is located in the sulfide rich part of the intrusive bodies (Figure 1 and 2), relatively small amounts of sulfide minerals are dispersed throughout the intrusion and in the immediate country rocks of the metamorphosed Paleoproterozoic Michigamme Formation and further in the Archean granite-gneiss which forms the basement rock of the Baraga Basin area of UP Michigan (Ding et al., 2012; Hinks, 2016). $\delta^{34}\text{S}$ ‰ (V-CDT) values have been determined from sulfide minerals of the Eagle and East Eagle intrusions. The distribution trends in the isotope ratio has been studied with respect to spatial directions as well as rock compositions.

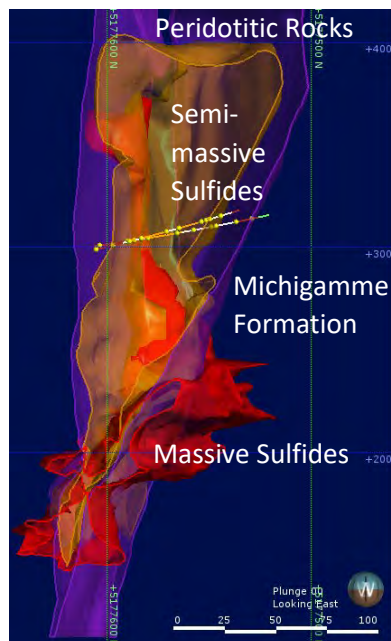


Figure 1: 3-D model of main Eagle intrusion, drill holes EA0300 and EA03301, looking to the east. (Source: Eagle Mine)

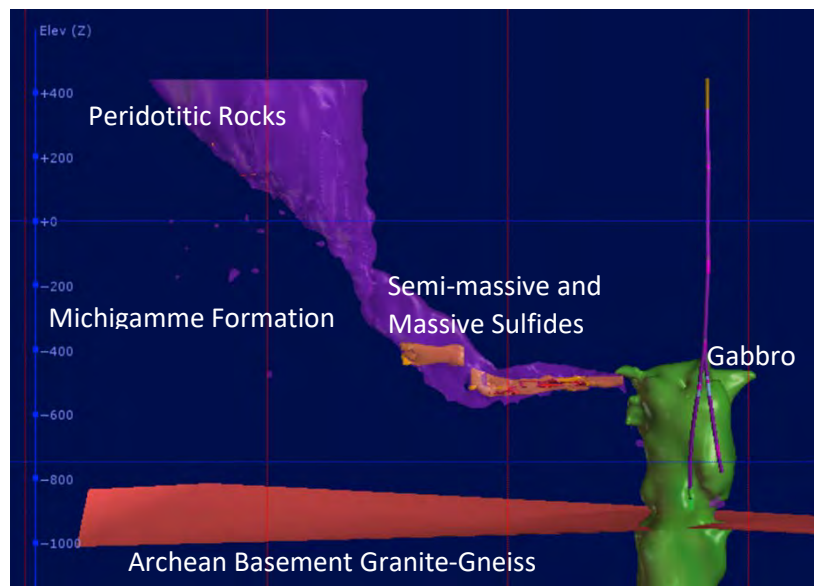


Figure 2: 3-D model of Eagle East intrusion, looking to the north, with drill hole 17EA364 and 17EA364A. (Source: Eagle Mine)

Based on previous (Hinks, 2016) and present studies, $\delta^{34}\text{S}$ values of pyrrhotite, chalcopyrite and pentlandite in the massive, semi-massive and disseminated sulfides vary within a range of 0‰ to 5‰. Disseminated pyrite and pyrrhotite in Michigamme Formation slates display $\delta^{34}\text{S}$ values from 6‰ to 32‰. Disseminated pyrite grains in the Archean basement rocks also display a wide range of $\delta^{34}\text{S}$ values from -11‰ to 7‰. The distribution of $\delta^{34}\text{S}$ data in the country and basement rocks, when observed from a directional standpoint along depths of drill-cores show a variation from 10‰ to 2‰ towards the intrusion from the surrounding rocks. However, variations in $\delta^{34}\text{S}$ values are more distinct from one rock type to another. New data from this study (Table 1) show that within the spatial domain of the sulfide deposit the $\delta^{34}\text{S}$ changes are more uniform and within a narrower range between 2‰ and 3‰ for the Eagle intrusion.

Drill Hole	Sample ID	$\delta^{34}\text{S}\text{‰}$	Unit
17EA364	KGR-03-a	32.6	MF
17EA360D	KGR-18-a	2.6	Gabbro
17EA360D	KGR-18-b	2.5	Gabbro
17EA360D	KGR-26-a	6.1	BSMT
EAUG 0300	KGR-37-a	2.6	SMSU
EAUG 0300	KGR-37-b	2.5	SMSU
EAUG 0300	KGR-38-a	2.9	SMSU
EAUG 0300	KGR-38-b	2.8	SMSU
EAUG 0300	KGR-39-a	3.1	SMSU
EAUG 0300	KGR-39-b	3.0	SMSU
EAUG 0300	KGR-40-a	3.0	SMSU
EAUG 0300	KGR-41-a	2.9	SMSU
MF-Michigamme Formation			
SMSU-Semi-Massive Sulfide Unit			
BSMT-Archean Basement Granite			

Table 1: Sulfur isotope ratios determined from sulfide minerals in the Eagle intrusion, the surrounding country, and basement rocks of the Baraga Basin.

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Preliminary Investigation of the East Eagle Intrusion Gabbro in Marquette County, Michigan

RUPP, Kevin¹, THAKURTA, Joyashish¹, and MAHIN, Robert²

¹*Department of Geosciences, Western Michigan University, 1903 W. Michigan Ave. Kalamazoo, MI 49008*

²*Eagle Mine, Lundin Mining Corporation, 4547 County Road, Champion, MI 49814*

The Eagle deposit is a high-grade, mafic to ultramafic Ni-Cu-bearing sulfide deposit located in Michigan's Upper Peninsula in Marquette County. The Eagle and East Eagle intrusions are associated with the ~1.1 Ga Midcontinent Rift System and are also associated with the east-west trending Marquette-Baraga dike swarm. Current proven and probable reserves for Eagle are 4.8 million tonnes with an average grade of 2.8% Ni, 2.4% Cu, 0.1% Co, 0.3 gpt Au, 3.4 gpt Ag, 0.7 gpt Pt, and 0.5 gpt Pd (Clow et al., 2017). Recent drilling programs have intersected a vertical gabbroic rock unit in contact with the high-grade mineralization zone of the East Eagle conduit (figure 1). Initial geochemical analysis indicate that the gabbro is depleted in Cu and PGE and becomes more enriched in MgO and FeO with depth. Intrusions depleted in metals often overlie massive sulfide deposits due to the preferential accumulation of metals within sulfide minerals. This is significant in that the gabbroic unit could indicate another massive sulfide deposit at the base of the intrusion.

This study attempts to determine the relationship between the gabbroic unit and the known Eagle intrusions based on petrological and geochemical data. Primary objectives of this project are: (1) age determinations using the U-Pb zircon/baddeleyite method, (2) comparison of the gabbroic samples with Eagle and East Eagle based on petrography, whole and trace element geochemistry, and mineral compositions, and (3) comparison of sulfur isotope values with the known values for the Eagle and East Eagle intrusions. The Eagle intrusions were radiometrically age dated and determined to be 1107.3 ± 3.7 Ma (Ding et al, 2010). If these ages are similar, the prospect for sulfide mineralization in a lower staging chamber will be heightened. Previous geochemical studies on the Eagle intrusion show FeO/MgO ratios and the Al₂O₃ contents of parental magmas to be within the range of picritic basalts erupted during early-stages of the Mid-continent Rift. Whole and trace element geochemical analysis, along with microprobe analysis, will aid in determining the genetic relationship between Eagle and the gabbroic unit. Textural and isotopic characteristics of disseminated sulfides hosted within the gabbro will also be analyzed using reflected light microscopy and a Delta V Mass Spectrometer.

Preliminary samples show high degrees of sericitic, propylitic, and carbonate alterations which decrease with depth away from the East Eagle intrusion. Pervasive alteration in many of the samples makes distinguishing individual mineral phases and textures difficult, but primary relict textures (mainly olivine) are seen throughout the samples. Most samples resemble a medium to fine-grained, olivine magnetite gabbro. Plagioclase (50-60%) occurs as subprismatic to lath-like grains that are moderately to strongly altered (up to 60% alteration minerals) to sericite. Olivine (2-8%) are distinguish by subprismatic to subhedral relict grains that altered (90-100% alteration minerals) to serpentine and iron-rich oxides. Subprismatic pyroxenes (10-20%) show varying degrees of chlorite alteration to chlorite. Disseminated sulfide mineralization is observed with major sulfide minerals consisting of pyrite, pyrrhotite, chalcopyrite, and pentlandite. Electron microprobe analysis is needed to determine the specific mineral compositions.

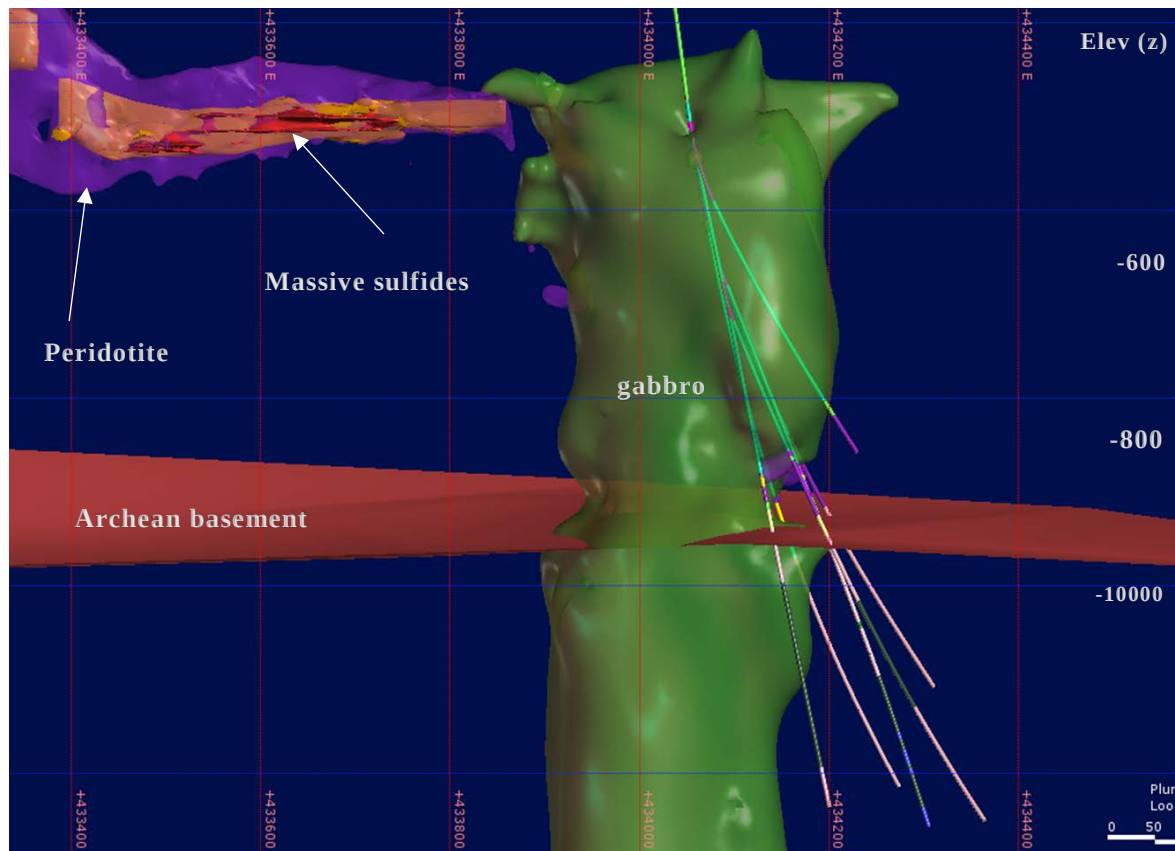


Figure 1: A North-facing 3D-model of the gabbroic unit adjacent to the massive sulfide deposit of East Eagle. Drill core 17EA360 is shown intersecting the gabbroic unit and continuing down through the Archean Basement (image courtesy of Lundin Mining Corporation. Special thanks to Espree Essig and the exploration team)

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High-technology metal behavior in ore-forming environments and its implication for the Vermilion District, northern Minnesota.

SCHARDT, Christian and DAVID, Mady

*Department of Earth and Environmental Sciences, University of Minnesota-Duluth, 1114 Kirby Dr.
Duluth, MN 55812*

High-technology metals (HTM), such as In, Ge, Ga, and Tl, are increasingly important for essential industrial applications as well as renewable energy technology. They typically occur in very low concentrations (~ 1 ppm; Terashima 2001) and may reach concentrations of up to 0.15 % in some deposits (e.g., Li et al., 2015). As they do not form ore minerals, they substitute for other metals (Cu, Zn, Sn) in ore mineral such as sphalerite, chalcopyrite, and stannite (Johan, 1988, Pavlova et al, 2015). As a consequence, these metals are sourced as byproducts from other ore deposits (Ishihara and Endo, 2007; Pavlova et al. 2015). While the formation of these ore deposits is relatively well understood, it remains unclear why these metals are restricted to certain ore deposits. This is due to our poor understanding of their general thermodynamic behavior, sourcing, transport, and enrichment mechanisms in selective ore deposition environments. In fact, there is a surprising lack of data regarding the concentration of these metals in various geological settings and their sourcing in ore-forming systems.

To better understand the behavior of these metals and gain insight into their enrichment, crustal abundances and concentrations in other sources (seawater, rivers, hydrothermal fluids) were collected along with available data from deposits with confirmed HTM enrichment (volcanogenic massive sulfides, Mississippi Valley Type, Sedimentary-Exhalative, tin granites). In addition, existing geochemical data from the Vermilion district (Peterson, 2001), assumed to host potential massive sulfide mineralization, have been supplemented by available till analysis provided by Larson (2018), and new analysis of various drill holes located within in the Vermilion district.

In, Ge, Ga, and Tl show lowest average values in seawater and river waters (< 1 ppb to 0.5 ppm), well below average crustal abundances (up to 15 ppm; see figure 1.). Hydrothermal fluids show concentrations between 0.1 and 10 ppm, close to average crustal averages. HTM values for continental crust (metamorphic, sedimentary, magmatic) show In having the lowest average values (0.1 - 0.5 ppm), increasing to 0.7 ppm for Tl, followed by Ge (1.4 ppm) and Ga (18 ppm; see figure 1). Limited data for the Vermilion district and the Duluth Complex are comparable to trends of other magmatic and volcanic averages, respectively. Results suggest that these HTM are not typically enriched in surface waters (< 1 ppm). Data for hydrothermal fluids show Tl enrichment (up to 20-fold) while In shows average concentrations. Ge and Ga, however, are significantly depleted (Ge: 5-fold; Ga: 2-fold) compared to average crustal abundances. This poses the question where and how HTM get enriched to values recorded in some sulfide deposits (≥ 1000 ppm) and why this process seems to be restricted to certain geological environments.

To study this issue, geochemical data from HTM-bearing ore deposits have been analyzed to determine if differences in the substitution behavior of HMT exist between different ore deposit types. Initial results indicate differences in the substitution behavior of HTM in host rocks (inset figure 1) as well as ore minerals (not shown), which may point to a) variable HTM sourcing, b) mineralization conditions, and/or c) different hydrothermal fluid chemistries as a function of formation environment. Further analysis is underway to determine if this also applies to the Vermilion district and its potential to host significant HTM concentrations.

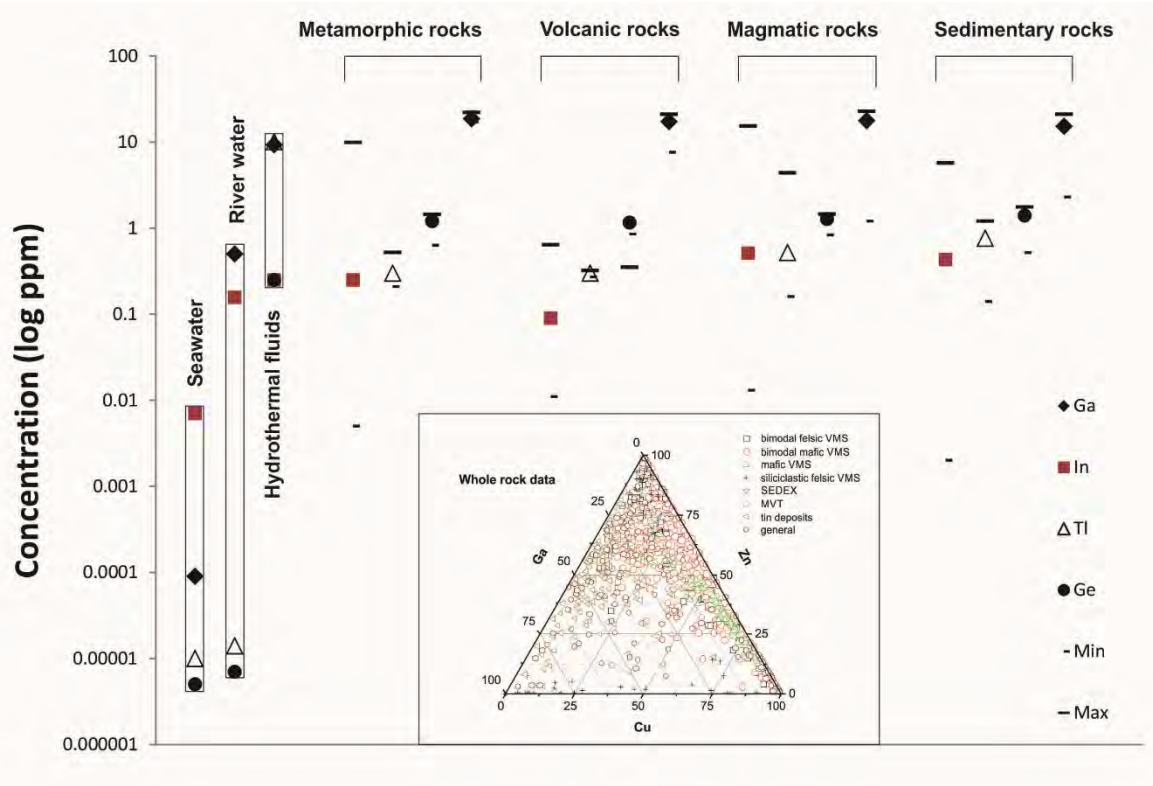


Figure 1 Minimum, average, and maximum concentrations of In, Tl, Ge, and Ga in crustal rocks and fluids. The Vermilion district and the Duluth Complex show patterns similar to other volcanic and magmatic rock data (not shown). Inset: Cu-Ga-Zn ternary plot for whole-rock data from major HTM-bearing deposits (VMS - volcanogenic massive sulfides). Differences exist between mafic/felsic volcanic, plutonic (tin deposits), and sedimentary settings (siliciclastic). Similar trends are also observed for other element combinations, including non HTM elements.

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Geochemistry of mafic rocks in Dickinson County, Michigan: Evidence for ~2.1 Ga Rifting

SCHULZ, K.J.¹, CANNON, W.F.¹, and WOODRUFF, L.G.²,

¹ U.S. Geological Survey, Reston, VA 20192, ² U.S. Geological Survey, Mounds View, MN 55112

Mafic rocks of purported Archean and Paleoproterozoic age are a significant and widespread component of the bedrock geology in Dickinson County, Michigan (James et al., 1961). For this study we have sampled mafic rocks that occur in the Carney Lake Gneiss and other Archean gneisses of the county as well as mafic rocks in the Dickinson Group and the Hardwood Gneiss. Field relations of the mafic rocks in the Archean gneisses are often ambiguous; some are clearly dikes but whether they are Archean or Paleoproterozoic in age is often uncertain.

Mafic rocks in the Carney Lake Gneiss and other Archean gneisses in the region range from highly deformed amphibolite inclusions in granitic gneiss to less deformed “salt and pepper” amphibolites to metadiabase dikes with no penetrative fabric and lower metamorphic grade. We have analyzed ten samples of the “salt and pepper” amphibolites and found two basaltic compositional types. Group 1 samples, two of which are from identified dikes, have relatively low MgO (~4 to 6 wt. %), moderately fractionated incompatible trace element patterns, and negative Nb-Ta anomalies on a primitive mantle normalized (PMn) trace element plot (Figure 1A). In contrast, Group 2 samples, for which field relations are ambiguous, have higher MgO (~6 to 10 wt. %), lower trace element contents than the first group, and distinctive flat PMn trace element patterns (Figure 1A).

The Dickinson Group is composed of the basal East Branch Arkose overlain by the Solberg Schist and Six Mile Lake Amphibolite (James et al., 1961). Two samples of amphibolite collected along strike in the East Branch Arkose have very similar tholeiitic basalt compositions characterized by moderately enriched light REE and no Nb-Ta anomalies on a PMn trace element plot (Figure 1B). A sample of a metadiabase dike cutting Archean granitic gneiss north of the East Branch Arkose sample location and an amphibolite from a road cut to the south near Felch are similar in composition except for a positive Th anomaly when normalized to primitive mantle, which is likely the result of crustal contamination. Samples of mafic rocks from the Solberg Schist range from basalt to andesite (~45 to 56 wt. % SiO₂; ~4 to 12 wt. % MgO), are more enriched in light REE than the amphibolite in the East Branch Arkose, and have negative Nb-Ta anomalies on a PMn trace element plot (Figure 1B). Samples of the Six Mile Lake Amphibolite, in contrast to the amphibolites in the East Branch Arkose and Solberg Schist, have much lower trace element contents and flat PMn trace element patterns much like the Group 2 amphibolites sampled in the Carney Lake Gneiss (Figure 1B). In addition, a large metagabbro body and a dike sampled in the Solberg Schist are similar in composition to the Six Mile Lake Amphibolite. This supports the interpretation that the Six Mile Lake Amphibolite is the upper, youngest part of the Dickinson Group (James et al., 1961).

Samples of mafic gneiss in the Hardwood Gneiss complex are generally similar in composition to the Six Mile Lake Amphibolite with similar low trace element contents and

relatively flat PMn trace element patterns (Figure 1C). One mafic gneiss sample is enriched in light REE and has a large negative Nb-Ta anomaly that is likely the result of contamination by felsic crustal rocks.

Three Paleoproterozoic dike swarms, the Marathon, Kapuskasing, and Fort Frances, which outcrop around the northern margin of Lake Superior and range in age from 2126 to 2067 Ma, are attributed to a long-lived mantle plume event that accompanied rifting along the southern margin of the Superior craton (Halls et al., 2008). Like the mafic rocks in the Dickinson Group, the older dikes (Marathon and Kapuskasing) show enriched and fractionated incompatible trace element patterns while the youngest (Fort Frances) are relatively depleted and have flat trace element patterns. The overlap in composition of the mafic rocks sampled in Dickinson County with the Paleoproterozoic dikes on the north side of Lake Superior suggests the Dickinson County mafic rocks also may be related to the final rifting of the Superior and Wyoming cratons. This is supported by the presence of 2.1 Ga detrital zircons in the East Branch Arkose (Craddock et al., 2013).

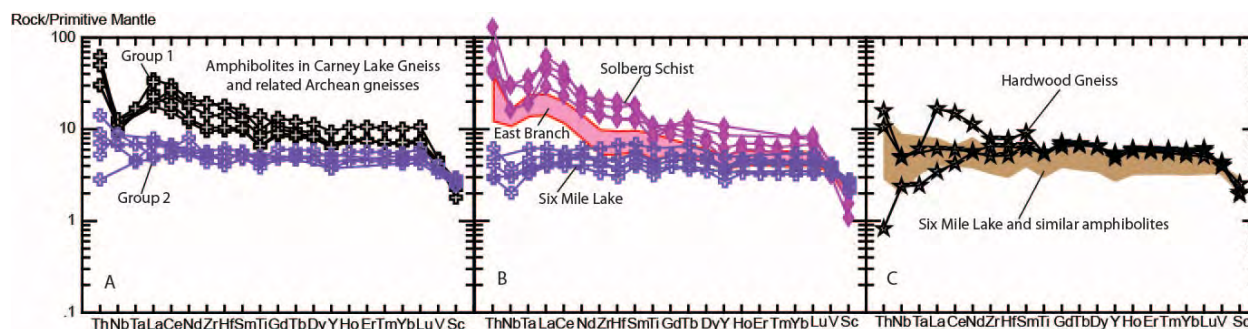


Figure 1. Primitive mantle normalized trace element patterns for mafic rocks from Dickinson County.

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Detrital Zircons in the Waterloo Quartzite, Wisconsin: Implications for the Ages of Deposition and Folding of Supermature Quartzites in the Southern Lake Superior Region

SCHWARTZ, Joshua J.¹, STEWART, Esther K.², and MEDARIS, L. Gordon Jr.³

¹Geological Science, California State University, Northridge, California 91330

²Wisconsin Geological and Natural History Survey, Madison, Wisconsin 53705

³Department of Geoscience, University of Wisconsin–Madison, Madison, Wisconsin 53706

Proterozoic supermature quartzites of the Baraboo Interval are a prominent and significant Precambrian feature of the southern Lake Superior region, covering an area of ~175,000 km². The Waterloo Quartzite in SE Wisconsin has long been correlated with other quartzites of the Baraboo Interval, based on similarities in sedimentary characteristics, geological setting, and chemical composition. Metapelites in the Baraboo and Waterloo sequences are among the most chemically mature sedimentary rocks in the geological record, having Chemical Indices of Alteration of 99.6 and 97.6, respectively. Although similar to the Baraboo Quartzite in many respects, the Waterloo Quartzite differs in having experienced pervasive K–metasomatism (Table 1). In addition, axial-planar cleavage is more strongly developed in quartzite at Waterloo compared to Baraboo, and Waterloo exhibits a higher grade of metamorphism, with Waterloo metapelite containing andalusite (amphibolite facies) and Baraboo metapelite containing pyrophyllite (greenschist facies).

	Waterloo		Baraboo	
	mean	1σ	mean	1σ
	n = 5		n = 4	
SiO ₂	66.19	3.25	66.13	6.85
TiO ₂	0.79	0.05	0.79	0.23
Al ₂ O ₃	17.86	1.77	21.18	4.46
Fe ₂ O ₃	5.02	3.86	5.25	2.14
MnO	0.01	0.01	0.01	0.00
MgO	0.39	0.16	0.04	0.08
CaO	0.13	0.06	0.03	0.01
Na ₂ O	0.19	0.03	0.05	0.04
K ₂ O	4.93	0.42	0.28	0.23
P ₂ O ₅	0.10	0.04	0.09	0.04
LOI	2.94	0.30	4.09	0.71
Sum	99.48		99.07	
CIA	97.6		99.6	

Seven samples of Waterloo quartzite and pebbly quartzite in Dodge county were collected for detrital zircon analysis to evaluate sources of sediment and to determine possible relationships to other supermature quartzites in the region. Samples include five quarried blocks in the Michels Materials Waterloo Quarry and individual samples from outcrops at Hubbleton and Mud Lake. Bedding orientations overlain on an aeromagnetic anomaly map of the area suggest that quartzite at the Michels quarry may be in a lower stratigraphic position than those at the Hubbleton and Mud Lake localities.

A relative probability plot for detrital zircons (filtered for dates <10% discordant) in the Waterloo Quartzite at the Michels quarry displays a strong geon 16 (Mazatzal) and geon 17 (Yavapai) signal, and diminished geon 18 (Penokean) and geon 25–27 (Algoman) signals (Fig. 1A). Maximum Ages of Deposition calculated from the youngest statistically homogenous population (MSWD ≤ 1.0) are 1759±13 (n=21), 1694±11 (n=36), 1671±14 (n=21), 1669±14 (n=21), and 1643±11 Ma (n=42).

In contrast, Waterloo quartzites at Hubbleton and Mud Lake are characterized by an absence of geon 16 zircons, a pronounced Penokean population, and a subdued, but distinct Algoman population (Fig. 1A).

Quartzites in the Baraboo Range, Sauk County, consist of a stratigraphically lower fluvial facies and an upper shoreface marine facies, whose detrital zircon populations differ from each other (Fig. 1B). Fluvial quartzites display a predominant geon 17–18 signal, and shoreface marine quartzites contain a pronounced geon 18–19 population and a distinct geon 25–27 population.

The Algonian, Penokean, and post-Penokean (Yavapai) populations of detrital zircons in the Baraboo quartzites are consistent with derivation from the proximal post-Penokean Montello Batholith and more distal, northerly Penokean and Archean basement; post-Penokean zircons are more abundant in the stratigraphically lower fluvial facies than in the higher shoreface marine facies, which was deposited after burial of the 1750 Ma Montello Batholith. Detrital zircons in Waterloo quartzites at Hubbleton and Mud Lake were also derived from the proximal Montello Batholith and more distal, northerly Penokean and Algonian terranes.

In contrast, Waterloo Quartzite at the Michels quarry is characterized by a relative abundance of geon 16 zircons and a pronounced population peak at 1700 Ma. Clearly, the provenance of this quartzite was different than that of the other analyzed quartzites. Geon 16 juvenile crust is absent in the southern Lake Superior region, but occurs in the subsurface south of Wisconsin as part of the transcontinental 1.68–1.60 Mazatzal belt (Whitmeyer and Karlstrom, 2007). Thus geon 17 and geon 16 zircons in quartzite at the Michels quarry were likely derived by northerly transport from the proximal Yavapai terrane and more distal Mazatzal terrane to the south. The shift in detrital zircon age populations between the Michels quarry and Hubbleton and Mud Lake outcrops reflects a change in transport direction from north to south.

Deposition of quartzite at the Michels quarry is bracketed between ca. 1643 Ma, its youngest maximum age of deposition, and 1452 Ma, the $^{40}\text{Ar}/^{39}\text{Ar}$ cooling age of muscovite in folded metapelite (Medaris et al., 2003). Because the Michels quarry lies stratigraphically below the Hubbleton and Mud Lake outcrops, the depositional age for quartzites at these localities must also be no older than ca. 1640 Ma. The extreme chemical maturity of Waterloo metapelite requires derivation from a region of subdued relief that experienced intense chemical weathering. Such chemical maturity, combined with geon 16 Maximum Ages of Deposition for quartzite at the Michels quarry, is consistent with deposition of the Waterloo Quartzite after the 1630 Ma Mazatzal Orogeny, with depositional space for the thick (~1000 m) quartzite sequence being provided by post-Mazatzal rifting. If this scenario is correct, it requires that deformation and folding of the Waterloo Quartzite occurred during the geon 14 Wolf River tectonomagmatic event.

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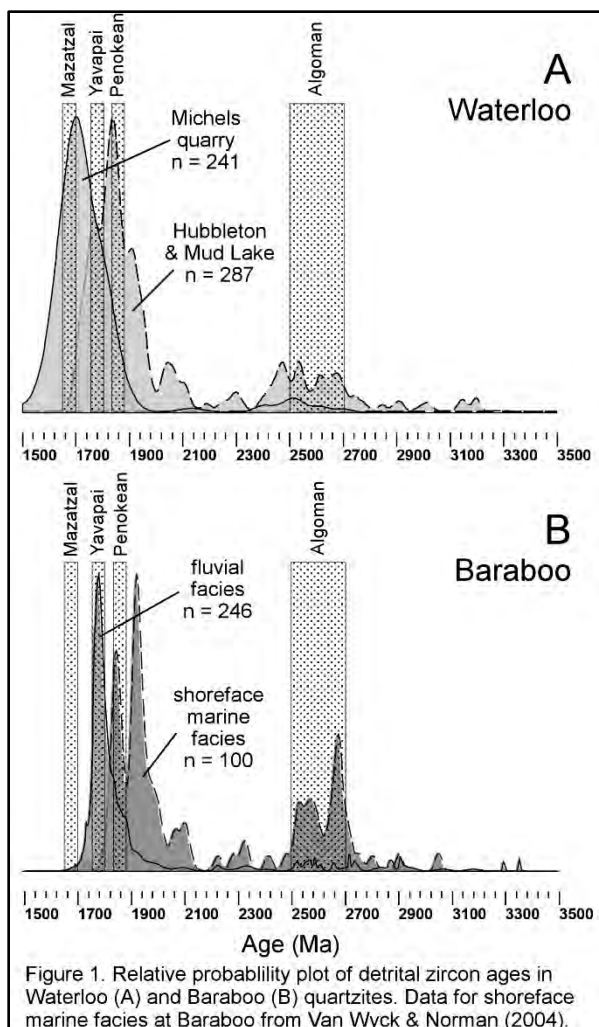


Figure 1. Relative probability plot of detrital zircon ages in Waterloo (A) and Baraboo (B) quartzites. Data for shoreface marine facies at Baraboo from Van Wyck & Norman (2004).

Compositional and geochemical characteristics of the Crystal Lake intrusion, Ontario

SMITH, Jennifer¹, BLEEKER, Wouter¹, ROSSELL, Dean² and LABERGE, Justin²

¹ Geological Survey of Canada, 601 Booth Street, Ottawa, Canada; email:jennifer.smith6@canada.ca

² Rio Tinto Exploration Canada Inc. 1300 Walsh Street, Thunder Bay, Canada

The 1.1 Ga failed rift system hosts a range of mafic-ultramafic, carbonatitic and alkaline intrusions (Bleeker et al., 2018), many of which are actively being explored for a range of commodities (e.g., Ni, Cu, PGE, Co, Cr, V, Nb). The discovery of the high grade, massive sulphide, Ni-Cu Eagle deposit in 2002, has resulted in a surge of exploration activity and interest in the Ni-Cu-PGE potential of the MCR. Early rift (1117 to 1106 Ma) conduit-type, ultramafic intrusions (e.g., Tamarack, Eagle), remain the most attractive but challenging exploration targets (Heaman et al., 2007). The 1099±1 Ma Duluth Complex and similar large, sheet-like intrusions (e.g., Sonju Lake, Mellen Complex, Echo Lake, Crystal Lake, Coldwell Complex) still remain prospective, although typically contain lower metal tenors (Ripley, 2014).

The 1099.1±1.2 Ma (Heaman et al., 2007) Crystal Lake layered intrusion, located 47 km southwest of Thunder Bay, contains low-grade Ni-Cu-PGE sulphide mineralisation and uneconomical chromite occurrences (Geul, 1970; Smith & Sutcliffe, 1987). Although mineralisation was first discovered in the 1950s and has been extensively explored since, the intrusion remains a prospective exploration target with Rio Tinto undertaking more recent drill programs in 2014-15 (Figure 1). This intrusion outcrops as a prominent Y-shaped body, intruding S-bearing shales, argillites and greywackes of the Paleoproterozoic Rove Formation.

Geochemically, the Crystal Lake intrusion can be distinguished from the more primitive conduit-type bodies by: olivine composition (Fo₅₁₋₇₉), low Ni/Cu and Pt/Pd ratios (<1), higher REE abundances, LREE enrichment and minimal fractionation of HREEs (Gd/Yb <2; Thomas, 2015). Previous work divided the intrusion into four discrete zones (Smith & Sutcliffe, 1987). The **Basal Zone** contains an aphanitic chill zone, with inclusions of S-bearing Rove sedimentary rocks. The overlying **Lower Zone** is characterised by medium to pegmatitic, vari-textured gabbro with irregular, coarse segregations of Cr-bearing leucogabbro and anorthosite. The **Middle Zone** marks the beginning of phase layering and comprises four magmatic cycles. Each cycle corresponds to an influx of magma (Cogulu, 1993a) and consists of a basal Cr-spinel bearing troctolite/olivine gabbro and an upper anorthositic gabbro. The Cr-spinel occurs in discrete layers and is recognised within orthocumulate and adcumulate rocks where it constitutes 8 to 36 modal%, respectively. Compositional differences in Cr-spinel occurrences have been attributed to the effects of *in-situ* re-equilibration (Cogulu, 1993a). The **Upper Zone** is marked by the disappearance of Cr-spinel and anorthositic layers. This unit consists of coarse-grained olivine gabbro and medium-grained troctolite. Low-grade, Ni-Cu-PGE sulphide mineralisation is developed throughout the Lower and Middle Zones, with the Upper Zone barren of sulphides.

The Lower Zone is characterised by disseminated to massive sulphides which are mainly concentrated towards the basal contact and within late pegmatitic zones. The association of sulphides with pegmatitic

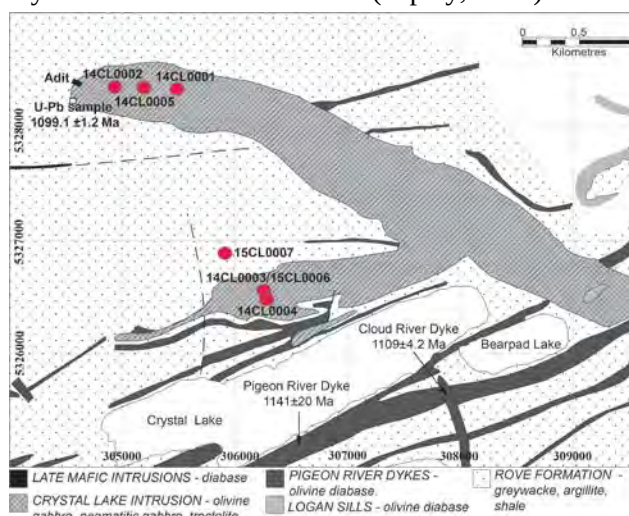


Figure 1. Crystal Lake intrusion and location of Rio Tinto's 2014-2015 boreholes. Adapted from Geul 1970.

phases is not unique to the Crystal Lake intrusion, also being recognised in the Coldwell Complex and other world-class deposits (e.g., Merensky Reef). Cogulu (1993b) noted that pyrrhotite dominates the basal assemblages. Middle Zone sulphides are disseminated and closely associated with volatiles. Here, assemblages are Cu-rich with lesser proportions of pentlandite and pyrrhotite (Cogulu, 1993b). From Rio Tinto's 2014-15 drill holes the following observations are made. The Lower and Middle Zones are characterised by low Pt/Pd (<0.3), Ni/Cu (<1) and mantle-like Cu/Pd values (10^3 - 10^4). Whilst the Ni/Cu increases into the Middle Zone, the Cu/Pd ratio decreases along with incompatible element concentrations. The Upper Zone is more homogeneous with higher Pt/Pd (0.5-1), Ni/Cu (often >1), and higher than mantle Cu/Pd ratios ($>10^4$). Ni/Cu decreases through the Upper Zone whilst Pt/Pd, Cu/Pd, and incompatible elements increase. The implications and cause of these geochemical trends has yet to be fully constrained.

The addition of crustal S is considered critical in the genesis of many of the MCR Ni-Cu sulphide deposits (Ripley, 2014). Preliminary $\delta^{34}\text{S}$ data indicate a strong crustal component throughout the Crystal Lake intrusion with $\delta^{34}\text{S}$ ranging from 1.4-16.5‰ (Thomas, 2015). The majority of data resides outside the mantle range of $0\pm 2\text{‰}$. Thomas (2015) argues that the intrusion was emplaced as a series of S-saturated magma pulses, with $\delta^{34}\text{S}$ variability attributed to contamination by different S-bearing horizons. S/Se ratios however, are more consistent with *in-situ* contamination with a footwall influence evident in the Lower Zone. The Middle and Upper Zones exhibit lower than mantle S/Se ratios, showing no evidence of a crustal control, which various processes may have masked (e.g., S-loss, upgrading, increased R-factor). To date, no proposed model accounts for all of these features. The Crystal Lake intrusion remains an interesting deposit. Whilst the mineralisation shows many parallels to those observed at the Duluth and Coldwell Complexes, various questions remain regarding the source characteristics and range of magmatic processes involved in their development.

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Petrology and ^{11}B Composition of Tourmaline within the 2685 Ma Ghost Lake Batholith and Mavis Lake Pegmatites

SMITH, Vittoria and ZUREVINSKI, Shannon

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

The Ghost Lake Batholith (GLB) and derived Mavis Lake Pegmatite group are an example of a granite-pegmatite system in which both the parent granite and least- to- most evolved pegmatites are visible and accessible. The GLB has been divided into eight internal units based on mineralogy and texture, while the Mavis Lake Pegmatite group is divided into three broad zones based on the mineralogy of the pegmatite bodies (Breaks and Moore, 1992).

Samples collected from the biotite granite phase (GLB-3) of the Ghost Lake Batholith have the mineral assemblage typical of an S-type peraluminous granite. The granite mineralogy is made up of mostly quartz, albite, potassium feldspar and biotite with accessory muscovite, garnet, zircon, and blue apatite. Pegmatitic segregations within the parent granite consist of potassium feldspar, quartz, and biotite, and accessory garnet. Apatite within this unit is typically associated with or included directly within the biotite and grains analyzed via SEM have been found to be LREE-enriched.

Pegmatite bodies within the beryl-columbite zone of the Mavis Lake Pegmatite group are hosted within mafic metavolcanic rocks and show considerable variation in mineralogy and texture. Pegmatites range from potassic to albitic, and garnet is occurring as an accessory phase. Tourmaline is common in various pegmatitic units within the beryl-columbite and spodumene-beryl-tantalite zone. Due to its commonality within the Mavis Lake group, tourmaline has been sampled and studied using major and trace element techniques to assess its usefulness as an indicator of fractionation between and within individual pegmatite bodies.

Tourmaline core compositions within the pegmatite throughout the Mavis Lake Group range between schorlitic in composition to dravitic (Fig.1). In the case of the Taylor emerald occurrence, the tourmaline species within the pegmatite range from dravitic in the border zone, to schorlitic within the pegmatite body, reflecting a decrease in Fe and an increase in Mg from rim to core. Tourmaline zoning profiles from tourmaline within the Taylor emerald occurrence show significant substitution between Fe and Mg in the Y- site and an inverse relationship between increasing Na contents and decreasing vacancies within the crystals X-site (Fig.2). Similarly, tourmaline from a nearby potassic pegmatite show similar progression in decreasing Na from core to rim with an increasing amount of vacancies. In contrast, the Fe contents in the Y-site steadily increase from core to rim, and Mg shows a closely inverse reaction to the Al contents, suggesting a proton-loss substitution. Boron isotope data collected in situ via SIMS report $\delta^{11}\text{B}$ values from pegmatites within the contact beryl zone between 8.1‰ to 13.9‰.

Variable mineralogy and major- and trace-element mineral chemistry within the Beryl-columbite zone suggest that the degree of host-rock interaction highly influences the tourmaline chemistry. This supports previous work by Breaks and Moore (1992), who had previously suggested that the high Mg contents within the Taylor pegmatites may be related to metasomatic transfer with the metavolcanic host units. While tourmaline is widely considered a petrogenetic indicator for the degree of fractionation within pegmatitic systems, this concept does not seem to apply to a system like Mavis Lake where tourmaline is restricted to the border zones of the pegmatites and is highly influenced by host-rock interaction.

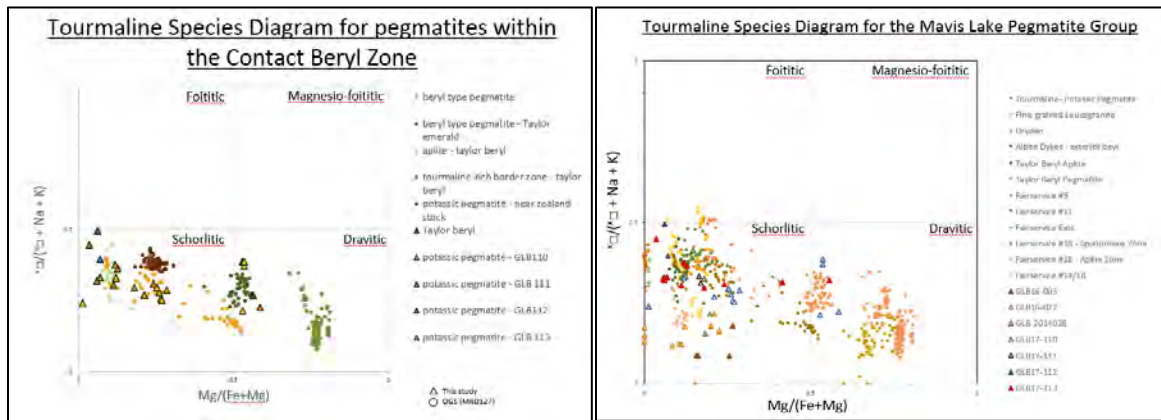


Figure1. Tourmaline speciation diagram for tourmaline within the Mavis Lake Group following the classification scheme of Henry et al., 2005.

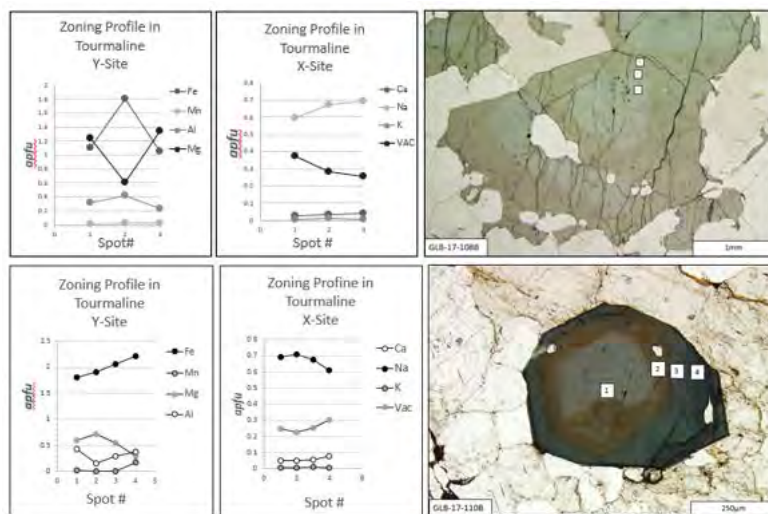


Fig. 2: Tourmaline zoning profiles for the X and Y sites within a euhedral crystal of tourmaline in potassic pegmatite.

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Geophysical, structural, and tectonic interpretation of the Yellow Medicine and Appleton shear zones, SW Minnesota and SE South Dakota: A work in progress

SOUTHWICK, David, CHANDLER, Val, and JIRSA, Mark

Minnesota Geological Survey, University of Minnesota, 2609 Territorial Rd, St. Paul, MN 55114 U.S.A.

The Yellow Medicine and Appleton shear zones (YMSZ and ASZ) are prominent geophysical features of the Minnesota River Valley (MRV) subprovince of the Superior craton. Maps of the first vertical derivative of the magnetic anomaly and the second vertical derivative of the gravity anomaly show that the two zones converge into a single strand in east-central South Dakota, and that the combined fault strand continues west-southwest as least as far as the east margin of the Paleoproterozoic Trans-Hudson orogen. Faulting in the YMSZ and ASZ is thought to have begun in the Sacred Heart accretionary event (ca. 2600 Ma) in which the MRV subprovince was amalgamated to the south margin of the Superior craton. Fault motion may have peaked during Yavapai tectonism, between ca. 1785 and 1775 Ma, in concert with a major episode of granitic magmatism and orogenic uplift.

The Minnesota segment of the YMSZ consists of an axial zone where there are multiple anastomosing sub-zones of concentrated fault damage and km-wide flanking zones of dispersed fault damage. The axial zone is well defined geophysically; the zones of dispersed fault damage are not. Drill cores reveal that the axial zone contains heterolithic crush breccia, fine crush breccia, crush microbreccia, protocataclasite, cataclasite, and protomylonite that were derived from identifiable quartzofeldspathic orthogneiss, foliated garnet-quartz-hornblende paragneiss, amphibolite, and plagiogranite. Graphite-rich fault rocks encountered in boreholes toward the east end of the YMSZ, near the west-northwest-verging tectonic front of the Penokean orogen, may be tectonically dismembered slices of Penokean metasedimentary rocks caught up in Yavapai faulting. Pseudotachylyte is relatively abundant in the axial zone of the YMSZ and in the narrow faults in the flanking zones of dispersed fault damage (Craddock and Magloughlin, 2005).

Diabase dikes of the Kenora-Kabetogama/Fort Frances swarm (ca. 2070 Ma) are offset by and/or terminated against the YMSZ and the ASZ, whereas hornblende andesite and ferrodiorite dikes that cut the 1792 Ma and younger intrusions of the composite East-Central Minnesota Batholith (ECMB) transect the YMSZ and ASZ without deviation. A U-Pb zircon age of ca. 1780 Ma inferred for one of the hornblende andesite dikes (Schmitz et al., 2018, in prep.) limits the timeframe of geophysically discernable fault motion to the period between 2070 Ma (pre-Penokean) and 1780 Ma (mid-Yavapai).

Geophysical patterns suggest that a considerable component of fault displacement on the YMSZ system was left-lateral strike slip that on a regional scale shifted the Morton block, south of the YMSZ, eastward relative to the Montevideo block on the north. We speculate that this displaced a NNW-trending piece of the southern Trans-Hudson orogen eastward from central South Dakota into far WSW Minnesota, where NNW geophysical trends are evident and as yet unexplained. This regional interpretation is based on potential-field images that were upward-continued to five km in order to even out resolution differences among the various data sets that were compiled in the source magnetic and gravity maps of North America (North American Magnetic Anomaly Group (NAMAG), 2002; Committee for the Gravity Anomaly Map of North America, 1988). Our interpretation in eastern South Dakota is submitted as an alternative to an earlier interpretation presented by McCormick (2010a, b) that was based on the original unlevelled magnetic and gravity maps.

Vertical displacement on the YMSZ, up on the north, is indirectly inferred from Yavapai K-Ar ages from rocks in the Montevideo block and the absence of K-Ar ages younger than late Neoarchean in rocks in the Morton belt (Goldich et al., 1961). These observations suggest that K-Ar systematics were reset in Montevideo rocks that were hotter and deeper in the crust prior to Yavapai convergence and associated uplift above the north-dipping YMSZ, whereas the Morton rocks remained higher in the crust and relatively cool. The possibility of mafic underplating having had a role in Montevideo reheating and uplift in mid-geon 17 is suggested by the observed higher-gravity signature of the Montevideo block, particularly toward its east end.

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New bedrock geologic mapping of Dodge County, Wisconsin provides evidence for Paleozoic reactivation of Precambrian structures

KINGSBURY STEWART, Esther, STEWART, Eric D., and ROUSHAR, Kathy

Wisconsin Geologic and Natural History Survey, 3817 Mineral Point Road, Madison, WI 53705

We present a preliminary 1:100,000-scale bedrock geologic map of Dodge County, Wisconsin (fig. 1). Bedrock is mostly buried beneath 6 to 18 meters (20 to 60 feet) of glacial deposits that locally exceed 60 meters (200 feet) within bedrock channels in the eastern part of the county. Due to the significant glacial deposits, mapping is based on integration of geophysical data (gravity and aeromagnetic anomaly data, passive seismic readings), subsurface data (drill core, downhole geophysical logs, geologic logs based on cuttings from municipal wells, and well construction reports of private water wells), and observations collected at sparse outcrops and quarries. To produce the map, we interpolated a bedrock elevation surface from the top of bedrock contact recorded in 3,831 geolocated wells. Depth-structure maps of the base of Paleozoic map units and the top of the Precambrian surface were gridded from map unit contacts picked in 882 wells. The intersection of the depth-structure maps and the bedrock elevation surface defines map unit contacts.

The bedrock geology is comprised of a Precambrian bedrock surface characterized by regional-scale folding and topographic relief overlain by upper Cambrian siliciclastics and Ordovician through Silurian dolostone and siliciclastics. The Paleozoic section thickens from west to east towards the Michigan Basin such that western Dodge County is underlain by the Cambrian through Middle Ordovician sandstone and dolostone while eastern Dodge County is underlain by Silurian dolostone of the Niagara Escarpment.

Results from the first three years of this four-year effort clarify the stratigraphy and structure of the Precambrian units as well as the influence of Precambrian structure on deposition of the overlying Paleozoic sediments. The Precambrian rocks include folded metasediments of the Baraboo interval (<1.7 Ga) that were intruded by ca. 1.4 Ga granite (Medaris et al., 2011). A bedrock core drilled as part of the mapping effort encountered a likely altered banded iron-formation that is known to be present ~40 miles (64km) to the northwest within the Baraboo interval stratigraphy. We tie this core to a characteristic, curvilinear aeromagnetic anomaly and extrapolate to calibrate the regional aeromagnetic data in Dodge County and thus map the distribution of Precambrian units. Map patterns of the Precambrian surface demonstrate that the Baraboo-interval metasediments were folded into east-northeast-trending, doubly-plunging anticlines and synclines with ~30km (18.6 mile) wavelength. Map patterns further demonstrate that the Waterloo quartzite, which outcrops in a broad syncline in southwestern Dodge County, is distinct from, and likely stratigraphically above, the Baraboo quartzite. Precambrian topography was mostly infilled by Cambrian sandstone such that the thickness of the Cambrian Elk Mound Group sandstone can vary by >82 meters (270 feet) over several miles while the thickness of the overlying Cambrian Tunnel City and Trempealeau Groups are relatively consistent. The Paleozoic units were then folded into broad, east-west trending, gentle anticlines and synclines with lengths of 13.6 km (8.5 miles) to 40 km (25 miles), widths of about 8 to 10.5 km (5 to 6.5 miles), and amplitudes of 20 to 100 meters (65 to 328 feet). Data from well cuttings and drill core suggest faulting locally uplifted the Precambrian basement through early Ordovician Prairie du Chien Group. The overlying Middle Ordovician Ancell Group unconformably overlies the Prairie du Chien Group. The overlying Sinnipee Group is gently folded with no clear evidence for fault offset. Sulfide mineralization is present throughout the Paleozoic section in Dodge

County and is preferentially located along faults near fold axes (Brown and Maas, 1992, this study). Fold geometry and preferential sulfide mineralization along fold limbs observed in Dodge County is similar to fold geometry and mineralization reported by Heyl et al. (1959) for the Upper Mississippi Valley Lead-Zinc District, suggesting similar controls on deformation and mineralization for southwestern and southeastern Wisconsin.

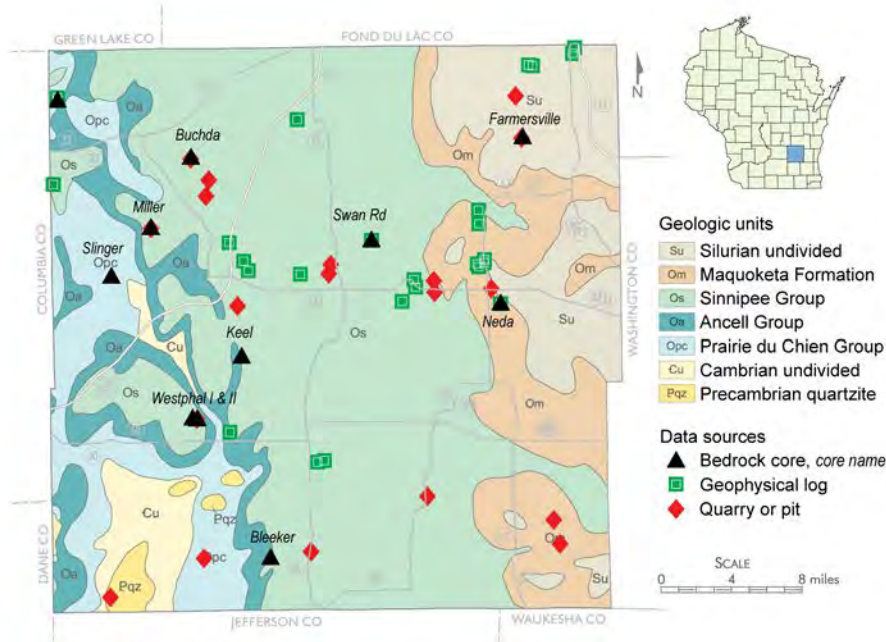


Figure 1. Generalized 1:1,000,000-scale bedrock geologic map of Dodge County showing data sources for 1:100,000-scale mapping. Inset map locates Dodge County (blue) in Wisconsin. Modified from Mudrey et al. (1982).

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Neoarchean to Paleoproterozoic reconstructions using metamorphic core complexes as evidence of continental transform plate motion and their implications in Archean tectonics

STINSON, V.R. and PAN, Y.

Department of Geological Sciences, University of Saskatchewan, 114 Science Place, Saskatoon, SK S7N 5E2 Canada

Paleotectonic reconstructions use geological, geophysical, and paleontological information to piece together cratons, continents, and supercontinents. Metamorphic core complexes commonly have transform, transpression, and transtension components which are underrepresented in paleotectonic reconstructions and may also be used to provide evidence of subduction, collision, and exhumation. Due to the nature of the medium to high-grade metamorphic and felsic plutonic igneous lithologies in the footwall they are typically well-preserved and yield robust minerals used in geochronology.

In this study we have combined literature review and field mapping, geochronology, and petrology to investigate the potential for reconstructing Archean cratons in transpressive to transtensional tectonic settings in the Neoarchean. This study recommends the use of metamorphic core complexes as evidence for transpression to transtensional plate motions in paleotectonic plate reconstructions including reconstructions for the Proterozoic and Archean eons as data is sparse or poorly preserved. Further multi-disciplinary tectonic studies are necessary to broaden our understanding of Archean tectonics and by using metamorphic core complexes as analogues for transform plate boundaries we may greatly enhance paleotectonic reconstructions.

The paleo-northeast-directed oblique collision between the Minnesota River Valley terrane with the southern Superior craton in the Neoarchean created predominantly dextral transpression in the Minnesota River Valley terrane and regional sinistral and dextral transpression to local sinistral transtension throughout the southern Superior craton. The rigid, Paleoproterozoic to Neoarchean Minnesota River Valley terrane collided into the recently formed, and rheologically weaker, southern Superior craton forming sinistral-oblique regional structures in the western Superior craton to the formation of metamorphic core complexes the eastern Superior craton suggesting transtension increased towards the east. This tectonic evolution from the formation of 2.700 Ga and 2.67 Ga MORB and arc to subduction to collision at 2.65-2.63 Ga to exhumation and lateral escape at 2.63 to 2.60 Ga is present in numerous Archean cratons worldwide with indistinguishable lithologies, structures, igneous and metamorphic petrology, geochemistry, geochronology, and mineral deposits. Evidence of this collision to transtensional tectonics and strike-slip deformation in the eastern Superior craton is preserved in the Archean cratons worldwide. Evidence of collision is preserved in the Paleoproterozoic to Neoarchean Minnesota River Valley terrane, Wyoming, Gawler, and West Antarctica and transpression to sinistral transtension due to lateral escape is preserved in Neoarchean Baltica (Central Kola Belt), Zimbabwe and Kaapvaal (Limpopo Belt), Yilgarn (Tropicana Gneiss), Eastern Antarctica, North China and Dharwar cratons.

The development of craton, continental, or supercontinent breakup may have been triggered due the subduction of a transform plate boundary in the Wawa and Abitibi subprovinces, the size or rheology contrast of the colliding plates, the angle of the collision, and the formation of the metamorphic core complexes, lack of decoupling between the mantle and lithosphere boundary triggering mafic dyke swarms, plutonism, and (super) continental breakup.

Keweenaw Fault Geometry and Kinematics along Bête Grise Bay, Michigan

Tyrrell, C.W.¹ Hubbell, G.E.¹, and DeGraff, J.M.¹

¹Michigan Technological University, Houghton, MI 49931

The Keweenaw Fault (KF) extends 350 km along the southern margin of the Midcontinent Rift System (MRS) from northwestern Wisconsin to near the tip of the Keweenaw Peninsula in Michigan (1). Reverse movement on the fault has thrust and tilted Portage Lake Volcanics (PLV, 1.1 Ga) over younger Jacobsville Sandstone (JS) (Fig. 1). The northeast portion of the fault near Keweenaw Point has been a matter of some interest since the USGS mapping campaign of the 1950s. Based on geophysical evidence, some have proposed that the fault continues offshore along an arc curving to the right by 90° to a southeasterly direction (1, 3-4).

The farthest northeast location where the Keweenaw Fault can be directly examined is along the south side of the Keweenaw Peninsula from Bête Grise Bay eastward (Figs. 1, 2A). Here USGS maps from the 1950s show five shoreline areas where PLV and JS strata are juxtaposed (5-6). Our detailed mapping under the USGS EdMap program reveals that the previously mapped fault trace, based in part on aeromagnetic data and showing all PLV-JS contacts as faulted, oversimplifies the geologic relationships in this area.

The anomalously sinuous, single fault trace mapped in the 1950s consists of at least five fault segments, generally striking ESE and forming a left-stepping pattern along the shoreline (Fig. 2B). At least three PLV-JS contacts previously mapped as faulted instead exhibit an unconformity between basal JS strata and older PLV lava flows. At one location, slightly deformed JS strata unconformably overlie fault breccia and gouge cutting PLV strata, indicating that one period of major slip on this KF segment occurred before local JS deposition. At other locations, JS strata are clearly cut and deformed along faulted contacts with PLV lavas, providing evidence for a second period of slip on the KF system after some or all JS deposition. Along shore near the Bare Hill rhyolite, PLV strata dip moderately to steeply SE to SSE for at least 3 km, a reversal of normal northerly dip that suggests an anticline developed north of this KF segment.

Faulted PLV-JS contacts in the area generally dip > 80° N but locally dip steeply south. Geologic relationships across one fault segment suggest a significant component of dextral strike slip, and secondary faults have surface markings that indicate a mix of strike-slip and dip-slip motion. Ongoing work to quantify these relationships is designed to determine the degree of strike-slip to dip-slip partitioning along this portion of the KF system.

The regional trace of the KF changes direction by over 70° from NNE near Houghton to ESE at Bête Grise Bay, which mimics the change in strike of PLV layers over the same distance (Fig. 1). Paleomagnetic work (7-8) suggests that this direction change is a primary geometric attribute of the fault and not a result of bending around a vertical axis. Large crustal-scale faults often curve and split into segments near their terminations (9-10). Our mapping results thus imply that the KF system may terminate near the end of the peninsula in a series of fault splays, possibly transferring slip to other faults farther east. We hypothesize that slip on the KF changes from dominantly reverse dip-slip movement along its NE-trending portion near Houghton to dominantly dextral strike-slip near the tip of the Keweenaw Peninsula, and that slip magnitude decreases over this same distance.

Acknowledgements: We appreciate the USGS funding this work and the timely field visit and comments last year by Bill Cannon, Klaus Schulz, and Laurel Woodruff, which does not imply their agreement or disagreement with these results.

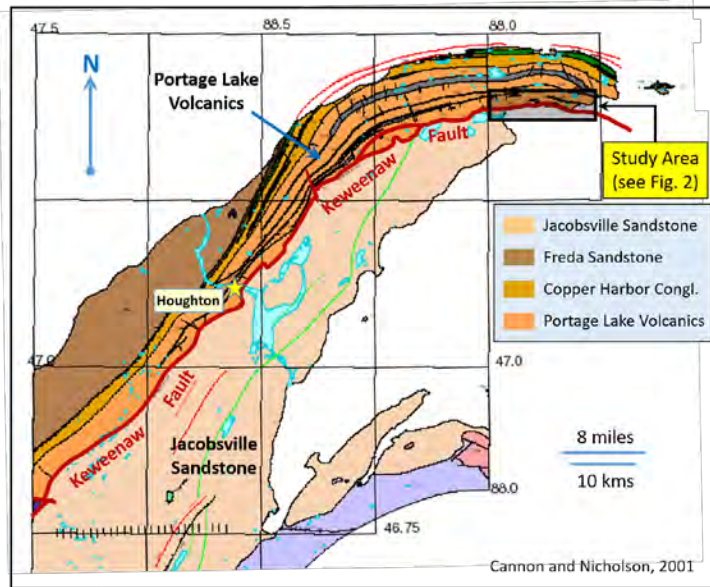
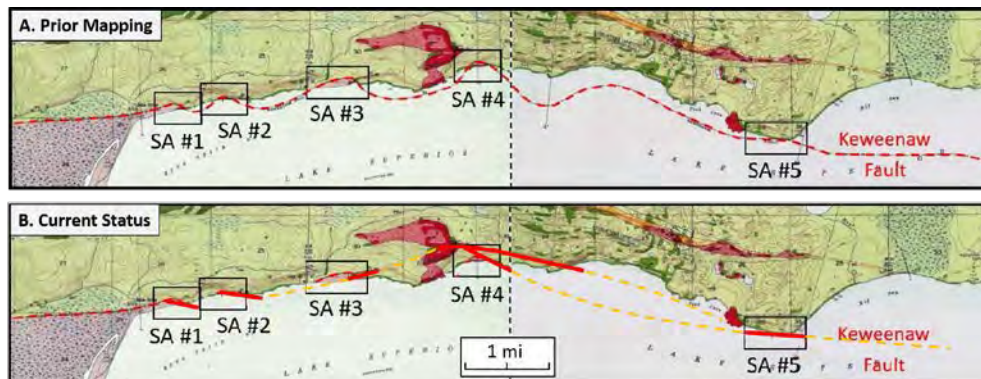


Figure 1: Keweenaw Peninsula where Portage Lake Volcanics are thrust over Jacobsville Sandstone. Black rectangle along the Keweenaw Fault near the tip of the peninsula marks focus area of **Figure 2**. (adapted from 2).

Figure 2: Focus area along the Keweenaw Fault from Bête Grise Bay eastward (adapted from 5-6). Major faults shown as dark red traces. **A)** USGS maps from 1950s. **B)** Status of current fault mapping overlaid on prior maps.



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Alteration Mineral Zonation and Geochemical Characteristics of the Back Forty Deposit, MI; a Replacement-style Zinc- and Gold-rich Volcanogenic Massive Sulfide Deposit

UPTON, Margaret¹, SCHARDT, Christian¹, HUDAK, George², QUIGLEY, Eric³

¹Department of Earth and Environmental Sciences, University of Minnesota - Duluth, 1114 Kirby Drive, 223 Heller Hall, Duluth, MN 55812

²Natural Resources Research Institute, University of Minnesota - Duluth, 5013 Miller Trunk Hwy, Duluth, MN 55811

³Project Geologist, Aquila Resources, 414 10th Avenue, Menominee, MI 49858

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

The main objectives of this work are to identify physical, mineralogical, and geochemical characteristics of hydrothermal alteration mineral assemblages associated with the Back Forty Deposit. Alteration mineral and geochemical characterization include drill core logging, lithogeochemical, petrographic, and SEM analysis to better understand detailed mineral assemblages and mineral species' chemical attributes. Core from nine drill holes (~ 2,950 meters), were logged to identify alteration mineral assemblages, intensity, and their textural characteristics. The deposit, hosted in felsic pyroclastic rocks, shows mostly sericite alteration, which was used to establish an alteration intensity scale of 1-4 (1: weak, 4: intense). Major alteration mineral assemblages observed were sericite $\pm$ silica $\pm$ chlorite. Sericite alteration is pervasive throughout the deposit (2-3) with silica alteration intensity ranging from 1-2 and a few areas of silica flooding (3-4). Weak chlorite alteration occurred throughout the deposit within the host rhyolite crystal tuff units as spotty chlorite associated with sulfide mineralization (1-2).

Whole rock and trace element lithogeochemistry will be evaluated using the alteration box plot (Large et al., 2001) and mass balance analysis, such as the ISOCON method (Grant, 1986; see fig. 1). Results will be essential to assess quantitative chemical changes associated with alteration mineral assemblages and their spatial distribution to identify likely hydrothermal fluid flow pathways and mineralization vectors within the deposit. Using petrographic analysis as well as structural and lithological data, cross sections identifying alteration mineral zonation and its relative extent will be created to determine the relationship between massive sulfide mineralization and alteration mineral assemblage presence and intensity. From these results, it

may be possible to use alteration mineralogy and geochemistry to determine the direction of hydrothermal fluid flow associated with mineral deposition and aid in future exploration efforts to locate additional mineralization on the Back Forty Deposit property, as most VMS deposits occur in clusters (Galley et al., 2007).

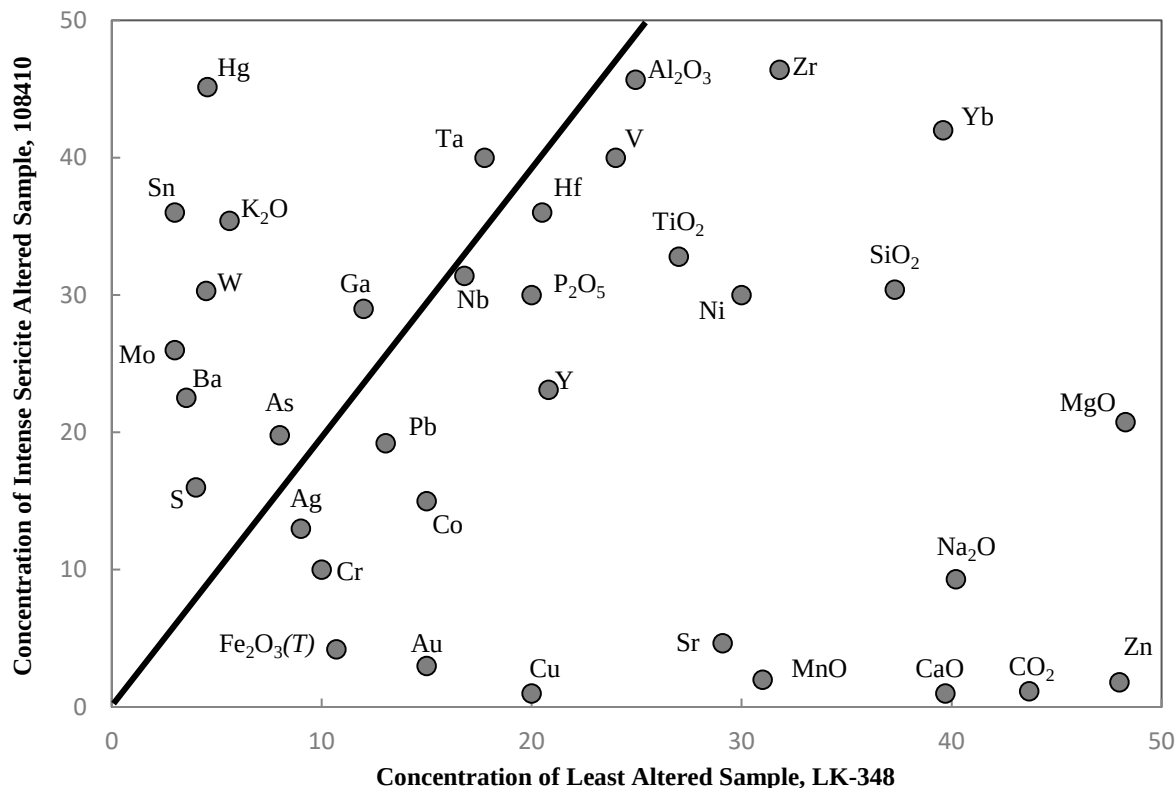


Figure 1. ISOCON plot of selected elements used to compare elemental gains and losses between least and most altered samples. Isocon line of best fit is defined by immobile elements (Hf, Nb, Ta, Zr). Components above the line are enriched; below are depleted (modified from Ross, 2011).

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Reconstruction of paleoenvironmental conditions and temporal patterns of ancient mining on Isle Royale using biogeochemical analyses of lake sediment

VALL, Kathryn G.¹, STEINMAN, Byron A.¹, POMPEANI, David P.², SCHREINER, Kathryn M.³, DEPASQUAL, Seth⁴

¹*Earth and Environmental Sciences, Large Lakes Observatory, University of Minnesota Duluth*

²*Department of Geography, Kansas State University, Manhattan, KS 66506*

³*Chemistry, Large Lakes Observatory, University of Minnesota Duluth 1049 University Dr, Duluth MN 55805*

⁴*Cultural Resources, Isle Royale National Park, 800 E Lakeshore Dr, Houghton MI 49931*

Isle Royale and the Keweenaw Peninsula of Michigan are home to some of the oldest examples of native North American metalworking and land use. The overarching objective of this research is to produce a reconstruction of the timing, spatial patterns, and environmental impacts of mining activities on Isle Royale through sedimentological and biogeochemical analysis of lacustrine sediments. We also seek to produce a parallel record of paleoenvironmental conditions in order to assess the potential impacts of environmental change on ancient mining cultures.

In 2016, we collected a 7.5 m long sediment core sequence from Lily Lake on Isle Royale, MI. Lily Lake lies approximately 100 m above the current water level of Lake Superior, and formed approximately ~11,000 years before present following the retreat of the Laurentide ice sheet. Lily Lake has been exposed to very little human land use change relative to other lakes on Isle Royale (e.g. there are no ancient mine pits in the immediate catchment), and thus is well suited for reconstructing past environmental changes. We analyzed weakly sorbed metal concentrations using ICP-MS to test hypotheses on the timing and transport mechanisms of potential metal pollution derived from ancient mining activities. In addition, we conducted EA-IRMS analysis (including carbon/nitrogen ratios, and the isotopic composition of organic C and N) on bulk organic sediment to provide a record of natural paleoenvironmental changes.

Preliminary results from the metals analysis provide evidence of Middle Archaic mining activity that is temporally consistent with radiocarbon dated artifacts and similar evidence from other lakes located adjacent ancient mine pits on Isle Royale and the Keweenaw Peninsula of Michigan. Additional work is required to assess the relative influence of natural versus anthropogenic processes that may have influenced metal concentrations in Lily Lake sediment and to determine a transport mechanism for the putative mining related pollution.

This study will provide a record of spatial/temporal patterns of mining activity and paleoenvironmental change in the Great lakes region that will aid in our understanding of large scale continental climate patterns, environmental responses, and the potential influence of climate/environmental variability on ancient land use and mining practices.



Michigan Geological Survey

Six years after assignment to Western Michigan University,

Where are we today?

John A. Yellich, CPG, Director, Michigan Geological Survey

The Michigan Geological Survey functionality was reduced in 1978 to conducting minimal research, scientific publications and data management. For the next 30 years, Michigan went through multiple oil and gas booms and busts, Superfund authorization, Leaking Underground Storage Tanks, Brownfields, some mining development, yet no funding for a functioning geological survey. Where could you go to get up to date geologic research or information? What was and is still being used are special publications from the USGS, associations or academia and a 1982 Surficial Geological mapped based on 1915 field mapping, 1955 updates and a color change with some soils in 1982, this is 1915 surface geology only.

The Michigan Geological Survey (MGS) was assigned in 2011, by legislation from the DEQ - Office of Oil Gas and Minerals to the Geological and Environmental Sciences (GES) Department at Western Michigan University (WMU), with no funding. MGS has functioned at the GES Department with WMU funding for two years, grants and a Special Appropriations (SA) from the Michigan Legislature in 2016, and has strived to establish a scientific value of a functioning geological survey by presenting programs and projects associated with the current day natural resources needs of Michigan. MGS surveyed the stakeholders and has been assessing some of the components of the noted societal needs, an integral segment of any survey today. A functioning geological survey is not the same as it was 25 or more years ago. Consequently, the users of geologic based data are not just the geoscientist, but regulators, county planners and development organizations, engineers, environmental scientists, extractive and land development industries, citizen scientists, anyone that has "boots" that touch the ground.

MGS has completed a significant portion of the demonstration process and presented results to all the State of Michigan functional departments and has received letters of recommendation to support the continued geological research and mapping efforts conducted to date. MGS was also recognized and a resolution submitted to the Governor by the twelve sovereign Michigan tribes as needing a funded functioning geological survey to map and assess the water resources of Michigan. Michigan and many other states have a new contaminant, PFAS, and MGS has presented a geological approach to assess the aerial magnitude of this impact, geology. All these products and projects are scientific societal needs, however, at this time, the Legislature and Governor's office has not seen fit to have an annual funding mechanism for the Michigan Geological Survey.

The Natural Resources of Michigan are and have been an economic foundation and provided societal benefits to Michigan since 1840's, over a 175 years. The identification and protection of these resources needs sufficient geologic information to assess, protect and manage all the components associated with any natural resources.

Since 2011, the MGS has published 14 quadrangles (4-UP; 10-LP) with four in process within those 6 years, having one full time staff, some faculty and two contractors. There are critical need areas of Michigan that need to be mapped, but it takes a commitment by the State and requests by society for funding. MGS has provided geologic guidance on water and chloride issues in Ottawa County and MGS projects and research have strongly supported geological science in all aspects of identifying, managing and accessing the water resources of Michigan. MGS was instrumental in support of Statewide airborne LiDAR and encouraged Michigan to develop a program to contact the users and identify the benefits. This airborne effort was then done at a reduced cost and with nearly half of the State flown we now have LiDAR that will provide greater benefits to scientists and the public. MGS initiated and completed research utilizing standard geophysical methods and is utilizing new methods and remote sensing to support the 3D mapping projects and derivative geological products. Tromino Passive Seismic, NASA Gravity Recovery and Climate Experiment (GRACE) and Interferometry to assess, bedrock depth and topography, water storage and surface movements, respectively. For example, a City of Portage bedrock valley mapping for water resources, GRACE projections of increased water storage in Cass, St. Joseph, Kent and Ottawa counties has presented scientific research projects that support Michigan natural resources and yet no full time funding. These successful scientific demonstrations have also supported students in MS theses and PhD dissertations. MGS has strongly supported regionally and in Washington, DC the USGS geologic, geophysical and FEDMAP programs for airborne and ground surveys to assess the buried geology, near surface geology, water resources and shoreline stability issues of the Great Lakes areas, to name a few.

The geologic community has a voice that has not been loud enough to be heard in Lansing and also, Washington, DC. Geoscientists must tell everyone that to understand our world today and tomorrow, we need geology. For example here we are in Michigan six years later, not knowing if we have sufficient water resources for some areas, questioning scientific data with “Wikipedia” type information, needing an updated geologic map of the UP bedrock and glacial systems and you as geoscientists not loudly proclaiming that validated geology needs to be done in priority areas of Michigan. You are the experts, what should the Geological Survey be doing?

The Origin of Layering in the Olivine Zone, Black Sturgeon Sill, Nipigon, Ontario **ZIEG, Michael J. and HONE, Samuel V.**

Department of Geography, Geology, and the Environment, Slippery Rock University, Slippery Rock, PA 16057

Layering in mafic intrusions is one of the most interesting, but also most controversial, aspects of igneous petrology. In this study, we explore the role of phenocrysts (entrained crystal cargo) versus in-situ fractionation in controlling layer development. Samples were taken from a continuous drill core through the Black Sturgeon sill (BSS), a 250 m mafic intrusion with a well-developed olivine zone from 120-200 m above its base. We analyzed bulk-rock geochemistry, modal mineralogy, and textures at 0.5 m intervals through this range, then used the resulting data set to investigate the petrogenetic processes responsible for the geochemical and petrographic variations in this part of the sill.

Principal component analysis was used to characterize and summarize variations in the standardized and log-normalized major and minor oxide abundances. The first three principal components are the most significant, accounting for over 90% of the system variance. Based on these components, the rocks in the olivine zone fall into four distinctive compositional groups (Fig. 1). We interpreted the petrogenetic significance of the principal components by comparing them to trace elements, modes, norms, textures, and fabrics. In this initial comparison, we identified strong correlations between: the first principal component (PC1) and Ni-Sr (Fig. 2a); the second principal component (PC2) and incompatible element abundances, particularly Cu (Fig. 2b); the third principal component (PC3) and Sc (Fig. 2c). Thus, we conclude that PC1 is controlled by the ratio of olivine to plagioclase, PC2 is controlled by the abundance of a fractionated interstitial liquid component, and PC3 is controlled by augite abundance.

Three fundamental observations are critical for understanding the significance of our results. (1) The olivine zone consists of four segments (a-d) defined by variations in the first principal component (Fig. 3a), which reflect the relative importance of olivine and plagioclase. (2) The olivine zone has a single coherent Z-shaped profile for PC2, controlled by smooth variations in incompatible element abundances (Fig. 3b). (3) PC2 and PC3 are positively correlated in Segments a, c, and d; they are negatively correlated in Segment b (Fig. 3c).

Each of the four segments represents a distinct batch of magma, with its own characteristic phenocryst assemblage. The average ratio of olivine to plagioclase generally increased upwards, suggesting either an upward increase in source primitivity or “subcretion” of increasingly evolved magma pulses. All segments intruded rapidly compared to solidification time; after emplacement was complete, crystal-mush compaction drove evolved interstitial liquids from Segment b up into Segment d. The relationships between PC2 and PC3 suggest that augite crystallized after compaction-driven redistribution of evolved liquids in Segments a, c, and d. In Segment b, however, it was part of the crystal cargo, and Sc was not depleted (as Cu was) by the expulsion of interstitial liquids.

In conclusion, the emplacement of multiple pulses of magma, each entraining a unique crystal cargo, controlled the basic layering structure and the major-oxide variability of the BSS olivine zone. Compaction-driven redistribution of interstitial liquids significantly modified trace element abundances, producing cryptic compositional layering incongruent with the modal assemblages. Although our results only address the formation of layering in this specific intrusion, the procedures we have developed can be applied to any system.

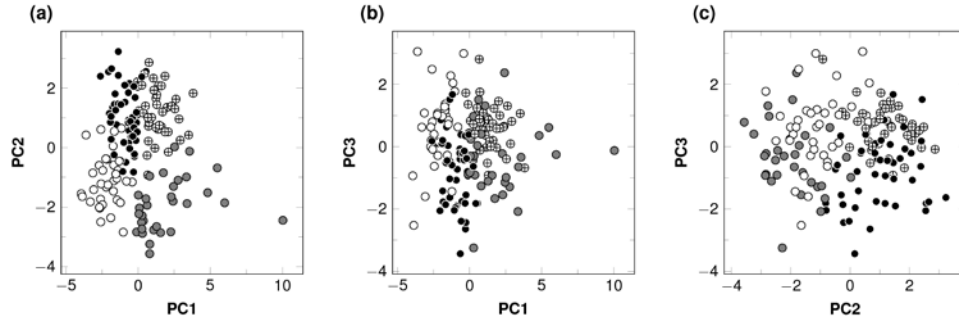


Figure 1. Compositional groups. Four compositional groups can be distinguished.

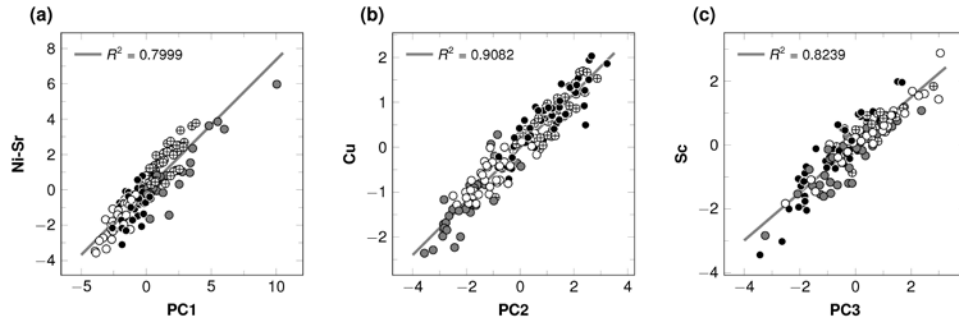


Figure 2. Interpretation of PCs. (a) PC1 reflects the olivine:plagioclase ratio. (b) PC2 reflects incompatible abundance. (c) PC3 reflects augite abundance.

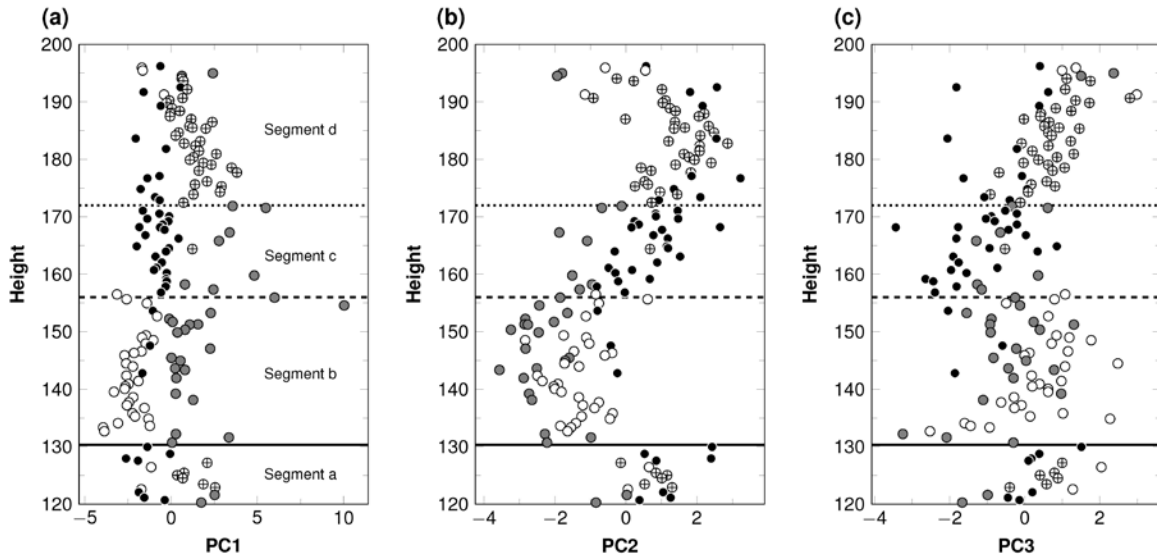


Figure 3. Stratigraphic profiles. (a) The olivine zone can be divided into four distinct segments. (b) Incompatible element abundances suggest compaction-driven redistribution of interstitial liquids. (c) Augite is correlated with incompatibles in Segments a, c, and d, but not in Segment b. This suggests that augite was a phenocryst phase in Segment b, but not in Segments a, c, or d.