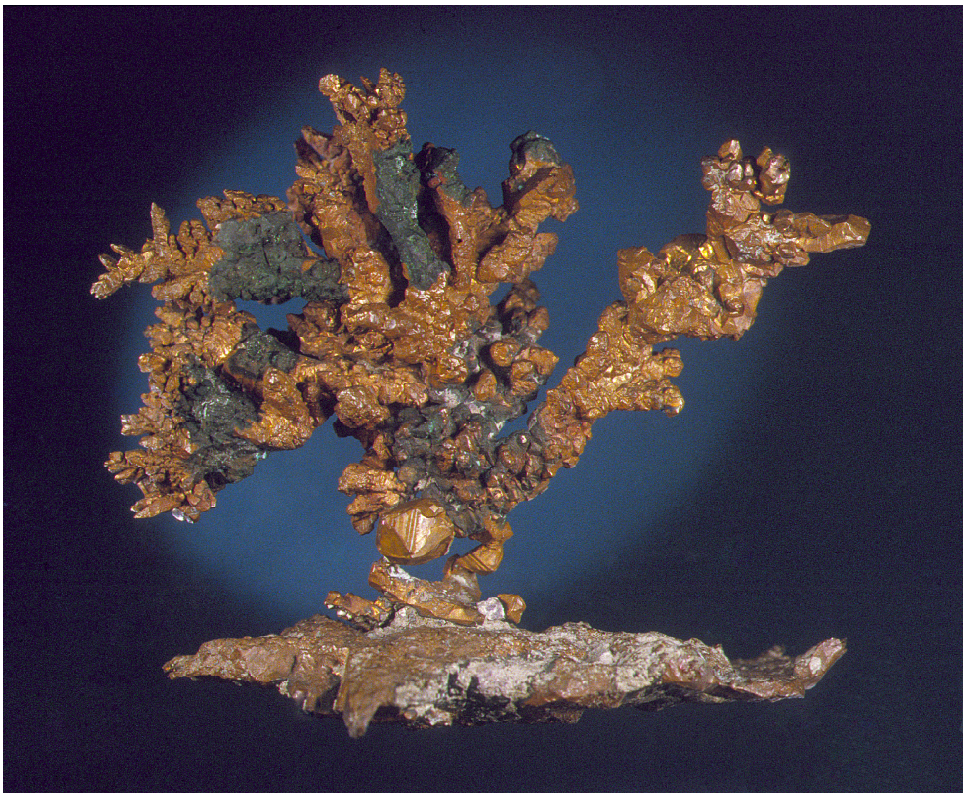
Institute on Lake Superior Geology

59th Annual Meeting

Houghton, Michigan May 8 - 11, 2013



Proceedings Volume 59
Part 1 - Program and Abstracts

Editors: Allan R. Blaske and Theodore J. Bornhorst

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Institute on Lake Superior Geology

59TH ANNUAL MEETING
MAY 8-11, 2013
HOUGHTON, MICHIGAN

SPONSORED BY:
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THEODORE J. BORNHORST AND ALLAN R. BLASKE

Co-Chairs

Proceedings Volume 59

Part 1 – Program and Abstracts

EDITED BY ALLAN R. BLASKE AND THEODORE J. BORNHORST

Cover Photo: Native copper from the Central Mine, Keweenaw Peninsula, Michigan. Collection of the A.E. Seaman Mineral Museum. Photograph by George Robinson.

59TH INSTITUTE ON LAKE SUPERIOR GEOLOGY

PROCEEDINGS VOLUME 59 CONSISTS OF:

PART 1: PROGRAM AND ABSTRACTS

PART 2: FIELD TRIP GUIDEBOOK

- **TRIP 1:** GEOLOGIC OVERVIEW OF THE KEWEENAW PENINSULA, MICHIGAN
- **TRIP 2:** CALEDONIA MINE, KEWEENAW PENINSULA NATIVE COPPER DISTRICT, ONTONAGON COUNTY, MICHIGAN
- **TRIP 3:** GEOLOGY OF SILVER MOUNTAIN, HOUGHTON COUNTY, MICHIGAN
- **TRIP 5:** GEOLOGY OF THE KEWEENAWAN SUPERGROUP, PORCUPINE MOUNTAINS, ONTONAGON AND GOGEBIC COUNTIES, MICHIGAN
- **TRIP 6:** GEOLOGY AND ENVIRONMENTAL SITE CONDITIONS OF THE COPPERWOOD DEPOSIT, GOGEBIC COUNTY, MICHIGAN

Reference to material in Part 1 should follow the example below:

Cannon, W. F. Woodruff, L. G., and Schulz, K.. J., 2013, The Hiawatha Graywacke of the Iron River-Crystal Falls district, Michigan: a megaturbidite triggered by seismicity related to the 1850 Ma Sudbury impact [abstract]: Institute on Lake Superior Geology Proceedings, 59th Annual Meeting, Houghton, MI, v. 59, part 1, p. 14-15.

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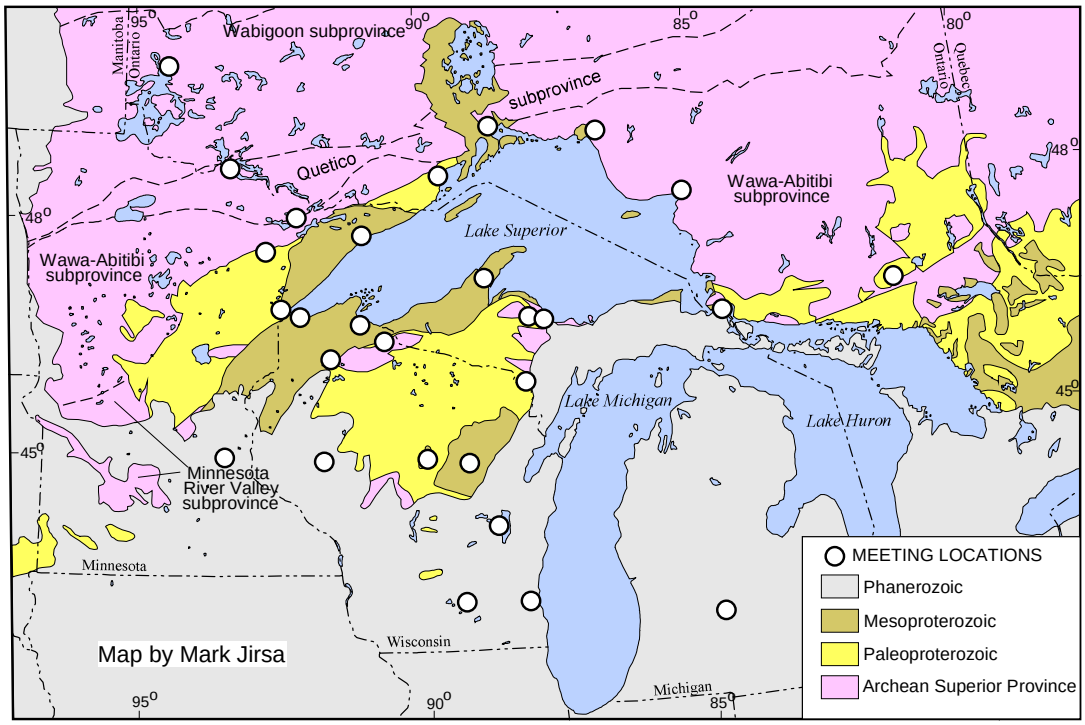
ILSG website: http://www.lakesuperiorgeology.org

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Table of Contents

Institutes on Lake Superior Geology, 1955-2013	iii
Sam Goldich and the Goldich Medal	vi
Goldich Medal Guidelines	viii
Goldich Medalists	x
2013 Goldich Medal Recipient	x
Goldich Medal Committee	x
Citation for Goldich Medal Recipient	xi
Memorial to Glenn Morey	xii
Memorial to Paul Sims	xiii
Eisenbrey Student Travel Awards	xiv
Joe Mancuso Student Research Awards	xv
Doug Duskin Student Paper Awards	xvii
Student Paper Awards Committee	xvii
Board of Directors	xviii
Local Committee	xviii
Session Chairs	xviii
Banquet Speaker	xix
Report of the Chair of the 58th Annual Meeting	xx
Sponsors	xxii
Program	xxiii
Poster Presentations	xxviii
Abstracts	1-83

Institutes on Lake Superior Geology, 1955-2013



#	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

#	Date	Place	Chairs
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
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

#	Date	Place	Chairs
50	2004	Duluth, Minnesota	S. Hauck & M. Severson
51	2005	Nipigon, Ontario	M. Smyk & P. Hollings
52	2006	Sault Ste. Marie, Ontario	A. Wilson & R.Sage
53	2007	Lutsen, Minnesota	L. Woodruff & J. Miller
54	2008	Marquette, Michigan	T. Bornhorst & J. Klasner
55	2009	Ely, Minnesota	J. Miller, G. Hudak & D. Peterson
56	2010	International Falls, Minnesota	M. Jirsa, P. Hollings, T. Boerboom, P. Hinz & M.Smyk
57	2011	Ashland, Wisconsin	T. Fitz
58	2012	Thunder Bay, Ontario	P. Hollings
59	2013	Houghton, Michigan	T. J. Bornhorst and A. R. Blaske

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

2013 GOLDICH MEDAL RECIPIENT

Tom Waggoner

Goldich Medal Committee

Serving through the meeting year shown in parentheses.

Laurel Woodruff (2013)	United States Geological Survey
Graham Wilson (2014)	Turnstone Consulting
Bernhardt Saini-Eidukat (2015)	North Dakota State University

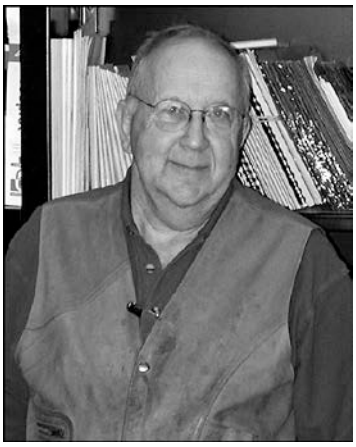
Citation for Goldich Medal Recipient

Tom helped Cliffs make the transition from underground mining of direct shipping ore to pellets, which are now the life blood of iron mining in the Lake Superior region. The success of his contributions is best measured by 40 years of continual production of pellets from the Empire and Tilden mines that together produce 13 to 14 million tons per year. The transition to pellets is public knowledge but much of the details are lacking. Before pellet production could begin iron formations had to be sampled for their recoverable iron content and ease of recovery. After mining, there had to be day to day adjustment in grinding time, depending on the hardness of taconite, and blending ores in order to control phosphorous contents. Tom's contribution to preserving iron mining in the Lake Superior region has been documented by his colleagues because the skills of company geologists are seldom part of the public domain.

During his long career with Cliffs (1965-1997), Tom actively participated in the teaching function of the Institute. He led 45 field trips for various organization and made numerous poster and oral presentations at annual meetings of the Institute. At his retirement in 1997, Tom was chief geologist. After his retirement he has continued to serve the mining industry. After the state of Michigan ended funding a curator for the core library at Harvey, Tom became the unpaid overseer of the facility and went looking for a building to assemble and preserve the large amount of additional core that exists at scattered location in the upper peninsula. Like the core library at Harvey it will be a repository for future exploration geologists who are essential for sustaining mining in the Lake Superior region. He found a building on the grounds of the closed K. I. Sawyer Air Force base that was suitable as a core library and has been actively seeking funding to acquire and maintain it.

Submitted by Ronald E. Seavoy

Memorial to Glenn B. Morey
1935-2012



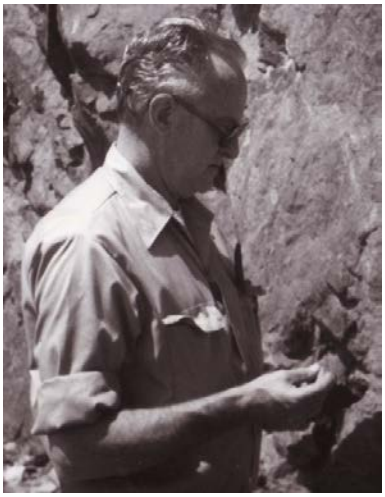
Glenn B. Morey, geologist, known to family, friends, and colleagues as "G.B." or "Morey," died at age 76 on August 2, 2012 in St. Paul, Minnesota. He spent the greater part of his 40-year career at the Minnesota Geological Survey in positions that ranged from junior geologist to associate director and chief geologist. He was a senior fellow of the Geological Society of America, a member of the Society of Economic Geologists, the History of Earth Sciences Society, and a life-long member of the Mesabi Range Geological Society and the Institute on Lake Superior Geology. He received the institute's Goldich Medal in 1986 for his contributions to geologic understanding of the Lake Superior region.

G.B. Morey was raised in Proctor, a town on the Duluth, Mesabi, and Iron Range Railroad through which the iron ore and taconite from the Mesabi range passed on its way to the port of Duluth and steel mills of the lower Great Lakes. He learned of iron mining from his father who worked on the railroad, and he devoted much of his professional career to studies of the stratigraphy, mineralogy, and genesis of the Biwabik Iron Formation—the geological source of prosperity in the mining towns of the Mesabi Iron Range and communities along the routes between mine and mill. Morey completed an M.S. degree in 1960 and a Ph.D. in 1965, both at the University of Minnesota-Twin Cities under professor F.M. Swain. Sedimentology and stratigraphy were the principal foci of his graduate program and continued to be his primary geological interests throughout his professional career. His M.S. thesis entitled "Geology of the Keweenawan sediments near Duluth, Minnesota" was the first of many papers he authored or co-authored on the Mesoproterozoic sedimentary sequences within the Midcontinent Rift. Likewise, his Ph.D. thesis entitled "The sedimentology of the Precambrian Rove Formation in northeastern Minnesota" was the precursor to his many publications on Paleoproterozoic clastic rock units associated with iron-formation on the Biwabik, Cuyuna, and Gunflint iron ranges. Morey's bibliography contains 100 refereed papers, 25 geologic maps, and many published abstracts and field trip guides—including those for the Institute on Lake Superior Geology.

G.B. Morey's professional accomplishments and adherence to high scientific standards are widely recognized and appreciated throughout the Great Lakes region. He mentored and critiqued many of us at the Minnesota Geological Survey and elsewhere, commonly playing the skeptic to extract the best from colleagues. G.B. was a credit to the survey, the University of Minnesota, and the geological profession as a whole. We who knew him celebrate his memory while we mourn our loss.

David L. Southwick, Mark Jirsa, and Paul Weiblen

Memorial to Paul K. Sims
1917-2011



Paul K. Sims joined the field trip from which no geologist returns on October 29, 2011 in Denver, Colorado. Born in Newton, Illinois on September 8, 1918, Paul excelled in basketball, and entered University of Illinois Business School. The geology bug bit him and by 1940 he was actively engaged in his Master's Degree (1942) based on rotary drilling in the coal beds of Illinois. After his degree, he began work with the USGS on zinc-lead deposits in Arizona and Washington before serving with distinction in the navy during World War II in the Pacific theater. Contacts at that time led him to Princeton University for his PhD (1950) on the Dover Magnetic District, New Jersey. He pursued many professional avenues while with the USGS, including international work, uranium geochemistry, editing, and geologic mapping.

Lake Superior called, on September 1, 1961, he took leadership of the Minnesota Geologic Survey as Director. Within a year, PK initiated programs in all parts of the stratigraphic column, and developed an annual report series highlighting programs and accomplishments that were used to advance MGS activities. He identified geologic mapping as the backbone of research and he and his colleagues produced numerous reports of local to regional interest. After departing Minnesota in 1973, he continued his mapping and tectonic analysis in Wisconsin and Michigan before resuming his pursuit of the Precambrian in the Rocky Mountains.

His geological mapping in the Lake Superior District and the western US led him to suggest that deformation during Archean and Proterozoic was not analogous to Phanerozoic plate-tectonic model, but instead consisted of oblique shortening and progressed from ductile to brittle. His work on Archean mantle gneiss domes resulted in his visualization of the Great Lakes Tectonic Zone north of which Archean volcanogenic assemblages prevail, and south of which Proterozoic continental collision and island arc basins dominated

Significant professional accomplishments included President of the Society of Economic Geologists (and many committees), Secretary of the Subcommission of Precambrian Stratigraphy (IUGS). Numerous awards included SEG Thayer Lindsley Lecturer (1984-1985) and Ralph Marsden Award (1989); USGS Meritorious Service Award; and ILSG Goldich Medal (1985).

PK was a reserved individual who was enormously unselfish and was quick to give credit to those with whom he collaborated. He encouraged all with whom he came in contact with. In his own work he was demanding and expected clear documentation of which page was fact and which was interpretation. He was a joy to be with, and always stimulated discussion.

He was a credit to our profession, and we mourn his passing.

Michael Mudrey

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 2012 the ILSG Board of Governors awarded five $500 awards from the Student Research Fund. The winners were:

Jonathan E. Dyess
University of Minnesota-Duluth
Dept. of Geological Sciences, 229 Heller Hall, 1114 Kirby Drive, Duluth, MN 55812
Current degree program: PhD Candidate (Advisor: Vicki Hansen)
Shagawa Lake shear zone

Elisa Piispa
Michigan Technological University
1400 Townsend Drive, 630 DOW, ESE Building, Houghton, MI 49931-1295
Current degree program: PhD in Geology
Paleomagnetism of the ~1140 Ma lamprophyre dykes in Ontario, Canada: Implications for the mantle plume hypothesis for Mid-Continental Rift origin

Evgeniy V. Kulakov
Michigan Technological University
Department of Geological and Mining Engineering and Sciences
617 Dow ESE Bldg, 1400 Townsend Drive, Houghton, MI 49931-1295
Current degree program: PhD
Paleomagnetism and Geochemistry of the Porcupine Volcanics and Lake Shore Traps: Implications for the Midcontinent Rift evolution.

Mark Leatherman
1001 E. 10th Street, Department of Geological Sciences, Bloomington, IN 47405
Current degree program: PhD
The Eagle and Tamarack Deposits

Craig Caton
Department of Geological Sciences
229 Heller Hall, 1114 Kirby Drive, University of Minnesota Duluth, Duluth, MN 55812
Current degree program: Masters
Petrogenesis and Metallogenesis of the Southern Troctolite Zone of the Bald Eagle Intrusion, Duluth Complex, Northeastern MN

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.

Student Paper Awards Committee

Helene Lukey – Cliffs Natural Resources

Tom Fitz – Northland College

Milt Gere – Michigan DNR (retired)

Board of Directors

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

Allan R. Blaske (Co-Chair) (2013-2016) – AECOM

Theodore J. Bornhorst (Co-Chair) (2013-2016) – Michigan Technological University

Tom Fitz (2011-2014) – Northland College

Peter Hinz (2010-2013) – Ontario Geological Survey

Pete Hollings - Secretary (2010-2013) – Lakehead University

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

Local Committee

Chair

Theodore J. Bornhorst – A. E. Seaman Mineral Museum,
Michigan Technological University

Allan Blaske – AECOM

Volume Editors

Theodore J. Bornhorst – A. E. Seaman Mineral Museum,
Michigan Technological University

Allan Blaske – AECOM

Robert Barron – Department of Geological and Mining Engineering and Sciences,
Michigan Technological University

Session Chairs

Jack Berkley – SUNY Fredonia

Marcia Bjørnerud – Lawrence University

Terry Boerboom – Minnesota Geological Survey

Paula Leier-Engelhardt – HydroGeo Solutions

Joe Maki – Michigan Department of Environmental Quality

Glenn Scott – Cliffs Natural Resources

Banquet Speaker

Dr. James W. Ashley

Postdoctoral Research Associate
Lunar Reconnaissance Orbiter Camera Science Operations Center
School of Earth and Space Exploration
Arizona State University

Rusty Metal at the Martian Equator: The Search for Life on the Red Planet

The pursuit of an answer to the ancient question "Are We Alone in the Universe?" leads scientists down many paths that cross a multitude of scientific disciplines. In the planetary sciences, the quest often results in the careful engineering of robotic spacecraft designed to answer specific questions about the planets they are sent to explore. Mars is a world that is both easily accessible at reasonable costs, and potentially habitable. We are interested in the roles that water may have played in Mars' geologic history because of its importance to life on Earth.

The Mars Exploration Rover (MER) mission was designed to last for 90 days on Mars in 2004. One of the two rovers (Opportunity) continues exploring today more than nine years later. Among the many discoveries made during this mission are several large, iron meteorites that show dramatic signs of corrosion and other effects of water interaction. MER science team member Dr. James Ashley lead the meteorite discovery and assessment campaign on the mission, and will show how rusty meteorites on Mars are giving us new insight into climate conditions at the red planet's equator.

Dr. James Ashley, a Grand Rapids native, earned his BS in geology at Grand Valley State University, his MS in geological science at Michigan State University, and his PhD under Philip Christensen at Arizona State University. He is currently a postdoctoral research fellow at the Lunar Reconnaissance Orbiter Camera (LROC) Science Operations Center at ASU, where he studies Earth's Moon using LROC instruments. His most recent work has focused on Si-rich volcanic complexes on the Moon, potentially cavernous systems beneath the lunar surface, and the understanding of impact melt on the lunar far side. He is the executive director of Minor Planet Research, Inc., a non-profit company dedicated to mitigating the asteroid impact hazard, and has made many appearances on the History and Discovery Channels discussing the threat from near-Earth asteroids. Prior to his work in the planetary sciences, Dr. Ashley worked full time as a consulting hydrogeologist, and is a member of the American Institute of Professional Geologists.

Report of the Chair of the 58th Annual Meeting

Thunder Bay, Ontario

The 58th ILSG was held in Thunder Bay, Ontario on May 16-20, 2012. The meeting was chaired by Pete Hollings (Lakehead University) with the considerable assistance of the local organizing committee (Bill Addison, Mark Smyk, Peter Hinz, Al MacTavish & Dorothy Campbell), the meeting was attended by a total of 240 delegates. Thanks to very generous support from our corporate sponsors (Goldcorp Inc. – Musselwhite Mine, Osisko Mining Corporation, Activation Laboratories Ltd. (Actlabs), Cliffs Natural Resources Inc., Magma Metals (Canada) Limited, MMG Limited, Rio Tinto, Stillwater Canada Inc., Fladgate Exploration, Thunder Bay CEDC, Mega Precious Metals Inc., Rainy River Resources Ltd., Metals Creek Resources Corp., Midwest Institute of Geosciences and Engineering (MIGE), Benton Resources Corp. & Rare Earth Metals Inc.) we were able to provide free registration to the 60 students who attended.

The two-day technical session began on Thursday morning with oral presentations on regional geology and then proceeded in chronological order from Archean topics through Friday afternoon's presentations on Quaternary geology. A total of 27 talks were given, 7 of which were presented by students. A total of 31 posters were displayed, 15 of which were presented by student authors. The 2011 Goldich Medal was awarded to Jim Miller from the University of Minnesota Duluth. Mark Smyk presented the award during the annual banquet and supplied numerous examples of Jim's passion for the geology of the Lake Superior region. David Overstreet gave the banquet address, discussing Human Adaptation to Late Pleistocene Landscapes - A View from Southeastern Wisconsin. For the first time we ran a core shack during the meeting with core from the Ring of Fire chromite deposits provided by Cliffs, from the Current Lake Ni-Cu-PGE deposit provided by Magma Metals Ltd. and core from Musselwhite Mine provided by Goldcorp Inc.

The meeting offered 13 field trips that highlighted the geology of Thunder Bay region. Four pre-meeting trips were run on Wednesday, including the Lac des Iles Pd mine led by John Corkery (North American Palladium Ltd.), the Sudbury Impactoclastic Debrisites at Thunder Bay led by Bill Addison and Greg Brumpton, the Geology of the Sibley Peninsula led by Dr. Philip Fralick (Lakehead University) Mark Smyk & Riku Metsaranta (Ontario Geological Survey) and the Shebandowan greenstone belt led by Alan Aubut (Sibley Basin Group Geological Consulting Services Ltd.) and Dorothy Campbell (Ontario Geological Survey). On the Friday afternoon three trips were offered, the Geology of the City of Thunder Bay led by Mark Smyk (Ontario Geological Survey), the Panorama Amethyst Mine led by Steve Kissin (Lakehead University) and the Port Arthur building stone walking tour led by Peter Hinz (Ontario Geological Survey). Following the meeting, Goldcorp Inc. flew a lucky group of individuals up to the Musselwhite Mine for a tour led by John Biczok (Goldcorp Inc., Musselwhite Mine). Mark Puumala (OGS) led a trip to examine the Rehabilitation of the Past-Producing Shebandowan and North Coldstream Mines. Scott Hamilton (Lakehead University) took a group to look at the Geoarchaeology of Thunder Bay. Rob Cundari & Pete Hollings (Lakehead University) and Mark Smyk (Ontario Geological Survey) led a trip to look at the Midcontinent Rift intrusions. Greg Brumpton led a reprise of the Ejecta trip and Mark Smyk (OGS) and Philip Fralick (Lakehead University) took a group on a two-day trip to examine the geology along the Highway 527

Transect. Many of the trips sold out and all were well-attended. On Friday evening the organizers hosted a barbeque social event for ILSG participants at the Whitewater Golf Club.

The Institute's Board of Directors met on May 17 to discuss the business of the Institute. The meeting was attended by Al MacTavish, Peter Hinz, Mark Smyk, George Hudak, Bill Addison, Dorothy Campbell, Mark Jirsa and Pete Hollings.

ILSG Secretary Hollings took the minutes of the meeting, that are as follows:

1. Accepted the report of the Chair for the 58th ILSG, Ashland, Wisconsin; as printed in the 2012 Proceedings Volume, and minutes of last Board meeting, May 19, 2011.
2. Accepted the 2011-2012 ILSG Financial Summary.
3. Accepted the 2011-2012 ILSG Secretary's report.
4. Appointed Al MacTavish as the on-going ILSG Board Member.
5. Discussed and approved 2013 (59th annual) meeting location.
6. Replaced Mary Louise Hill as "academic member" on Goldich Committee with Bernhardt Saini-Eidukat.
7. Discussed and approved the naming of the student research award after Joe Mancuso and student paper awards after Doug Duskin

The Chair would like to thank all those who assisted with the running of this year's meeting either by chairing sessions, running field trips or helping with the Registration desk. He is particularly appreciative of the work of the local organizing committee who made his job much easier through their tireless efforts.

Respectfully submitted,

Pete Hollings
Chair, 58th Institute on Lake Superior Geology

Sponsors

The following organizations made general contributions to the 59th Annual Meeting. We thank them for their commitment to the Institute on Lake Superior Geology.

For the past 59 years this organization has thrived as a result of the interest of individuals, corporations, universities and government agencies. The dedication to an exchange of scientific ideas and a passion for field trips has enabled the Institute to provide one of its primary objectives – to promote better understanding of the geology of the Lake Superior region.

AECOM



Rio Tinto

EAGLE MINE

PROGRAM

WEDNESDAY MAY 8, 2013

8:00 a.m. **FIELD TRIP 1: GEOLOGIC OVERVIEW OF THE KEWEENAW PENINSULA, MICHIGAN**
Ted Bornhorst, *Michigan Tech*

8:00 a.m. **FIELD TRIP 2: CALEDONIA MINE, KEWEENAW PENINSULA NATIVE COPPER DISTRICT, ONTONAGON COUNTY, MICHIGAN**
Robert Barron, *Michigan Tech*
Richard Whiteman, *Red Metal Minerals*
Ted Bornhorst, *Michigan Tech*

8:00 a.m. **FIELD TRIP 3: GEOLOGY OF SILVER MOUNTAIN, HOUGHTON COUNTY, MICHIGAN**
Evgeniy Kulakov, *Michigan Tech*

5:00 p.m. **Return of Trips 1, 2, and 3**

4:00 p.m. - 8:00 p.m. **Registration at Franklin Square Inn, 7th Floor**

7:00 p.m. - 9:00 p.m. **Ice Breaker Social and Poster Session, Franklin Square Inn, 7th Floor**

THURSDAY MAY 9, 2013

Note: Asterisk * denotes a student eligible for Best Student Paper Award
+ denotes students which qualify for travel awards, but not Best Student Paper awards

8:00 a.m. - 2:40 noon **REGISTRATION**

8:20 a.m. **INTRODUCTORY REMARKS**
Theodore J. Bornhorst and Allan R. Blaske, Co-Chairs, 2013 ILSG

TECHNICAL SESSION I

Session Chairs: Marcia Bjørnerud – Lawrence University
Terry Boerboom – Minnesota Geological Survey

8:30 a.m. **Peter Hollings and Mark Smyk**
Preliminary geochemical analysis of the Nipigon Bay granites, northern Lake Superior

8:50 a.m. **Emily Smyk*, Pete Hollings, and John Biczok**
Geochemical and petrographic study of a Mesoarchean felsic metavolcanic unit near Musselwhite Mine, North Caribou greenstone belt, northwestern Ontario

9:10 a.m. **Aubrey Lee* and Jim Miller**
The Igneous Stratigraphy of the Bad Vermilion Intrusion, Mine Centre, Ontario, Canada: Which Way is Up?

9:30 a.m**. Skylar Schmidt* and Mary Louise Hill**
North American Palladium's Lac des Iles mine: Evidence for high temperature deformation and possible control on Pd mineralization

9:50 a.m**. Ben Kuzmich*, Pete Hollings, and Michel G. Houlé**
Preliminary Investigations of the Fe-Ti-V-P mineralization associated with the Thunderbird and Butler gabbroic intrusions within the McFaulds greenstone belt, Superior Province, Northern Ontario, Canada

10:10 a.m. to 10:30 a.m. **COFFEE BREAK AND POSTER SESSION**

10:30 a.m. **Ian R. Dasti* and Stephen A. Kissin**
The Geochemistry and Mineralogy of the Sulfides within the Ni-Cu-PGE Shakespeare Deposit, Ontario

10:50 a.m. **Erik Haroldson and Philip Brown**
Fluid Inclusion study of the Magino Archean Gold Deposit; Implications for Regional Mineralizing Systems

11:10 a.m. **Sarah Canning, Zoran Madon, and Keith Wallace**
A Geological Model and Resource Update for the Hammond Reef Gold Deposit

11:30 a.m. **LUNCH BREAK – 2013 ILSG Board Meeting** (by invitation)

TECHNICAL SESSION II

Session Chairs: Paula Leier-Engelhardt – HydroGeo Solutions
Glenn Scott – Cliffs Mining Service Company

1:00 p.m. **Phillip Larson**
Chemostratigraphy of the Biwabik Iron Formation: Implications for Basin Longevity and Evolution

1:20 p.m. **Christopher Yip*and Philip Fralick**
Sedimentology and Geochemistry of a Regressive Surface in the Chemical Sediments of the Paleoproterozoic Gunflint Formation

1:40 p.m. **Gordon Medaris Jr., Terry Boerboom, Brian Jicha and Brad Singer**
The McGrath metasaprolite: viewing Paleoproterozoic weathering through a veil of metamorphism and metasomatism

2:00 p.m. **Mark Puumala**
Natural Groundwater Geochemistry in Bedrock of the Thunder Bay Area

2:20 p.m. – 2:40 p.m. **COFFEE BREAK AND POSTER SESSION**

2:40 p.m. **William F. Cannon, Laurel G. Woodruff, and Klaus J. Schulz**
The Hiawatha Graywacke of the Iron River-Crystal Falls district, Michigan: a megaturbidite triggered by seismicity related to the 1850 Ma Sudbury impact

3:00 p.m. **Monica M. Karman* and Philip W. Fralick**
Sedimentology and Paleographic Reconstruction of the Strata Adjacent to the Sudbury Impact Layer in a Cored Drillhole

3:20 p.m. **Daniel LaFontaine* and Philip Fralick**
Sedimentology and geochemistry of the Espanola Formation, Huronian Supergroup

3:40 p.m. **Breanne Beh*and Philip Fralick**
Depositional Processes Operating on the Paleoproterozoic Gowganda Ice Margin

4:00 p.m. **SESSION ENDS**

6:00 p.m. **ICE BREAKER – MIXER – CASH BAR**
7:00 p.m. **ANNUAL BANQUET AND AWARD PRESENTATION**

- **Announcement of 60th Annual Meeting Location**
- **2013 Goldich Award Presentation to Tom Waggoner**
- **2013 Banquet Address by Dr. James W. Ashley, Postdoctoral Research Associate LROC, School of Earth and Space Exploration, Arizona State University**

All registered participants are welcome to the banquet address

FRIDAY MAY 10, 2013

8:25 a.m. **INTRODUCTORY REMARKS**
Theodore J. Bornhorst and Allan R. Blaske, Co-Chairs, 2013 ILSG

TECHNICAL SESSION III

Session Chairs: Jack Berkley – SUNY Fredonia
Joe Maki – Michigan Department of Environmental Quality

8:30 a.m. **Teresa Johnson*, Richard Wendlandt, and James Shannon**
Geochemistry of reversely-polarized intrusions along the SW limb of the Midcontinent rift system, Carlton County, Minnesota

8:50 a.m. **Raymond Anderson and Ryan Clark**
The Northeast Iowa Intrusive Complex; a Duluth Complex analog? What we know as the investigation begins.

9:10 a.m. **Benjamin Drenth, Raymond Anderson, Val Chandler, William Cannon, Klaus Schulz, Joshua M. Feinberg, Paul Bedrosian, and Andy M. Kass**
High-resolution, multi-method geophysical imaging of a portion of the Northeast Iowa Intrusive Complex

9:30 a.m. **Robert Cundari, Peter Hollings, and Mark Smyk**
Geochemistry of the Logan Igneous Suite and implications for the magmatic evolution of the northern part of the Midcontinent Rift

9:50 a.m. **Jack Berkley**
Lithospheric Delamination during Midcontinent Rifting

10:10 a.m. – 10:30 a.m. **COFFEE BREAK AND END OF POSTER SESSION**

10:30 a.m. **Connor Mulcahy, Edward Hansen, Theodore Bornhorst, and Dieter Rhede**
Chemical Zoning in Calc-Silicate Minerals Associated with Native Copper from the Keweenaw Peninsula, Michigan

10:50 a.m. **Alex C. Brown**
Brine viscosity vs. temperature: A key to copper deposition in the finest-grained basal Nonesuch Formation, White Pine-Presque Isle district, northern Michigan

11:10 a.m. **Stanley L. Vitton**
Glacial Lake Ontonagon and the Development of Large Scale Landslides

11:30 a.m. **Bruce A. Brown**
Hydrofrac Sand: A major mining boom in the upper Midwest

11:50 a.m. **Val W. Chandler and Richard S. Lively**
Passive-aggressive geophysics: An update on using the horizontal-to-vertical spectral ratio (HVSR) passive seismic method for determining glacial deposit thickness in Minnesota

12:10 p.m. **Presentation of Student Awards**
Student Travel Awards
Best Student Paper Awards

12:30 p.m. **LUNCH BREAK AND END OF TECHNICAL SESSIONS**

2:00 p.m.–7:00 p.m. **FIELD TRIP 4: OPEN HOUSE AT A. E. SEAMAN MINERAL MUSEUM, MICHIGAN TECH, 1404 E. SHARON AVENUE, HOUGHTON**
Ted Bornhorst, *Museum Director*

FIELD TRIP 5 PRESENTATION AT 8:00 P.M., AMERICINN, SILVER CITY, MI

SATURDAY MAY 11, 2013

8:00 a.m. **FIELD TRIP 5: GEOLOGY OF THE KEWEENAWAN SUPERGROUP, PORCUPINE MOUNTAINS, ONTONAGON AND GOGEBIC COUNTIES, MICHIGAN**
William Cannon, Laurel Woodruff, Klaus Schulz, Suzanne Nicholson, *USGS*

LEAVES FROM AMERICINN, SILVER CITY

7:00 a.m. **FIELD TRIP 6: GEOLOGY AND ENVIRONMENTAL SITE CONDITIONS OF THE COPPERWOOD DEPOSIT, GOGEBIC COUNTY, MICHIGAN**
Ted Bornhorst, *Michigan Tech*
Allan Blaske, *AECOM*
Dave Anderson and Tom Repaal, *Orvana Resources US Corp.*

MEETS AT ORVANA RESOURCES US CORP OFFICE IN IRONWOOD, MICHIGAN AT 8:30 AM CDT
LEAVES HOUGHTON FRANKLIN SQUARE INN AT 7:00 EDT

5:00 p.m. Return of Trips 5 and 6

END OF 59TH ANNUAL INSTITUTE ON LAKE SUPERIOR GEOLOGY

POSTER PRESENTATIONS

Steven D. J. Baumann, Alex B. Cory and David Wilson

Precambrian Faulting in the Ripon Wisconsin Area and Its Impacts on Groundwater Contamination, Originating at Superfund Site Ripon NN/FF Landfill

Craig Caton

Crystallization of Chrome Spinel in the Southern Troctolite Zone of the Bald Eagle Intrusion, Duluth Complex, Northeastern MN

Jonathan Dyess* and Vicki Hansen

Application of LiDAR to resolving regional tectonic and glacial fabrics in glaciated terrane: An example from an Archean granite-greenstone belt in NE Minnesota

Jonathan Dyess* and Vicki Hansen

Structural and Kinematic Analysis of the Shagawa Lake Shear Zone and Snowbank Lake Stock, Superior Province, NE Minnesota

Ellen Fehrs[+], Edward Kenny[+], John Kuchma[+], Sarah Sauer[+], William Sylvester[+], and George Hudak

Bedrock Geologic Map of the Putnam Lake Area, St. Louis County, NE Minnesota – Precambrian Research Center Capstone Project

George Hudak, Stephen Monson Geerts, Larry Zanko, April Severson, Allison Severson, Stuart Kramer and Bryan Bandli

The Minnesota Taconite Workers Health Study: Environmental Study of Airborne Particulate Matter - 2013 Update

Mark A. Jirsa

Bedrock geologic map of the western Gunflint Trail area, northeastern Minnesota

Mark A. Jirsa, Dale R. Setterholm, and V. W. Chandler

Minnesota River Valley subprovince as depicted on a new bedrock geologic map of Renville County, southwestern Minnesota

Katrina Korman[+], Suzanne Craddock[+], Michael Doyle[+], Jessica Walter[+], Aubrey Lee[+], and Mark Jirsa

Geologic mapping of Neoarchean and Paleoproterozoic rocks near Ester Lake by students of the Precambrian Research Center's 2012 field camp – Precambrian Research Center Capstone Project

Mark Leatherman*, Edward Ripley, Dean Rossell, Andrew Ware, and Chusi Li

Geochemistry and origin of slate-hosted massive sulfides of the Eagle Ni-Cu-PGE Deposit, northern Michigan: A preliminary study.

Aubrey Lee*, and Jim Miller

Field, Petrographic, and Geochemical Study of the Bad Vermilion Intrusion, Mine Centre, Ontario, Canada

Adam Leu[+], Lionel Djon[+], Emily LaPietra[+], Zech Martin[+], Ricardo Martinez[+], and Jim Miller

2012 Precambrian Field Camp Mapping in the Wilder Lake Intrusion, Lake County, Northeastern Minnesota – Precambrian Research Center Capstone Project

Steven Losh and Ryan Rague

Silica Remobilization in the Biwabik Iron Formation, Minnesota USA

Brynley Nadziejka* and Marcia Bjørnerud

Contrasting pressure-temperature-time paths for high-grade metamorphic rocks in the interior of the Penokean-Yavapai orogenic belt, southern Lake Superior region

Matthew Schmus*, Prajukit Bhattacharyya, and David Hart

Effects of Preexisting Fractures on Groundwater Flow Today

Klaus J. Schulz, William F. Cannon, and Laurel G. Woodruff

The Parent Lake Volcanics: Product of a phreatomagmatic eruption of basalt during deposition of the Michigamme Formation?

Brent Trevisan*, Pete Hollings and Doreen Ames

Petrology, mineralization, and alteration of the Thunder mafic to ultramafic intrusion, Midcontinent Rift, Thunder Bay

Peter Voice, William Harrison, and Joyashish Thakurta

A Preliminary Survey of the Geology of the Pre- Michigan Basin Rocks of the Southern Peninsula

The Northeast Iowa Intrusive Complex; a Duluth Complex analog? What we know as the investigation begins.

ANDERSON, Raymond and CLARK, Ryan

Iowa Geological and Water Survey, 109 Trowbridge Hall, Iowa City, Iowa 52242-1319

The Northeast Iowa Intrusive Complex (NEIIC) is defined by a suite of gravity and magnetic anomalies that stretch from east-central Iowa to southeast Minnesota and are currently interpreted as mafic intrusions. They are characterized by a series of intersecting circular positive gravity anomalies and corresponding positive and negative aeromagnetic anomalies (Figs 1, 2). The NEIIC was described by Pals and Anderson (2011) who proposed that the complex was of Keweenawan age and analogous to the Duluth Complex. These anomalies were sampled by drilling in four locations (Figs 1, 2). Cores in Minnesota penetrated a "gabbroic rock" (B-1) and a metagabbro (BO-1) that was dated at 1760 Ma (Van Schmus et al., 2007) and may be country rock to the NEIIC. In northeast Iowa a 90 year-old oil test (Pioneer #1) penetrated 480 m of "troctolite" or "olivine gabbro" which yielded a Rb/Sr age of 1,130 Ma (Lidiak et al., 1966); no samples are currently available. A mineral exploration core recovered from northeast Iowa (A1-2) sampled 220 m of serpentenite and troctolite from a dike-like anomaly. Drill data and other interpretations suggest that the Precambrian basement surface lies about 350 m (north) to about 900 m (south) below the land surface.

Many of the geophysical anomalies associated with the NEIIC have been surveyed and modeled by geology students (Fig 3). These anomalies have been interpreted as mafic intrusives, including lopoliths, dikes, and plug-like intrusions (see Dixt, 1984; Heathcote, 1979; Kittleson, 1975; Stepanek, 1978). Two of the modeled intrusives (Dixt, 1984; Heathcote, 1979) were interpreted as mafic lopoliths with maximum diameters of 47 km and 37 km with density contrasts of +0.3 g/cm3 with the felsic country rocks. Heathcote's (1979) model displayed a Koeningsberger ratio (remanent to induced magnetism) of 6.78 and model remanent vectors consistent with Keweenawan directions and angles. Her model also featured a magnetic field reversal (normal to reverse) captured during the cooling of the intrusive (Fig 4). Kittleson's (1975) analysis of the Osborne A1-2 core revealed an ultramafic composition composed of cyclic layers of olivine cumulates and olivine-plagioclase cumulates that constituted the upper portion of a dike-like intrusive with a width of about 300 m and a depth extent of about 4.8 km.

The age of these intrusives is currently interpreted as Keweenawan based on several lines of evidence. The rocks into which the NEIIC was intruded were interpreted as Yavapai (geon 17) by Van Schmus and others (2007). The only subsequent major magmatism in the area was the widespread felsic anorogenic events (ca. 1,470 and 1,370 Ma) which produced low density plutons with gravity anomalies lower than regional values. Additionally, the 1,130 Ma age (Pioneer #1), the use of Keweenawan remanence vectors in pluton modeling (see above), and the trend of the NEIIC, subparallel to the Keweenawan Midcontinent Rift System, argue for a Keweenawan age.

The U.S. Geological Survey, working with the state geological surveys of Iowa and Minnesota, has recently began investigation the potential of the NEIIC for Duluth Complex-like platinum group, nickel, and copper mineralization. Initial stages include acquisition of additional geophysical data and comprehensive modeling and interpretation, with possible core drilling to follow.

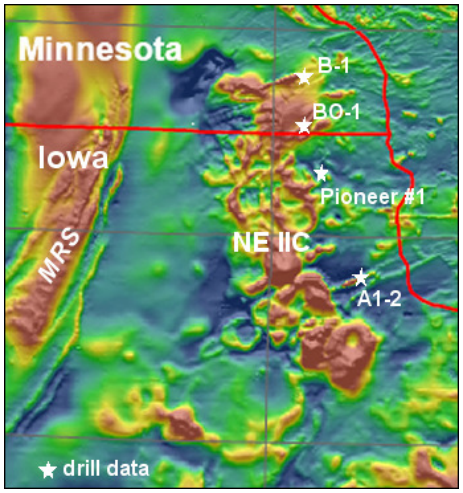


Figure 1. Shaded relief total magnetic intensity map of NEIIC and Midcontinent Rift System (MRS) (http://www.mngs.umn.edu/nicegeo/niceimgs.htm)

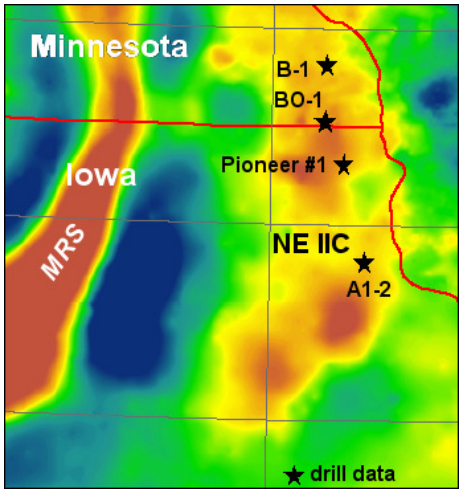


Figure 2. Bouguer gravity anomaly map of NEIIC (http://www.mngs.umn.edu/nicegeo/niceimgs.htm)

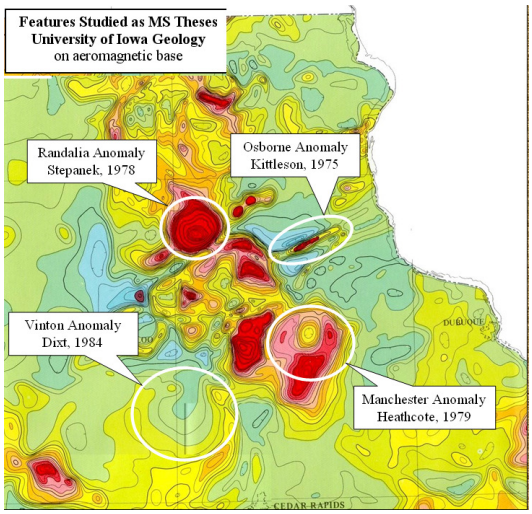


Figure 3. Map identifying NEIIC intrusives that were modeled by geology students on Aeromagnetic Map of Iowa

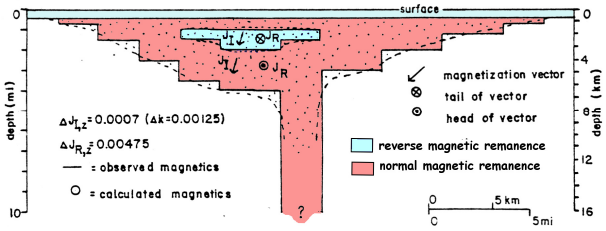


Figure 4. Magnetic model for north-south profile across Manchester Anomaly (Heathcote, 1979)

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Precambrian Faulting in the Ripon Wisconsin Area and Its Impacts on Groundwater Contamination Originating at Superfund Site Ripon NN/FF Landfill

BAUMANN, Steven D.J.[1], CORY, Alex B.[1] and WILSON, David[2]
[1]*Geology Section, Midwest Institute of Geosciences and Engineering, 2328 W. Touhy Ave. Chicago, IL 60645*
[2]*Superfund Division, U.S. EPA Region 5, 77 West Jackson Blvd. Chicago, IL 60604*

Faults are known to serve as conduits for the migration of contaminants, especially in the subsurface. One case of particular interest is the Superfund site designated as the Ripon NN/FF Landfill (Ripon Superfund), center of which is located 1,000 feet south-southeast of the junction of County Road FF and South Koro Road (GPS: 43.866850°, -88.870945°). This superfund site has historically shown vinyl chloride contamination in several off-site monitoring wells. The nearest potable well for the city of Ripon has also shown contamination. The contamination has spread in a manner that is inconsistent with traditional modeling techniques, suggesting that something unknown is occurring at the Precambrian-Cambrian contact. Thanks to information provided by David Wilson of the United States Environmental Protection Agency (U.S. EPA) new insight has been gained about the subsurface geology. The reason for the unusual migration of contaminants is most likely due to unmapped parallel faults in the Precambrian basement rock.

A detailed bedrock geologic map was compiled by Steven Baumann in 2011 of Ripon and the surrounding area, to include the Ripon Superfund location. Faults in the basement rock were expected at the time the bedrock map was compiled, but could not be confirmed. In 1993 a deep borehole (P-107D) into the bedrock was drilled through the glacial cover, through the underlying Cambrian sands, and down into the Precambrian basement rock. During the compilation of the Ripon Wisconsin bedrock map (Baumann 2011), the superfund borings were unknown to the author. Even without the Superfund logs the surficial field work conducted in the Ripon area yielded several distinct and prominent structural features. No faults were observed extending up through the youngest surface rocks. Although faulting was suspected at the time of mapping, the available data did not provide direct evidence of the presence of faults.

Based on the detailed log for boring P-107D (the only detailed log to significantly penetrate the Precambrian) the basement consists of a thin layer of purple quartzite on top of a thick red granitic or syenite sequence, similar to the rocks exposed in the Baraboo Wisconsin area. The Precambrian geology of Ripon is expected to be similar to that of Baraboo. At Baraboo, there is highly fractured Precambrian quartzite on top of igneous rocks, which in turn are covered by thick sequences of Cambrian and Ordovician rocks. The only real difference between Baraboo and Ripon is the thick cover of glacial outwash deposits present at Ripon. The western half of the Baraboo Precambrian exposures are part of the “Driftless Area” and were not glaciated. The similarities between Baraboo and Ripon, give justification for modeling structural features in the Ripon area in a similar manner to the structures observed in the Baraboo area.

The presence of quartzite on the bedrock high penetrated by P-107D is a strong indication of local faulting. Based on the orientation of known local structures in the Cambrian and Ordovician a fault just south of P-107D is expected to trend N55W to N75W based on the orientation of the nearby Ripon Arch. However, near the theoretical north limit of the Ripon Arch (near Arcade Acres) does turn more north then west-northwest. The understanding of any local faulting in the Precambrian is of key importance due to the likelihood of the faults serving as a route of contamination, possibly leading to the City of Ripon’s #9 Supply Well (Wilson 2012).

Any faults in the area are probably roughly parallel to each other and the Ripon Arch. The faults likely show fracturing 60 feet or so within the Precambrian-Cambrian (PC-C) boundary and most likely fade out within the Cambrian Wonewoc Formation. Although fracturing is very likely near the PC-C boundary, the faults are probably tight deeper than 30 feet below the PC-C boundary. The total displacement of the faults is likely on the order of 40 to 80 feet. This will greatly affect groundwater flow direction in the deepest hydrogeologic unit designated as "Layer 4" (Wilson 2012). "Layer 4" is the basal known confined aquifer in the Cambrian and it likely connects to the groundwater in the faults and fractures in the Precambrian basement. Weathering patterns at the PC-C boundary were not noted in the P-107D log. However, using the PC-C boundary at Baraboo, it is likely that the contact is significantly lithified, yet extremely porous. Although the groundwater in P-107D at the PC-C boundary is likely connected to "Layer 4" a definite connection cannot be ascertained without additional data.

At present fault dynamics and contaminant migration cannot be definitively determined at present. Additional deep basement down gradient sentinel wells will need to be drilled in order to develop a good model and plan to stop additional contaminants from reaching the Ripon #9 Supply Well.

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DEPOSITIONAL PROCESSES OPERATING ON THE PALEOPROTEROZOIC GOWGANDA ICE MARGIN

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Glacial sedimentary rocks of the Huronian Supergroup crop out along the north shore of Lake Huron and were likely deposited on what is thought to have been a divergent continental margin (Fralick and Miall, 1981; 1989). The rocks of the Gowganda Formation record one of three glacial events preserved in the Supergroup and are therefore of interest for developing further glaciomarine models (Puffett, 1974) and furthering understanding of this early stage in Earth's history. Data has been collected in five main study areas in an attempt to cover as much of the ancient continental margin as possible. The study areas include Espanola; Elliot Lake; Thessalon; and Cobalt, Ontario; and Marquette, Michigan. There are two glaciogenic formations in the Marquette area of Paleoproterozoic age, the Reany Creek Formation and the Enchantment Lake Formation. The Enchantment Lake Formation has been chronostratigraphically correlated to the Huronian Supergroup based on U-Pb age determination on detrital zircon, 2317±6 Ma, and diagenetic xenotime, 2133±11 Ma (Vallini et al., 2006). As these formations are present in such close proximity to each other, and there are no Archean glacial events recorded in the rest of the Canadian Shield, it is reasonable to correlate them with the Gowganda Formation, the thickest and most commonly preserved of the three Huronian glacial events.

Stratigraphic sections were compiled in each of the study areas and the sedimentary rocks were grouped into seven lithofacies associations (LA): 1) Planar Cross-Stratified Sandstone LA, 2) Basal Breccia LA, 3) Diamictite LA, 4) Interlayered Siltstone and Fine-Grained Sandstone LA, 5) Slump LA, 6) Heterogeneous Sandstone LA and 7) Quartz-Rich Sandstone LA. These lithofacies associations likely represent a sequence of depositional environments on a shallow continental shelf. Initially, the shelf was dominated by what were likely large-scale, low-angle sandwaves (Figure 1A), interbedded with successions of wavy bedding and possible hummocky cross-stratification indicating an open-water setting with tidal and storm processes reworking the sediments. The shelf then gradually evolved into an environment dominated by diamicite layers. The diamictite layers have dropstones (Figure 1B) as well as evidence of current activity indicating outsized clasts were likely being introduced into the environment as ice-rafted debris. Resedimentation events in the form of debris flows are thought to account for conglomeratic layers that are common in the Diamictite LA. The Interlayered Siltstone and Fine-Grained Sandstone LA, along with the Slump LA (Figure 1C), seem to indicate deposition from suspension in a prodelta setting where large slump events are common. The gradual transition into a more sandstone dominated LA, with an abundance of current-related sedimentary structures, is indicative of the shallowing and coarsening upwards succession common to deltaic deposits. A final transition into the Quartz-Rich Sandstone LA indicates a return to a sandy, current-dominated open continental shelf environment with abundant tidally generated sedimentary structures such as herringbone cross-stratification (Figure 1D). The Cobalt study area differs from this overall model in that evidence of grounded ice is present. Less exposure in the Marquette study area makes it difficult to draw overall conclusions on the evolution of the continental shelf but deposition in a subaqueous glacial outwash fan is hypothesized.

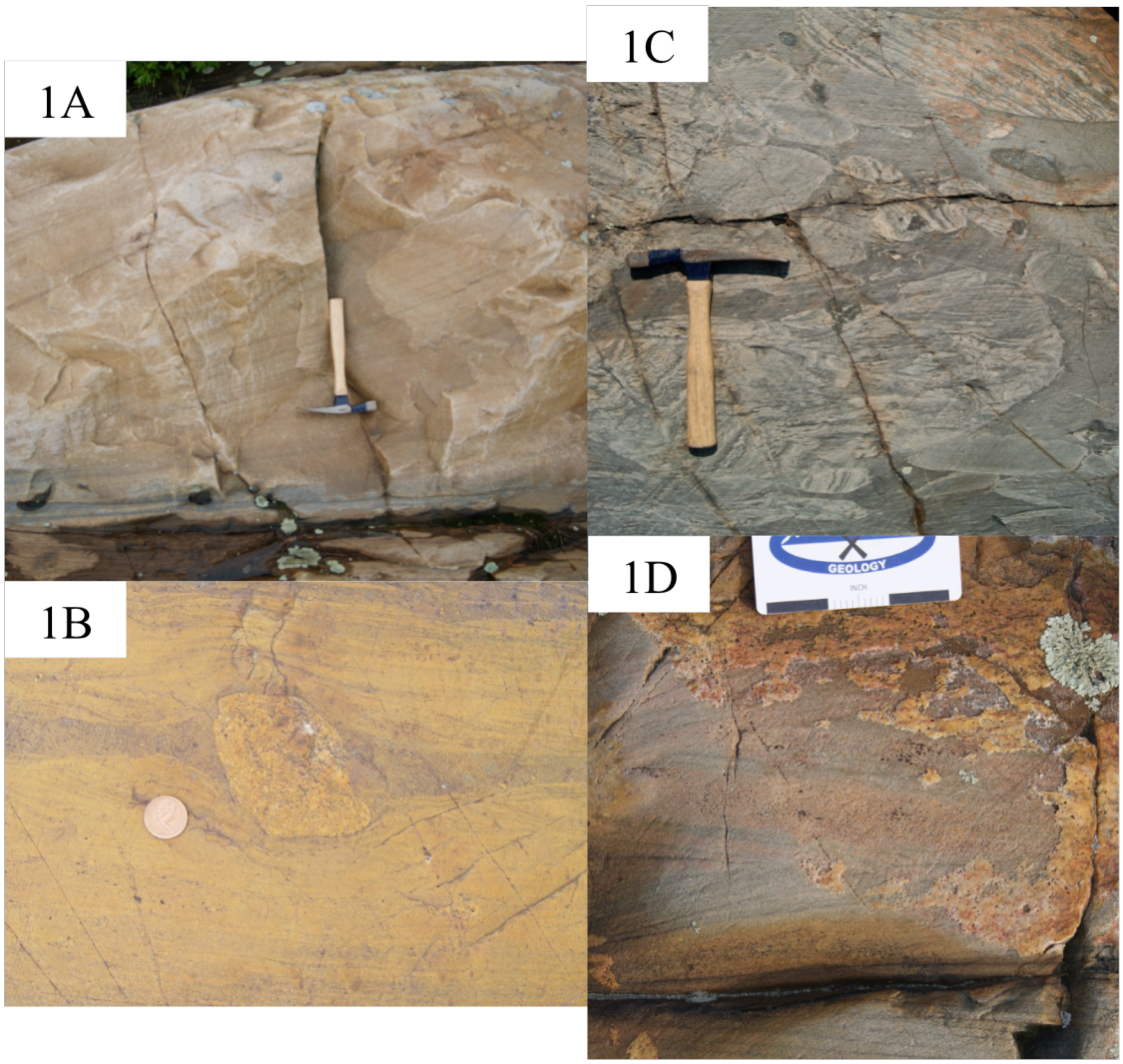


Figure 1. A) Large-scale, low-angle planar cross-stratified sandstone. B) A dropstone compressing underlying laminations. C) A mud-block conglomerate of slumped prodelta deposits. D) Herringbone cross-stratified sandstone.

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Lithospheric Delamination during Midcontinent Rifting

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The process of delamination, briefly defined as the physical peeling off and descent of a cold lithospheric slab into ascending hot mantle asthenosphere, has historically been applied mostly to convergent orogenic systems (Fig. 1a) involving continent-continent collision and subduction (e.g. Bird, 1979; Hamilton et al., 2004). Delamination has been invoked to explain perplexing tectonic-topographic expressions such as the Colorado Plateau, as well as massive collisional fold and thrust belts like the Himalayas, Alps, and more ancient terrains, notably the Mesoproterozoic Grenville Orogen (e.g., Wallner and Schmeling, 2010; Hamilton et al., 2004).

Continental rift terrains (Fig. 1b), although dominated by extensional rather than convergent stress fields, are formed in the same general geophysical milieus as convergent systems (i.e., 30 km+ low-density crust plus upper mantle lithosphere -- overlying hot, low-viscosity asthenosphere). Rift terrains (Fig. 1b) are also subjected to upwelling heat sources with liberated volatiles (esp. water) that function to exacerbate the weakening of previously hyper-strained lithosphere. Given a few extenuating circumstances (see below), upper mantle delamination is predictable, or at least possible.

(a) (b)

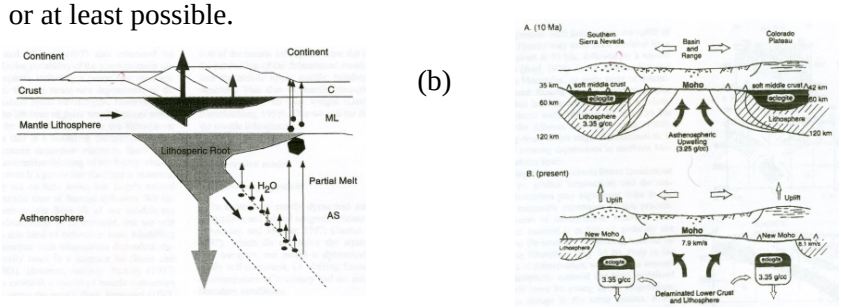


Figure 1: (a) Convergent delamination of a mantle lithospheric root (gray) (from Schott and Schmeling,1998). (b) Extensional delamination in the Basin-Range province, USA (from Meissner and Mooney, 1998).

If delamination played a controlling role in the production of magmatic suites of the Mid-continent Rift (MCR) specifically in the well-exposed Lake Superior region, what criteria can be used to detect that influence? Much depends on the precise sub-surface structural configuration underlying the rift environment, conditions that can vary widely from region to region – and, more importantly, along strike in the MCR. Recent and past studies show that the MR consists of two linear branches, the Western branch that extends northeast from Kansas to Lake Superior (active interior continental rift), and the Eastern branch (leaky transform fault) that extends southeast from Lake Superior to SE Michigan, and possibly as far as Kentucky. The bulk of igneous activity occurs in the Lake Superior basin due to the likely influence of a deep mantle plume (e.g., Merino et al., 2012; Davis and Green, 1997). Deep earth tomography reveals that early rift-induced normal faults have later transitioned to low-angle thrust faults in response to west-directed Grenville orogenic compression. In that light, conditions required for rift-induced delamination ("RID", Wallner and Schmeling, 2010) include: (1) a thermal anomaly (e.g., plume), (2) low-strength lower crust, and (3) lateral density variations within the lower crust.

Excess temperature and *low yield stress* at depth are especially critical parameters. The Lake Superior region meets the *prima facie* criteria required for delamination, although that fact does not guarantee that delamination has, in fact, occurred. On the other hand, the presence of late Grenville thrusting could provide a facilitating factor missing in most rift environments. Most confirmed or suspected delamination events occur during compressive, crust-thickening stress events, as in the relative nearby Grenville fold belt (as in the Adirondacks, e.g., Hamilton et al., 2004).

Although not exhaustive, the following observations could be used to evaluate the role of delamination in the Lake Superior region: (1) Magmas produced by delamination would be primarily mafic (melting of hot mantle asthenosphere), but a variety of voluminous felsic magmas would also be expected from melting of Archean crust or differentiation of ponded mafic plutons, (2) Igneous rocks directly produced by delamination should show relatively young ages compared to, say, purely plume-generated magmas, and should be restricted in age, (3) Assuming a progressively peeling off and sinking lithospheric slab (or *slabs*) ages of pluton series may vary older-to-younger laterally across surface exposures, (4) Seismic studies show one or possibly two highly disrupted deep crustal zones under Lake Superior (Hamilton and Mereu, 1993) in which mantle material displays up-welling high up into crustal layers. Obviously, such areas should be considered prime targets for possible delamination effects on geographically associated igneous exposures.

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Brine viscosity vs. temperature: A key to copper deposition in the finest-grained basal Nonesuch Formation, White Pine-Presque Isle district, northern Michigan

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The sulfide-dominant main-stage stratiform copper (SSC) mineralization in the fine-grained carbonaceous Nonesuch Formation at White Pine, northern Michigan, has long been attributed to a vertical influx of oxidized low-temperature cupriferous brine from the underlying Copper Harbor Conglomerate aquifer during early Nonesuch diagenesis. However, despite the difficult influx of brine from a good aquifer into a fine-grained aquitard, the best-mineralized Nonesuch of the White Pine district is hosted by the *finest*-grained basal Nonesuch. This dilemma was addressed by White (1971) and Swenson et al. (2004) who showed, in 2-dimensional profiles, that brines driven southward out of the Lake Superior rift basin by compaction could have been forced upward into the basal Nonesuch where the Copper Harbor thins abruptly over a large volcanic dome (Porcupine Volcanics) located directly below the White Pine mine district. However, in 3-dimensions, those brines should have escaped largely to the east and west *around* the volcanic dome where the Copper Harbor is thick. Furthermore, compaction brines should have equilibrated with ferrous constituents of the aquifer and thus been too reducing to carry significant amounts of copper.

On the other hand, copper may be carried in very significant amounts in oxidized low-temperature brines such as generated during meteoric recharge (Brown, 2005). Furthermore, latent heat from a dormant or extinct resurgent caldera, represented here by the Porcupine Volcanics, could have locally increased the temperature of brine hosted by the Copper Harbor Conglomerate to ~100ºC, the estimated maximum temperature experienced by the basal Nonesuch Formation at White Pine (Grigorita and Brown, 2002; Fig. 1). By analogy to modern calderas (e.g., the Valles caldera, New Mexico), heat may have emanated from the Porcupine Volcanics for more than one

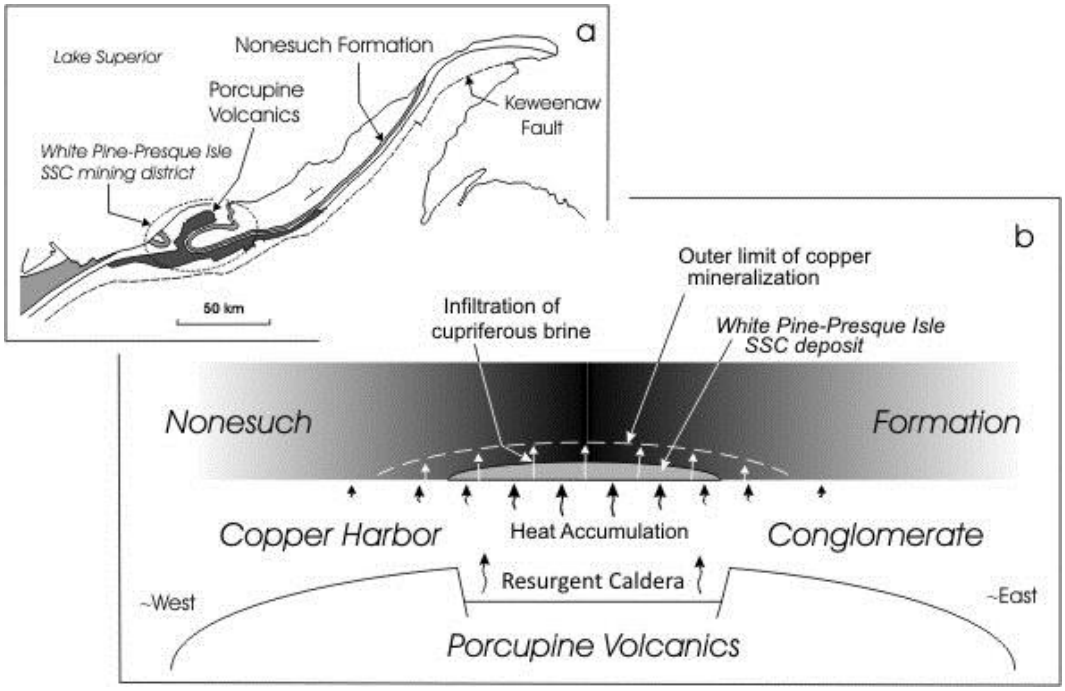


Fig. 1. a) Location map. b) A schematic illustration of resurgent caldera heat, from the recently dormant or extinct Porcupine Volcanics dome, inducing an exceptional brine infiltration into fine-grained basal Nonesuch beds in the White Pine-Presque Isle area. Lateral grain-size gradations within the Nonesuch are represented by shading: dark gray = very fine-grained, lighter gray = coarser grained.

million years at rates (e.g., up to 2500 mW/m^2; Goff and Gardner, 1994) far above the normal heat flow of intracontinental rifts (e.g., 60 to 120 mW/m^2). Thermal blanketing by the fine-grained Nonesuch would have aided in the accumulation of anomalous heat in the Copper Harbor brine over the resurgent caldera. Heating of the brine from 20 to 100°C would have decreased its density by about 5% and thus encouraged upward buoyant circulation. More significantly, warming of the brine would have lowered its viscosity to ~30% of its viscosity at 20°C (Fig. 2). On the basis of density and viscosity changes alone, the vertical flux of brine into the basal Nonesuch in the area underlain by the resurgent caldera should have been ~3.5 times the flux in cooler distal areas. Applying Darcy's law (Ingebritsen and Appold, 2012), a larger infiltration of brine into the basal Nonesuch is found even if the permeability of the finest-grained Nonesuch was 1/2 order of magnitude less than the permeability of more distal, coarser-grained Nonesuch.

Furthermore, if brine infiltration into the basal Nonesuch was more rapid where it was warmed locally by a recently dormant or extinct resurgent caldera, replacement brine in the Copper Harbor aquifer should have been drawn *laterally* toward this area from surrounding areas (Fig. 3). This convergent supply of ore-forming brine in the Copper Harbor aquifer would have been more efficient than the ore-forming process of a linear meteoric recharge-driven scenario.

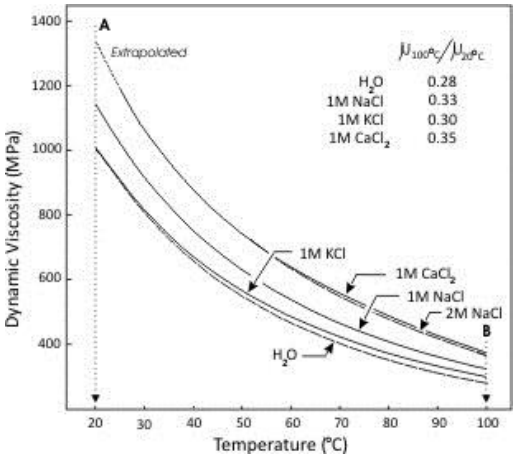


Fig. 2. Viscosity (μ) vs. temperature from 20 to 100°C, for H_2O and various brines.

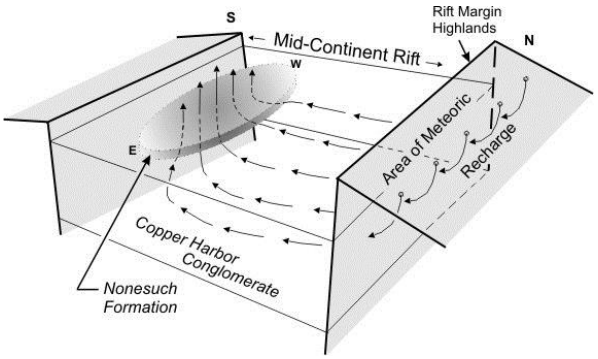


Fig. 3. Sketch illustrating the convergence of meteoric recharge-driven brine (curved arrows) toward the base of the fine-grained Nonesuch Formation (due to anomalous heat accumulated there as a result of thermal blanketing) with a consequently high rate and focus of brine infiltration. Location of highland area is schematic only.

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Hydrofrac Sand: A major mining boom in the upper Midwest

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The phenomenal growth of the hydrofrac sand industry in Wisconsin, Illinois, and Minnesota in the last five years has resulted in a mining boom the likes of which has not been seen since the discovery of lead-zinc and iron in the 19th century. In 2008 there were less than ten industrial-sand mines in Wisconsin, including foundry sand mines. In 2012 the count was more than one hundred, almost exclusively hydrofrac sand operations.

The sand boom is the direct result of the successful application of improved horizontal drilling techniques and hydraulic fracturing to hydrocarbon-rich shales that were previously too impermeable to develop by conventional vertical drilling. The hydraulic fracturing process involves applying high pressure to a well sufficient to fracture a hydrocarbon-bearing formation of low permeability. The pressure opens fractures around the well bore, and a proppant, usually sand grains, is injected into the well to prop the fractures open after the pressure is released, allowing oil or natural gas to flow into the well. To be useful as a proppant, sand must be pure quartz, of specific grain size, have high roundness and sphericity, and a high compressive strength. Hydrofrac sand has been produced in the region for over fifty years. The Jordan, Wonewoc, and Mount Simon sandstones of Cambrian age and the Ordovician St. Peter sandstone have long been recognized as excellent sources of proppant sand. Most of the new mines produce from the Wonewoc Formation, which is a good source of the finer (40-70) sand used for gas drilling. The Jordan and Mount Simon Formations are coarser and produce more of the 20-40 mesh sand favored for oil drilling. The St. Peter in Wisconsin and Minnesota is too fine for hydrofrac sand but is mined as a source for foundry sand.

The rapid growth of natural gas drilling, particularly in Pennsylvania, Texas, and North Dakota resulted in an acute shortage of sand and high prices for proppant. Energy companies, established sand producers, and entrepreneurs with little experience in the industry rushed to the region to get into the proppant business. In late 2012 a surplus of natural gas resulted in a drop in demand for the finer grades of sand, just at the time that several large mines were coming on line. The industry is now facing the prospect of excess production capacity.

The future of hydrofrac sand mining in the upper Midwest looks favorable. Hydraulic fracturing is the key to energy independence for the United States, and the Cambrian sandstones of Wisconsin and Minnesota are the best source of proppant sand in the country. The next few years will be interesting as the industry deals with overcapacity and with an ever-growing list of regulatory and land use issues that have resulted from rapid growth.

A Geological Model and Resource Update for the Hammond Reef Gold Deposit

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The Hammond Reef Gold Deposit is located about 210 km west of Thunder Bay and 25 km north-east of Atikokan. On January 28, 2013, Osisko Mining Corporation released a new resource estimate of 7.2 Million ounces after completion of an aggressive definition drill program. The company drilled over 2,100 holes for a total of 629,000 m in the last 2 years and was able to upgrade 75% of the gold inventory into the Measured and Indicated category. Using a 0.5 g/t cut-off, the deposit contains 5.43 Million oz Measured+Indicated @ 0.86 g/t and 1.75 Million oz Inferred @ 0.72 g/t.

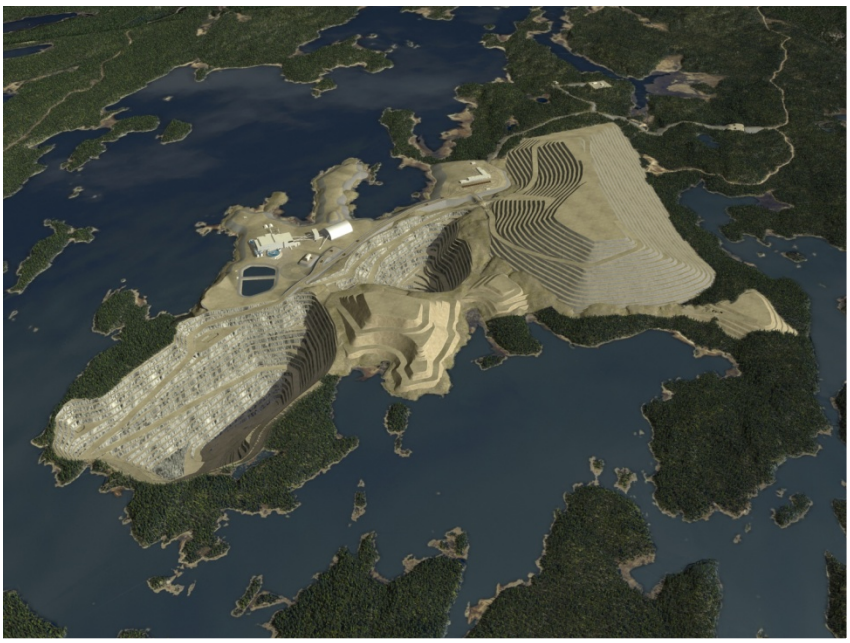


Figure 1: Artist's rendition of the Hammond Reef open pit and infrastructure.

Permitting for mine development continues. The company recently submitted a Draft Environmental Impact Study/Environmental Assessment Report to both the Canadian Environmental Assessment Agency and the Ontario Ministry of Environment. The Project Feasibility Study is on schedule and expected to be finished by the second quarter of this year. Osisko has received letters of support from all Métis and First Nations communities affected by the project and continues its dialogue with them.

Hammond Reef is situated in the Marmion batholith of the Wabigoon Subprovince near the north-east trending contact with the Finlayson greenstone belt. The Mesoarchean Marmion is a diverse assemblage of felsic intrusive rocks, predominantly tonalitic in composition that was later invaded by several intrusive pulses. These units are all variably sheared and altered along a 1 to 6 km wide anastomosing deformation corridor (Marmion Deformation Corridor - ***MDC***) that is sub-parallel to the contact with the Finlayson volcanics. The ***MDC*** is the locus of numerous gold occurrences. As with many structurally-controlled gold deposits, Hammond Reef occurs within a significant flexure of the ***MDC***.

The ***MDC*** displays numerous characteristics of brittle-ductile deformation, including moderately to strongly sheared rocks, brecciation, veining and stockwork. The ***MDC*** is also characterized by a sericite-chlorite-ankerite-hematite alteration overprint. Gold was most likely introduced during this late Archean hydrothermal or metamorphic episode, along with pyrite and accessory sulfides and tellurides.

Gold mineralization occurs in all lithological phases of the Marmion batholith, associated with fracture-controlled stockwork and pyrite. Native gold blebs are usually found within pyrite crystals – along py-py grain boundaries as well as healed fractures and inclusions. Free gold grains are found rarely on sericitic foliation planes. Accessory minerals include chalcopyrite, galena and hessite.

Three main ore types were identified in the geological model that was developed for the Hammond Reef gold deposit. These include – 1) gold in structurally confined and pervasively altered tonalites, 2) gold impinging into partially altered tonalites, and 3) gold impinging into “unaltered” tonalites.

The Hiawatha Graywacke of the Iron River-Crystal Falls district, Michigan: a megaturbidite triggered by seismicity related to the 1850 Ma Sudbury impact

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The Hiawatha Graywacke is a coarse clastic unit, which includes breccias with fragments as large as a meter. It is underlain and overlain by chemical sediments and very fine clastic rocks of the Riverton Iron-formation and Stambaugh Formation respectively. The Hiawatha has long been interpreted as a submarine slump deposit generated by a strong earthquake (James and others, 1968). A connection to the 1850 Ma Sudbury impact event was established with recognition of shock metamorphic features (quartz grains with relict planar deformation features), as well as small fragments of devitrified glass (Cannon and others, 2009).

The Hiawatha Graywacke was deposited in a backarc basin along the southern margin of the Superior craton and is the southernmost and deepest water occurrence of the Sudbury Impact Layer so far identified. It is about 20 m thick in the east, where it is almost entirely breccia, and 150 m or more thick in the west, where breccia is mostly near the base and is overlain by massive graywacke with interlayers of siltstone and breccia. The breccia is derived largely from the underlying Riverton Iron-formation. Clasts are chert and siderite, and rarely other sedimentary rocks. The matrix is predominantly fine-grained siderite. Sand-sized clasts of quartz are widespread and typically compose a few percent of the breccia matrix, indicating that material other than iron-formation also was incorporated into the breccias. Quartz grains that contain well preserved planar deformation features, indicative of impact shock, are widespread but generally sparse. A greater abundance of shocked quartz is found in the upper parts of the formation than in basal breccias. Massive siltstone beds in the upper part of the Hiawatha have the greatest abundance of shocked quartz that we have found in the Lake Superior region. This suggests that the breccias are largely locally derived by disaggregation and submarine slumping of the Riverton Iron-formation with incorporation of only minor amounts of other material, whereas the upper parts of the Hiawatha have a greater component of ejecta particles that arrived in the area while submarine slumping was in progress. In the western part of the district, a layer, as much as a few meters thick near the middle of the Hiawatha, is composed mostly of vesicular glass fragments with abundant shocked quartz, indicating that ejecta deposition locally overwhelmed deposition of terrestrial material**.**

The Sudbury impact, about 550 km east of the Iron River-Crystal Falls area, generated an earthquakeof probably roughly magnitude 10.5 based on computer model results. This is about 30 times more powerful than the largest recorded earthquake. The first seismic wave arrived here about 1.5 minutes after the impact and disrupted the seabed, composed of partly consolidated chert and siderite. This material flowed down the paleoslope toward deeper parts of the basin. About 4 minutes later the first airborne ejecta arrived and settled through the water column to be incorporated to variable degrees into the still active submarine slumps. Thicker parts of the Hiawatha in the Iron River area have some stratigraphic variation in mineralogy suggesting that multiple sediment sources were sampled by multiple lobes of turbidites. A third catastrophic event caused by the impact should have been massive tsunami waves, arriving about an hour after the ejecta. We have not identified evidence of tsunami activity, but perhaps upper parts of the Hiawatha were reworked by tsunamis, followed by settling of suspended sediment from the water column to produce the more prominent bedding that characterizes the upper part of the formation.

Accumulation of a large volume of slump debris in the western part of the basin requires a comparable amount of denudation elsewhere. Some areas in the southeastern part of the district are devoid of the Riverton Iron-formation and, more locally, of the underlying Dunn Creek Slate,

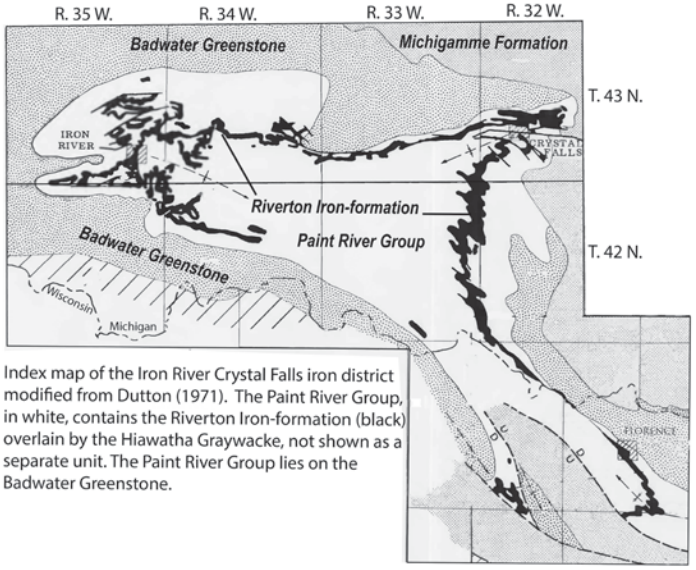
so that the Hiawatha lies directly on older volcanic rocks. Perhaps these areas were the source for slump debris that was transported and deposited as the basal breccias farther west in the basin. Submarine slumps, well studied in many other parts of the world, commonly begin by mass wasting of large slabs of sediments, some of which become successively disaggregated and water-saturated, grade into debris flows, and eventually into true turbidites. We suggest that this process happened here as well and that there are unrecognized megaclasts of the Riverton within the western part of the basin. A peculiarity of the western part of the basin is a chaotic folding style shown both on maps and cross sections. The western folds are much more complex than in the eastern part of the district and all surrounding areas, where folding is intense but has a regular pattern of deformation. We suggest two possibilities for this unique structural style that might be related to massive slumping. (1) Parts of the Riverton in the western part of the basin may be megablocks of slump material that were folded during slumping. Extremely large blocks of this nature, some many kilometers in extent and hundreds of meters thick, are known elsewhere in the world (ref?). Perhaps part of the Riverton is such a block that was emplaced already folded, so that subsequent tectonic folding formed the uniquely complex pattern seen there. 2) The Hiawatha in the western part of the basin is a sedimentary mélange containing numerous megablocks of Riverton Iron-formation. Previous maps and cross sections of the area were interpreted on the assumption, perhaps unwarranted, of a continuous unit of Riverton and a coherent stratigraphy. By that assumption, all occurrences of iron-formation had to be connected to all others and stratigraphic relationships had to be maintained. To satisfy these requirements many folds had to be inferred. In contrast, if the Hiawatha is a sedimentary mélange containing megaclasts of the Riverton, many of these inferred folds are not required and the structural style, although still complex, may be simpler than previously interpreted.

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Index map of the Iron River Crystal Falls iron district modified from Dutton (1971). The Paint River Group, in white, contains the Riverton Iron-formation (black) overlain by the Hiawatha Graywacke, not shown as a separate unit. The Paint River Group lies on the Badwater Greenstone.

Crystallization of Chrome Spinel in the Southern Troctolite Zone of the Bald Eagle Intrusion, Duluth Complex, Northeastern MN

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Duluth Metals had acquired mineral rights to portions the Bald Eagle Intrusion (BEI), located in the Duluth Complex about 35 km southeast of Ely, MN as a target for Ni-Cu-PGE potential. Exploration drilling by Duluth Metals in the BEI, a funnel-shaped (Weiblen, 1965; Green et al., 1966), differentiated mafic layered intrusion within the 1.1 Ga Duluth Complex in northeastern Minnesota, has identified multiple stratiform intervals enriched in chromium spinel (Cr-spinel) mineralization. Centimeter-scale layers enriched in up to 50 vol. % Cr-spinel occur within troctolite host rocks, which compose most of the southern BEI (Weiblen, 1965).

The principal objective of this study is to characterize the mineralogy and textural occurrence of these chromite layers in order to understand their genesis and the magmatic history of the BEI. This information will be used as an exploration tool for further exploration of the BEI and other mafic intrusions within the Duluth Complex. This poster presents the observations made of textures and stratigraphic occurrences of Cr-spinel enriched intervals found in the troctolitic cumulates of the Bald Eagle Intrusion as well as the chemical variations throughout the study area. These observations are focused on three Duluth Metals drill holes that have been logged and assayed for whole rock geochemistry. Using these data along with petrographic descriptions and mineral chemistry from SEM of Cr-spinel layers and adjacent lithologies, possible models for emplacement and crystallization can be theorized.

Core logging and follow-up petrographic observations show a sharp basal contact to all semi-massive oxide intervals that denote the start of a cyclic unit. In general, a cycle consists of a lower semi-massive oxide interval followed by an ultramafic section that grades to troctolitic followed by anorthositic compositions. Variations of a cycle sequence may occur. Inclusions are often present in oxide units, however the origin of these inclusions under interpretation. These descriptions suggest that individual cycles could be the product of additional magma inputs with fractional crystallization, or a result of changes to the stability field at the contact between cycles.

Research is ongoing and further interpretations will be made using data collected via SEM and microprobe to constrain petrogenesis of cyclical units and metallogenesis of Cr-spinel in the southern BEI.

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Passive-aggressive geophysics: An update on using the horizontal-to-vertical spectral ratio (HVSR) passive seismic method for determining glacial deposit thickness in Minnesota

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Considerable progress has been made on evaluating the horizontal-to-vertical-spectral ratio method (HVSR or sometimes H/V) for determining the thickness of glacial deposits in Minnesota. The HVSR method is used to estimate the primary resonant frequency (shear wave) of unconsolidated overburden. At this frequency, the horizontal components of oscillation are amplified relative to the vertical component. By dividing the averaged horizontal spectra by the vertical spectrum, a HVSR spectrum is produced, ideally with a pronounced peak at the primary resonant frequency. If the acoustic impedance (density*seismic velocity) at the overburden-bedrock contact differs by a factor of at least 2, the thickness (Z) of the unconsolidated materials can be estimated by the relationship:

$$Z=af_0^b$$

where f_0 is the estimated primary resonant frequency, and a and b are parameters that are determined empirically for a given region from control points that have a range of known bedrock depths. The HVSR method has been used in several Minnesota Geological Survey (MGS) projects, with data acquired at over 675 sites state-wide. Roughly 40% of these were located at control points whose distribution allows the HVSR method to be evaluated in three different geologic environments; the seven-county Twin Cities Metropolitan area, south-central Minnesota, and the floodplains and terraces along major streams, including the Mississippi, Minnesota, and St. Croix Rivers.

The 7-county Twin Cities Metropolitan area is particularly favorable for the HVSR method. Paleozoic strata comprising the bedrock surface are generally rigid, with little soft material, such as saprolith or Cretaceous sediment present and the glacial sequence is fairly simple, consisting chiefly of late Wisconsinan deposits. Analysis of 41 selected control points exhibiting single, high-amplitude (>3.5) HVSR peaks produced a fitted curve in the form of the above equation with an R value (Correlation Coefficient) = 0.968. Depth estimates at the 41control points have an average error of 13% and 90% are within +/-25% of the known bedrock depths. These figures serve as a proxy for expected error using HVSR peaks of similar quality in areas that lack well control. For low-quality peaks the error can be significantly greater; applying the same fitted curve to 20 control stations that exhibited flat-topped peaks, interfering multiple peaks, or low-amplitude (<3.5) peaks produced an average error of 26% and only 60% of the estimates were within +/-25% of known bedrock depth. Regardless of error for individual depth estimates however, the HVSR method is still very useful as a simple mapping tool, for example, it was highly effective for mapping the trace of a buried bedrock ravine in central Washington County which had been largely missed by drillhole and seismic data.

The terrain of south-central Minnesota presents some sobering challenges to the HVSR method. Glacial deposits, which include both Wisconsinan and Pre-Wisconsinan materials, tend to be thick, complex, and have dense, over-consolidated tills in the lower parts of the section. These deposits may also overlie a bedrock surface composed of soft materials, such as saprolith or Cretaceous sediment. Hence, impedance contrasts that can produce a HVSR peak and depth information may actually occur within the glacial sequence and may miss the bedrock surface

altogether. In some instances, the HVSR data may also produce a trough in addition to a peak (at 2 time the frequency of the peak) and occasionally the trough provides a better indication of bedrock depth than the peak, especially for depths of >100 meters. In other instances no useful HVSR signal can be confidently extracted from any of the data. The effect of soft bedrock was evaluated by comparing control points reporting either saprolith or Cretaceous strata against an idealized power-curve, based on 27 control points where these soft materials appeared to be either thin or absent. Correlation for this curve has an R value = 0.953. Use of this curve tends to overestimate the depth to saprolitic bedrock by as much as 30-50%, implying that the HVSR signal is picking up an interface below the bedrock surface, likely somewhere in the transition to fresh bedrock. For areas with a Cretaceous bedrock surface, the overestimate can be much worse, and it appears that the HVSR signal is actually responding to the Pre-Cretaceous surface rather than the Cretaceous bedrock surface. Overall the HVSR method must be applied cautiously in south-central Minnesota, and in other areas that are likely to have similar conditions. Nonetheless, useful information can still be derived at many locations.

In contrast to south-central Minnesota the floodplains and terraces along major streams in eastern Minnesota provide an almost ideal environment for the HVSR method. The channels in this part of the state served as sluiceways for melt-water during the closing stages of the Wisconsinan glaciation, and the valley bottoms have been largely swept clean of soft materials such as Cretaceous strata, saprolith, or earlier glacial deposits, and replaced by poorly consolidated outwash, fluvial and lacustrine deposits. A strong acoustic impedance contrast is expected at the bedrock surface and the observed HVSR peaks, which usually have single, very high-amplitude (>5) signatures, are consistent with this. Using 37 control stations a curve was established with an R correlation value = 0.951. Curve-based depth estimates at the control points have an average percentage error of 20% and 82% are within +/-25% of observed bedrock depths. The greatest errors generally occur at depths less than 20 meters, and may reflect sloping or uneven bedrock surfaces near valley side-walls. In any case, the relationship derived here should be useful for rough estimates of bedrock depth along the bottoms and terraces of the major river valleys in eastern Minnesota and adjacent areas

Although, the HVSR method does not quite match conventional seismic profiling for accuracy and derivative information, the advantages of passive seismic for determining depth to bedrock include rapid data collection (usually 16 minutes recording time), much lower equipment and field costs, relative ease of data analysis and large number of samples that can be collected within a given area. In addition, rough estimates of depth with a denser array of points are quite adequate for many kinds of geological applications. Finally, the HVSR method can be readily applied in areas of significant cultural noise, where conventional seismic profiling is difficult.

ACKNOWLEDGEMENTS
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Geochemistry of the Logan Igneous Suite and implications for the magmatic evolution of the northern part of the Midcontinent Rift

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Recent field work and interpretation of geochemistry has focussed on defining the emplacement sequence of Midcontinent Rift (MCR)-related units and evaluating their geochemical sources and contamination characteristics so as to better understand the magmatic evolution of the Logan Igneous Suite (Cundari, 2012). New geochemical discriminators applied to the Nipigon sills (e.g. Cundari et al., 2012) have been applied to a larger data set in order to identify previously unrecognized relationships between units. The plot of Nb/Yb_{pm} versus Th/Yb_{pm} (Fig. 1) illustrates a mixing model between mantle-derived melts and crustal sources. Separate trends with distinct ranges of Nb/Yb_{pm} scattering away from the field of mantle-derived melt compositions towards higher Th/Yb_{pm} suggests the presence of separate, geochemically distinct magma source types within the Logan Igneous Suite which have undergone separate crustal contamination histories. The plot of Th/Yb_{pm} versus Nb/Th_{pm} (Fig. 2) also delineates distinct primary source compositions, as separate trends curve away from the field of mantle-derived melt compositions towards lower Nb/Th_{pm} and higher Th/Yb_{pm}. The position of the ultramafic units (i.e. Hele, Disraeli, Seagull, Kitto), which plot within or towards the field of mantle-derived melts in Figures 1 and 2, support previous work suggesting the ultramafic units are the best indicators for the primary magma formed from a deep-seated mantle plume (Nicholson et al., 1997; Hollings et al., 2007). Based on these criteria, four distinct distributions are noted (Figs. 1 and 2): the Nipigon sill trend; the Jackfish, McIntyre, Inspiration and Logan trend (JMIL); the Dyke trend (including the Pigeon River dykes, Cloud River dykes, Mount Mollie dyke and the Crystal Lake gabbro); and the Devon volcanics and the Riverdale sill trend (DR).

Field work in the Logan Basin has delineated the following timing sequence between units, from oldest to youngest: Riverdale sill; Devon volcanics; Logan sills; Pigeon River dykes; Cloud River dykes; Mount Mollie dyke and Crystal Lake gabbro. In light of these relative ages, the mantle source characteristics are shown to become more depleted in incompatible elements as rift development progresses, each trend having been derived from a geochemically distinct mantle source. The mantle source of the Devon volcanic and the Riverdale sill magmas is the most enriched. The mantle source of the Logan sills is relatively more depleted and the mantle source of all dyke sets is the most depleted of all units in the Logan Basin. Furthermore, although all three dyke sets display similar source characteristics, younger dykes display progressively stronger crustal contamination signatures (i.e., higher Th/Yb_{pm} and more negative $\varepsilon_{Nd(t=1100Ma)}$) consistent with the magma having spent progressively more time in the magma chamber.

A similar incompatible element depletion trend in mantle sources, akin to that in the Logan Basin units, is also apparent in the Nipigon Embayment. It is widely accepted through geochronological data and field relationships that the Nipigon sills post-date the ultramafic units of the Nipigon Embayment (e.g. Heaman et al., 2007). Geochemical source characteristics for the Nipigon sills and the ultramafic units show that the ultramafic units were derived from a more enriched source when compared to a more depleted source for the Nipigon sills (Figs. 1 and 2). Logan sills of the Logan Basin and ultramafic units of the Nipigon Embayment all show similar source characteristics (Figs. 1 and 2), suggesting an overlapping magmatic history. From the geochemical data presented here, in conjunction with known emplacement sequences, it is proposed that magma which produced units of the Logan Igneous Suite were derived from

geochemically distinct mantle sources showing a progressive depletion in incompatible elements as MCR development progressed.

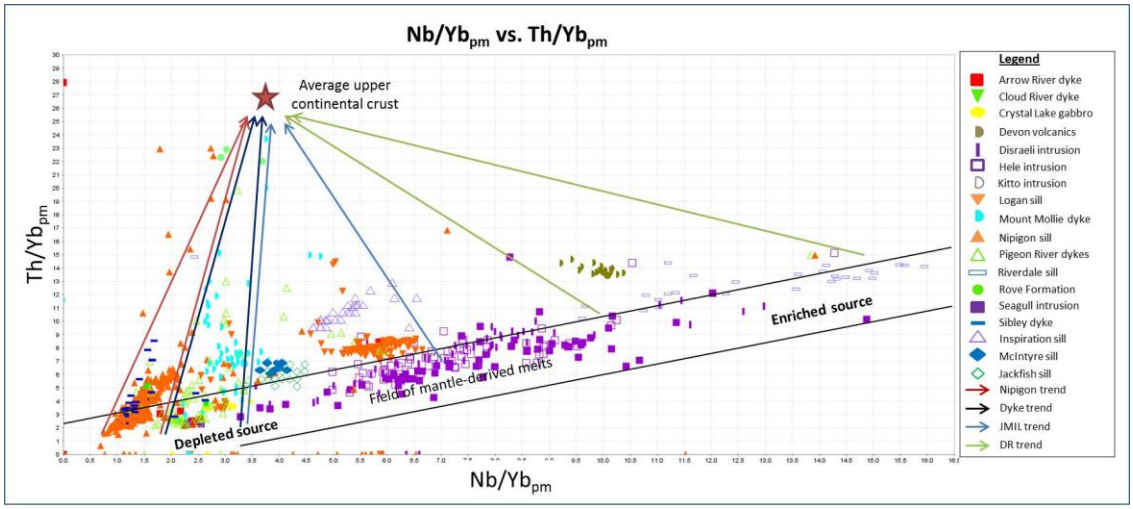


Figure 1: Diagram showing variations in Nb/Yb_{pm} and Th/Yb_{pm} ratios for Midcontinent Rift-related mafic rocks. Normalizing values from Sun and McDonough (1989).

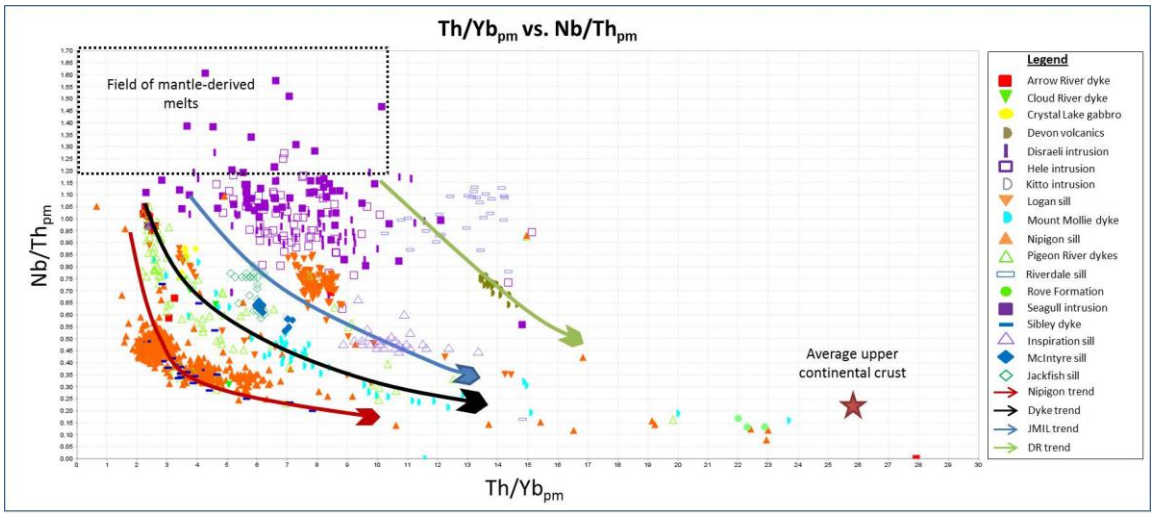


Figure 2: Diagram showing variations in Th/Yb_{pm} and Nb/Th_{pm} ratios for Midcontinent Rift-related mafic rocks. Normalizing values from Sun and McDonough (1989).

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The Geochemistry and Mineralogy of the Sulfides within the Ni-Cu-PGE Shakespeare Deposit, Ontario

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The 2217 Ma Shakespeare deposit, located 70 km west of Sudbury, Ontario, is part of the 2.2 Ga Nipissing Gabbro suite and is hosted within the metasediments of the 2.45-2.2 Ga Huronian Supergroup. The past producing Ni-Cu -PGE Shakespeare Mine, which has probable reserves of 11.8 Mt grading 0.87 g/t PGE+Au, 0.33% Ni, and 0.35% Cu, is hosted in the Shakespeare deposit (Prophecy Platinum, 2013). The majority of the mineral reserves are in the form of disseminated sulfides located within the Shakespeare melagabbro. Other significant sulfide mineralization is in the form of 2-5 cm heavily disseminated blebs to net-textured and locally semi-massive sulfides immediately above the disseminated sulfides. The aforementioned sulfides are collectively known as "interconnected sulfides" and straddle the contact between the Shakespeare quartz gabbro and melagabbro. The Shakespeare deposit is situated below the Mississagi Quartzite and above the unmineralized Nipissing Gabbro.

Sulfide mineralogy within the disseminated and heavily disseminated portions of the deposit is largely dominated by pyrrhotite, pentlandite, and chalcopyrite. A detailed SEM study has also led to the discovery of rarer minerals, such as molybdenite, several compounds containing tellurium and bismuth, a rhenium sulfide, argentopentlandite, and gersdorfite . Agentopentlandite seemed to show an affinity for chalcopyrite, forming discreet, euhedral grains along the edges of chalcopyrite crystals. Interestingly, the bismuth tellurides also rarely contain abundant silver, up to 20 percent, and antimony. The SEM study also showed that gersdorfite was rarely encountered in its pure form but rather was usually in solid solution with cobaltite and arsenopyrite . Platinum and palladium minerals were not observed, suggesting they could be present in concentrations lower than 2-3% or as nuggets that were not encountered. However, a rhenium sulfide nugget was encountered on a few occasions, and because Re, Pt, and Pd are expected to act similarly under the geochemical conditions present, it is likely that Pt and Pd occur as minerals in the form of nuggets.

Previous workers (Sproule et al., 2005) have suggested a contamination event lead to sulfur saturation in the magmas of the Shakespeare deposit, but those works do not comment as to whether the contamination event contributed significant sulfur to the magmas . Nine samples were taken from various stratigraphic depths in the deposit for sulfur isotope analysis and returned $\delta^{34}S$ values from 0.01 ‰ to 2.38 ‰, averaging 1.14 ‰ (table 1). Sulfur data obtained by LECO analysis and preliminary selenium data obtained by ICP-MS provide S:Se ratios between 1245 and 3271, averaging 1810 (table 2). The data strongly suggest that the sulfur source for the Shakespeare deposit is dominantly magmatic, with little to no input from crustal sources. Additionally, the rocks of the Huronian Supergroup ((Mississagi through Matinenda Formations) are devoid of a sulfur source with which to contribute sulfur to the magmas that led to the formation of the Shakespeare deposit.

Table 1. Sulfur isotope data

Sample*	$\delta^{34}S$ ‰
119-304.5	2.38
119-324	1.83
119-346	1.05
119-360	1
119-378	0.5
122.396.2	1.43
122-417	0.01
122-437.7	1.38
122-464.7	0.72
mean	1.14

First three digits = drill-hole,
Next digits = depth in metres

Table 2. Sulfur and selenium data and S/Se ratios ratios for mineralized samples

Sample	Se (ppm) (ICP-MS)	S % LECO	S/Se ratio
119-340	3.3	0.53	1607
119-350	8.4	1.44	1714
119-366	10.2	1.27	1245
119-378.6	9.4	1.35	1436
122-435.7	5.2	0.88	1692
122-440.7	9.2	3.01	3272
122-442.7	11.1	2.37	2135
122-444.7	7.5	1.32	1760
122.451.7	14.9	2.92	1960
122-454.7	6.9	1.05	1522
122-455.7	11.3	1.77	1566
		mean	1810

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High-resolution, multi-method geophysical imaging of a portion of the Northeast Iowa Intrusive Complex

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Numerous large amplitude regional aeromagnetic anomalies and ground gravity highs over northeast Iowa and southeast Minnesota (Fig. 1) suggest the presence of a buried intrusive complex made up of mafic/ultramafic rocks. This complex is known as the northeast Iowa Intrusive Complex (NE IIC) (e.g., Pals and Anderson, 2011). The NE IIC lies along the eastern margin of the Midcontinent Rift System (MRS) and occupies a minimum estimated area of 17,000 square kilometers, making it comparable in size to the Duluth Complex. Country rocks are thought to be accreted island arc terranes of the Paleoproterozoic Yavapai Province (1.7-1.8 Ga), implying at least a somewhat younger age for the NE IIC. While not yet directly dated, these considerations suggest that a Keweenawan (MRS) age for some or all of the NE IIC is possible and imply significant potential for undiscovered Ni-Cu-PGE deposits. Alternatively, the NE IIC could include Mesoproterozoic (~1450 Ma) gabbro-anorthosite-rapakivi granite intrusions like the Wolf River Batholith in Wisconsin. Only four boreholes are known to reach the complex, which is covered by 200-500 meters of Phanerozoic sedimentary rocks and sediments. Geophysical methods are thus critical to developing a better understanding of the fundamental nature and resource potential of the NE IIC.

A high-resolution, multi-method geophysical mapping program was initiated in 2012 as a collaborative effort between the U.S. Geological Survey Mineral Resources Program, the Iowa Geological and Water Survey, and the Minnesota Geological Survey. An initial 3,333 line kilometer airborne data collection campaign in the region of Decorah, Iowa, included magnetic, gravity gradient (AGG), and time-domain electromagnetic (TDEM) data along flight lines spaced 400 m apart. At the time of this writing, only preliminary versions of these data are available for inspection. The preliminary data show numerous magnetic anomalies that are paired with AGG highs, indicating widespread strongly magnetized and dense rocks of likely mafic/ultramafic composition. In the Decorah region, a prominent horseshoe-shaped, 15 kilometer diameter magnetic- and gravity-field high is correlated with the occurrence of basement rocks that have been described as unaltered gabbro and troctolite, suggesting a ring-shaped anomaly source. A Yavapai age layered(?) metagabbro pluton (Van Schmus et al., 2007) is suspected to produce complex magnetic and gravity anomalies with different forms than the other basement rocks nearby. The TDEM data appear to image crystalline basement rocks in select locations, and it is expected that the data will ultimately provide important constraints on depths to the NE IIC and other Precambrian basement rocks.

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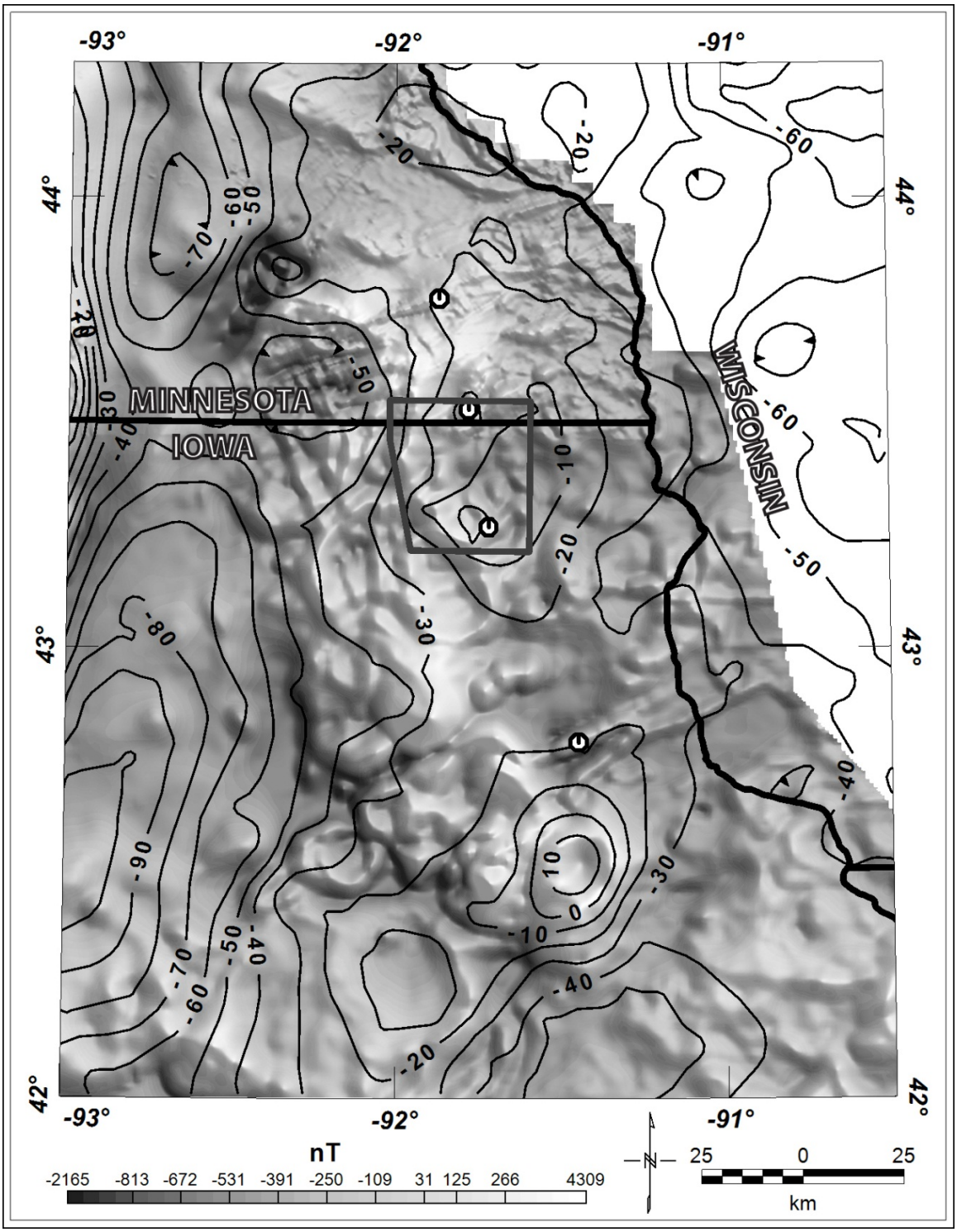


Figure 1: Regional aeromagnetic total-field (grayscale) and complete Bouguer gravity anomalies for the NE IIC region. Gravity contour (black lines) interval 10 milligals. White dots indicate wells that reach Precambrian rocks. Area of recent survey in region of Decorah, IA, shown as gray polygon.

Application of LiDAR to resolving regional tectonic and glacial fabrics in glaciated terrane: An example from an Archean granite-greenstone belt in NE Minnesota

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Regional tectonic fabrics define the broad structural architecture of an area and commonly have an associated topographic expression that may be identified via remote sensing (Chardon et al., 2002, 2008, 2009; Bedard et al., 2003). Glaciation commonly forms a geomorphologic fabric in the form of drumlins, flutes, valleys, eskers, and crag and tail features (Smith et al., 2006; Sharp, 1953). Overprinting of glacial fabrics, vegetation, and sediment cover commonly obscure topographic lineaments and hinder identification of lineament fabrics via high-resolution aerial photography and low to moderate resolution satellite imagery. Airborne LiDAR (light detection and ranging) systems provide high-resolution altimetry in vegetated areas (e.g., Haugerud et al., 2003). Although LiDAR altimetry is a useful tool for mapping small–scale geologic structures (e.g., Pavlis and Bruhn, 2011) and glacial geomorphologic features (e.g., Smith et al., 2006), previous studies do not constrain whether LiDAR altimetry may be used to differentiate between tectonic fabrics and overprinted glacial fabrics within the same area.

In this study, we examine an Archean granite-greenstone terrane in NE Minnesota to illustrate the application of high-resolution LiDAR altimetry to mapping regional tectonic fabrics in glacially striated, forested areas. More specifically, we describe how to distinguish between tectonic and glacial fabrics and the effect of glaciation on the overall topographic expression of the tectonic fabric. A 1-m posted LiDAR derived bare-earth DEM (digital elevation model) collected as part of the Minnesota Elevation Mapping Project and shaded relief images constructed from the bare-earth DEM comprise the raw data for this study. Data processing and lineament mapping were done using ESRI ArcGIS software. Evaluation of the bare-earth DEM and shaded relief images revealed that shaded relied images provide the most potential for lineament mapping. In order to maximize the chance of mapping lineaments at all orientations, we constructed shaded relief images with a sun elevation of 45˚ and varying sun azimuth at 45˚ intervals. Using ESRI ArcScene, we draped shaded relief images over the bare-earth DEM to create a 3D perspective view of the field area and to visualize the topographic surface.

Mapping revealed two suites of lineaments. Suite A consists of relatively short (1-2 km), discrete lineaments with a unimodal orientation distribution and a mean trend of 045. We recognize multiple striated deposits of sediment across the study area. Sediment deposits contain suite A lineaments only. Suite B consists of lineaments ranging in length from 1-30 km. Suite B lineaments are more continuous than suite A and have a quasi-bimodal orientation distribution. Suite B lineaments have a mean trend of 065 across the study area with local areas trending 090. In areas where suite A parallels suite B only one pervasive lineament set is visible. Where suite A and suite B are at high angles to one another, suite A lineaments are shorter and pervasive while suite B lineaments longer and spaced. We interpret suite A as a geomorphological fabric related to glaciation and suite B as the regional tectonic fabric. Field measurements of foliation trajectory (Goodman, 2008; Erickson, 2008; Dyess, unpublished field data) are largely consistent with suite B lineaments across the study area. Although not all suite B lineaments correlate to mapped structures, our analysis demonstrates that high-resolution LiDAR altimetry may be used to map regional tectonic fabrics in glaciated terrane.

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Structural and Kinematic Analysis of the Shagawa Lake Shear Zone and Snowbank Lake Stock, Superior Province, NE Minnesota

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The Archean (3.85-2.5 Ga) Superior Province, to a first approximation, consists of a series of east-west trending subprovinces of supracrustal rocks (greenstone belts) and granitoid rocks interpreted as a series of microcontinents, remnant arcs, oceanic terranes, and accretionary prisms that accreted to a growing continental block during dextral transpression driven by NW-directed oblique subduction (e.g., Percival et al., 2007, and references therein). Transpression plate-tectonics would predict the formation of faults/shear zones that record significant unidirectional strike-slip displacement at or near terrane boundaries (Sleep, 1992). The Vermillion District, southern Superior Province, is a Neoarchean (2.8-2.5 Ga) granite-greenstone terrane dominated by a series of NE-striking subvertical shear zones with ovoid to circular granitic bodies scattered throughout. Vermillion District shear zones have been interpreted as primarily dextral strike-slip shear zones formed during terrane assembly driven by NW oblique subduction (Hudleston et al., 1988; Bauer and Bidwell, 1990; Schultz-Ela and Hudleston, 1991). Others interpret Vermillion District shear zones as zones of dominantly oblique to dip-slip shear possibly formed during greenstone sagduction between rising granitoid diapirs (Erickson, 2008, 2010; Wolf, 2006; Goodman, 2008; Karberg, 2009). Differing interpretations of Vermillion District shear zones invoke different assumptions about displacement direction during non-coaxial shear. Displacement direction (flow direction) is genetically tied to foliation and elongation lineation orientation. Within the Shagawa Lake shear zone of NE Minnesota, displacement direction remains undetermined. Adjacent to the Shagawa Lake shear zone is the Snowbank Lake stock, a 30 km^2 composite stock dominated by syenite and granodiorite (Sanders, 1929). Due to the proximity of the Shagawa Lake shear zone to Quetico and/or Wawa subprovince boundary, tectonic fabrics within the Shagawa Lake shear zone have implications for crustal assembly of the southern Superior Province. If the Shagawa Lake shear zone records significant unidirectional strike-slip displacement, then supported plate-tectonic models for Vermillion District formation will be further constrained. If the Shagawa Lake shear zone does not record significant unidirectional strike-slip displacement, then existing plate-tectonic and structural models of terrane amalgamation along the Vermillion District require reevaluation.

We conducted a structural and kinematic analysis of the Shagawa Lake shear zone in three phases: 1) analysis of regional tectonic fabrics through Light Detection and Ranging altimetry data; 2) structural analysis of outcrop-scale structures through detailed field mapping; and 3) analysis of shear-sense indicators through kinematic analysis of thinsections. The Shagawa Lake shear zone contains a regional subvertical metamorphic foliation with an average strike of 065 but varies locally from 065 to 100. Near the Snowbank Lake stock foliation deviates from the regional trend and turns roughly parallel to the stock boundary. We recognize two types of elongation lineation within the Shagawa Lake shear zone. These include ridge-in-groove striations on C-foliation surfaces (Lc) as well as stretching lineations on S-surfaces (Ls) (Lin and Williams, 1992; Lin et al., 2007). The Shagawa Lake shear zone hosts unimodal Lc and Ls ranging from dominantly steep plunge to moderate plunge. Asymmetric fabrics occur in foliation-perpendicular, lineation-parallel planes and symmetric fabrics occur in foliation-perpendicular, lineation-perpendicular planes, which is consistent with non-coaxial shear with lineation forming parallel to shearing. Therefore, in high pitch domains, displacement was vertical to oblique, and microstructures record both north-side-up and south-side-up displacement in different samples. Samples with oblique lineation record an apparent dextral strike-slip shear-sense despite varying lineation orientation. Our data indicate the Shagawa Lake shear zone

experienced both N-side-up and S-side-up dip- to oblique-slip with relatively minor apparent dextral strike-slip and does not record significant unidirectional strike-slip displacement.

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Bedrock Geologic Map of the Putnam Lake Area, St. Louis County, NE Minnesota

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Each year, students from the Precambrian Research Center (PRC) geology field camp complete "capstone" projects that encompass approximately one week of detailed field mapping followed by one week of mapmaking and map publishing. During the fifth and sixth weeks of the 2012 field camp, five PRC field camp students, under the direction of PRC Associate Director George Hudak, mapped Neoarchean rocks on the southwest side of the Tower-Soudan Anticline in the vicinity of Putnam Lake (Fehrs et al., 2012). This capstone mapping project sought to: 1) identify the lithologies and determine the detailed stratigraphy within the Neoarchean supracrustal strata in this area; 2) define and characterize the nature of the contacts between various units of the Neoarchean supracrustal strata and intrusive rocks; 3) obtain a better understanding of geological structures and their orientations within the area; 4) produce a detailed geological map in an area on the south side of the Tower-Soudan anticline, which has previously only been mapped at a regional scale; and 5) test the utility of LiDAR for mapping in heavily forested greenstone belt terranes.

Prior to mapping, detailed 1:5000 scale laminated field mapping sheets were produced. One side of each field mapping sheet consisted of a georeferenced air photo, and the other side of the mapping sheet consisted of a corresponding georeferenced topographic map using recently released LiDAR- based elevation data available from the Minnesota Geospatial Information Office. Mapping was completed by means of numerous traverses through the bush, as well as traverses along the lakeshore of Putnam Lake. Following each day of field mapping, students and faculty transferred their field data to a master map, enabling the detailed geology of the region to be established by the middle of the fifth week of field camp. During the sixth week of field camp, students produced a digital version of the field map utilizing a variety of software (ArcView, AutoCad, Surfer, Adobe Illustrator).

Previous mapping (Peterson and Jirsa, 1999; Peterson, 2005) established that the Neoarchean supracrustal rocks in this area comprise a NW/SE striking, SW facing homoclinal sequence that makes up the southern limb of the Tower-Soudan Anticline. This regional mapping indicated that the area consisted of rocks comprising the Lower Member of the Ely Greenstone Formation (Armstrong Lake / Central Basalt mafic-intermediate lava flows, dacite lava flows, and local Algoma-type oxide facies iron formations), the Soudan Member of the Ely Greenstone Formation (Algoma-type banded oxide-facies iron formation), and the Upper Member of the Ely Greenstone Formation (South Limb Basalts, comprising massive- to pillowed-facies basalt lava flows), as well as synvolcanic hypabyssal diabase/gabbro sills and dikes, and post-volcanic quartz-feldspar porphyry, hornblende-feldspar porphyry, and lamprophyre intrusions. The contact between the Soudan Member and Upper Member of the Ely Greenstone Formation was interpreted as a minor shear zone associated with regional D_2 deformation (Peterson, 2005)

In light of lithological characteristics obtained from mapping in the vicinity of Soudan Underground Mine State Park and Lake Vermilion State Park (Peterson and Patelke, 2003; Radakovich et al., 2010; Heim et al., 2011), we now believe that supracrustal rocks in this part of the Tower-Soudan anticline comprise part of the Soudan Member of the Ely Greenstone Formation. In this area, the Soudan Member is composed of: a) medium to light gray laminated to very thinly bedded chert; b) light gray to red to dark gray laminated to very thinly bedded interlayered horizons of chert, jasper, and magnetite-rich Algoma-type oxide facies iron formation; c) interbedded light green to medium green, sparsely amygdaloidal, sparsely plagioclase-phyric massive sheet flow- and pillowed-facies basalt lava flows locally interbedded with 0.10-1.0 meter thick laminated oxide facies iron formation horizons; d) light

green-gray to medium green, sparsely amygdaloidal, sparsely plagioclase-phyric massive sheet flow-facies basalt lava flows; e) light green-gray to medium green, sparsely amygdaloidal, sparsely plagioclase-phyric pillow-facies basalt lava flows; and f) green-gray, locally amygdaloidal, plagioclase-phyric dacite lava flows that are locally interbedded with chert and argillite horizons. Unfortunately, outcrop areal distribution (about 1% of the field area) was not sufficient to identify, or map out, individual lava flows with confidence.

Locally, synvolcanic and post-volcanic sills and dikes intrude the supracrustal assemblage in the area. Synvolcanic diabase/gabbro sills and dikes are medium green-gray to dark green, fine- to medium grained, subophitic and locally plagioclase-phyric. Post-volcanic intrusions include: a) light gray to pinkish-gray hornblende- and plagioclase-phyric dacite sills and dikes; b) light gray to light pinkish-gray quartz- and plagioclase-phyric rhyodacite sills and dikes; and c) light to medium-gray, fine- to medium-grained biotite-phyric lamprophyre dikes.

Based on our mapping, the following sequence of geological events is believed to have formed the stratigraphic succession in this part of the Vermilion District: 1) early mafic volcanism dominated by massive sheet flow-facies lava flows; 2) deposition of several horizons (up to 50 meters thick) of Algoma-type oxide facies iron formations during breaks in mafic volcanism; 3) resumption of extrusive mafic volcanism forming both massive sheet flow-facies and pillowed-facies basalt lava flows with local extrusion of dacite lava flows and minor, intermittent hydrothermal activity to form thin (less than 10 meters thick) Algoma-type banded iron formations; 4) extrusive mafic volcanism forming both massive sheet flow-facies and pillowed-facies basalt lava flows followed by local intrusion of diabase/gabbro sills and dikes; 5) intrusion of sills and dikes of both hornblende- and plagioclase-phyric dacite and quartz- and plagioclase-phyric rhyodacite; 6) development of the Tower-Soudan anticline; 7) D_2 deformation forming a penetrative east-west-trending foliation; and 8) intrusion of biotite-phyric lamprophyre intrusions.

Based on the similarity of the basalt lava flows mapped in this area to the Soudan Basalts mapped in other parts of the Vermilion District, it appears that the Upper Member of the Ely Greenstone Formation may be absent on the southern limb of the Tower-Soudan anticline. More mapping, petrographic studies, and lithogeochemical studies will be necessary to further evaluate this preliminary interpretation. As well, we found that LiDAR-based topographic maps provided excellent base maps, and were extremely useful for identifying small topographic features in heavily forested areas that were later found to be outcrops that had never been previously mapped.

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Fluid Inclusion study of the Magino Archean Gold Deposit; Implications for Regional Mineralizing Systems

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The Magino gold deposit is located approximately 45 km's Northeast of Wawa, Ontario, Canada in the Goudreau-Localsh area of the Michipicoten Greenstone Belt. The Archean Lode Gold deposit is a newly enlarged gold resource in a mining camp historically known to host deposits of ≤1 Moz. in total endowment. As of October 2012; the Magino resource is reported (NI 43-101) as having 6.25 Moz of gold, and there remains potential for expansion. Gold was first discovered on the Magino project in 1917. Production on the property has been from two generations of historical mining. The first generation was in the 1930's and approximately 10,000 oz of gold were produced. The second more recent underground venture operated from 1987 to 1993 and an additional 105,000 oz of gold was produced. Recently Argonaut Gold Inc. has taken ownership of the property through the acquisition of Prodigy Gold Inc. Argonaut Gold is planning a Pre-Feasibility study for 2013 which will look to exploit the Magino deposit as an open pit mine.

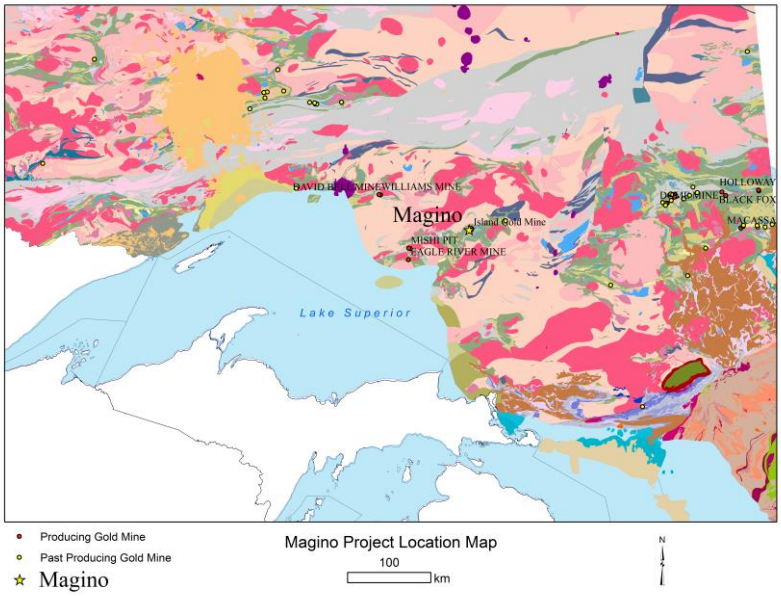


Figure 1 shows the location of the Magino mine project in Northern Ontario, Canada. Geology data is from OGS: Bedrock Geology of Ontario 1:250.000 (Revised MRD 126)

The objective of the study is to better understand the mineralizing system(s) responsible for forming this gold deposit and to put that information in the context of the regional geology to better understand the economic potential of the deposit along with the surrounding greenstone belt. Fluid inclusion research will constrain the geologic conditions at the time of mineralization, as well as provide clues towards the water-rock interactions prior to and during ore deposition. Initial work involves microscopy of polished thick sections and microthermometry to establish fluid inclusion assemblages. To better aid the assignment to and interpretation of fluid inclusion assemblages, the fluid inclusion thick sections are being imaged in a Scanning Electron Microscope using variations in cathodoluminescence signatures to differentiate various hydrothermal quartz generations from earlier deformed primary quartz phenocrysts associated with the host trondhjemite intrusion. Raman spectroscopy will be

utilized to interpret carbonic-rich fluid inclusions for CH_4 content and to aid in pressure interpretations.

The recent expansion of the Magino resource raises the exploration potential of the surrounding Michipicoten greenstone belt significantly. The opportunity exists to aid in discovery of new and expansion of known similar type gold deposits in the region. Fluid inclusion studies in the region have been somewhat inconclusive as to understanding the nature of the gold mineralizing system(s). In the Michipicoten Greenstone belt, fluid inclusion studies including my preliminary work on the Magino deposit have hinted strongly at a regional genetic link between the various widespread study areas. Fluid inclusion study will form the foundation to more rigorous study of the Michipicoten Greenstone Belt evolution and most importantly the gold mineralization.

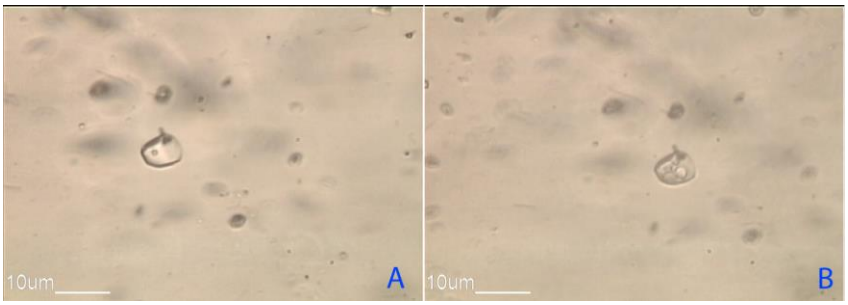


Figure 2 (A) shows a methane rich fluid inclusion at room temperature; notice small bright unknown solid and dark cluster of unknown solids near top. (B) shows the same inclusion after cooling to -100°C; notice a frozen CO_2 solid (darker) and a Ch_4 vapor bubble (lighter) which formed while cooling at ~ -98°C.

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Preliminary geochemical analysis of the Nipigon Bay granites, northern Lake Superior

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The granitic basement to exposed, overlying Mesoproterozoic Sibley Group sedimentary rocks in Nipigon Bay, northern Lake Superior, was first identified by diamond drilling in 1997 (Wells, 1997). A series of three, prominent magnetic anomalies delineates these magnetite-bearing granitoids in the subsurface (Fig. 1). These granitic intrusions occur at a confluence of three regional-scale structures: the northeast-trending Gravel River fault; the north-northeast-trending Jackpine River fault; and the west-southwest-trending North Shore fault, which forms the base of the Osler Group volcanic rocks of the Midcontinent Rift. The boundary between the Neoarchean Wawa and Quetico subprovinces has also been extrapolated beneath Proterozoic cover under Nipigon Bay (Williams, 1989). Sampling of drill core for geochemical and geochronologic analysis was recently undertaken in order to describe and characterize these intrusive rocks.

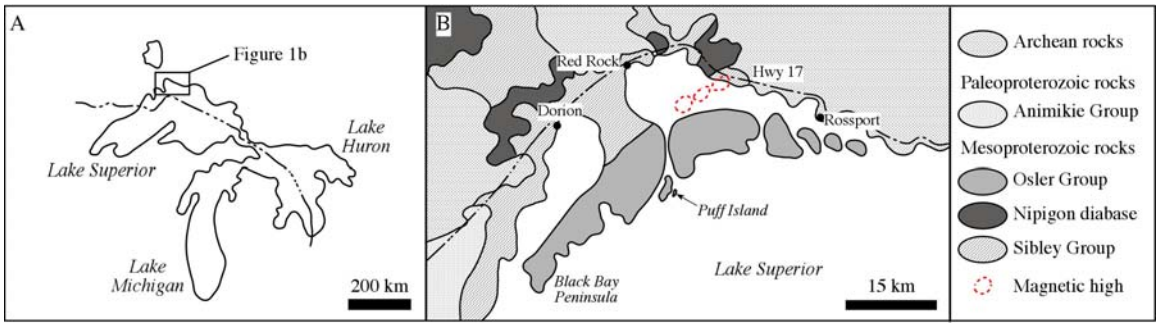


Figure 1. A) Map of upper Great Lakes showing the location of the study area. B) Regional geology map showing the location of the Nipigon granites.

Granitic rocks from beneath Nipigon Bay are characterised by enriched LREE (La/Sm_n = 2.9 to 7.7) and flat to weakly fractionated HREE (Gd/Yb_n = 1.4 to 3.1) with pronounced negative Nb anomalies (Nb/Nb* = 0.1 to 0.2). The granites are metaluminous and plot within the field of volcanic arc granites on the granite discrimination diagrams of Pearce et al. (1984). When compared to other granite suites in the area, the Nipigon Bay granites most closely resemble the I-type granites of the Dog Lake chain (Kuzmich et al., 2012) rather than the S-type Neoarchean granites of the Pukaskwa batholith (Beakhouse et al., 2011) and nearby Georgia Lake area (Breaks et al., 2008), or the Mesoproterozoic anorogenic English Bay granites in the Nipigon Embayment (Hollings et al., 2004).

The granites of the Dog Lake chain, 80 km west-southwest of Nipigon Bay, appear as a series of distinct aeromagnetic “highs” along the southern boundary of the Quetico subprovince. Kuzmich et al. (2011) interpreted the granites to have formed within a suprasubduction mantle and were subsequently emplaced along crustal-scale faults that form terrane boundaries. Similarities in geochemistry, magnetic signature and regional tectonic setting suggest that the Nipigon Bay and Dog Lake granites may have formed in a similar manner. Pending geochronologic and geochemical data for both the Dog Lake and Nipigon Bay intrusions will help to elucidate this possible relationship.

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The Minnesota Taconite Workers Health Study: Environmental Study of Airborne Particulate Matter - 2013 Update

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Since 2008, the Natural Resources Research Institute (NRRI) has been conducting a detailed characterization of mineral dust in northeastern Minnesota. The purpose of this research is to evaluate the effects of past and present emissions from taconite mining and processing on air quality throughout the Mesabi Iron Range (MIR) by characterizing airborne particulate matter within taconite operations, in communities surrounding taconite operations on the MIR, in population centers in other regions of northeastern Minnesota, and non-MIR locations, as well as particulate matter deposited in lake sediments (Figure 1). NRRI's sampling and characterization work represents the community/environmental component of the Minnesota Taconite Workers Health Study, a broad University of Minnesota (UM) research effort investigating long-standing questions regarding the impact of dust derived from mining and processing of taconite (iron ore). The UM School of Public Health (SPH), with whom NRRI is collaborating, is responsible for the human health- and exposure-related components of that effort, which include: 1) an occupational exposure assessment; 2) a mortality study; 3) a cancer incidence study; and 4) a respiratory health survey of taconite workers and spouses.

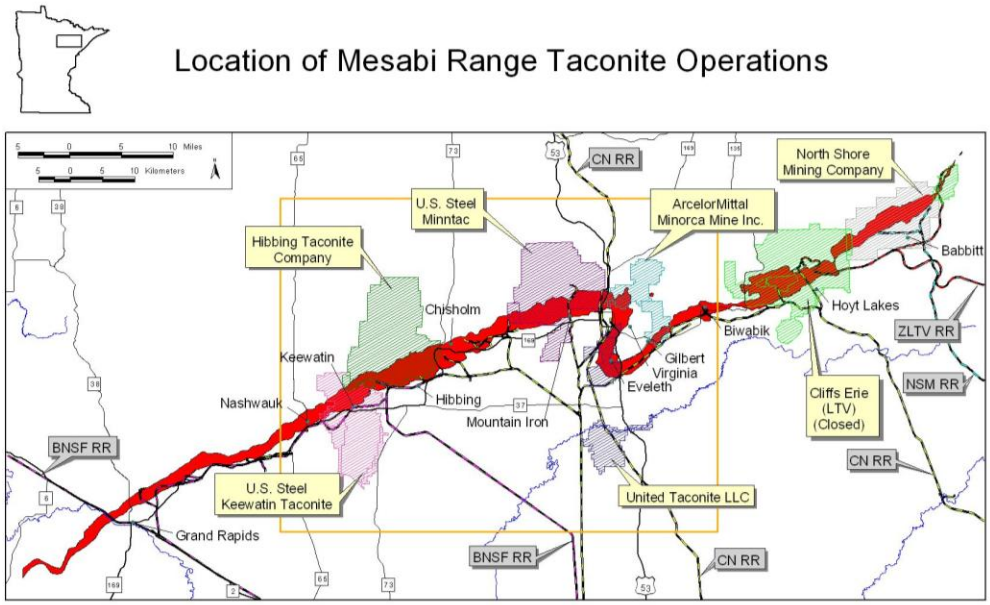


Figure 1. Locations of taconite processing plants on the Mesabi Iron Range being sampled during this study (after Oreskovich and Patelke, 2006)

Air sampling is performed within taconite operations, MIR communities, and non-MIR communities by NRRI scientists during both winter and summer seasons. Sampling at taconite operations takes place at four locations: 1) secondary crushers; 2) magnetic separators/concentrators; 3) agglomerators/ ball drums; and 4) kiln/pellet discharge area. Sampling within MIR communities takes place on the rooftops of public buildings, whereas sampling in non-MIR communities occurs on rooftops or in remote locations so that background air quality can be evaluated. Airborne particles are collected using: 1) a micro orifice uniform

deposit impactor (MOUDI) (Marple et al., 1991), which enables size-fractionated particulate matter collection; and 2) a total suspended particulate filter (TSP). Particulate matter is evaluated via gravimetric analysis and subsequently subjected to comprehensive particulate matter characterization that includes: 1) scanning electron microscopy (SEM) imaging; 2) energy dispersive x-ray spectroscopy (EDS); 3) electron backscattered diffraction (EBSD); 4) proton induced x-ray emission (PIXE); 5) the Minnesota Department of Health's 852 Method Transmission Electron Microscopy (TEM) Analysis for Mineral Fibers in Air; and 6) the International Standard Organization's Method 10312 Ambient air – Determination of Asbestos Fibers – Direct-Transfer TEM Method (ISO 10312, 1995).

During the past year, the NRRI has been evaluating particulate matter physical data (including gravimetric data, and particulate matter morphology data), particulate matter mineralogical compositions, and particulate matter chemical compositions obtained from both MIR taconite operations, MIR communities, and non-MIR communities, including 14 sampling events at taconite operations and 79 sampling events at locations within communities and sites in northeastern Minnesota (73) and Minneapolis (6), as summarized in Table 1. Lake sediment analysis continues, and will provide important data regarding potential mineralogical inputs from iron mining and processing from ~1840 (which pre-dates iron mining on the MIR) to the present, which includes the period where the transition from natural ore mining to taconite mining took place. Continued analysis, interpretation and reporting will take place in 2013.

In-Plant Sampling Events

Taconite Facility	***Sampling Events***	***Taconite Facility***	***Sampling Events***
United Taconite	2 events while active	Keetac	1 event while active, 1 event while inactive
Hibbing Taconite	1event while active, 1 event while inactive	Northshore	1 event while inactive, 3 events while active
Minntac	1 event while active	Minorca	3 events while active

Community Sampling Events

Community Sampling Location	***Sampling Events and Number per Season***
Keewatin Elementary School	7 Events (3 Winter / 4 Summer)
Hibbing High School	9 Events (4 Winter / 5 Summer)
Virginia City Hall	10 Events (5 Winter / 5 Summer)
Babbitt Municipal Building	16 Events (7 Winter / 9 Summer)
Silver Bay High School	13 Events (4 Winter / 9 Summer)
Ely Fernberg Site	6 Events (3 Winter / 3 Summer)
Duluth NRRI Rooftop	12 Events (7 Winter / 5 Summer)
UMN Mech. Eng. Rooftop	6 Events (3 Winter / 3 Summer)

Table 1. Summary of in-plant and community sampling events.

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Bedrock geologic map of the western Gunflint Trail area, northeastern Minnesota

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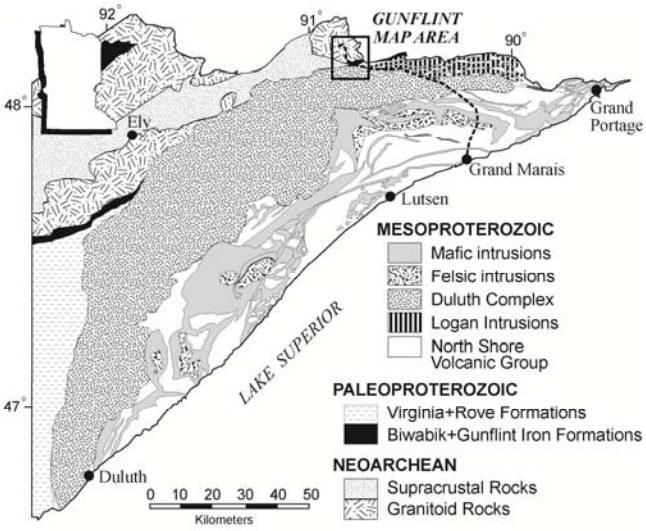


Figure 1—Generalized map of northeast Minnesota showing geologic setting of map area along the western end of the Gunflint Trail (dashed line).

The 2007 Ham Lake forest fire provided an opportunity for detailed mapping in a classic area of Precambrian geology along the western Gunflint Trail corridor into the Boundary Waters Canoe Area Wilderness (Fig. 1). Because the area is a favorite of campers and resorters, the map was designed somewhat differently from other products of the MGS to provide more "general interest" content, including highlights of the unique geologic features that lie along the many well maintained hiking trails (Fig. 2). The burn covers more than 120 mi^2, but nearly 2/3 of it is in adjacent Canada—the Gunflint map encompasses most of the U.S. portion. Mapping was supported in part by U.S. Geological Survey STATEMAP element of the National Geologic Mapping Program, and the results were published in 2011 as MGS Miscellaneous Map M-191.

The western part of the Gunflint trail provides a transect across well exposed rock units of Neoarchean, Paleoproterozoic, and Mesoproterozoic age. Archean granite-greenstone terrane of the Wawa subprovince of Superior Province is represented by a succession of metavolcanic rocks locally known as the Paulson Lake sequence (ca. 2720 Ma), and the Saganaga Tonalite (ca. 2690 Ma). Diabasic dikes of imprecisely known age cut the Archean bedrock. Both they and the Archean rocks are unconformably overlain by Paleoproterozoic metasedimentary strata of the Animikie Group (ca. 1870-1830 Ma), which includes the Rove Formation and Gunflint Iron Formation. The stratigraphic top of iron-formation is marked by a thin sequence of ejecta from a meteorite impact that occurred near Sudbury Ontario, ca. 1850 Ma. This sequence forms a discontinuous ejecta blanket that is present throughout the Lake Superior region in Ontario, Michigan, and elsewhere in Minnesota (Jirsa and others, 2011, and references therein). Mesoproterozoic rifting is manifest in hypabyssal dikes and sills of the Logan intrusions (ca. 1115 Ma), and several phases of the Duluth Complex (ca. 1100 Ma) emplaced into both Archean and Proterozoic rocks.

Stratigraphic facing directions in Neoarchean supracrustal rocks, based on pillowed metabasalt flows, indicate that the sequence forms a northwest-trending, steeply south-dipping and younging homocline. Much of the temporal distinction between various geological elements in the Archean rocks is based on regionally consistent fabrics that resulted from three major phases of deformation, denoted D_1, D_2, and D_3. All three deformation events are the result of N-S- to NW-SE-directed compression. Regionally, D_1 deformation folded, tilted, and thrust faulted large sections of the supracrustal rocks, but did not produce significant metamorphic mineral assemblages or cleavage and schistosity. The timing of D_1 deformation is bracketed between deposition of the volcanic and clastic rocks at about 2722 Ma (Peterson and others, 2001), and emplacement of the Saganaga Tonalite at 2690.83 Ma (Driese and others, 2011). The effects of D_2 deformation in this area include moderate to mild flattening of minerals and inclusions near the margins of the Saganaga Tonalite; and strong schistosity, metamorphism, folding of tonalite

dikes, and flattening of pillow structures in the immediately adjacent supracrustal rocks. U-Pb dates of intrusions that bracket D_2 place the regional deformation and metamorphic event between about 2674 Ma and 2685 Ma (Boerboom and Zartman, 1993). D_3 deformation produced faults and shear zones.

Much of the map's apparent complexity in areas of Paleoproterozoic strata and Logan intrusions is a product of the shallow dip and differential erosion of these formations, local faults and shallowly plunging folds, and moderate to high topographic relief. Deformation associated with the Lookout Fault grades from a distinct fault structure on the west—where Paleoproterozoic iron-formation is folded and faulted against Archean rocks—to a sympathetic drape structure in the eastern part of the area that is dominated by higher stratigraphic levels of iron-formation and Rove slate. The drape structure is manifest in a shallowly east-plunging, anticline-syncline pair that shows progressive flattening of limbs toward the southeast. The depiction of the Mesoproterozoic Logan intrusions differs significantly from previous mapping that implied the intrusions were folded. New field work indicates that the intrusions are semi-concordant with adjacent strata where dips are gently southeastward, but are locally discordant, particularly along the north-dipping limb of the anticline-syncline pair. Although the sills generally mimic fold structures, their local discordance implies that much of the deformation associated with the Lookout Fault and related structures predated emplacement of Logan intrusions.

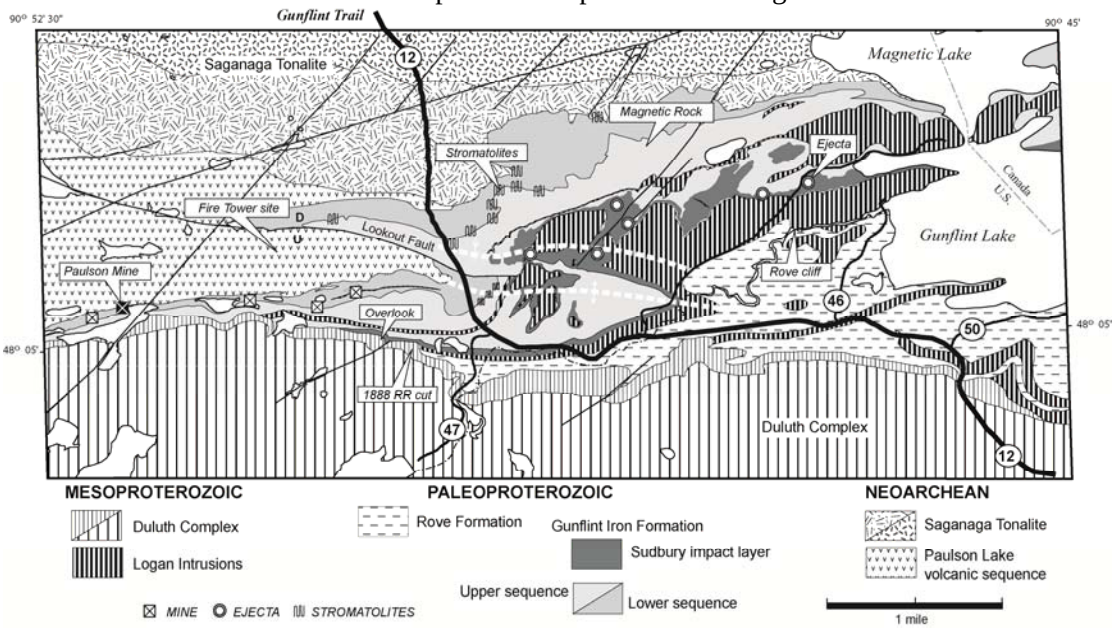


Figure 2. Geology of the southern part of Gunflint map area showing sites of geologic interest.

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Minnesota River Valley subprovince as depicted on a new bedrock geologic map of Renville County, southwestern Minnesota

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The bedrock geology of Renville County has a long history of geologic study related to the apparent antiquity of the bedrock, and commercial interest in quarrying, clay mining, and early speculation about coal resources. The bedrock ranges in age from Paleoarchean (~ 3500 Ma) to Late Cretaceous (~90 Ma), and records a complex history involving multiple igneous, sedimentary, metamorphic, tectonic, and weathering events. The interpretation presented here focuses on the Archean and Paleoproterozoic geology. The map derives from published and unpublished mapping, augmented with high-resolution geophysical data, scant drill core, and field work by the authors in a narrow strip of scattered exposure along the Minnesota River that forms the county's southern border.

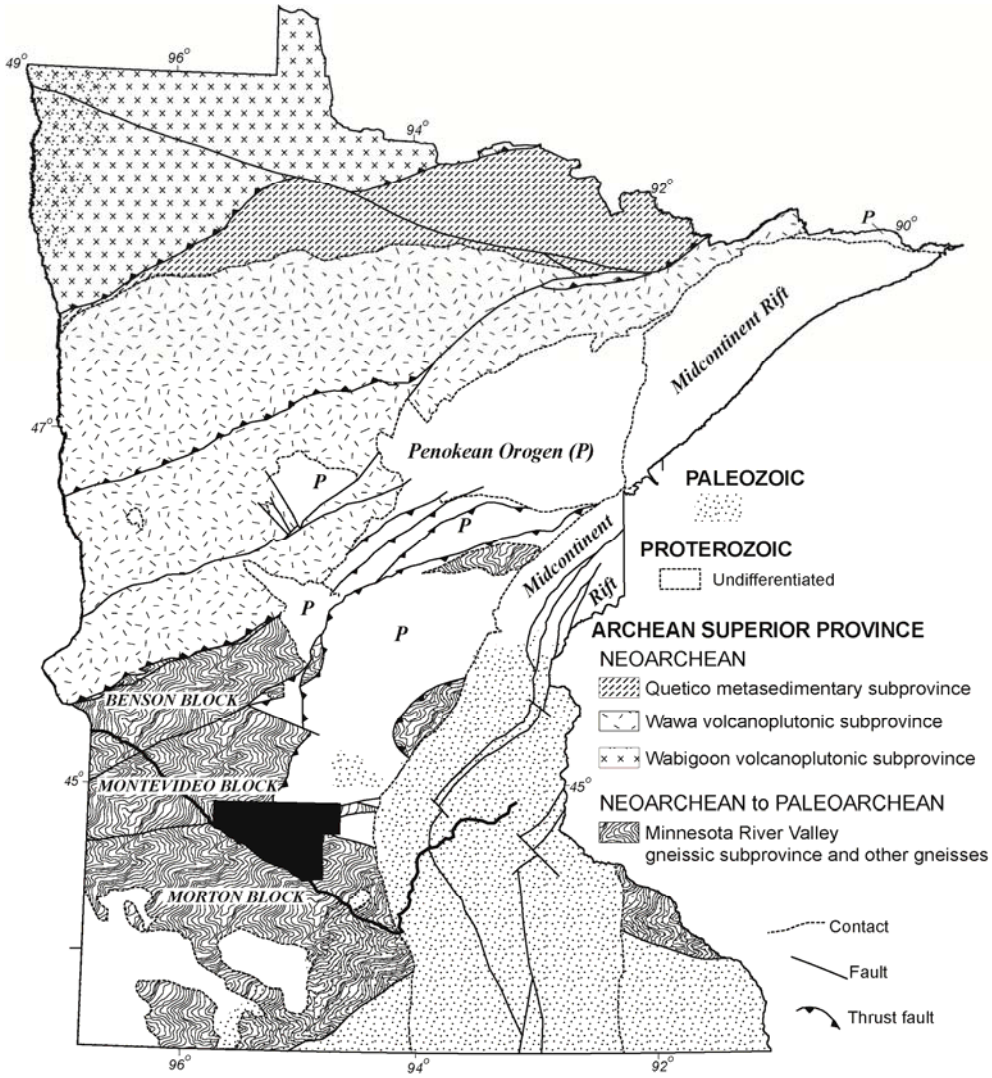


Figure 1. Generalized geologic map of Minnesota showing Renville County (black) adjacent to the Minnesota River (bold line) and within block subdivisions of the Minnesota River Valley subprovince of the Archean Superior Province.

The Minnesota River Valley subprovince is divided into largely fault-bounded blocks, each having distinctive attributes. Renville County straddles two of those blocks—the Montevideo block to the north, and the Morton block to the south (Fig.1). Both blocks are characterized by gneissic bedrock, but they differ from one another in composition and grade of metamorphism of the gneisses contained therein. The Montevideo block consists of variably layered granitic to gabbroic gneisses, metamorphosed under granulite facies conditions and collectively referred to as the Montevideo Gneiss. The Morton block contains tonalitic to granitic migmatitic gneiss with amphibole-rich rafts, metamorphosed under upper amphibolite facies conditions; and granitic neosome occurring as diffuse pods, lenses, and discrete intrusions. Collectively, these rock types comprise the Morton Gneiss. The two blocks are separated by the geophysically distinct Yellow Medicine shear zone. The complex intrusive, metamorphic, and deformation history of the gneisses and intrusions has been partially unraveled by recent high-precision U-Pb geochronologic studies. The apparently oldest components of the gneissic bedrock in both the Montevideo and Morton blocks range in age from 3535±4 Ma (Bickford and others, 2006), to 3422±1 Ma (Schmitz and others, 2006). Collectively, the ages indicate that gneisses formed in the Paleoarchean (3600-3200 Ma), were multiply intruded, deformed, and metamorphosed during Mesoarchean (3200-2800 Ma) and Neoarchean (2800-2500 Ma) time, and intruded by granitic magmas at ca. 2600Ma.

Geologic mapping by the authors and structural analyses by previous workers indicate that the gneissic bedrock underwent two major periods of regional deformation (designated D_1, D_2), and two later events that can be distinguished locally. The D_1 event produced high-grade metamorphism and gneissic foliation (S_1). The D_2 event folded this foliation into shallowly northeast-plunging antiforms and synforms, localized doubly-plunging dome and basin structures, and zones of semi-ductile shear. Much of the apparent complexity of map patterns is inferred to be the result of these open, shallowly plunging F_2 folds of the early-formed, nearly horizontal D_1 metamorphic fabric. D_2 also produced a localized foliation (S_2) subparallel to fold axes. Movement along the Yellow Medicine shear zone was likely complex and protracted, but at least some of the deformation is inferred to represent north-over-south thrusting associated with crustal shortening during the Neoarchean (~2680 Ma) Minnesotan Orogeny. Drill core from two holes in the northern part of the county indicate that primary foliation and localized shearing in and near the Yellow Medicine shear zone dips northward, which is consistent with geophysical modeling conducted for this study. It is likely that the Yellow Medicine shear zone was reactivated during the Paleoproterozoic (2500-1600 Ma) to juxtapose strata inferred to be part of the Little Falls Formation against older bedrock during the Penokean and/or Yavapai orogenies. The gneissic bedrock in both blocks is cut by a variety of intrusions, including granite, granodiorite, and quartz monzonite of likely Archean age; discretely bounded felsic to mafic intrusions that could be either Archean or Proterozoic; and diabasic dikes of Paleoproterozoic and perhaps Mesoproterozoic age.

The Bedrock Geology of Renville County is Plate 2 of the Minnesota Geological Survey's County Atlas C-28 (http://www.mngs.umn.edu), which was supported by the Renville County Board of Commissioners and the Department of Natural Resources Division of Waters.

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Geochemistry of reversely-polarized intrusions along the SW limb of the Midcontinent rift system, Carlton County, Minnesota

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The early rifting phase (1115-1100 Ma) of the Midcontinent rift system (MCR) is characterized by the emplacement of reversely-polarized extrusive and intrusive basaltic rocks. Comprehensive studies of the basalts from this early rifting period have delineated three distinct compositions, type I, II and III, which can be correlated throughout the rift system (Nicholson et al., 1997). These three basalt types are recognized in the Ely's Peak Basalts along the southwest limb of the rift near Duluth, Minnesota. The reversely-polarized intrusions in this location are the diabase dikes of the Carlton Dike Swarm (CDS), the evolved Fe-Ti rich gabbro of the Esko intrusion and the Ni-Cu-PGE mineralized ultramafic Tamarack Intrusion. This study evaluates the diabase dikes of the Carlton Dike Swarm and their petrogenetic relationship to the other MCR reversely-polarized rocks.

Previously, the CDS was characterized as a Ti- and Fe-enriched quartz tholeiite (Green et al., 1987; Reichhoff, 1987). This study evaluates four geochemical subgroups of dikes, types A-D (Table 1). Within the main NE-trending Carlton Dike swarm, three compositional subgroups are observed. The majority of dikes (type A) are classified as high-TiO_2 (2.9-4.6 wt%) and outcrop mainly along the St. Louis River and include the prominent columnar-jointed dike outcropping south of the Thomson Reservoir. The two other dike types include: a similar high-TiO_2 dike (type B) with a greater percentage of hydrous minerals (5%), and the steepest HREE slopes; and a low-TiO_2 dike (1.2-1.3 wt%) (type C) locally known as the Cloquet dike. The Cloquet dike is recognized as the longest dike (55 km) in the swarm based on its aeromagnetic signature. In addition, a smaller subset of NW-trending dikes (type D) is also distinguished by aeromagnetics, with the most prominent dike located approximately 50 km to the southwest of the main CDS. This dike has major and trace element compositions that are analogous to type A dikes. The Esko Intrusion is a circular-shaped aeromagnetic feature located on the NE corner of Carlton County. The intrusion is also geochemically similar to the high-TiO_2 CDS with a greater abundance of hydrous minerals similar to the type B dikes.

The CDS diabase dikes have geochemical similarities to type II and III basaltic compositions, which is consistent with the timing of CDS dike emplacement near the end of the early reversal period (Green et al., 1987). The higher Mg#'s associated with the basaltic composition type I are not found in the diabase dikes sampled during this study or in previous research (Table 1). The type C dike is comparable to type II basalts with a similar Mg# and TiO_2 but has a nearly horizontal HREE pattern and more pronounced negative Nb and Ta anomalies (Figure 1). Type A, B & D dikes are most similar to type III basalts. Type A & D dikes have the most evolved Mg#'s like type III basalts, while type B is less evolved. The trace-element and REE patterns of type D dikes overlap with the type A field, and both are more enriched in HREE than type III basalts (Figure 1). A significant difference, arguably, is the depletion of Nb relative to Th in the type A dikes, which is interpreted as indicating late contamination by a similarly sourced magma. The type B dikes and type III basalts have similar slightly negative Nb anomalies although the dikes are characterized by a positive Eu anomaly and steeper HREE pattern (Table 1).

Nicholson and Schulz (2011) propose that type I and III basaltic compositions are possibly related by fractionation and variable amounts of contamination. Other investigators (e.g. Hou et al., 2011) have modeled sources of high-Ti basalts by fractional crystallization from high-Mg, low-Ti basalts. To evaluate possible genetic relationships between different dike groups, fractional crystallization models involving the most primitive samples (e.g. type C) along with basalt types I, II and III are being used. Thermodynamic modeling of the origin of high-Ti basaltic compositions is enhanced by low fO_2 and a high Mg#, but possible influences of assimilation and magma mixing remain a complexity.

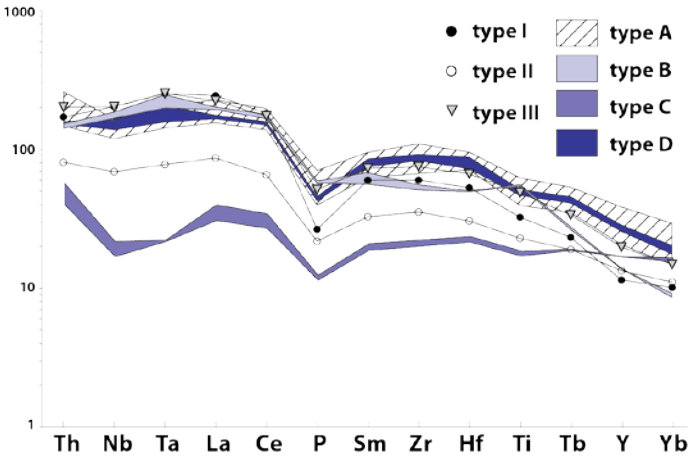


Figure 1: Chondrite normalized trace-element patterns. Normalization factors from McDonough & Sun (1995) except for P from Thompson et al. (1983). Data for basalt type I, II and III from Nicholson et al. (1997).

	TiO2 wt%	Mg#	La_N/Yb_N	n
type I	2.41±0.26	0.63	22.88	5
type II	1.70±0.22	0.56	7.43	18
type III	3.62±0.63	0.39	14.32	10
type A	4.21±0.48	0.35	7.17	9
type B	4.12±0.08	0.45	21.16	2
type C	1.29±0.05	0.55	1.99	3
type D	3.66±0.17	0.38	8.44	5
Esko	3.37±0.32	0.35	16.49	18

Table 1: Chondrite normalized as indicated (McDonough & Sun, 1995); FeO=0.85FeOT; Mg# = Mg/Mg+Fe (mole percent); n, number of samples

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SEDIMENTOLOGY AND PALEOGRAPHIC RECONSTRUCTION OF THE STRATA ADACENT TO THE SUDBURY IMPACT LAYER IN A CORED DRILLHOLE

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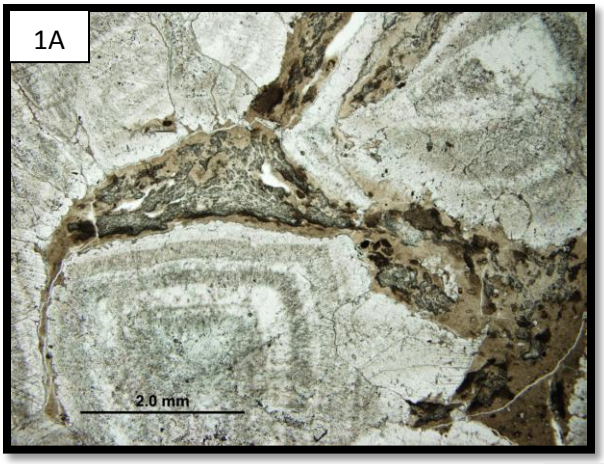
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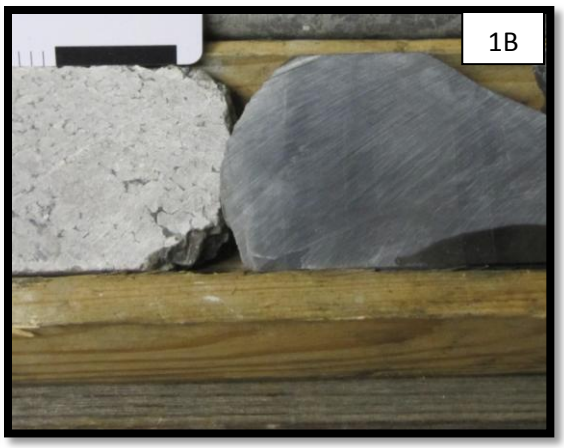
Drill core BDQ-2, extracted adjacent to Highway 588 near Thunder Bay, Ontario, Canada revealed stratified layers of the 1878.3 $\pm$ 1.3 Ma (Fralick et al., 2002) Gunflint Formation, the 1850 Ma (Krogh et al., 1984) Sudbury Impact Layer, and the overlying 1832 $\pm$ 3 Ma (Addison et al., 2005) Rove Formation. A limestone unit in the drill core, situated just above the Sudbury Impact Layer, and immediately below the fine-grained siliciclastic sediment of the Rove Formation, was analyzed to determine its mode of formation.

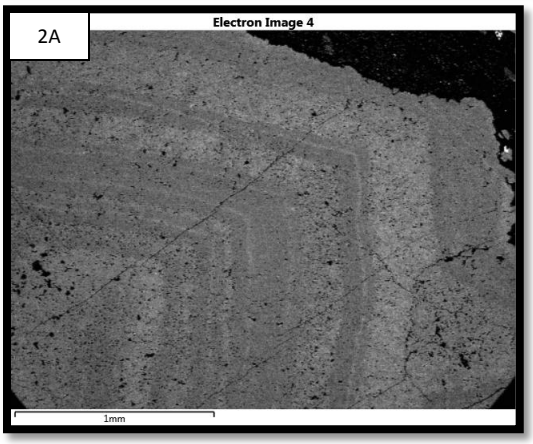
The approximately three meters of chemical sediment overlying the ejecta layer has evidence of silicification below the uppermost meter. The top meter is composed of euhedral and subhedral calcite crystals with thin wisps of dark material separating the crystals and forming a chicken-wire texture (Figure 1A). The crystals consist of, on average, CaO 46.1%, MgO 0.68%, FeO 0.54% and MnO 0.19%. Five points in the carbonate unit were analyzed: point 1 being at the top of the analyzed unit, and going sequentially downward, through to point 5 at the bottom of the analyzed unit. Point 1 is situated at a sharp contact with the Rove Formation (Figure 1B). This point contains the largest carbonate crystals in the unit, consisting of ~3-5mm euhedral and subhedral zoned calcite crystals, in encasing fine-grained material (Figure 1A). The size of the calcite crystals decreases down the drill core, in the direction of the Sudbury Impact Layer, and at point 5 are ~200μm-1.0mm in size.

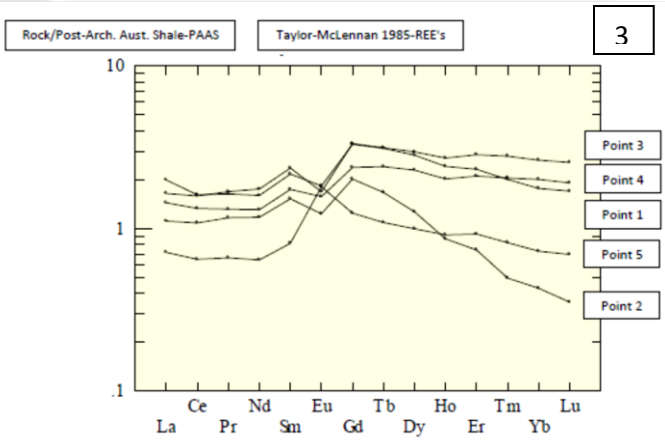
Results from SEM-EDX analysis using elemental mapping show zoned calcite crystals (Figure 2A) with Fe enrichment (Figure 2B) adjacent to the Mg enrichment (Figure 2C). The fine-grained sediment present between the calcite crystals was also analyzed and is an assortment of clay minerals and calcite. Results from ICP-AES and MS analysis show low vanadium and chromium abundances in samples from points 1 to 4, but with much higher values, two orders of magnitude and one order of magnitude respectively, for the sample from point 5. PAAS normalized rare earth element curves for points 1 to 4 (Figure 3) have similarities with curves for meteoric water, whereas the curve for point 5 is similar to Paleoproterozoic seawater.

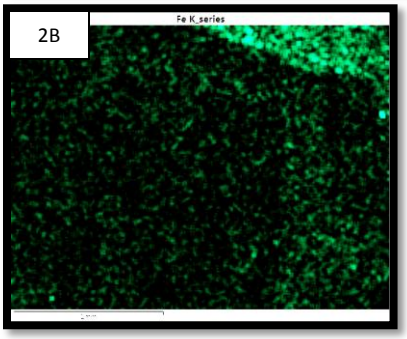
Somewhat oxygenated meteoric water is needed for the transport of the vanadium and it would have precipitated under more reduced conditions in the sub-aerially exposed marine carbonate sediments. The fine-grained siliciclastic sediments above this were more oxygenated resulting in no vanadium enrichment though calcite crystals were precipitated from the meteoric waters creating a chicken-wire fabric. No modern analogs to this type of diagenetic alteration exist.











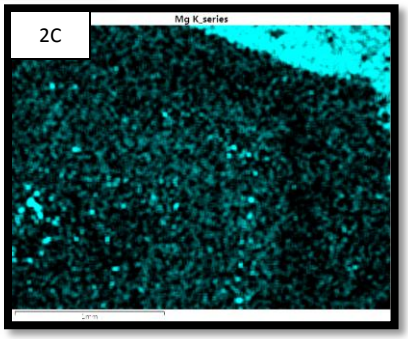


Figure 1A) Calcite crystal chicken wire texture. Figure 1B) Contact between Rove Formation and carbonate unit. Figure 2A) SEM image of zoned calcite crystal. Figure 2B) Fe enrichment. Figure 2C) Mg enrichment. Figure 3) REE's for Points 1-5 (PAAS).

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Geologic mapping of Neoarchean and Paleoproterozoic rocks near Ester Lake by students of the Precambrian Research Center's 2012 field camp

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The University of Minnesota-Duluth's Precambrian Research Center conducted its sixth annual field camp in 2012, and this presentation is one of a series that show some of the results. During the fifth and sixth weeks of camp, teams of students participate in "capstone projects" that test student skills by creating new geologic maps in areas of poorly known geology. This capstone project involved mapping an area of the Boundary Waters Canoe Area Wilderness accessed by 12 lakes, with Ester Lake at its center (Fig. 1). The map provides details about the complex depositional and deformation history of a Neoarchean, largely metasedimentary terrane that is part of the Wawa subprovince of Superior Province.

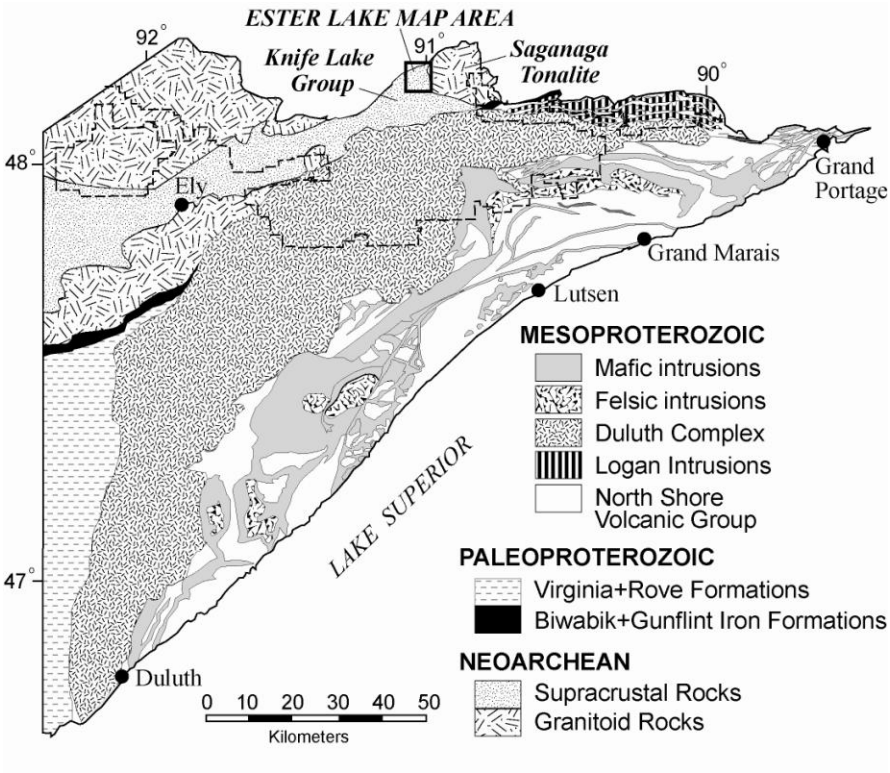


Figure 1. Generalized bedrock geologic map of northeastern Minnesota showing the Ester Lake capstone area. The unit labeled "Knife Lake Group" also encloses older volcanic sequences that are not delineated separately at this scale. Dashed line is the border of the Boundary Waters Canoe Area Wilderness.

The Ester Lake map area lies along and west of the boundary between the Saganaga Tonalite (ca. 2690 Ma), and sedimentary strata of the Knife Lake Group that are inferred to have been derived in part from it. Both rock units were tilted, folded, faulted, and metamorphosed to low

greenschist facies during a regional deformation event at about 2680 Ma, which provides an approximate minimum age for the Knife Lake Group. Our mapping demonstrated that strata of the Knife Lake Group in this area form a broad, northeast-trending synclinorium that is bounded by the Saganaga Tonalite on the east, and an apparently uplifted fault-block of metabasalt on the west (*see cross section on poster*). The limbs of this large structure are marked by smaller sympathetic folds, and are dissected by several faults and shear zones. Mapping to the east revealed an erosional unconformity at the contact between Saganaga Tonalite and basal Knife Lake strata. The tonalite appears to have been weathered and is overlain by sandstone containing both subrounded and angular quartz pebbles—approximately the same size as quartz phenocrysts in the tonalite—in a sandy matrix of altered plagioclase grains and fine grunge that resembles reworked granitoid saprolite. To the west, this basal unit grades stratigraphically upward into irregularly interbedded sequences of arkose; conglomerate containing amoeboid clasts of tonalite ("Fish Lake conglomerate"); hornblende-phyric, trachyandesite-bearing coarse pebble to cobble conglomerate; polymictic conglomerate with metabasalt clasts; gritstone composed of subangular sand grains of hornblende and plagioclase; and graywacke and slate containing rare, thin lenses of banded iron-formation. Collectively, this arrangement of stratigraphic facies indicates that Saganaga Tonalite and the rocks it intruded were uplifted and subaerially eroded to provide detritus to nearby basins, now manifest as Knife Lake strata. However, the diverse lithologic character of these strata indicates that a great variety of sediment source regions and depositional settings existed.

The Saganaga Tonalite was likely weathered to form saprolite, which was eroded by slope-wash, alluvial fan, and fluvial processes to produce the quartz pebble sandstone, and to contribute clasts to various conglomeratic layers. We attribute the several hundred-foot-thick arkosic unit to reworking of saprolite in a near-shore marine or lacustrine environment. The Fish Lake conglomerate, containing matrix-supported amoeboid (paleosaprolitic) tonalite clasts, is interpreted to be channelized alluvium deposited in a rapidly subsiding basin. Conglomerate containing hornblende-trachyandesite clasts likely formed from erosion off the informally named Jasper Lake volcanic sequence of Knife Lake Group, which lies southeast of the map area (Jirsa and Starns, 2008). Graywacke and slate are interpreted to represent deposition in a lacustrine or marine setting, and the interlayered coarser polymictic clastic strata may represent braided stream, alluvial fan, or subaqueous fan deposition of sediment shed off the uplifted flanks of the basin. The layered strata exhibit chaotic soft-sediment deformation features, local growth faults, and abrupt facies changes, suggesting that deposition was synchronous with episodic basin subsidence. Thin layers and lenses of jasper-bearing iron-formation that are associated with graywacke and slate are interpreted as chemical precipitates into what may have been a shallow marine environment. The lithologic diversity and structural complexity is consistent with a model of deposition in rhombochasms created during strike-slip or extensional faulting. The general fining-upward character of Knife Lake strata, albeit irregular, may represent increasing water depth over time within the depocenter. The western, fault-bounded metabasalt unit contains abundant tightly packed mattress-size pillows that lack amygdules, implying deposition in fairly deep water. These attributes, along with the vertical dip of metabasalt flows, are similar to parts of the ca. 2720 Ma Ely Greenstone and Newton Lake Formation, and represent a very different tectonic and depositional setting from that of the adjacent Knife Lake Group. A small unit of metadiabase identified during mapping may be part of a swarm of mafic intrusions seen elsewhere in the region that are inferred to be Paleoproterozoic in age.

This and other maps produced by capstone projects can be viewed at www.d.umn.edu/prc.

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Preliminary Investigations of the Fe-Ti-V-P mineralization associated with the Thunderbird and Butler gabbroic intrusions within the McFaulds greenstone belt, Superior Province, Northern Ontario, Canada

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The McFaulds Lake area (i.e., Ring of Fire) located in northern Ontario (Canada) has been the site of recent mineral exploration leading to the discoveries of several mineralization types such as chromite and nickel sulfide deposits. Although the majority exploration has been focused on chromium, this area also contains significant Fe-Ti-V-P mineralization associated with gabbroic intrusions, in which the Thunderbird and Butler occurrences are the best defined.

These gabbroic intrusions are widely distributed throughout the McFaulds Lake area and maybe grouped into two main types of occurrences: (1) large mafic-dominated intrusions and (2) subconcordant to slightly discordant mafic-dominated sills/dikes characteristic of the Thunderbird and the Butler intrusions respectively. These intrusions are composed of an evolved mafic suite termed the 'Ferrogabbro' characterized by the presence of Fe-Ti oxides. Through detailed core logging, it has been recognized that both intrusions are largely composed by very similar lithologies including iron-rich gabbros, leucogabbros, and anorthosites. Two types of mineralization occur in these intrusions: (1) Fe-Ti-V and (2) Fe-Ti-P mineralization. Fe-Ti-V mineralization occurred within both intrusions whereas the Fe-Ti-P mineralization have been only identified within the Thunderbird intrusion. The mineralization occurs dominantly as disseminated magnetite and ilmenite (1-10%), but also present as semi-massive (50-80%), to massive layers (>80%). These layers typically contain distinct sharp, stratigraphically lower contacts and gradational upper contacts typical of primary igneous layering. The massive oxide layers are composed of magnetite and ilmenite typically at a ratio of 10:1. The ilmenite occurs as anhedral to subhedral crystals and to a lesser extent, as very fine-grained exsolutions within anhedral magnetite grains. Vanadium grades range from 0.30% to more than 0.60% (V_2O_5) and titanium grades range from 2.5% to more than 4.5% (TiO_2) whereas Vanadium grades, at Butler, range from 0.42% to more than 1.17% (V_2O_5) and titanium grades range from 0.46% to more than 11.3% (TiO_2).

Sedimentology and geochemistry of the Espanola Formation, Huronian Supergroup

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The Huronian Supergroup is a southerly thickening wedge of Paleoproterozoic sediments with a maximum thickness of 12 km and an age range of 2450 Ma to 2219 Ma (Bennett et al., 1991). The area is hypothesized to be a divergent continental margin with the paleo-ocean directly to the south (Fralick and Miall, 1989). The Huronian Supergroup contains evidence of three separate glacial related formations, including the Ramsay Lake Formation, Bruce Formation and the Gowganda Formation. The immense size of similar glacial formations and their sedimentary deposits at tropical paleo-latitudes led geologists (ie., Paul Hoffman) to put forth the Snowball Earth theory. Geochemistry from the Espanola Formation may very well help identify possible reflections of atmospheric composition, specifically related to carbon dioxide and oxygen content. The Espanola Formation is a lone cap carbonate sandwiched between the Bruce and the Gowganda Formations. It is classically divided into three individual members; the lower Limestone member, the middle Siltstone member and; the upper Dolomitic Cap. The sediments of the Espanola were deposited on a carbonate shelf post-glaciation that begin to reflect a shallowing upwards sequence later in stratigraphy. This can be attributed to post-glacial isostatic adjustment. This abstract will discuss the lithofacies associations of each member, their depositional environments and possible oceanic geochemical signatures. Sediments deposited consist of a terrigenious sediment source with a carbonate cement as well as carbonate minerals precipitated directly from seawater. Partial dissolutions in acetic acid, of selected samples, were analyzed by ICP MS to better understand the geochemistry of the carbonates. Yttrium is not removed from seawater like it's geochemical twin Holmium (due to differing surface stabilities) and seawater generally displays high Y/Ho ratios that may range between 44-74 (Nagarajan et al., 2011). The Espanola geochemical results, represented by Figure 1 in a graph of Yttrium verses Holmium, displays a low ratio of ~28 which, is indicative a dominant chondritic terrigeneous sediment source (Nagarajan et al., 2011), possibly attributed to river run-off systems fed by the glacial melt waters. Using the same samples, the spider diagram in Figure 2 displays a distinct "hat-like" pattern of MREE enrichment. This is not consistent with carbonates precipitating from Paleoproterozoic seawater but analogous with the MREE enriched patterns of major modern river systems (Matsaranta, 2006). This MREE enrichment supports a non-marine water components in the near-shore waters from which the carbonates precipitated . The possibility that the carbonate precipitation in the middle siltstone member was simply carbonate cement is likely with the high amount of siliciclastic material, while the upper and lower members are dominated by carbonate precipitates. Geochemical evidence does not indicate a stratigraphic control that classically divides the Espanola members but rather suggests a lateral geographic change away from the shore-line in limestone/dolostone precipitation. The Espanola represents a period of minor increases in oxygen content and future thesis work will hopefully aid in drawing conclusions regarding paleo-atmospheric composition.

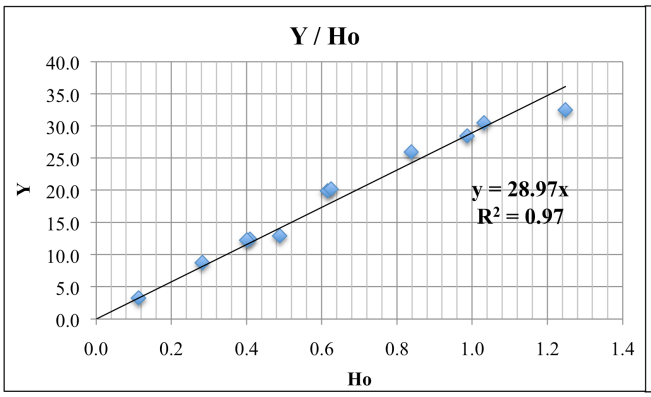


Figure 1. Spider plot of Espanola samples from partial dissolution in acetic acid analyzed by ICP MS. The low ratio, linear trend is indicative of a dominant chondritic terrigeneous sediment source possibly attributed to river run-off systems fed by glacial melt waters.

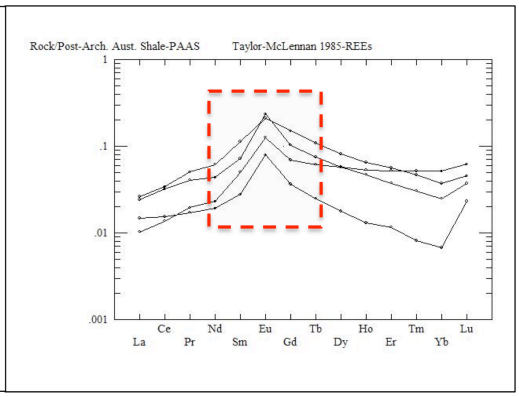


Figure 2. Spider plot of Espanola samples from partial dissolution in acetic acid analyzed by ICP MS. Highlighted by the red box is a "hat-like" pattern indicating MREE enrichment.

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Chemostratigraphy of the Biwabik Iron Formation: Implications for Basin Longevity and Evolution

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The Paleoproterozoic Biwabik Iron Formation (BIF), an ~200m thick iron-formation in northeastern Minnesota, USA, is traditionally subdivided into four conformable members: Lower Cherty (LC), Lower Slaty (LS), Upper Cherty (UC), Upper Slaty (US), comprised predominantly of granular (cherty) and banded (slaty) iron-formation. Basin geometry and depositional environment of the iron-formation in the BIF and other 1.88 Ga circum-Superior Craton iron-formation has been a topic of speculation for decades. Recent work suggests deposition on a clastic sediment-starved stable platform is a viable model for explaining the sedimentological and geochemical characteristics of circum-Superior iron-formations, as well as their widespread distribution. Geochemical evidence from the BIF in the Virginia Horn area provides further evidence in support of this model, and offers additional insight into both basin longevity and basin evolution.

The BIF is composed predominantly of chemically precipitated sediment, reflected in Fe, Si, Mn, P, Mg, and Ca concentrations. A minor detrital clastic component is reflected in Al, Ti, and K concentrations. Al_2O_3 (the predominant detrital component) concentration ranges from 0.03% in granular iron-formation to 3.79% in slaty iron-formation, averaging 0.35% (sd=0.38%) (Fig. 1). Assuming a PAAS shale-like composition (Taylor and McLennan 1985), this corresponds to a detrital component averaging 2.3%, comparable to the detrital component found in modern platform carbonates.

In contrast to the variability in detrital content, the Al_2O_3:TiO_2 ratio is remarkably consistent through the thickness of the BIF, with the exception of a break in ratio corresponding to the top of the 'Variably-Bedded and/or Mottled Unit' of the LC member of Severson and others (2009) (Fig. 2). Below this horizon, Al_2O_3:TiO_2 in the lower LC is 29:1, while above this horizon Al_2O_3:TiO_2 in the LC-LS-UC-LS is 10:1. These constant ratios suggest that detrital material input to the BIF was sourced from long-lived, homogeneous reservoirs, likely as fine-grained, windborne dust. The constant ratios also suggest that variation in detrital concentration is a function of variation in chemical precipitate accumulation rates, rather than variation in detrital deposition rates.

The two Al_2O_3:TiO_2 ratios suggest two fundamentally different detrital source areas contributed to the BIF; the 29:1 ratio is comparable to that of modern airborne particles sourced from mature continental sediment in the Sahara, while the 10:1 ratio may reflect a volcanic source. The abrupt transition between the high Al_2O_3:TiO_2 lower LC and the overlying low Al_2O_3:TiO_2 LC-LS-UC-US sequence suggests that this contact represents a significant depositional hiatus, accompanied by a fundamental reorganization of atmospheric circulation and (or) emergence of a new detrital source area.

Modern windborne dust accumulation rates in south Florida are on the order of 1.25 $g \cdot m^{-2} \cdot yr^{-1}$.; assuming similar deposition rates during BIF accumulation, it is possible to calculate rates and the duration of iron-formation accumulation from detrital concentration. Assuming s.g. 3.34, instantaneous accumulation rates range from 1.5 to 189 m/m.y., averaging 32 m/m.y. (Fig. 3). Granular iron-formation subunits are notably characterized by significantly higher accumulation rates than banded iron-formation subunits, both in the LC and LS-UC-US members.

Overall, for the BIF in the Virginia Horn area, 1.6 myr of accumulation in the 63 m thick lower LC and 13.6 myr of accumulation in the upper 150 m thick LC-LS-UC-LS are indicated.

The presence of a significant disconformity internal to the LC member challenges the assumption that accumulation of iron-formation in the BIF (and in other circum-Superior iron-formations) is the product of a single conformable depositional sequence, and particularly suggests re-evaluation of the traditional four member (LC-LS-UC-LS) subdivision of the BIF is warranted.

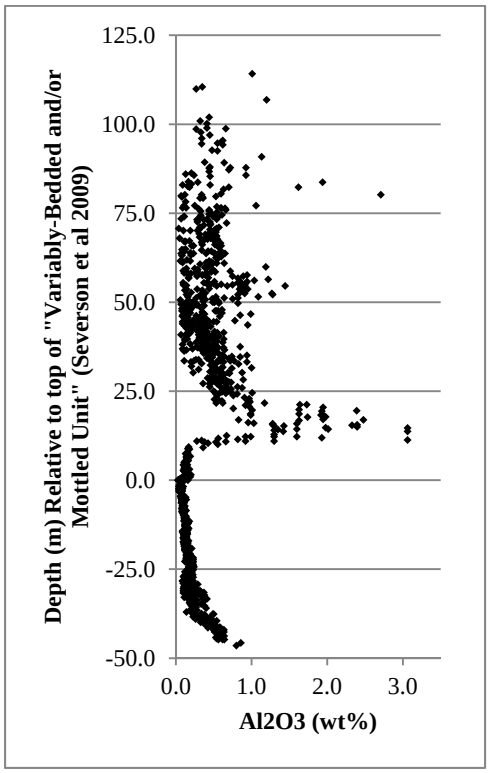


Figure 1. Al_2O_3 in the Biwabik Iron Formation, Virginia Horn area, Minnesota. n=1341

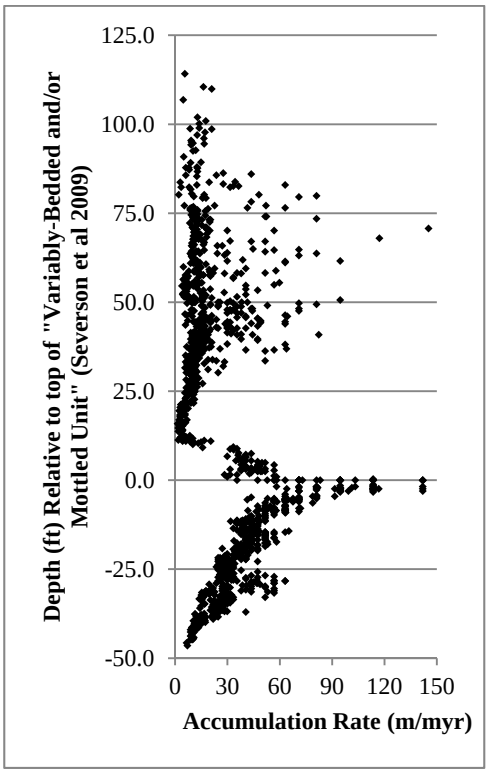


Figure 3. Iron-formation accumulation rates in the Biwabik Iron Formation, Virginia Horn area, Minnesota.

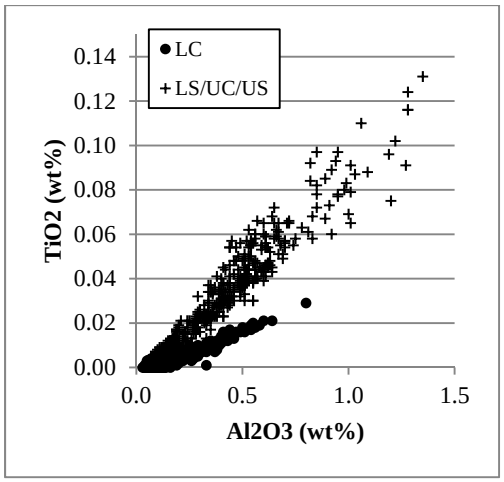


Figure 2. Al_2O_3 and TiO_2 in the Biwabik Iron Formation, Virginia Horn area, Minnesota. n=917

Geochemistry and origin of slate-hosted massive sulfides of the Eagle Ni-Cu-PGE Deposit, northern Michigan: A preliminary study.

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The Eagle Ni-Cu-PGE sulfide deposit is located within the Baraga Basin in northern Michigan. It is also located just south of the 1.1 Ga Midcontinent Rift System axis. Sulfide mineralogy consists of pyrrhotite-chalcopyrite-pentlandite. Primary ore types consist of disseminated, semi-massive (net-textured), and massive that are associated with the main feldspathic peridotite-melagabbro intrusion.

Recent drilling has revealed three additional classes of sulfides that are hosted in black slates of the Michigamme Formation. Class 1 consists of massive sulfide analogous in appearance to that of igneous-related massive mineralization (Figure 1). Class 2 consists of sulfides with quartz veins thought to be hydrothermal in origin. Some of these occurrences are associated with localized soft-sediment deformation. Also, neither of these sulfide classes shows evidence of lobate margins and dissolution. Class 2 sulfides can further be divided based on their appearance. Class 2a sulfides have fragments of sulfide entrained in predominant quartz (Figure 2a), whereas class 2b has approximately equal quartz and fine-grained sulfide intermixed (Figure 2b). Class 3 consists of discrete lenses or pods of massive pyrrhotite (class 3a) or chalcopyrite (class 3b). Furthermore, class 3 sulfides are enigmatic due to there being no obvious emplacement mechanism within slate (Figure 3a, b). Sulfur isotope and petrographic evidence suggests a dual igneous-replacement and thermal-sedimentary origin for the slate-hosted sulfides. Class 1 sulfides show $\delta^{34}S = 1.2 – 3.9$ and minimal quartz along the sulfide-slate contact (origin). Class 2 sulfides show $\delta^{34}S = 7.5 – 11.8$ and sharp sulfide-slate contacts with no noticeable alteration mineralogy. Class 3a sulfides display $\delta^{34}S = 5.4 – 10.3$ along with acicular muscovite forming along the sulfide-slate boundary, protruding into the former, and are distal from the igneous intrusion; whereas class 3b displays $\delta^{34}S = 1.6 – 2.9$, acicular Mg-rich chlorite, and are located proximal from the intrusion.

Class 1 sulfides are thought to be magmatic in origin with some minor interaction with crustal sediments at lower temperatures. Class 2a sulfides are hypothesized to form as a result of pre-Eagle tectonic activity and remobilization whereas class 2b sulfides are inferred to have originated via aqueous fluids that were initiated by heat flow supplied by intrusives. The class 3b chalcopyrite is suggested to be magmatic in origin with some crustal interaction, produced as a result of fractional crystallization of an immiscible sulfide liquid. Minor crustal interaction is indicated given: 1) petrographic evidence showing quartz and other silicates entrained in sulfide, 2) presence of Mg-bearing phases along slate-sulfide contact, and 3) the development of lobate sulfide-silicate contact zones. A hypothesis on the emplacement mechanism of slate-hosted chalcopyrite is that they are replacements of older sedimentary sulfides (i.e. trace pyrite). The class 3a pyrrhotite is thought to be of a thermal-sedimentary origin based on the following: 1) moderately high $\delta^{34}S$ values, 2) lack of mafic alteration phases along the slate-sulfide contact, and 3) significant spatial separation from the intrusion. Sedimentary pyrite may be converted to pyrrhotite in C-rich sedimentary rocks via reactions such as: $FeS_2 + 3H_2O + 5/2C = FeS + H_2S + 3/2CO_2 + CH_4$. It is clear that multiple periods of sulfide generation occurred in the area of the Eagle intrusion, all related in some manner to thermal effects associated with rift-related magmatic activity.

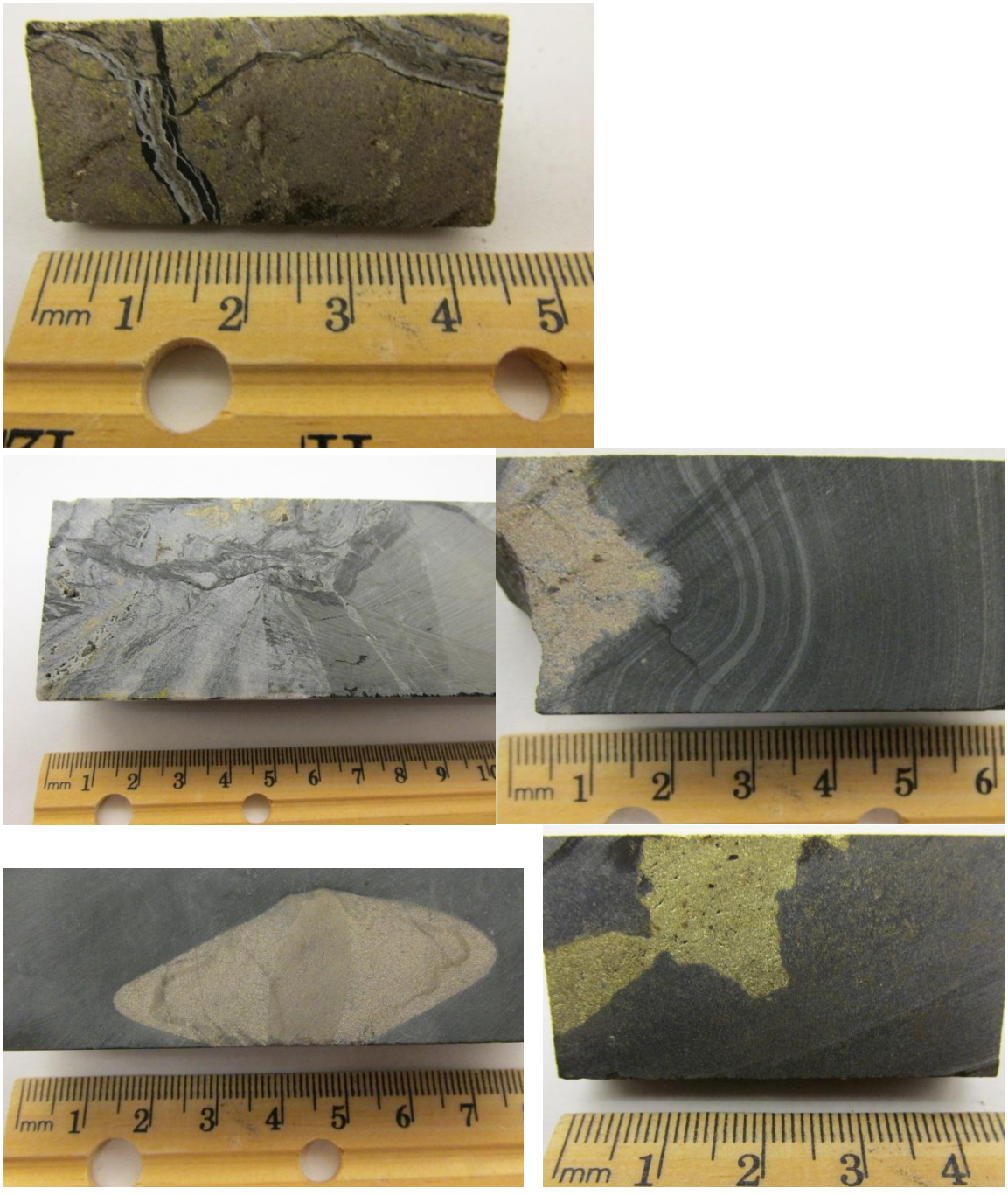


Figure 1 (top): Class 1 sulfide showing evidence of hydrothermal-sedimentary involvement. **Figure 2a (middle-left):** Class 2a sulfide – fragments in majority quartz thought to be from pre-Eagle tectonism. **Figure 2b (middle-right):** Class 2b sulfide intermixed with quartz showing localized soft-sediment deformation. **Figure 3a (bottom left):** Pod of massive pyrrhotite (class 3a sulfide) encased in slate with no noticeable sedimentary deformation. **Figure 3b (bottom right):** Bleb of massive chalcopyrite (class 3b sulfide) encased in slate.

Field, Petrographic, and Geochemical Study of the Bad Vermilion Intrusion, Mine Centre, Ontario, Canada

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During the summer of 2011, Aubrey Lee was contracted by Numax Resources, Inc. to map the bedrock geology of the Bad Vermilion Intrusion (BVI) which lies within Numax subsurface claims in Mine Centre, Ontario, Canada (Fig. 1b, Lee et al., 2012). The objective was to establish continuity of massive oxide units along the northern shore of Bad Vermilion Lake which had previously been documented by White and Albers (2010) along the northern shore of Seine Bay (Rainy Lake) to the west. In addition to facilitating accurate predictions for future exploration targets, the field work was to provide data for a field, petrographic, and geochemical study of the BVI as Aubrey's master's thesis at the University of Minnesota, Duluth. This study seeks to characterize the lithologic, petrographic, and geochemical attributes of the BVI in order to evaluate the potential for economic concentrations of Fe-Ti oxides, as well as PGE reef mineralization. The map (Fig. 1b) was presented last year at the 58th annual ILSG meeting in Thunder Bay (Lee et al., 2012). This poster presentation displays geochemical data and petrographic observations which provides a more comprehensive depition of BVI geology.

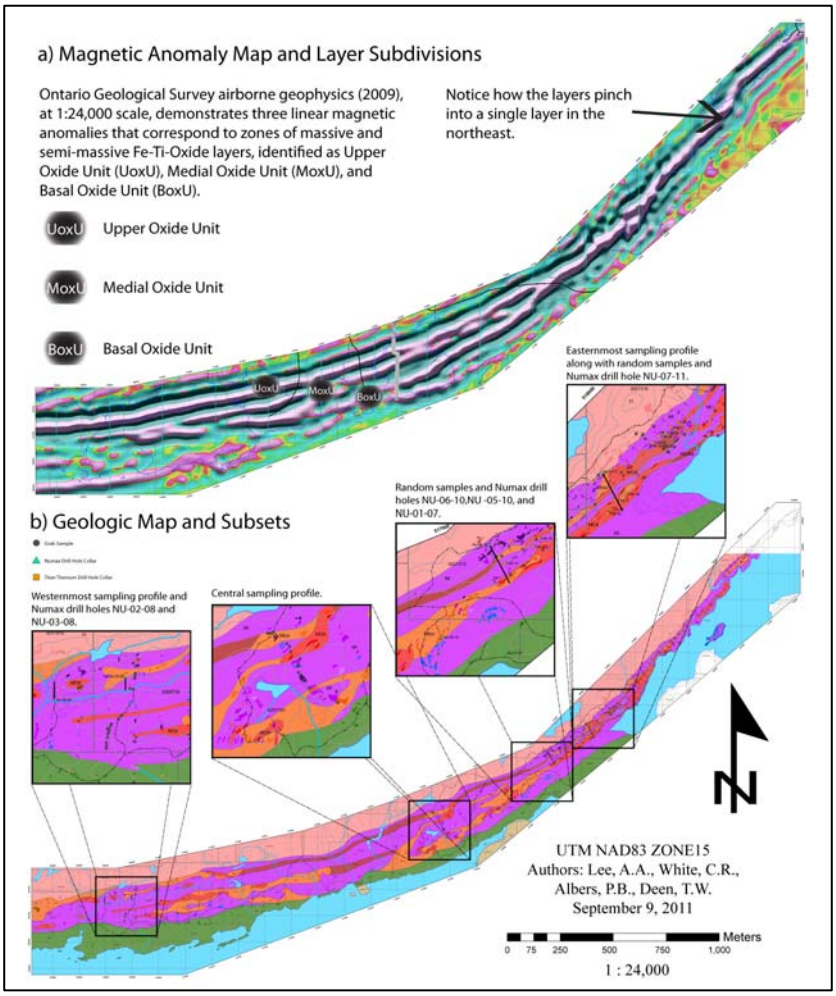


Figure 1: a) Magnetic Anomaly Map and Oxide Unit Correlation of the BVI; Ontario Geological Survey (2008). b) Geologic Map with subsets showing sampling profiles, drill collar locations, and plan-view extents of drill holes.

The BVI is a 14 km long and 1-3 km wide, sub-vertically dipping, sill-like, layered plutonic sequence of gabbroic rocks exposed along the shores of Seine Bay (Rainy Lake) and Bad Vermilion Lake in Northwest Ontario, Canada (Fig. 1b; White and Albers, 2010). The intrusion is situated at the boundary between the metavolcanic-plutonic Wabigoon subprovince to the north and the metasedimentary Quetico subprovince to the south in the Superior Province of the Canadian Shield Precambrian terrain (Poulsen, 1986). It occurs within a dextral

wrench fault zone bounded by the Quetico fault to the north and the Rainy Lake-Seine River fault to the south. The BVI lithologically consists of a mafic layered intrusive package of anorthositic, gabbroic, pyroxenitic rocks with layers/lenses of semi-massive to massive Fe-Ti oxides that have been significantly altered and possibly metamorphosed. The intrusion is exposed between felsic intrusive rocks at its northern contact and mafic volcanic rocks at its southern contact. The nature of these contacts and the magmatic relationship between each unit is enigmatic.

Magnetic surveys of the Mine Centre area reveal three distinct magnetic highs extending the length of the intrusion and merging in the northeast where the exposure of the intrusion narrows along Bad Vermilion Lake (Fig. 1a; Ontario Geological Survey, 2008). Correlation of bedrock mapping with magnetic surveys indicates that the anomalies correspond to massive, semi-massive, and disseminated Fe-Ti oxide layers which are generally persistent along the length of the intrusion, though they may pinch, swell, and anastomose. The economic importance of the BVI lies in these oxide layers which contain significant concentrations of iron, titanium, vanadium and/or phosphorous (White and Albers, 2010).

Four Numax drill holes (Fig. 1b) in the BVI highlight Fe-Ti mineralization, though only two on the west end of the intrusion have been fully geochemically assayed. Two near the central and east areas will eventually be assayed and incorporated into this study. During 2011 mapping, samples were collected along three profiles in the west, central, and eastern areas to supplement core data. Geochemical assays of field samples and drill core have helped establish petrologic and mineralogic continuity along the strike of the intrusion and document the igneous stratigraphy of the BVI. The western drill holes both intersected a thick package of melagabbroic rocks with 10 cm – 30 m intervals of massive oxide among oxide-bearing melagabbros. There are at least four massive oxide intervals with continuity between the two holes (600 m apart along strike). It is likely that these units pinch and swell, evidenced by variations in unit thickness and strong shearing at oxide layer contacts.

In addition, 200 thin sections from field samples and drill core are being viewed in both reflected and transmitted light to delineate mineralogy, texture, alteration and, most importantly, to establish oxide mineralogy. Oxide layers were originally thought to be hosted by pyroxenite or gabbro, but petrographic analysis shows that the rocks are significantly altered and metamorphosed. Chlorite, talc, and amphibole alteration is dominant, though quartz-carbonate veining is also common. Photomicrographs of samples taken from the “top” of the intrusion indicate that primary apatite is strongly associated with massive oxides in the upper zones of the BVI. The most common oxides are expected to be secondary magnetite and ilmenite after primary titanomagnetite which will be verified through reflected light petrography.

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The Igneous Stratigraphy of the Bad Vermilion Intrusion, Mine Centre, Ontario, Canada: Which Way is Up?

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The Bad Vermilion Intrusion (BVI) is a layered plutonic sequence of gabbroic rocks exposed along the shores of Seine Bay (Rainy Lake) and Bad Vermilion Lake in Northwest Ontario, Canada (White and Albers, 2010). The intrusion is the subject of a field, petrographic, and geochemical study as Aubrey Lee's master's thesis at the University of Minnesota-Duluth. The BVI is sill-like, approximately 14 km long and ~1 km wide, and stretches along the northern shores of Seine Bay in the southwest and Bad Vermilion Lake in the northeast with the town of Mine Centre marking its northeast extent. The BVI lithologically consists of a mafic layered intrusive package of altered and metamorphosed anorthositic, gabbroic, and pyroxenitic rocks with layers/lenses of semi-massive to massive oxides. Primary apatite occurs near the upper (northern) zones and is strongly associated with massive oxide units. Within the east-west elongate block bounded by the Quetico and Rainy Lake-Seine River fault zones (Poulsen, 1986), the BVI dips sub-vertically (85˚ N-NW shallowing to 60˚ N-NW in central region) between felsic intrusive and mafic volcanic rocks (Fig. 1). The Mud Lake Trondhjemite to the north and the Bad Vermilion Tonalite to the south (along Bad Vermilion Lake) are concordant with the BVI while the mafic volcanic rocks (chiefly basalt) to the south (along Seine Bay) are weakly discordant. The nature of these contacts and the magmatic relationship between the BVI and the country rocks is poorly known. It is also unclear as to whether the intrusion tops to the north or south.

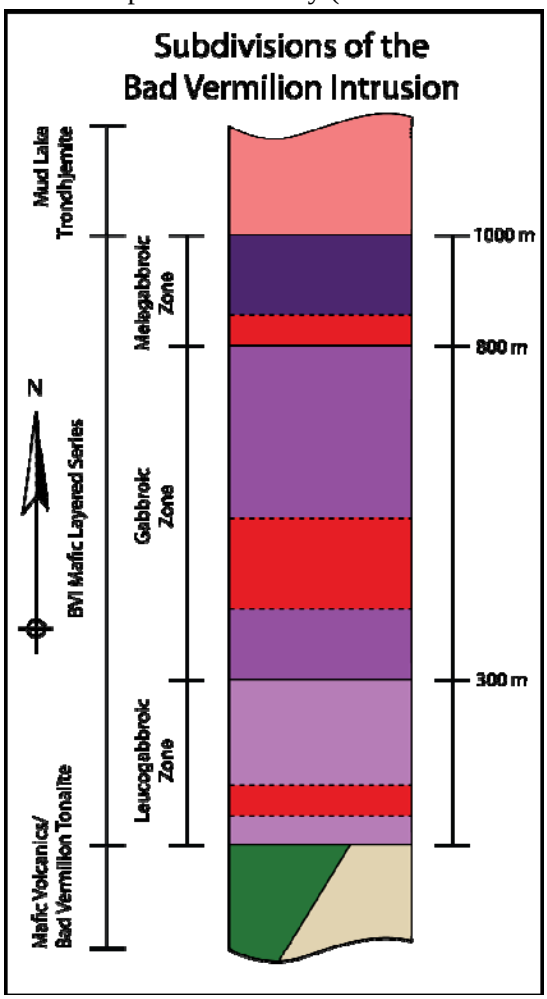


Figure 1: Idealized igneous stratigraphy of the BVI showing the main zones of the mafic layered series and the approximate locations of the three oxide units. Vertical scale is approximate.

Bedrock mapping (Lee et al., 2011), magnetic surveys, and petrographic analysis helped to establish subdivisions within the intrusion (Fig. 1). This was also made possible by the fact that the sub-vertical dip of the BVI exposes the entire stratigraphy of the intrusion in near-true thickness. On a large scale, the region can be divided into a Mafic Layered Series, bounded on the northern side by the Mud Lake Trondhjemite, in the southeast by the Bad Vermilion Tonalite, and in the southwest by mafic volcanics. The Mafic Layered Series can be further subdivided into three zones; the Leucogabbroic Zone to the south, the central Gabbroic Zone, and the Melagabbroic Zone to the north. Although all zones contain oxide-bearing lithologies throughout, each zone contains an oxide "unit" that is composed of multiple layers of massive to semi-massive Fe-Ti oxides concentrated in discrete intervals, typically toward the base of the zones. The oxide "units", which range from 20 – 200 m in thickness, all

contain more than one layer/lens of massive oxide which are typically 10 cm – 1 m thick. However, one oxide unit within the Melagabbroic Zone is up to 30 m thick, as observed in core and field exposures. Though all three oxide units are evident in the western and central areas of the BVI (White and Albers, 2010), they thin and appear to coalesce toward the northeast (Lee et al., 2011). Geochemical and petrographic analysis will hopefully help to resolve how the eastern extent of the BVI correlates with the thicker sequences to the west.

In White and Albers' (2010) mapping of the central and western BVI, they interpreted the southern Mafic Volcanic Sequence and Bad Vermilion Tonalite to be the footwall and the Mud Lake Trondhjemite the hanging wall of the BVI. North topping was originally determined based on graded layering of mafic to feldspathic lithologies which occur throughout the intrusion. This is especially evident in the northernmost Melagabbroic Zone near the contact with the Mud Lake Trondhjemite, and can locally be traced for up to 400 m. Typically, the base of each layer is dominated by clinopyroxene with plagioclase abundance increasing upward and a sharp contact with the base of the next layer. Moreover, apatite abundance in the massive oxides of the Melagabbroic Zone indicates P-enrichment to the north. However, if the BVI does indeed top to the north, one would expect the abundance of plagioclase to increase from south to north on a large scale. Instead, the general south-to-north progression is from plagioclase-rich rocks (Leucogabbroic Zone) to mafic rocks (Melagabbroic Zone) and may indicate that the intrusion is slightly overturned and that the Mud Lake Trondhjemite is actually the footwall of the BVI.

The nature of the contacts between the BVI and its bounding rocks are difficult to interpret. There is no evidence for faulted contacts. Moreover, the felsic intrusive rocks on either side of the BVI are clearly not upper differentiates given their tonalitic/trondhjemitic composition and the abrupt transition from mafic to felsic lithologies. Rather, the mafic volcanics at the southwestern contact of the BVI show effects of contact metamorphism and thus imply an intrusive contact (White and Albers, 2010). The contact between the BVI and the Bad Vermilion Tonalite to the southeast is concealed beneath Bad Vermilion Lake, but has also been considered intrusive by Poulsen (1984). The nature of the northern contact between the BVI and the Mud Lake Trondhjemite is more enigmatic. Although the trondhjemite is concordant with the BVI, grades into the melagabbro zone over a narrow interval of quartz gabbro, and has the same strike length as the BVI, it is petrologically unlikely that fractionation of the BVI would generate a trondhjemitic differentiate. Rather, given that the trondhjemite is bounded on the north by an extensive region of felsic volcanics (Poulsen, 1984), it is possible that the trondhjemite represents a partially melted zone generated by underplating of the hot BVI magma beneath the felsic volcanics. Narrow compositional grading from melagabbro to quartz gabbro to trondhjemite at the northern contact of the BVI is perhaps evidence for a gradational partially melted upper contact, but back-veining of the trondhjemite into the BVI supports the idea that the trondhjemite is actually the basal intrusive contact. This latter interpretation also fits better with the southward mafic to felsic progression of BVI zones. It is hoped that evaluation of geochemical cryptic layering through the BVI will help resolve which way is up.

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2012 Precambrian Field Camp Mapping in the Wilder Lake Intrusion, Lake County, Northeastern Minnesota

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In the summer of 2012, the Precambrian Research Center of the University of Minnesota-Duluth held its sixth annual Precambrian field camp in northeastern Minnesota. As in years past, the fifth and sixth weeks of the camp are dedicated to student's "capstone" mapping projects during which detailed geologic mapping is conducted in areas of poorly understood geology and digital geologic maps are generated. Three of last summer's capstone projects focused on areas of the Duluth Complex affected by the Pagami Creek fire, which burned a 160-square-mile area within the Boundary Water Canoe area wilderness in the fall of 2011. The intense burn created a time-sensitive opportunity to map inland exposures that were previous difficult to access due to thick woods and blow-down areas created from a 1999 windstorm.

Our capstone mapping project focused an area centered on the Wilder Lake Intrusion (WLI), which had been previously reconnaissance mapped only along shoreline exposures (Phinney, 1972; Miller, 1986; Turnbull and Miller, 2004). When it was recognized that the most intense burn area of the Pagami Creek fire was centered in the Wilder Lake area, Jim Miller successfully applied for a USGS EDMAP grant to have a UMD graduate student map the newly created exposures of the WLI. He recruited Adam Leu, an alum of the 2011 PRC field camp, to make this mapping project the centerpiece of his MS thesis at UMD and to be a teaching assistant for the 2012 Precambrian field camp. The objective of the WLI capstone mapping project was to map now easily accessible inland areas of the western WLI. This new mapping would be intergrated with the previous shoreline mapping of Miller (1986) and Turnbull and Miller (2004) to create more complete and detailed geologic map of the western part of the WLI. This mapping would also serve as the anchor point for continued mapping of the WLI by Adam to the east. This area has no lake access and therefore could only be mapped by overland traverses. Adam completed much of the eastward mapping in the fall of 2012, and will return next summer to finalize the mapping. What will be presented at this poster presentation is the 1:24,000-scaled geological map created from the capstone mapping of a two square-mile area of the western end of the WLI (LaPietra et al., 2012). A pdf version of this and other Precambrian field camp capstone geologic maps can be downloaded from the PRC website: www.d.umn.edu/prc/fieldcamp/capstone.

The Wilder Lake intrusion (WLI) is a mafic layered intrusion emplaced within the anorthositic series, and is part of the layered series of the Duluth Complex (Miller et al., 2002). The few studies conducted on the WLI show it to be one of the most distinctive intrusions of the layered series by virtue of its northward dip, emplacement entirely within the anorthositic series, reversed cryptic variation, and unique cumulate stratigraphy (oxide before augite) (Miller and Ripley, 1997; Miller et al., 2002). The WLI was first recognized by reconnaissance mapping by Phinney (1972), who documented exposures of well-foliated and layered gabbros and troctolites that extend from North Wilder Lake to the west and Arrow Lake to the east; a strike-length of about 10 kilometers. Phinney noted that internal layering and foliation dips to the north-northeast between 15° and 35°, which contrasts with the southerly to easterly (riftward) dip of most layered intrusions of the Duluth Complex. Miller (1986) conducted reconnaissance mapping of the western extent of the WLI in the Wilder Lake area and term the body the Wilder Lake gabbro. Miller and Ripley (1997) reported olivine and augite data which define a reversed cryptic variation in mg# for both phases. Unpublished mapping and geochemical data from Joy Turnbull

acquired in 2002-04 verified the basic cumulate stratgraphy identified by Miller (1986) in the Wilder Lake area and the reversed cryptic variation defined by olivine and augite. Turnbull's mapping in the South Wilder Lake area (Turnbull and Miller, 2004) revealed a variation in the thickness of cumulate units and the occurrence of a lower olivine gabbro unit that is not evident in the western part of the intrusion mapped previously by Miller (1986).

2012 capstone mapping verified the basic cumulate stratigraphy of the approximately 1-2 km-thick intrusion previously describe by Miller (1986), but added considerably more detail and insight to the origin of that stratigraphy.. As noted previously by Turnbull and Miller, (2004), the basal contact of the WLI is a varitextured olivine gabbro to augite troctolite in sharp contact with coarse-grained anorthositic series rocks. This taxitic basal unit grades into a thick sequence of troctolitic (Pl+Ol) cumulates. The troctolite progress from a lower ophitic augite interval, which locally shows well developed modal layering, into a more homogeneous troctolite containing abundant anorthositic series inclusions. Overlying the troctolite unit is a thin (20-30m-thick) oxide troctolite unit defined by the abrupt cumulus arrival of Fe-Ti oxide. This unit is then overlain by a well foliated, four-phase olivine oxide gabbro cumulate (Pl+Cpx+Ox+Ol). Miller (1986) noted that the four-phase cumulate abruptly gives way back to a troctolite and puzzled as to the significance of this cumulus regression. He speculated that it could represent a recharge event, or perhaps crystallization of troctolite from the roof zone down to a sandwich horizon represented by the four-phase olivine oxide gabbro. Detailed mapping this past summer showed unequivocally that the upper troctolite is a latter intrusive pulse that actually cut down into the four phase gabbro and is locally in contact with the oxide troctolite unit. Another revelation from last summer's mapping is that the western contact of the WLI is not a fault as speculated by Miller (1986), but rather is an intrusive contact between the WLI and anorthositic series rock, wherein a taxitic margin is developed along the WLI.

Adam Leu's MS thesis will integrate this capstone map along with previous mapping by Phinney, Miller and Turnbull and new mapping of now well exposed areas in the eastern WLI in order to piece together a complete geological picture of this unique intrusion. This research aims to verify and evaluate the origin of some of its enigmatic petrologic features (early cumulus oxide arrival, reversed cryptic variation) by conducting detailed field mapping and sampling, petrographic analyses, mineral chemical analyses, and lithogeochemical analyses from a suite of samples collected along several profiles across the intrusion.

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Silica Remobilization in the Biwabik Iron Formation, Minnesota USA

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Excess silica in magnetite separated from iron formation in the Mesabi Range of northern Minnesota can diminish the quality of taconite pellets made there. Normally, silica comprises less than 5 wt% of magnetic concentrate, a desirable level, but it can exceed 10% in some instances. The source and nature of this silica has been enigmatic; it has been noted in and near oxidized zones and in particular stratigraphic units in the mined iron formation, but it has proven difficult to characterize in terms of its nature and distribution. To better understand silica behavior in magnetite ore, we applied petrographic, SEM, fluid inclusion, and bulk geochemical methods to samples collected from three mines, the Hibbing Taconite Mine, the Thunderbird Mine, and the Fayal Reserve Mine, to document the occurrence and origin of quartz that is likely included in magnetite in the separation process.

We found that silica-filled microfractures and pits typically form in coarse magnetite within faulted iron formation near both low-angle and high-angle faults, the latter being everywhere associated with oxidation. Silica reprecipitation accompanied early oxidation, in which magnetite was variably oxidized to hematite (martite) and iron silicates were oxidized to goethite and recrystallized quartz near high-angle faults. In unoxidized magnetite in and near low-angle (bedding-parallel) faults, diagenetic inclusions and microfractures host quartz. For both high- and low-angle faults, this microfracturing/silica remobilization event took place at diagenetic temperatures (150° – 200° C) and involved oxidizing, relatively high-salinity aqueous (late diagenetic) fluids. In contrast to quartz retention and recrystallization that is the hallmark of the early oxidation event, later supergene (lateritic) oxidation, the stage that produced the high-grade hematite/goethite 'natural ores,' extensively dissolved quartz.

In magnetite grains in iron formation near faults, silica-filled microfractures are typically less than 5 microns in width; silica-filled pits are commonly less than 40 microns across, many less than 20. Ore is typically ground to -325 mesh (-44 microns), significantly coarser than these quartz inclusions. Image analysis shows that these features can comprise up to 11% of the magnetite by volume, potentially accounting for much of the excess silica in concentrate.

The McGrath metasaprolite: viewing Paleoproterozoic weathering through a veil of metamorphism and metasomatism

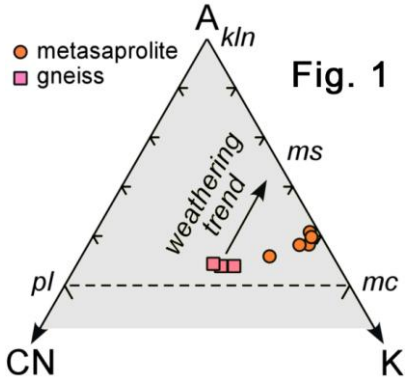
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Paleosols are important indicators of ancient weathering processes and climatic conditions. However, many Precambrian paleosols have been metamorphosed and metasomatized, thereby obscuring their pedogenic features and modifying their original chemical compositions. A metamorphosed saprolite occurs in eastern Minnesota in the Archean McGrath Gneiss beneath the Paleoproterozoic Denham Formation. A detailed investigation has been undertaken of this metasaprolite to distinguish the effects of weathering from those of subsequent metamorphism and metasomatism and to evaluate the depth, characteristics, and magnitude of weathering.

The McGrath Gneiss is granitic in composition, containing quartz, microcline, plagioclase, biotite, and muscovite. The upper ~400 cm of gneiss is devoid of plagioclase and rich in muscovite, consisting of quartz, microcline, muscovite, and minor biotite, and is interpreted to be a metasaprolite, from which plagioclase has been removed by weathering. The base of the Denham Formation is composed of metamorphosed siltstone, arkosic sandstone, and lenses of pebble conglomerate that contain abundant microcline grains and gneiss fragments derived from the underlying McGrath Gneiss.

The age of weathering is thought to be ~2100 Ma, as constrained by the age of the McGrath protolith (2557 ± 15 Ma; Holm *et al*., 2005), the youngest age of detrital zircon from the base of the Denham Formation (2072 ± 17 Ma; Wirth *et al*., 2006), and the age of volcanic rocks in the Denham Formation (2197 ± 39 Ma; Beck, 1988). Metamorphism in the area, which reaches staurolite grade, was largely a Yavapai event, based on geon 17 U-Pb and ^{207}Pb-^{206}Pb ages of monazite and xenotime in the Little Falls Formation (Schneider *et al*., 2004; Holm *et al*., 2007), which overlies the Denham Formation.

In a plot of molar Al_2O_3– ($CaO+Na_2O$) –K_2O, a.k.a. A–CN–K, the compositions of metasaprolite deviate markedly from the trend expected for weathering of the McGrath Gneiss (Fig. 1). Such deviation is ascribed to K metasomatism, in which kaolinite formed by weathering has been transformed to muscovite by the introduction of K. Potassium metasomatism is a common phenomenon in paleosols and is exhibited by many Precambrian saprolites in the Lake Superior region (Medaris *et al*., 2012). Step heating of muscovite from the uppermost sample of metasaprolite (depth = 80 cm) yields a ^{40}Ar/^{39}Ar spectrum with a well-defined plateau at 1742 ± 3 Ma, which includes 88% of ^{39}Ar released. Thus, K metasomatism was probably associated with Yavapai-age metamorphism, although the ^{40}Ar/^{39}Ar result only places an upper limit on the age of muscovite growth, because metamorphism occurred at temperatures above the blocking temperature for Ar diffusion in muscovite.



Potassium metasomatism precludes use of the Chemical Index of Alteration as an indicator of the intensity of weathering in the McGrath metasaprolite. Instead, the Plagioclase Index of Alteration [molar $(Al_2O_3-K_2O)/(Al_2O_3+CaO+Na_2O+K2O)$], which is a measure of plagioclase removal, may be used and yields values increasing from 67.4 at a depth of 370 cm to 93.5 at 80 cm.

The % changes in selected oxides and elements with depth, relative to Al_2O_3 in the mean McGrath Gneiss, are illustrated in Fig. 2, in which the compositional trends

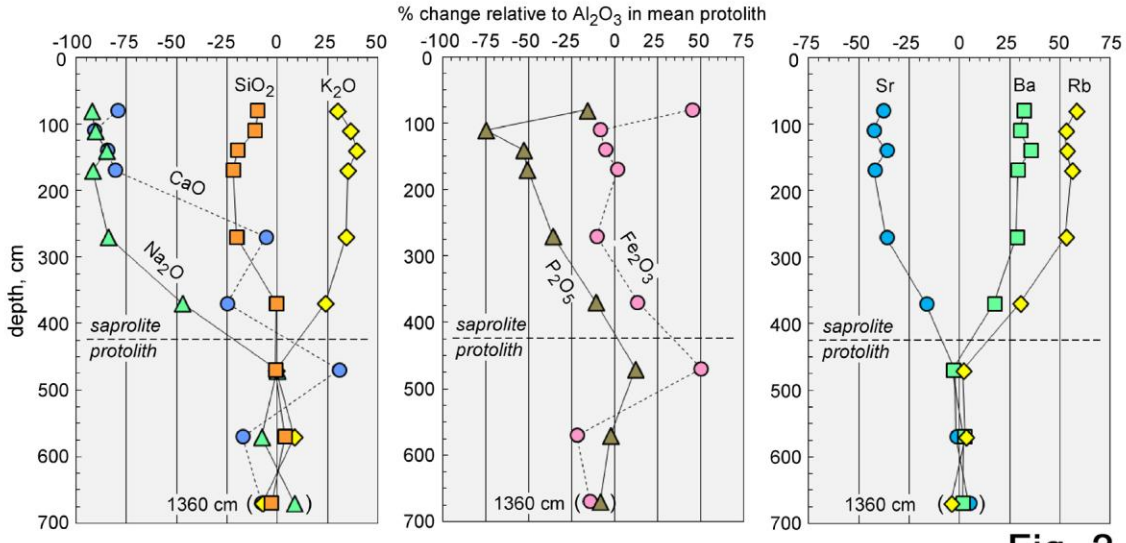


Fig. 2

reveal that weathering extended to a depth of ~400 cm. The removal of CaO, Na_2O, and Sr reflects the weathering of plagioclase, and the addition of K_2O, Ba, and Rb is attributed to post-weathering metasomatism. SiO_2 has been substantially removed over much of the weathering profile (10 to 20%), as has P_2O_5 (10 to 75%). The three protolith samples appear to be heterogeneous in their Fe_2O_3 contents, with little significant change in Fe_2O_3 in the weathering profile, except for the uppermost sample.

The magnitude of weathering of the McGrath metasaprolite, i.e. the mass removal of SiO_2, CaO, and Na_2O integrated over the depth of weathering, is 2.2 moles/cm^2. Assuming a duration of weathering of 100,000 years and following Sheldon's (2006) method, atmospheric pCO_2 was 5 times that of the pre-industrial level.

Although the McGrath metasaprolite represents an important episode of Paleoproterozoic weathering in the Lake Superior region, its degree of weathering was less than that of some other Paleoproterozoic paleosols. For example, the ~1700 Ma Baraboo paleosol has a larger magnitude of weathering, 4.3 *vs.* 2.2 moles/cm^2, greater depth of weathering, 7.9 *vs.* 4 meters, and complete removal of potassium feldspar in addition to plagioclase, perhaps reflecting a warmer and wetter climate for Baraboo.

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Chemical Zoning in Calc-Silicate Minerals Associated with Native Copper from the Keweenaw Peninsula, Michigan

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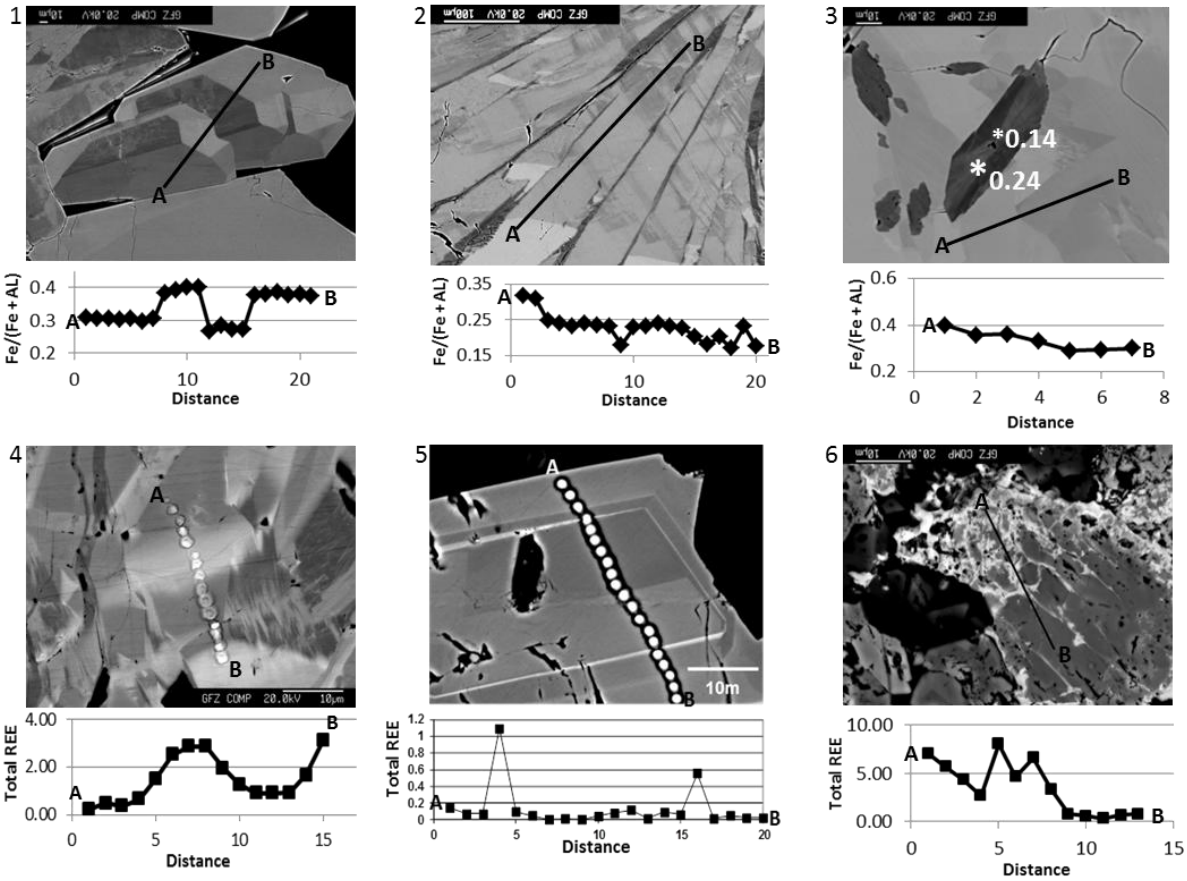
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Calc-silicate minerals occur in clusters in hydrothermally altered basalts and rhyolite-pebble conglomerates associated with native copper deposits in the Keweenaw Peninsula. We studied chemical zoning in these minerals hosted by basalts from the Kearsage, Isle Royale, and Caledonia Mines and by rhyolite-pebble conglomerates and sandstones. All basalt and some conglomerate samples came from the research rock collection of the A.E. Seaman Mineral Museum, Michigan Tech. Additional conglomerate samples came from personal collecting from rock piles at the base of Bumbletown Hill. Samples were examined with the Scanning Electron Microscope at Hope College. Quantitative mineral analyses were carried out using a JEOL JXA-8500F field emission electron microprobe (hyperprobe) at the Deutsches GeoForschungsZentrum, Potsdam (GFZ).

Calc-silicate masses in the basalt samples consist of pumpellyite, titanite, and epidote +/- prehnite. Veins of epidote cut pumpellyite, and pumpellyite occurs as inclusions in epidote, indicating that the formation of pumpellyite preceded the growth of epidote. Variations in brightness can be seen within epidote, prehnite and pumpellyite grains in SEM backscatter images (Figure 1, 2, and 3). Electron microprobe analyses indicate that the brighter regions are characterized by higher Fe/(Fe + Al) (*fe* ratio) (Figures 1, 2 and 3). In epidote these bright regions with relatively high *fe* ratios frequently exhibit regular geometric forms (Figure 1). Within these forms the *fe* ratio is relatively constant but decreases rapidly at the boundaries. Zones with regular geometric forms correspond to crystallographic faces (Figure 1) and areinterpreted as sector zoning in which the variation in *fe* ratios is due to the propensity of different crystal faces to incorporate different amounts of iron during mineral growth. However, some epidotes contain irregularly shaped bright patches and electron microprobe traverses across these patches show gradational changes in the *fe* ratio. This zoning may represent changes in the compositions of hydrothermal fluids during the growth of epidote. Zoning of rare earth elements (REE) in epidote was observed in samples from the Isle Royale mine where approximately rectangular patches are enriched in REE within larger epidote crystals (Figure 4). Hour glass zoning has been observed in pumpellyite grains (Figure 3) and this is also interpreted as sector zoning. Zoning in prehnite (Figure 2) is perpendicular to the elongated axes, and increases in the *fe* ratio may be a result of an increase in temperature, pH, the activity of Fe^{+3}, or the activity of Ca^{+2} in the fluid phase.

Calc-silicate clusters in conglomerates consist of epidote + titanite +/- andraditic garnet. Zoning was not detected in the garnet. The *fe* ratio zoning patterns in epidote hosted by conglomerate are very similar to patterns in epidote hosted by basalts. REE-zoning was found in epidote grains. Narrow zones enriched in REE outline crystal forms of epidote and are interpreted as a relatively brief increase in activities of REE elements during growth of the epidote (Figure 5). REE–enriched zones in epidote grains either at their margins or along fractures are interpreted as the replacement (by dissolution recrystallization) of ordinary epidote by REE-enriched epidote after the main period of hydrothermal epidote growth (Figure 6). This replacement could be due to a decrease in temperature, but could also be due to a decrease in the activities of F or Cl both of which form complexes with REE. The REE flurocarbonate synchysite was

found from the Allouez mine. REE minerals appear to be more abundant in the conglomerate host rocks than in basalt host rocks suggesting that the REE may have been remobilized from the rhyolite clasts.



Figures: Back-scatter-SEM images of calc-silicate minerals. The graphs below each image give either Fe/(Fe+Al) (*fe* ratios) or total REE concentrations (in wt%) across the traverse (A-B) marked in the image.

Figure 1: Fe-Al sector zoning in epidote grains from the Kearsage mine.

Figure 2: Fe-Al zoning parallel to growth direction in prehnite from the Kearsage mine.

Figure 3: Fe-Al zoning in an epidote grain containing a pumpellyite inclusion with hourglass sector zoning from the Kearsage mine. The *fe* ratios of the two analyzed spots on the pumpellyite grain are given in white lettering directly on the image.

Figure 4: REE-zoning in epidote from the Isle Royale mine.

Figure 5: Epidote from a conglomerate showing narrow growth zones enriched in REE (bright lines). The broader zones (lighter to darker gray) with sharp rectilinear boundaries reflect variations in the *fe* ratios.

Figure 6: Epidote grain from a conglomerate showing REE-enriched, BSE-bright veins following fractures.

Contrasting pressure-temperature-time paths for high-grade metamorphic rocks in the interior of the Penokean-Yavapai orogenic belt, southern Lake Superior region

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Amphibolite-facies metamorphic rocks occur in a narrow band in the internal part of the Paleoproterozoic orogenic belt south of Lake Superior in Michigan, Wisconsin and Minnesota. Peak metamorphic temperatures were once thought to have been reached during Penokean tectonism (ca. 1830-1850 Ma), but recent monazite and $^{40}Ar/^{39}Ar$ dating has shown that these relatively high-grade rocks have a more complex thermal history that spans both the Penokean and Yavapai (ca. 1760-1740 Ma) events (Holm et al., 2007). Furthermore, the timing and causes of the thermal maxima appear to be different in different parts of this tectonic zone.

The 'metamorphic nodes' in the Upper Peninsula of Michigan, such as the one near Republic, are classic examples of Barrovian metamorphism, with peak temperatures of 550-615°C and pressures of 0.2-0.3 GPa (Attoh & Klasner, 1989). The current consensus is that the nodes record post-Penokean development of gneiss domes and juxtaposition, via normal-sense shear zones, of sedimentary rocks against hot, remobilized Archean basement (Tinkham & Marshak, 2004). Gravitational instability may have been enhanced by tectonically thickened piles of dense iron formation. Monazite ages from the highest-grade rocks at Republic suggest that the thermal maximum occurred in Yavapai time at 1758-1768 Ma (Holm *et al*., 2007), consistent with petrographic observations that porphyroblasts overprint Penokean foliations. The full P-T-t path for these rocks would be clockwise, with Penokean burial preceding Yavapai heating.

In east central Minnesota, rocks of the Denham Formation experienced comparable peak temperatures (520-590°C) but higher peak pressures (0.5-0.6 GPa) (Holm & Selverstone, 1990). Petrographic analyses point to one main period of porphyroblast growth, but monazite and zircon dates indicate distinct thermal pulses at ca. 1830, 1800, and 1780 Ma, with the third pulse apparently related to a combination of Yavapai doming and emplacement of the East-Central Minnesota batholith (Holm *et al*., 2007; Boerboom, 2010). The P-T-t path for these rocks is thus more complex than for the Republic node, but still consistent with an overall clockwise trend.

The relatively high-pressure kyanite-bearing rocks of the Watersmeet Terrane in northern Wisconsin seem to have a significantly different metamorphic history from those in Michigan and Minnesota. In samples of schist taken near Powell, Wisconsin, the primary minerals are biotite, quartz, albitic feldspar, garnet, kyanite and rare staurolite. The rather coarse (2-3 mm) biotite grains define a crude planar fabric, with garnet, feldspar, and staurolite occurring in biotite-poor domains. Muscovite is notably absent, and quartz is less abundant than feldspar. The few staurolite crystals in the samples tend to be fragmented, and the feldspars typically have serrate grain boundaries, suggesting they have undergone partial recrystallization following ductile deformation. The garnets are relatively small (ca. 1 mm) and contain abundant inclusions, though not well-defined inclusion trails, of quartz, biotite, and in at least one case, staurolite. The kyanite crystals are as long as 4 cm and show a weak alignment. Most significantly, kyanite grains contain inclusions of quartz, biotite, feldspar and garnet and clearly overprint the planar fabric.

Based on these textural relationships, we infer that staurolite and feldspar grew early in the metamorphic history, followed by garnet and finally kyanite. Biotite was likely an early phase that continued to grow over time as the later minerals formed. Most of the deformation occurred prior to the formation of both the garnet and especially the kyanite.

Garnet-biotite geothermometry on rocks from the Powell area by Geiger and Guidotti (1989) placed T_{max} in the range 630-680° C. Using the garnet-plagioclase-Al_2SiO_5-quartz barometer and the coexistence of sillimanite and kyanite in some specimens, they estimated P_{max} at 0.75 GPa. Monazite dates from the Watersmeet terrane samples record two major thermal events at 1830 Ma and 1765 Ma (Holm *et al*., 2007). The fact that kyanite clearly postdates all the other metamorphic phases seems to preclude a clockwise P-T-t path for the rocks of the Watersmeet terrane. Unless

nucleation and growth of kyanite had for some reason been kinetically suppressed earlier in the rocks' history, the textural relationships require that at least one of the thermal maxima preceded the eventual pressure maximum. In addition, the combined geochronologic and textural constraints indicate that the pressure maximum post-dates Penokean time. These observations must be incorporated into orogenic models for the Penokean and Yavapai events.

Schneider *et al*. (2004) proposed that orogenic 'channel flow' in Yavapai time could account for the exhumation of the high-pressure rocks of the Watersmeet terrane. They depict the channel as bounded by a south-dipping normal fault at the southern boundary of the terrane and a south-dipping reverse fault at the northern boundary. Crustal thickening in Yavapai time could account for the late high-pressure metamorphism recorded by the petrographic relationships, but the kyanite-bearing rocks would initially have had to be in the footwall beneath the channel to experience elevated pressures, then subsequently incorporated into the channel, perhaps by northward migration of the lower channel boundary.

Ductile extrusion of the Watersmeet terrane is predicted by the channel flow model, but the rocks from the Powell area show little evidence of deformation after the formation of the kyanite. However, deformation in channel flow is more concentrated at the boundaries, and it could be that the available outcrops represent the central part of the channel. The channel flow model for northern Wisconsin is also an imperfect match with the geometry of the ductile channel in the modern Himalaya, where the phenomenon was first recognized. In the Himalaya, the channel boundaries (Main Central Thrust, South Tibetan Detachment; Beaumont, *et al*. 2001) dip in the same direction as the subduction zone, while in the Watersmeet terrane, the proposed boundaries dip south while Yavapai subduction is thought to have been north-directed.

Another requirement of the channel flow model is rapid erosion of the extruded rock mass. One interesting implication of the model could be the interpretation of the Baraboo Quartzite as the distal part of a clastic wedge formed by intense erosion of the Yavapai orogen. This is consistent with the ages of detrital zircons from the Baraboo and correlative quartzites (1782-1712 Ma) and with evidence that these units were deposited in a warm, humid climate (Medaris *et al*., 2003).

Whether or not the channel flow model is appropriate for the Watersmeet terrane, there remains the question of why the P-T-t path for metamorphic rocks in northern Wisconsin differs so markedly from those in Michigan and Minnesota. Differences in the plate boundary configuration, location within the orogen, and nature of the Archean basement are among the factors that should be explored.

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Natural Groundwater Geochemistry in Bedrock of the Thunder Bay Area

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During 1978 and 1979, the Ontario Ministry of the Environment (MOE) carried out a groundwater quality sampling program in the Thunder Bay area (McMullen, 1985). This program involved the collection of 354 groundwater samples from private drinking water wells completed in both overburden (153 samples) and bedrock (201 samples). The data were used in the production of two groundwater resource evaluation reports for the privately-serviced rural areas of the City (McMullen, 1985; Trow Hydrology Consultants, 1988). Some significant geochemical variations between hydrogeologic units were noted in each report. However, limited work was done to understand the reasons for these differences. The purpose of this study was to take a more detailed look at the MOE data set to gain a better understanding of how the geology of the major bedrock formations in the Thunder Bay area influences groundwater geochemistry.

The study area is located on the Canadian Shield, at the boundary between the Archean-age rocks of the Superior Province, and the Proterozoic-age rocks of the Southern Province. The northern half of the study area is underlain by Neoarchean-age metavolcanic, metasedimentary, and intrusive rocks (Brown, 1995), while the southern half is underlain by the flat-lying and relatively un-deformed Paleoproterozoic-age Animike Group sedimentary rocks of the Gunflint and Rove formations (Sutcliffe, 1991). These sedimentary rocks are intruded by Mesoproterozoic Logan diabase sills and dikes associated with the Midcontinent Rift (Sutcliffe, 1991).

For the purposes of this study, the Archean-age rocks, Gunflint Formation, Rove Formation and diabase are considered to be four distinct hydrogeologic units. Although the Archean-age rocks include a diverse range of lithologies, they are grouped together because they are all sparsely-fractured crystalline rocks with similar water-transmitting characteristics (McMullen, 1985).

This study focussed on data from the 201 bedrock wells that were sampled by MOE in 1978-79. Each well was classified according to the 1:250 000 scale bedrock lithology mapped on the ground surface at that location (Ontario Geological Survey, 2011). The numbers of wells assigned to each hydrogeologic unit were as follows: 65 Archean; 81 Gunflint; 41 Rove; 3 Diabase. Eleven wells are in an area of deep overburden where the Gunflint/ Rove contact has not been defined and were classified as “Gunflint/Rove contact area” wells.

All of the groundwater samples were analyzed for the following list of geochemical parameters: hardness, pH, colour, turbidity, conductivity, bicarbonate, sulphate, chloride, Na, K, Ca, Mg, Fe and Mn. 17 samples were also tested for the following additional list of parameters: Cd, Co, Cu, Zn, Pb, Ni, Hg and As.

Data analysis for this study included the plotting of major ion data (Ca, Mg, Na, K, Cl, sulphate, bicarbonate) on Piper tri-linear diagrams, and the calculation of mean values and ranges for conductivity, hardness, chloride, sulphate, Fe and Mn. Both of these methods were used to evaluate the major ion geochemistry of each hydrogeologic unit, including variability and possible groundwater geochemical evolution trends. The results of this analysis showed that the Archean, Gunflint and Rove hydrogeologic units each have distinctive groundwater geochemical signatures that are attributable to differences in lithology. The data set for the diabase unit was too small to allow for any meaningful assessment of its groundwater geochemistry.

Groundwater sampled from drinking water wells drilled into the Archean crystalline rocks typically had the lowest levels of dissolved solids and the least geochemical variability. The water is also typically of the Ca + Mg bicarbonate-type. The combination of low dissolved solids content and Ca + Mg bicarbonate dominated geochemistry is indicative of recently-recharged groundwater that has had limited time to interact with aquifer solids. This is consistent with what would be expected for a data set collected from relatively shallow wells in low permeability, competent bedrock units such as these. Although the major ion geochemistry of the Archean crystalline rock groundwater was relatively consistent regardless of lithology, there were some differences noted for iron and manganese, with higher mean concentrations in wells sourced from metasedimentary rock (possibly related to the weathering of biotite).

Groundwater in the Gunflint Formation displays much more geochemical variability and has a much higher mean concentration of dissolved solids than in the Archean hydrogeologic unit. Although most groundwater in the Gunflint has a geochemical signature indicative of recent recharge, two important apparent geochemical evolution trends were noted. The dominant trend is from a Ca + Mg bicarbonate-type toward a Ca + Mg chloride-type groundwater. The second trend is toward a mixed cation chloride-type groundwater (i.e., higher relative proportion of Na). The second trend has a close spatial association with the argillite tuff horizon mapped by Moorhouse (1960), and is interpreted to be related to groundwater interaction with this stratigraphic unit. Because the Gunflint Formation is not known to contain evaporite minerals, the most likely source of chloride in this formation is connate brine that was trapped during diagenesis (Hem, 1985).

Rove Formation groundwater has the highest mean dissolved solids content, and also shows significant geochemical variability. Similar to the Gunflint, there are two apparent geochemical evolution trends in the Rove. However, these trends are distinct from those seen in the Gunflint. The dominant trend is from Ca + Mg bicarbonate-type toward Ca + Mg sulphate-type groundwater, with a second trend toward sodium bicarbonate-type. The dominant trend toward a sulphate-type geochemistry is likely to be due to the weathering of pyrite, which is locally present in Rove Formation shale (Sutcliffe, 1991). The second trend is accompanied by elevated pH and may be related to the weathering of albite (Kehew, 2001). This trend also shows a close spatial association with diabase sills and appears to be characteristic of groundwater in altered/ metamorphosed contact zones between the Rove Formation and diabase.

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North American Palladium's Lac des Iles mine: Evidence for high temperature deformation and possible control on Pd mineralization

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North American Palladium's Lac des Iles Mine is located in a mafic to ultramafic intrusive complex just north of the Wabigoon-Quetico subprovince boundary. The Mine Block intrusion, host to the economic palladium mineralization, preserves evidence of a complex history of high-temperature deformation suggesting that the intrusive complex is pre- or syntectonic, not post-tectonic as commonly presumed. If so, deformation may be significant to mineralization and provide insight on future targets for exploration. The potential link between heterogeneous deformation and palladium enrichment will be further investigated.

The Mine Block intrusion is elongate in a northeast-southwest direction, parallel to regional deformation and is composed of mainly gabbro-noritic rocks. Locations of investigation to date include the Baker zone, the North VT rim and the Sheriff zone. The Baker zone is the discovery outcrop of the property and is located near the centre of the intrusion as a topographic high. The North VT rim is located along the north edge of the intrusion and is characterized by variable grain size, and the Sheriff zone is an area of mineralization located to the south-east of the pit. In the Baker zone, northeast-striking mafic dikes are boudinaged and disaggregated, with narrow shear zones preserved along some of the boudin margins. In the Sherriff zone, felsic dikes and narrow ductile shear zones are mutually overprinting, indicating progressive brittle-ductile deformation. Economic Pd mineralization is commonly associated with chlorite-actinolite schist; some sulfide grains occur along cleavage planes in the metamorphic silicate minerals. The East Gabbro is mylonitized at the contact with the chlorite-actinolite schist and deformation decreases further from the contact.

Microstructural analysis provides further evidence for deformation in the Mine Block intrusion. In the Baker zone, plagioclase has deformation twins and with some grains showing subsequent deformation of these twins. Subgrains in plagioclase, and small strain-free grains along margins of larger strained grains, provide evidence of dislocation creep in plagioclase in the Baker zone, Sherrif zone, and North VT rim. In the Baker zone, some sulfide grains have been fractured and healed, indicating subsequent deformation after initial formation.

Effects of Preexisting Fractures on Groundwater Flow Today

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Crystalline rocks are not normally considered aquifers, but when joints and fractures are present, there is a very real chance for pathways to emerge as conduits for groundwater flow. Three bore holes were drilled in Pittsville, WI (Figure 1) within the Marshfield terrene. This area was the stage where orogeny and volcanism occurred when the Marshfield terrene collided with the Wausau terrene and Superior craton forming multiple episodes of deformation (Schulz and Cannon, 2007). Data from the boreholes was collected by Dr. David Hart, and was analyzed at University Wisconsin-Whitewater. The data includes orientations of five different surfaces, including (a), major and minor open joints or fractures, (b), partially open joints or fractures, (c), filled fractures or joints, (d), bedding, banding, or foliation planes, and (e), induced fractures. We investigated orientations of regional stress directions based on the fracture orientation data using T-Tecto software (Figure 2). We combined stereographic projection analyses and borehole gamma logs to investigate how the orientations of different types of fractures might have changed with depth, mainly focusing on the orientations of open and filled fractures as those might provide the best insights within past and present fluid flow patterns. We have determined the locations where the fractures might intersect with each other below surface by using apparent dip data of the fracture planes on vertical planes through any two of the three studied boreholes (Figures 3 and 4). Eventually we aim to create a three-dimensional model of the fracture network using three-dimensional visualization tools within the ArcScene® software package. Preliminary data shows that dominant fracture orientation patterns change with depth in each of the three bore holes, and the fracture orientation patterns in each of the three boreholes have little or no similarity with each other (Figure 5). Some of the fractures show evidence of past fluid flow in the form of filled veins. Since some of the fractures are not filled, this might indicate multiple episodes of fracture formation which would be consistent with the tectonic history of the area. This is also indicated by the T-Tecto plots, which show multiple stress directions (Figure 2). Also two dimensional models of fracture plane intersections have shown possible intersection points among different fracture types that may be conduits for groundwater flow. Here we will present our data, and discuss the potential implications of our analyses on understanding past and present groundwater flow in the studied region.

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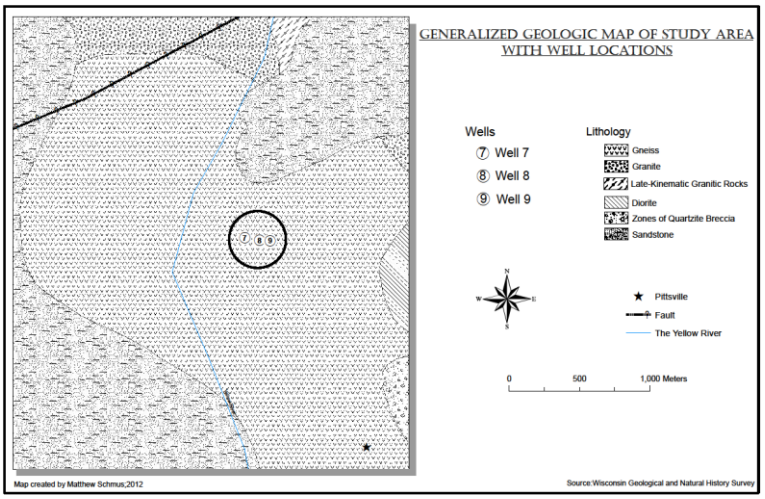


Figure 1: Map of Study Area Pittsville Wisconsin

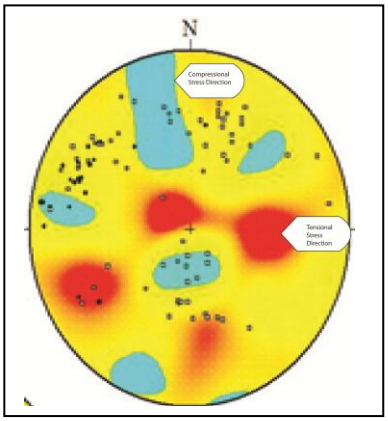


Figure 2: T Tecto Plot of all fractures in well 9

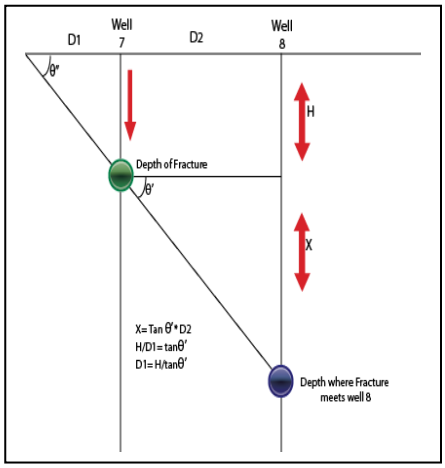


Figure 3: Calculations used to determine depth at which different fracture planes intersected the three boreholes

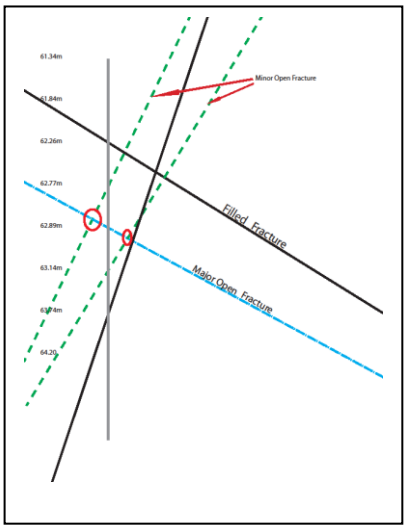


Figure 4: 2D graph showing possible fluid flow connection.

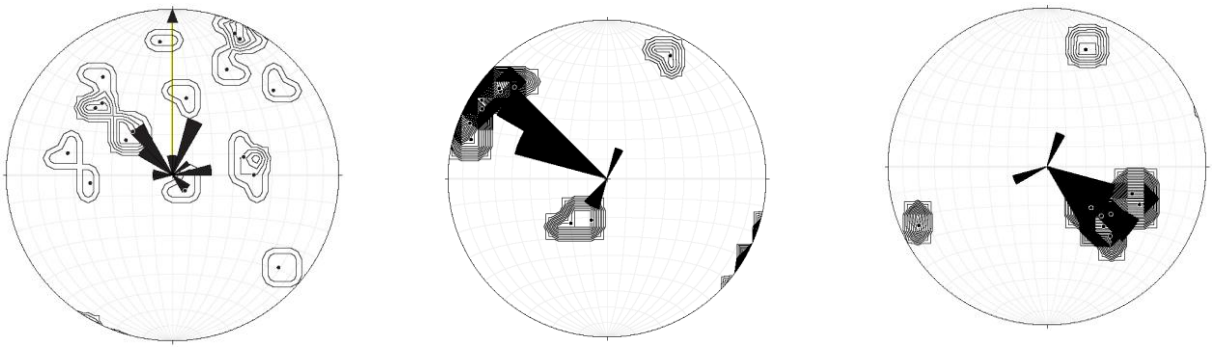


Figure 5: Stereographic Projections (left to right)Well 7 data filled fractures depth between 90-120 Well 8 data filled fractures depth between 80-110 Well 9 data filled fractures depth between 80-110

The Parent Lake Volcanics: Product of a phreatomagmatic eruption of basalt during deposition of the Michigamme Formation?

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An unusual mafic volcanic layer occurs within an otherwise monotonous sequence of turbidites of the Michigamme Formation in a set of outcrops about 40 km south of L'Anse (NW ¼ Sec. 9 and NE ¼ Sec. 8, T. 48 N., R. 33 W), at the extreme west end of the Marquette trough in Michigan's Upper Peninsula. The volcanic rocks are about 150 m thick and dip steeply (80-85 degrees) to the south. However, they are overturned and face north as indicated by both graded beds in adjacent graywacke and bedding-cleavage relations within the volcanic rocks. Typical Michigamme graywacke both underlies and overlies the mafic volcanic rocks, although the upper contact is intensely sheared and may not be a depositional contact.

The mafic volcanic rocks are divided into two units. The lower unit is a fine-grained, mafic pyroclastic rock having fragments of highly vesicular basalt typically less than a few centimeters in long dimension. It is massive to crudely layered and shows greenschist metamorphic assemblages, including a colorless amphibole, chlorite, and clinozoisite as the most common minerals; secondary carbonate is abundant. The upper unit is a coarse breccia containing fragments of both vesicular basalt and exotic fragments of crystalline rocks, presumably derived from the underlying Archean basement and older Paleoproterozoic sedimentary rocks. These fragments are as much as 1 m diameter and commonly are well rounded. Lithologies include a variety of granitic rocks and quartzose sedimentary rocks. The breccia is crudely bedded in meter-scale layers; the matrix is intensely sheared and contains abundant secondary carbonate.

A distinctive feature of some exotic fragments is a rind or shell of fine vesicular material that is more resistant to weathering than the matrix of the breccia (Fig. 1). These clasts look similar to cored bombs that formed during phreatomagmatic eruptions in some recent marr/diatreme complexes (Hanson and Elliot, 1996; Rosseel and others, 2006; Sottili and others, 2010). Cored bombs display a chilled shell of juvenile material, generally basalt, surrounding a lithic core, reflecting the thermal interaction of magma with fragments of wall rock in the vents of marr/diatreme complexes (Sottili and others, 2010). The highly vesicular, fragmental, and crudely bedded and graded nature of the Parent Lake mafic volcanic units, as well as the presence within them of angular to rounded clasts of basement rocks—some with the appearance of cored bombs—are all features compatible with formation by highly explosive basalt eruptions in a marr/diatreme complex (Hanson and Elliot, 1996). However, the location of the source vent for these deposits is unknown. Although not common, other largely fragmental mafic volcanic units are present in the Michigamme Formation, including the Clarksburg Volcanics to the east (Cannon, 1975) and unnamed mafic volcanics north of Iron River to the south (Cannon and Klasner, 1980).

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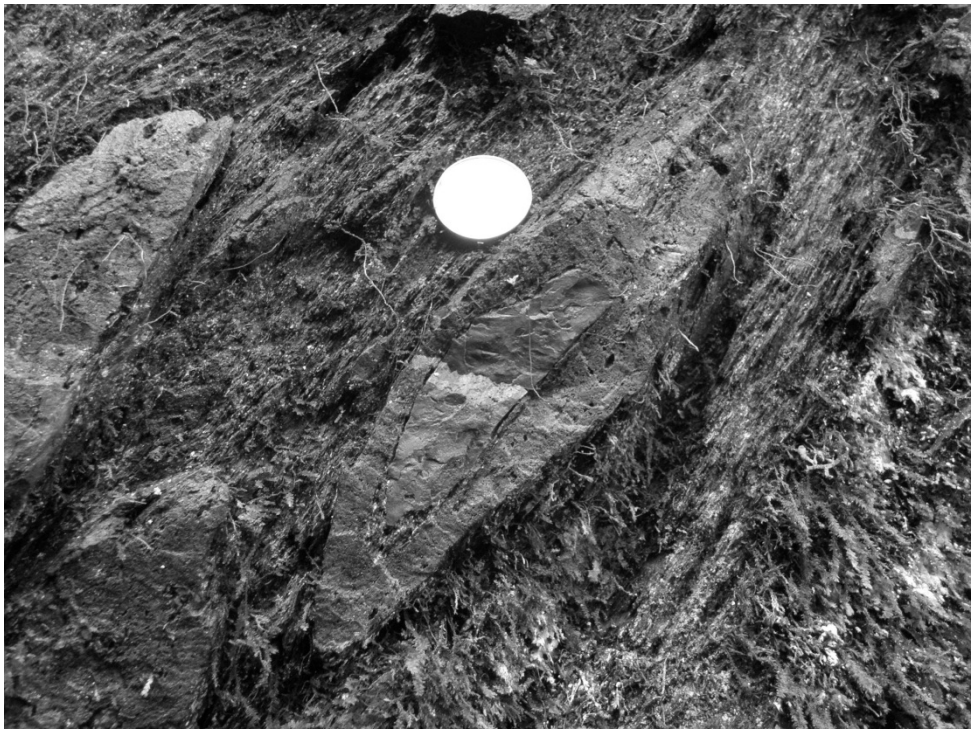


Figure 1. Chert clast with a rind of fine vesicular basalt in the upper unit of the Parent Lake volcanics. Quarter for scale.

Geochemical and petrographic study of a Mesoarchean felsic metavolcanic unit near Musselwhite Mine, North Caribou greenstone belt, northwestern Ontario

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The ~3 Ga North Caribou greenstone belt, North Caribou Terrane, Superior Province, comprises greenschist- to upper amphibolites-facies, ultramafic to felsic metavolcanic and metasedimentary rocks, intruded by 3000 to 2700 Ma felsic plutonic rocks. The study area is centered on a thin (~100m wide), north-trending, felsic metavolcanic unit on the western side of Opapimiskan Lake, 5 km northwest of Musselwhite Mine, in the South Rim Volcanic Unit (SRV). This rhyolitic unit has yielded a preliminary U-Pb age of 3053 Ma (McNicoll, unpublished data). The unit was mapped in detail over a distance of 2 km. Samples of the felsic rocks as well as the associated metabasalts and metapelites were collected. The metavolcanic and metasedimentary lithologies were classified by their petrography and whole rock geochemistry.

The metarhyolitic units are characterised by a mineral assemblage of quartz + plagioclase + K-feldspar with accessory muscovite + biotite + chlorite ± titanite ± clinozoisite ± zircon. Field observations identified some possible tuffaceous and pyroclastic felsic units as well as possible flows. The calculated anhydrous SiO_2 values for the felsic metavolcanic rocks in the SRV range from 75 to 81 wt%. These high-silica, calc-alkaline rhyolites have been classified as FII-type rhyolites (based on a classification by Lesher et al. [1986]). The unaltered felsic metavolcanic rocks are characterised by LREE-enrichment and ε_{Nd} values of -2.79 and -0.89 (Fig. 1).

The tholeiitic and calc-alkaline basaltic and komatiitic-basaltic units have been metamorphosed to amphibolites consisting of plagioclase and hornblende with accessory titanite + chlorite + opaques ± rutile ± biotite ± zircon. The komatiitic-basalt has an MgO value of 14 wt% (compared to the range of 3 to 9 wt% MgO for the basalts) and has higher Ni and Cr contents. The basalts can be subdivided into two groups based their REE contents (Fig. 2). The ε_{Nd} values are +0.78 and +0.58 for the flat REE basalts and -1.58, -1.61 and -3.35 for the LREE-enriched basalts.

The three outcrops of metasedimentary rock found in this area have been metamorphosed into schists and a quartzite. The protolith of the schists was likely pelitic sedimentary rocks based on the mineral assemblage of strongly foliated quartz + biotite + muscovite + chlorite ± garnet ± zircon ± clinozoisite. These schists are associated with the felsic metavolcanic rocks. The quartzite is similar to the felsic metavolcanic units but does not contain feldspars. Its mineral assemblage contains quartz + muscovite + biotite + garnet.

The rhyolites are calc-alkaline rocks with consistent LREE enrichment and negative Nb and Ti anomalies consistent with a suprasubduction zone environment. However, the negative ε_{Nd} values indicate that these rocks have been contaminated by older continental crust suggesting emplacement in a continental arc. The tholeiitic mafic volcanic rocks with the flat REE is consistent with an oceanic island plateau environment generated by a mantle plume (Hollings and Kerrich, 1999). The positive εNd values support this conclusion as a positive value implies that the melt was derived from a depleted mantle source.

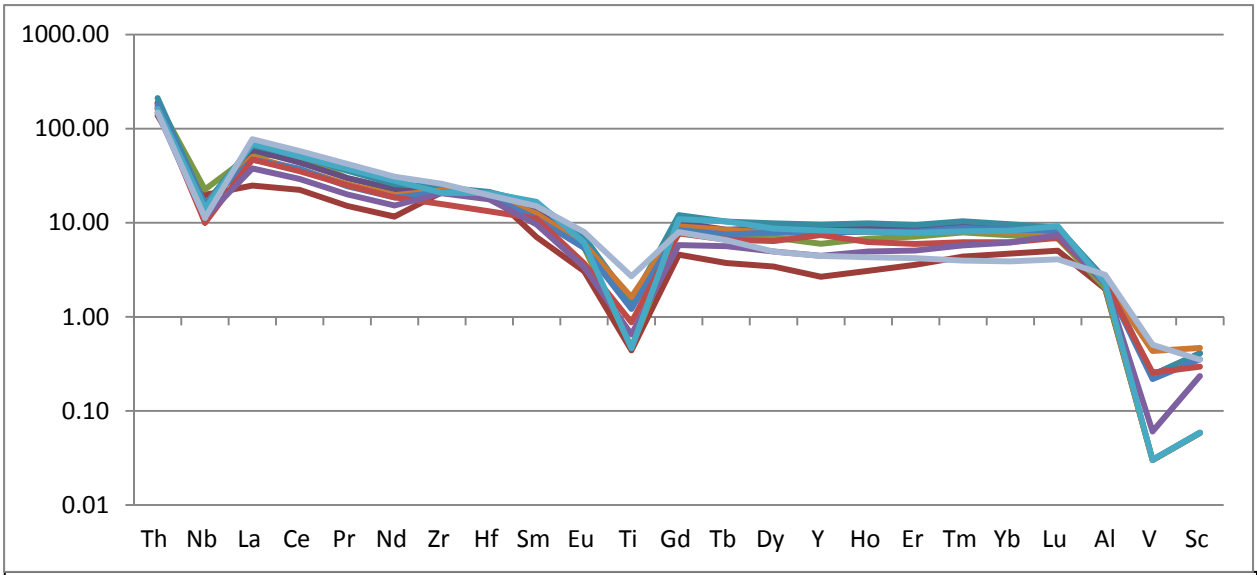


Figure 1: Trace elements of the felsic metavolcanic rocks plotted on a primitive mantle-normalized plot.

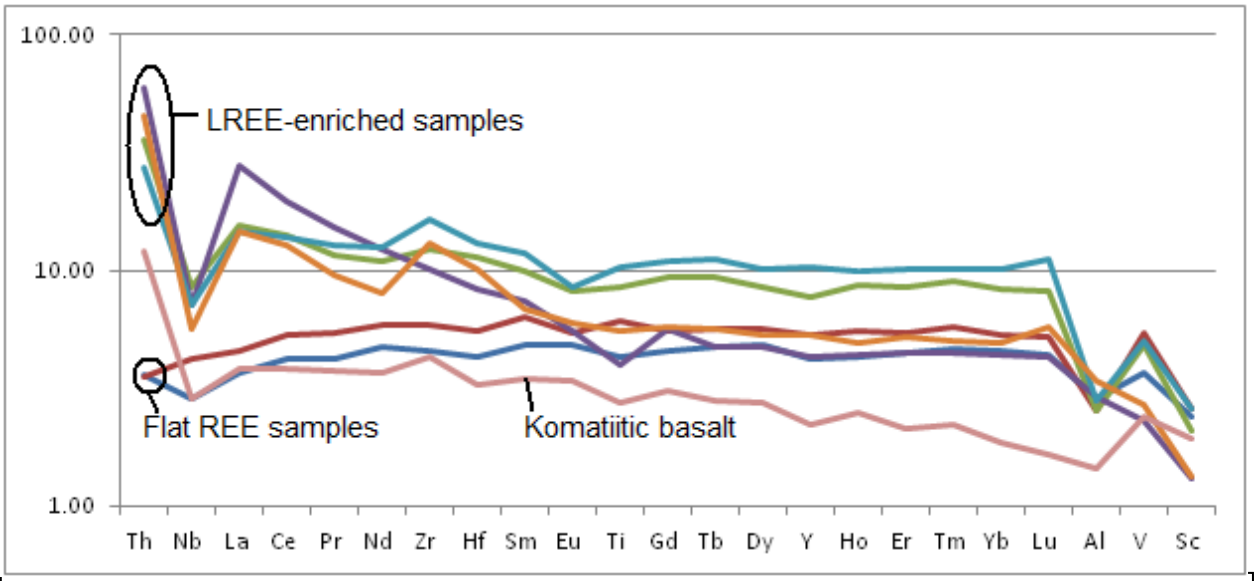


Figure 2: Trace elements of the mafic metavolcanic rocks plotted on a primitive mantle-normalized plot.

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Petrology, mineralization, and alteration of the Thunder mafic to ultramafic intrusion, Midcontinent Rift, Thunder Bay

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The northern Lake Superior region is host to a large segment of the North American Mesoproterozoic Midcontinent Rift (MCR). Since the discovery of high grade Ni-Cu-PGE mineralization hosted by mafic to ultramafic intrusions at the Current Lake deposit in Ontario, and the Eagle deposit in Minnesota, considerable exploration activity has been focused within the region. However, the small size of these buried deposits makes them difficult to locate both on the ground and on regional magnetic survey maps.

The Thunder prospect is a mineralized mafic to ultramafic intrusion located on the outskirts of the City of Thunder Bay with mineral claims currently held by Rio Tinto (formerly Kennecott Canada Exploration Inc.). The intrusive body has been interpreted to be associated with the early magmatic stages of the MCR based on geochemical similarities with rocks of the Nipigon Embayment (Hollings et al., 2007). However, unlike other mineralized MCR intrusions, the Thunder intrusion has relatively low Ni grades (< 0.08%) and a large range in PGE tenors (combined platinum-palladium values > 0.5 g/t; Bidwell and Marino, 2007). The Thunder intrusion is also the only mineralised MCR intrusion hosted within the Archean Shebandowan greenstone belt as others, including Current Lake, intrude the Mesoproterozoic Sibley Group and/or the Archean Quetico metasedimentary subprovince (Williams et al., 1991; Hart and McDonald, 2007). This MSc study will characterise the petrology, mineralization, and alteration footprint of the Thunder intrusion and place it within the context of the MCR as a whole, in order to identify criteria for vectoring towards mineralization.

The ~800m x ~800m Thunder intrusion consists of a mafic-ultramafic basal section that is overlain by a mafic sill-like body termed the “gabbroic cap”. The contact is xenolith-rich and lacks a well-developed chill margin. The mafic-ultramafic basal section of the intrusion consists of three transitional cumulate igneous phases: olivine websterite, olivine melagabbro, and olivine gabbro. Olivine websterite hosts up to 30% disseminated pyrrhotite, chalcopyrite, pyrite, rare bornite, and unknown platinum group minerals along its intrusive contact with significant drill intercepts including 20m at 0.22% Cu, 0.06% Ni, 0.25 g/t Pt, 0.29 g/t Pd, and 0.04 g/t Au (Bidwell and Marino, 2007). The Thunder gabbroic cap consists of three igneous phases: gabbro, pegmatitic gabbro, and leucogabbro all of which display a subophitic texture. The gabbro and leucograbbro are transitional and host up to 15% vein and

disseminated chalcopyrite, pyrite and rare bornite however, no significant mineralisation was intercepted (Bidwell and Marino, 2007). The pegmatitc gabbro occurs along the contact between the two intrusive components of the Thunder and locally cross-cuts the olivine websterite. This unit has been interpreted to be a late magmatic phase of the Thunder.

Marginal country rocks include metavolcanic and metasedimentary assemblages of the Shebandowan Greenstone Belt that have been structurally deformed and overprinted by regional greenschist facies metamorphism (Williams et al., 1991). The intrusive contact between the Thunder intrusion and the marginal country rock is sharp, xenolith-rich, lacks a well-developed chill margin, and contains blebs of granophyric material which suggests partial melting of the wall rock and/or wall rock assimilation. Within 100m of the Thunder intrusion a contact metamorphic aureole overprints the country rock consisting mostly of pervasive hornfels alteration. During Kennecott's 2005 drill program a drill hole located ~400m southeast of the Thunder intrusion intercepted a mineralized unit 58m down depth. This peculiar unit is 4m thick, runs 1.7 g/t Au and 0.53% Cu, and was initially interpreted to be a massive sulphide magnetite garnet skarn associated with the emplacement of the Thunder intrusion (Marino and Bidwell, 2007). However, recent findings and discussions have challenged classifying this mineralized unit as skarn alteration and it is currently being investigated.

Additional petrography, whole rock geochemistry, and SEM and S-isotopic analyses are currently being applied in order to further characterise the Thunder intrusion, mineralization and alteration assemblages both within the Thunder and the marginal country rock. In addition, this study will date the intrusion using U/Pb of zircon and/or baddeleyite.

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Glacial Lake Ontonagon and the Development of Large Scale Landslides

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A massive landslide occurred in 2005 along the East Branch of the Ontonagon River in northern Michigan adjacent to US-45 (Figure 1A). The landslide initially blocked the river causing it to redevelop a new flow channel. While other massive landslides occur along this section of the river, they tend to be infrequent with respect to the general form of mass wasting such as slope regression due to river under cutting and surface erosion. An investigation of the landslide indicated two very distinct soil units that appear to correspond to the two phases of glacial Lake Ontonagon (Figure 1B). The two soil units have a relatively distinct boundary as seen in Figure 1C. The lower unit consists of a red till, which forms the floor of the valley, grading upward into alluvial sand (Figure 1D), while the upper unit is a distinct lacustrine soil deposit (Figure 1E).

The massive landslide failure zone developed in the lower soil unit. It is unclear at this point as to whether the failure was due to softening of the lower red till or liquefaction induced failure caused by increased pore pressure development during the spring runoff in the alluvial sand. Due to the extensive development of soil liquefaction features (Figure 1F), however, it is believed that failure was induced via liquefaction in the transitional zone between the red till and the clean sand in the lower soil unit where the percent of fines in the sand prevent adequate drainage. Additional analysis of the soil's strength and dynamic properties are needed, however, to make a more definitive determination (Smith, 2012).

The origins of glacial Lake Ontonagon was first addressed by Leverette (1929) and later by Hack (1965), Farrand and Drexler (1985) and Attig, Clayton and Mickelson (1985). The formation Lake Ontonagon soils are believed to have developed in the post-Twocreekan time, around 11,800 Before Present (BP). The post-Twocreekan glacier advance completely filled the Lake Superior basin with two ice lobes that were split by the Keweenaw Peninsula. The Superior lobe reached the position of the Nickerson moraine southwest of Duluth, while the Lake Michigan-Green Bay lobe moved southward across the northern peninsula of Michigan, ultimately reaching the Two Rivers moraine at Manitowoc, Wisconsin, about 11,800 BP. Following the Two Creek advance, de-glaciation formed lakes and drainage channels in front of the glacier lobes in which glacial lakes Duluth and Ontonagon formed. Lake Ontonagon drained westward into Lake Ashland and eventually to the St. Croix River, which drained southward to the Mississippi River at about 11,000 BP. Between 11,000 and 10,700 BP the glacier retreated into the Lake Superior Basin forming a much larger Lake Duluth and eventually as the ice retreated and the glacial rebound occurred lowering Lake Duluth to form Lake Algonquin. It is believed that the lower soil unit formed during this period of time.

At about 10,000 BP, however, the last glacial re-advance, known as the Marquette Phase, advanced back into the Lake Superior Basin covering most of the northern portion of the Upper Peninsula. At about 9,900 BP the ice retreated again forming a series of lakes along the front of the ice sheet. Lake Ontonagon reformed at this time along with Lake's Ashland and Nemadjic. Eventually the lakes became confluent and drained westward to the St. Croix outlet. At that time the lake levels for Ashland and Nemadjic dropped about 20 feet. Lake Ontonagon, on the other hand, dropped about 200 feet, (Leverett, 1929) leaving much of its lake bed dry land surface. It is believed that the upper lacustrine soil unit formed during this period of time.

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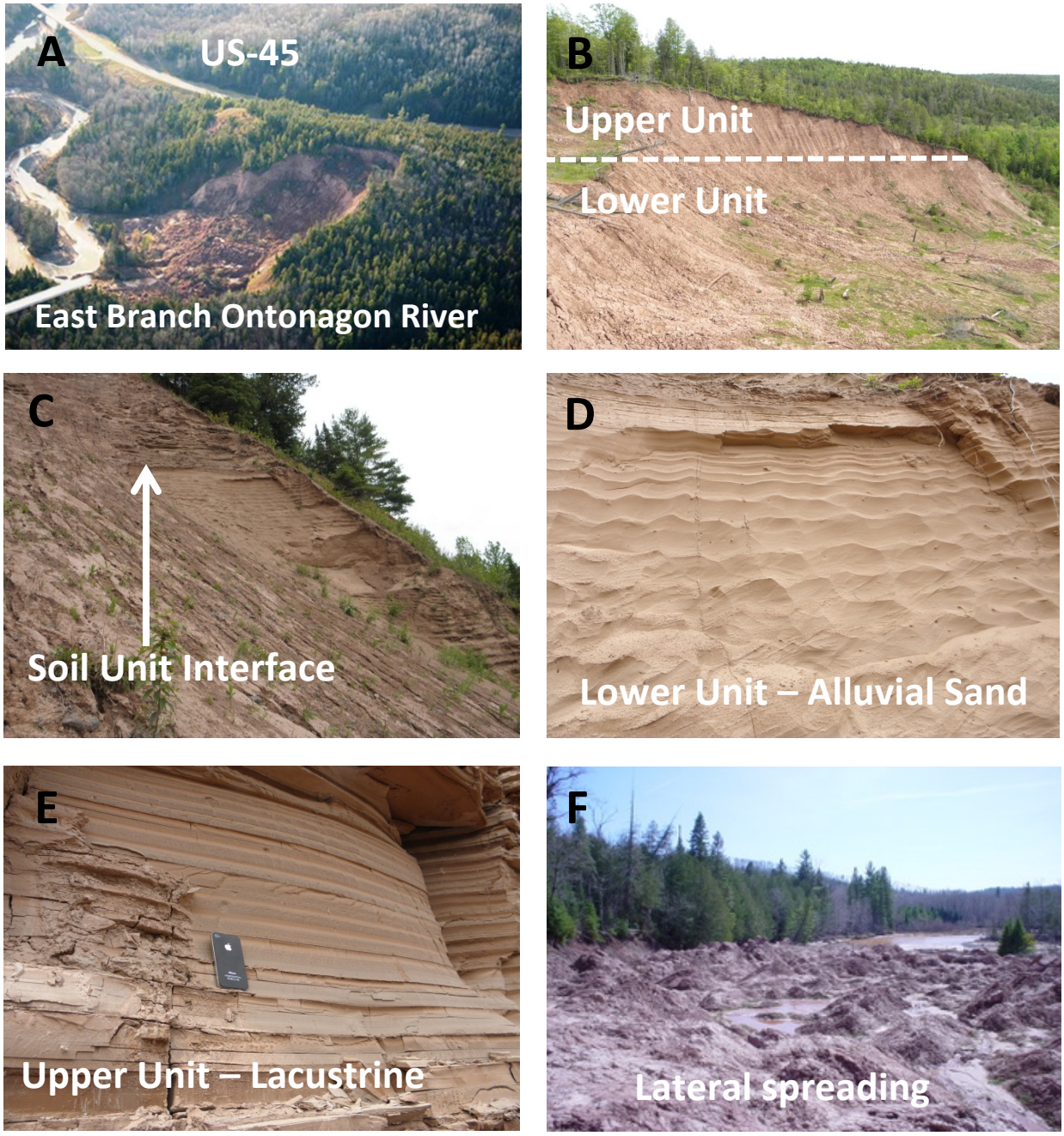


Figure 1. A) Large scale landslide adjacent US-45 on the East Branch of the Ontonagon River. B) Two soil units. C) Interface between soil units. D) Lower soil unit - alluvial sand. E) Upper soil unit – lacustrine soil unit. F) Liquefaction induces lateral spreading.

A PRELIMINARY SURVEY OF THE GEOLOGY OF THE PRE-MICHIGAN BASIN ROCKS OF THE SOUTHERN PENINSULA

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The Michigan Geological Repository for Research and Education (MGRRE) is the premier core repository for Michigan Basin sedimentary rock materials. The collection holds roughly half a million linear feet of core. Archived with the MGRRE collection are multiple wells with cores (9 total) and a larger number of wells with drill cuttings (35 total) from pre-Basin rocks (Fig. 1). The majority of wells identified with pre-Basin rocks are from southern and southeastern Lower Peninsula.

A handful of age dates are available from these wells, though most of the analyses for geochronological results were determined in the 1960s. Cuttings rich in biotite were age dated with both Rb-Sr and K-Ar from the McClure #2 State Beaver Island well and obtained ages of 1,040 and 1,090 Ma respectively (Lidiak et al. 1966). These dates suggest a relationship with the Mid Continent Rift System. The St. Blair 2-24 from Grand Traverse County was age dated with U-Pb from zircons from granite and yielded an age of 1,472 Ma (Hoppe et al. 1983). The St. Blair 2-24 well does have core though it is not archived with MGRRE. A series of wells from the southeastern Lower Peninsula were sampled for granite and granite-gneiss cuttings. These samples were dated with both the Rb-Sr and K-Ar systems and yield ages between 840 and 970 Ma (Lidiak et al. 1966, Summerson, 1962). Hinze et al. (1975) interpreted these rock units as being part of the Grenville province.

Initial investigation of the collection of available cores has shown a complex set of lithologies preserved in the basement of the Michigan Basin in Branch and St. Joseph counties. Four closely spaced wells alternate between porphyritic granite and biotite-rich gneisses. A deep stratigraphic test drilled in Gratiot Co. cored through fine-grained turbiditic sediments interpreted to being part of the Mid Continent Rift System (Fowler and Kuenzi, 1978). The southeastern Lower Peninsula (Arenac, Huron and St. Clair counties) wells with core exhibit a diverse assemblage of metasediments, granites, and granite gneisses.

Hinze et al. (1975) published a basement provinces map for the Lower Peninsula interpreted on the basis of limited well data, mostly from descriptions on driller's reports and the geochronological results published by Lidiak et al (1966) and Summerson (1962). The addition of more than twice as many wells into the Lower Peninsula basement rock data set provides the opportunity to update Hinze et al.'s (1975) province map and produce the first basement geologic map of Michigan's Lower Peninsula. To aid this effort, we are attempting to generate detailed lithological descriptions and a new geochronology of events.

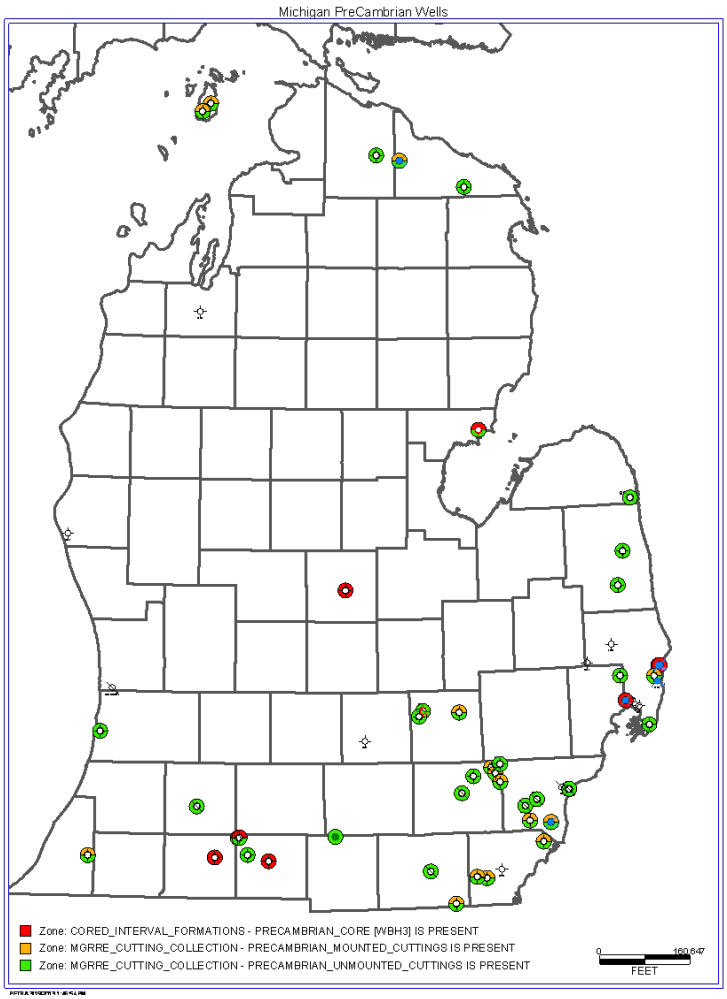


Figure 1. Distribution of wells in the Lower Peninsula of Michigan that drilled into the basement beneath the Michigan Basin.

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Sedimentology and Geochemistry of a Regressive Surface in the Chemical Sediments of the Paleoproterozoic Gunflint Formation

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The 1878 ±1Ma Gunflint Formation is a chemical-sedimentary unit deposited in the Animike Basin; it shows a sequence of transgressive-regressive cycles. Wolff (1917) and Broderick (1923) divided the Gunflint into several individual members; lower cherty, lower slaty, upper cherty and upper slaty. These members were then grouped into two different sequences; the upper and lower sequences. The first and most extensive transgressive- regressive cycle is made up of the lower cherty member, while overlying transgressive-regressive cycles are made up of the lower slaty member, the lower cherty member and the upper slaty member.

An outcrop present near Mink Mountain UTM: 329,520 E/5,338,163N, shows a complete section through the peak lower regressive-transgressive sequence. A detailed description of the section was logged through this sequence, which was divided into three main units; 1) a grainstone unit is the bottom unit and lies directly below 2) stromatolites which is capped off by a 3) oncolithic unit. The grainstone directly below the stromatolites is brecciated and shows injections of jasper and hematite throughout (Fig 1A). Microscopically the grainstone unit is composed of angular to rounded grains of chert. The cement is predominantly chert with some blocky quartz found forming at grain boundaries. The stromatolite unit is present above the pre-lithified grainstone unit and contains distinct stratiform and columnar stromatolites. The top unit is an oncolith-rich grainstone. The grains have a nucleus composed of either microquartz-rich chert or blocky quartz. The cement of the unit is composed of a combination of a chalcedony-rich chert and blocky quartz. Several samples were taken up through this section and sent to the OGS lab in Sudbury for ICP-MS analysis for rare earth elements. The results were normalized to Taylor and McLennan (1985) Post Archean Australian Shale values and plotted (Fig 2A,B). All the samples taken from the grainstone layer and three samples taken from the stromatolite show a characteristic europium anomaly and a distinct positive cerium anomaly. The Ce anomaly is indicative of an oxidized environment where Ce (IV) was being precipitated and scavenged by the sediments (Peters, 2003). This requires oxygen production in the near-shore, and precipitation of Ce from sea-water that had not been previously exposed to significant oxygen.

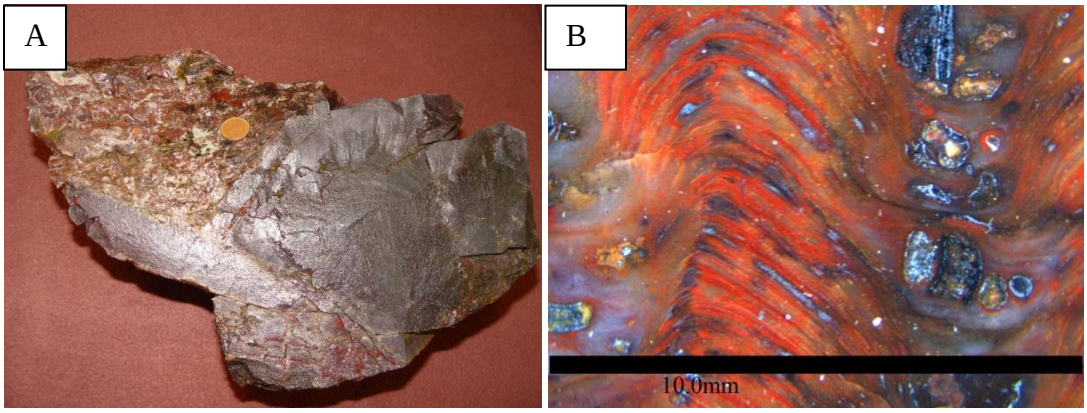


Figure 1. A) The lithified surface directly beneath the stromatolite section at Mink Mountain. B) A close up photograph of stromatolite lamiae and oncoliths in the depression between stromatolites from a polished hand sample.

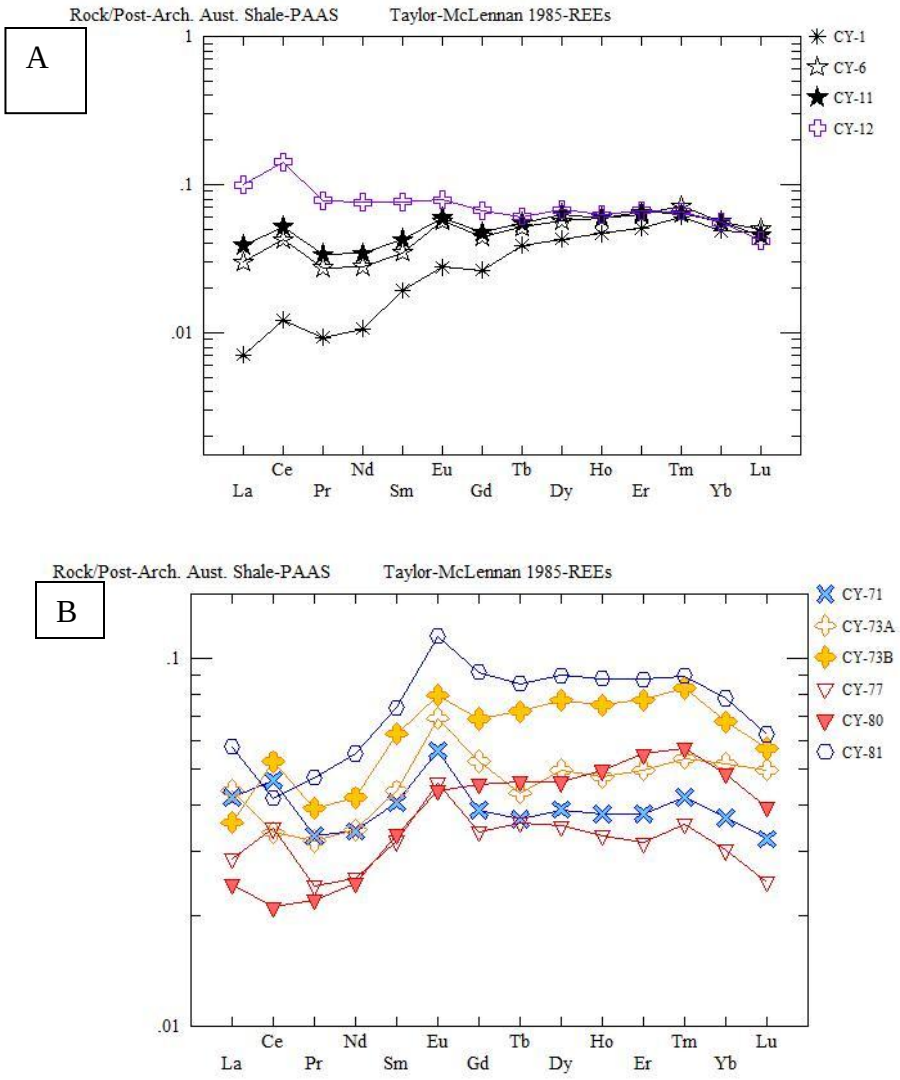


Figure 2. A) Rare earth element spider diagram for the grainstone unit at Mink Mountain. B) Rare earth element spider diagram for the stromatolites from Mink Mountain.

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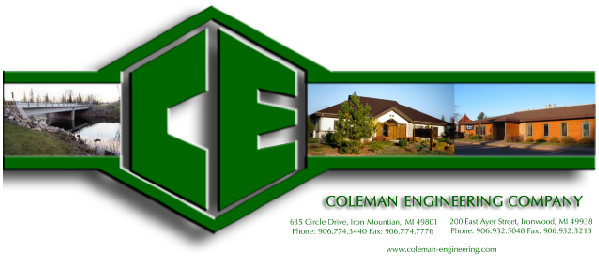
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