



INSTITUTE ON LAKE SUPERIOR GEOLOGY
Hibbing, Minnesota
May 14-17, 2014



ANNUAL MEETING

PROCEEDINGS VOLUME 60
PART 1 – PROGRAM AND ABSTRACTS



Institute on Lake Superior Geology

60TH ANNUAL MEETING
May 14-17, 2014
Hibbing, Minnesota

Sponsored by

PRECAMBRIAN RESEARCH CENTER, UNIVERSITY OF MINNESOTA DULUTH
and
MINNESOTA GEOLOGICAL SURVEY

James D. Miller and Mark A. Jirsa

Co-Chairs

Proceedings Volume 60

Part 1 – Program and Abstracts

Edited by Jim Miller, University of Minnesota Duluth

Cover Photo Credit

View of mines and the city of Hibbing looking south. Gray area in foreground is the footprint of Hibbing Taconite's mining; partially flooded, dark red areas in the mid-ground are remnants of historic natural (hematite) ore mines, including the Hull-Rust, Mahoning, Susquehanna, and Scranton; City of Hibbing in background, showing location of meeting hotel (oval). Modified from image provided by Dave Witt—Aero-Environmental Consulting, LLC, Cook, MN

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Field trip authors, date, title: Institute on Lake Superior Geology Proceedings v. 60, Part 1, p. XX.

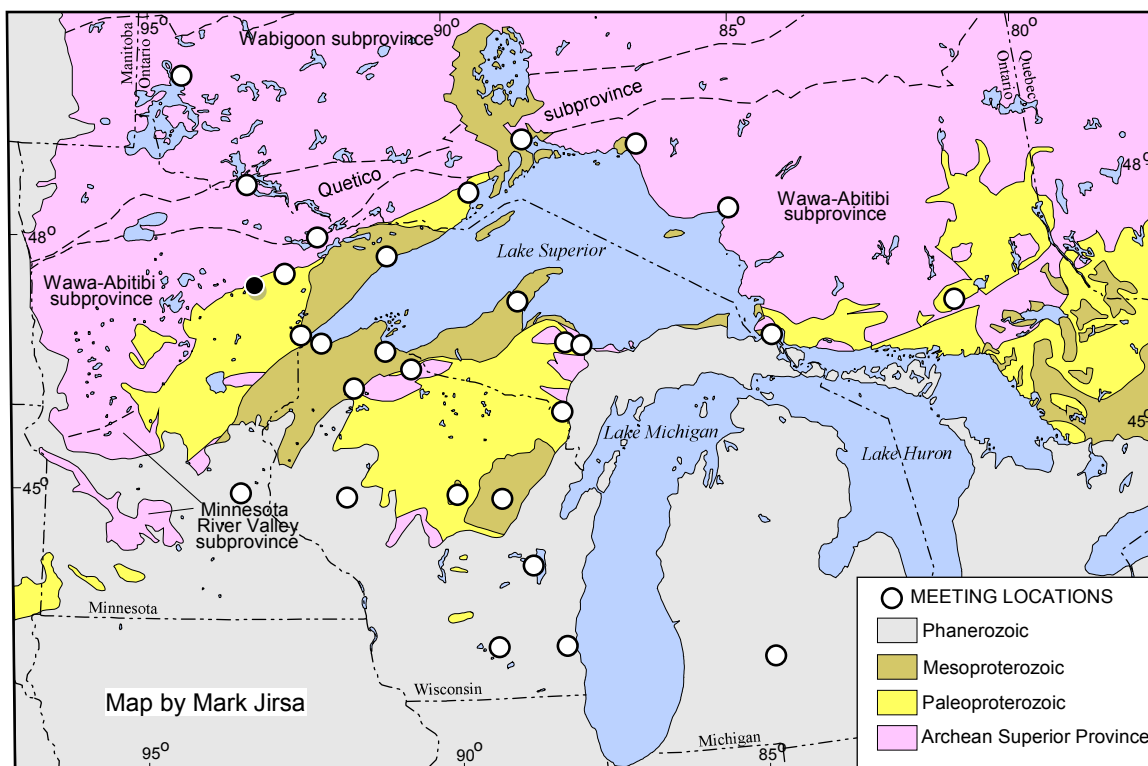
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Some figures in this volume were submitted by authors in color, but are printed grayscale to conserve printing costs. Full color imagery will appear in the digital version of the volume when it is available on-line at <http://www.lakesuperiorgeology.org>.

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Institutes on Lake Superior Geology, 1955-2014



#	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

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

<u>#</u>	<u>Date</u>	<u>Place</u>	<u>Chairs</u>
50	2004	Duluth, Minnesota	S. Hauck & M. Severson
51	2005	Nipigon, Ontario	M. Smyk & P. Hollings
52	2006	Sault Ste. Marie, Ontario	A. Wilson & R. Sage
53	2007	Lutsen, Minnesota	L. Woodruff & J. Miller
54	2008	Marquette, Michigan	T. Bornhorst & J. Klasner
55	2009	Ely, Minnesota	J. Miller, G. Hudak, & D. Peterson
56	2010	International Falls, Minnesota	M. Jirsa, P. Hollings, & T. Boerboom, P. Hinz & M.Smyk
57	2011	Ashland, Wisconsin	T. Fitz
58	2012	Thunder Bay, Ontario	P. Hollings
59	2013	Houghton, Michigan	T. Bornhorst & A. Blaske
60	2014	Hibbing, Minnesota	J. Miller & M. Jirsa

Sam Goldich and the Goldich Medal

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

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

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

Reference:

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

Prepared by various Goldich Medal Awardees, 2007



INSTITUTE ON LAKE SUPERIOR GEOLOGY GOLDICH MEDAL

Goldich Medal Guidelines

(Adopted by the Board of Directors, 1981; amended 1999)

Preamble

The Institute on Lake Superior Geology was born in 1955, as documented by the fact that the 27th annual meeting was held in 1981. The Institute's continuing objectives are to deal with those aspects of geology that are related geographically to Lake Superior; to encourage the discussion of subjects and sponsoring field trips that will bring together geologists from academia, government surveys, and industry; and to maintain an informal but highly effective mode of operation.

During the course of its existence, the membership of the Institute (that is, those geologists who indicate an interest in the objectives of the ILSG by attending) has become aware of the fact that certain of their colleagues have made particularly noteworthy and meritorious contributions to the understanding of Lake Superior geology and mineral deposits.

The first award was made by ILSG to Sam Goldich in 1979 for his many contributions to the geology of the region extending over about 50 years. Subsequent medallists and this year's recipient are listed in the table below.

Award Guidelines

- 1) The medal shall be awarded annually by the ILSG Board of Directors to a geologist whose name is associated with a substantial interest in, and contribution to, the geology of the Lake Superior region.
- 2) The Board of Directors shall appoint the Goldich Medal Committee. The initial appointment will be of three members, one to serve for three years, one for two years, and one for one year. The member with the briefest incumbency shall be chair of the Nominating Committee. After the first year, the Board of Directors shall appoint at each spring meeting one new member who will serve for three years. In his/her third year this member shall be the chair. The Committee membership should reflect the main fields of interest and geographic distribution of ILSG membership. The out-going, senior member of the Board of Directors shall act as liaison between the Board and the Committee for a period of one year.
- 3) By the end of November, the Goldich Medal Committee shall make its recommendation to the Chair of the Board of Directors, who will then inform the Board of the nominee.
- 4) The Board of Directors normally will accept the nominee of the Committee, inform the medallist, and have one medal engraved appropriately for presentation at the next meeting of the Institute.
- 5) It is recommended that the Institute set aside annually from whatever sources, such funds as will be required to support the continuing costs of this award.

Nominating Procedures

- 1) The deadline for nominations is November 1. Nominations shall be taken at any time by the Goldich Medal Committee. Committee members may themselves nominate candidates; however, Board members may not solicit for or support individual nominees.
- 2) Nominations must be in writing and supported by appropriate documentation such as letters of recommendation, lists of publications, curriculum vita's, and evidence of contributions to Lake Superior geology and to the Institute.
- 3) Nominations are not restricted to Institute attendees, but are open to anyone who has worked on and contributed to the understanding of Lake Superior geology.

Selection Guidelines

- 1) Nominees are to be evaluated on the basis of their contributions to Lake Superior geology (*sensu lato*) including:
 - a) importance of relevant publications;
 - b) promotion of discovery and utilization of natural resources;
 - c) contributions to understanding of the natural history and environment of the region;
 - d) generation of new ideas and concepts; and
 - e) contributions to the training and education of geoscientists and the public.
- 2) Nominees are to be evaluated on their contributions to the Institute as demonstrated by attendance at Institute meetings, presentation of talks and posters, and service on Institute boards, committees, and field trips.
- 3) The relative weights given to each of the foregoing criteria must remain flexible and at the discretion of the Committee members.
- 4) There are several points to be considered by the Goldich Medal Committee:
 - a) An attempt should be made to maintain a balance of medal recipients from each of the three estates—industry, academia, and government.
 - b) It must be noted that industry geoscientists are at a disadvantage in that much of their work is not published.
- 5) Lake Superior has two sides, one the U.S., and the other Canada. This is undoubtedly one of the Institute's great strengths and should be nurtured by equitable recognition of excellence in both countries.

Goldich Medalists

1979	Samuel S. Goldich	1997	Ronald P. Sage
1980	<i>not awarded</i>	1998	Zell Peterman
1981	Carl E. Dutton, Jr.	1999	Tsu-Ming Han
1982	Ralph W. Marsden	2000	John C. Green
1983	Burton Boyum	2001	John S. Klasner
1984	Richard W. Ojakangas	2002	Ernest K. Lehmann
1985	Paul K. Sims	2003	Klaus J. Schulz
1986	G.B. Morey	2004	Paul Weiblen
1987	Henry H. Halls	2005	Mark Smyk
1988	Walter S. White	2006	Michael G. Mudrey
1989	Jorma Kalliokoski	2007	Joseph Mancuso
1990	Kenneth C. Card	2008	Theodore J. Bornhorst
1991	William Hinze	2009	L. Gordon Medaris, Jr
1992	William F. Cannon	2010	William D. Addison & Gregory R. Brumpton
1993	Donald W. Davis	2011	Dean M. Rossell
1994	Cedric Iverson	2012	James D. Miller
1995	Gene La Berge	2013	Tom Waggoner
1996	David L. Southwick		

2014 GOLDICH MEDAL RECIPIENT

Laurel Woodruff

Goldich Medal Committee

Serving through the meeting year shown in parentheses.

Graham Wilson (2014)	Turnstone Consulting
Bernhardt Saini-Eidukat (2015)	North Dakota State University
Mark Smyk (2016)	Ontario Geological Survey

Citation for the Goldich Medal Award to **Laurel G. Woodruff**

It is my pleasure and honor to present the 2014 Goldich Medal to Laurel G. Woodruff. Laurel has been one of the most active and involved members of the Institute for more than 20 years. During that time she has chaired or co-chaired three annual meetings (47th, 49th, 53rd) and served corresponding terms on the board of directors. She was chair of the board of directors in 1995-1996, 2002-2003, and 2006-2007. She has served twice on the student paper award committee, and most recently, from 2010-2013, was a member of the Goldich Award committee, and chaired the committee in 2012-2013. In addition, she has been co-leader of three Institute fieldtrips and has made numerous technical presentations at Institute meetings. In case no one has yet noted, this is the first Goldich citation in which the pronoun “she” has been used.



Laurel in the Brooks Range, Alaska in 2007 during the Alaska Soil Geochemistry Transect.

Most of Laurel’s career, spanning more than thirty years, has been with the USGS mineral resources research program, with more than 25 of those years in the Lake Superior region. Prior to that Laurel received her formal education at University of Michigan (BS in Geology 1973), Michigan Technological University (MS in Geology 1977), and the University of Chicago (PhD in geology 1989). After completing her MS degree and beginning a PhD at Chicago, Laurel was hired to run the light stable isotope laboratory at the University of Wisconsin-Madison and she participated in a broad variety of stable isotope research. The highlight of this part of her career was research on modern seafloor hydrothermal deposits, which culminated in publication of her *Journal of Geophysical Research* paper on the stable isotope geochemistry of seafloor hydrothermal vent systems.

Laurel joined the USGS in 1983. Her initial assignment was establishing the light stable isotope laboratory in the Branch of Eastern Minerals Resources. When the laboratory became operational, she was responsible for light stable isotope analyses (S, O, and C) of rocks, ores, and mineral samples from a number of locations throughout the world in support of research on seafloor sulfide formation, and precious metal mineralization. In 1986-87 Laurel returned to the University of Chicago to complete her PhD and conducted her dissertation research on diabbases of the eastern U.S. Triassic basins as part of a large USGS project on the mineral potential of

those basins. Laurel's scientific contributions to the geology of the Lake Superior region began in the late 1980's when she became a member of a USGS project team studying the geology and mineral potential of the Midcontinent Rift in Michigan and Wisconsin. Laurel's contributions included: 1) field work to collect bedrock and mineral deposit samples, 2) preparation of geologic maps and reports, 3) stable isotope analyses to constrain metal sources and characterize regional alteration patterns, and 4) geochemical and 2-D thermal modeling to better understand the origin and distribution of copper mineralization in the rift

In the past decade, Laurel has become increasingly involved in environmental research and has been a leader in fostering the incorporation of geology and geochemistry into multidisciplinary studies of the behavior of elements of concern such as arsenic and mercury. Her studies of the effect of forest fires on the mercury content of soils in the Lake Superior region and the cycling of mercury in aquatic ecosystems, conducted in cooperation with colleagues in soil science, hydrogeochemistry, and aquatic biology have provided fundamental new understanding of the mercury cycle. Laurel also has been a key figure in establishing procedures for and conducting geochemical baseline studies from local to national scale. The recently completed soil geochemical survey of the conterminous U.S. has produced a new database and a national geochemical atlas based on 15,000 samples from about 5,000 sites across the country. Laurel was a key member of that project from the earliest planning phase, through pilot studies, and the full survey, to the current activities of producing interpretive research papers. Laurel also continues her research on the Precambrian geology and resources of the Lake Superior region and is the coordinator of a new USGS multidisciplinary project on metallogeny and mineral potential of the St. Croix horst in Wisconsin and Minnesota.

On a personal note, Laurel has been a great friend and colleague for more than 25 years as we have wended our way through a kaleidoscope of research from hard rocks, through glacial deposits, and soils, to lake-bottom muck; wanderings across Alaska, the "death marches" on Isle Royale, and hard days of canoeing and portaging through the Boundary Waters and Voyageurs Park. Many of the most vivid and pleasant (at least in hindsight) memories of my career are from those days. Our research has commonly been guided by Laurel's often expressed philosophy of "Let's do something even if it's wrong!" She's shown over and over through her proclivity for action and her eagerness to plunge into new work, that it is so much easier to make mid-course corrections of something in progress than it is to overcome the inertia of over planning, indecision, and inaction; an attribute that has been unfailingly valuable in so much of what she has done during her career. So, in recognition of her decades of accomplishments and of her dedication to the geology of the Lake Superior region and to the Institute on Lake Superior Geology it is my pleasure to present the 2014 Goldich Medal to Laurel.

Bill Cannon, Geologist Emeritus

U.S. Geological Survey

In Memoriam **Ernest K. Lehmann** **(1929-2013)**



On December 13, 2013, the Institute on Lake Superior Geology lost one of its industry giants with the passing Ernest (Ernie) K. Lehmann. Ernie was an exploration geologist whose lifelong work in the mining industry took him around the globe. He was awarded the ILSG's Goldich Medal in 2002 for his pioneering contributions to base and precious metal exploration in the Lake Superior region, especially in Minnesota and Wisconsin. He tirelessly contributed his time and talents to professional organizations such as SME and AIPG, mining advocacy groups such as Mining Minnesota, and minerals outreach programs such as the Minnesota Minerals Education Workshops. Ernie was admired by family, friends and colleagues for his honesty, integrity and perseverance and his ability to tell a tale. He was a quietly generous and caring man who will be greatly missed.

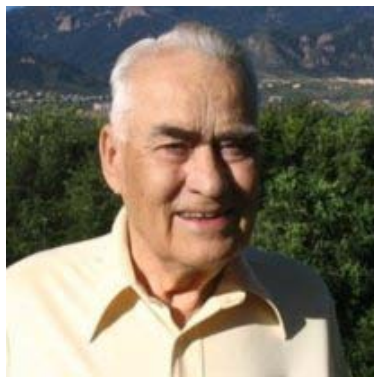
Ernie was born in Heidelberg, Germany and emigrated with his parents to the United States in 1935. He was educated in the public primary and secondary schools of New Rochelle, N.Y. and graduated from Williams College, Mass. in 1951 with highest honors in geology. In 1951-52, he did graduate study in geology at Brown University and in 1984 completed the Owners and Presidents Management Program at the Harvard Business School. His career in the mining industry began in 1950 when he worked as a miner and then geologist at a gold mine in Bannack, Montana and then joined Kennecott Copper's exploration subsidiary, where he was head of a team that discovered the south end of the "New Lead Belt" in Missouri in the 1950s. With the consulting firm he founded in 1958, he undertook a variety of successful exploration projects, including industrial limestone; gold in Montana, the Northwest Territories and Argentina and copper-nickel-platinum group metals in Minnesota. He managed a small fluorspar mine in southern France and undertook valuation of various mining projects in Africa, Indonesia, South and Central America and North America for IFC (International Finance Corporation), the World Bank, major mining companies and metal trading companies. He served as president of North Central Mineral Ventures (NCMV) since its incorporation in February 1986. NCMV has served as Manager of Vermillion Gold since December 2007.

Ernie served as a member of the Advisory Board to the Natural Resources Research Institute of the University of Minnesota and the MGS (Minnesota Geological Survey) State Mapping Advisory Committee. He served as a member of the Governor's Committee of Minnesota's Mining Future from 2004 to 2007 and as a member of the Minnesota Legislature's Mineral Coordinating Committee for over 10 years. He was an officer or director of several other private companies, including a Director of Silverthorn Exploration Inc. He was a charter and honorary member of the AIPG, of which he served as national President in 1985; a life member and fellow of the Society of Economic Geologists; a Legion of Honor member of the Society of Mining Engineers; and a member of several other professional and technical societies. Ernie was president of Mining Minnesota, a trade association representing Minnesota's non-ferrous and precious metals mining industry.

In Memoriam

Jack V. Everett

(1921-2013)



The ILSG lost another long-time supporter with the passing of Jack V. Everett, who slipped away peacefully on August 12, 2013 at his summer home on Ottertail Lake, MN. Jack will be most remembered for his sitting in the front row of ILSG meetings and snapping pictures of slide presentations. Jack lived in Duluth, MN for most of his professional career working as a consulting mining geologist.

Jack was born in Roseburg, Oregon, but spent most of his childhood in lower Michigan. He enrolled at Michigan State in the class of 1944 in wildlife management, conservation and zoology, but later chose to major in geology. World War II interrupted his studies and he enlisted on June 6, 1942 in ROTC in field artillery with basic training at Fort Bragg, NC, and was called for active duty on April 16, 1943. He married Eleanor Brown Everett, class of '44, from Onaway, Michigan at that time. The Army needed infantry officers and on May 6, 1944 sent his entire class to be retained as infantry officers at Fort Benning, GA. On July 18, 1944 he was assigned as a cadre training officer at Fort Meade, MD. After the Japanese surrendered, on September 3, 1945 he received orders to be transferred to Japan and was assigned to serve in the occupation forces of the 77th Division in Hakodate on the northern island of Hokkaido. He was discharged out of the service on September 5, 1946. He went back to MSU and graduated in 1947 with a B.S. degree, cum laude, in Geology. Honors included Phi Kappa Phi for scholastic, Sigma Gamma Epsilon for geologic, and Tau Sigma for scientific. Jack later served in various U. S. Army Reserve and Minnesota National Guard units in Brainerd and Duluth, and retired as a Major in June of 1972.

Jack's professional career started when he was hired as a District Geologist for Pickands Mather & Co. on the Minnesota Cuyuna Iron Range where he discovered four iron – manganese deposits near Emily, MN. These deposits are currently being developed for their manganese ore potential. In 1951 he took a position with W.S. Moore Company as Chief Geologist & Exploration Manager and moved to Duluth, MN. During the 50s and 60s he conducted exploration programs for iron ore deposits in various locations across the United States and Canada, and also Parana, Brazil.

In the 1960s he conducted major prospecting programs in unmapped areas of the Northwest Territories exploring for gold deposits from Yellowknife to the Arctic coast and was quoted as saying that for 20 years, he spent 50% of his life living in tents. He also conducted exploration programs in Northern MN and discovered one major copper nickel deposit. Jack started a career as a Certified Professional Geologist in 1971 and worked for more than 100 US and Canadian mining companies as an independent consulting geologist. He conducted exploration programs for copper and gold deposits in Wisconsin. Jack was an avid hunter and fisherman. Although he supported mining, he was a conservationist and supported preservation of unique natural resources and was on the Governor Elmer L. Andersen committee as a consulting geologist and first chair of the Duluth Chapter of the Citizens Committee for the establishment of Voyageurs National Park. In the 1980s he explored and developed placer gold deposits in Alaska. In later years he worked on a variety of geology, geotechnical and hydrology projects, including the tunnel projects on the North Shore of Lake Superior for the MnDOT. In 1995 he became Vice President-Exploration & Director of Leadville Mining and Milling Corp. where he was involved with the development, geology and exploration of their underground gold mine near Leadville, CO. More recently he worked on the geology and development of El Chanate Gold Project in Sonora, Mexico as a Director for Capital Gold Corporation. And most recently he has been working on the geology and development of Lake Victoria Gold deposit in Tanzania, Africa. He always joked that he planned to retire soon.

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 2013, the ILSG Board of Governors awarded three \$500 awards from the Student Research Fund. The winners were:

Michael Doyle

University of Minnesota-Duluth, Department of Geological Sciences

Current degree program: MS Candidate (Advisor: Jim Miller)

Geologic and Geochemical Attributes of the Beaver River Diabase and Greenstone Flow: Testing a Possible Intrusive-Volcanic Correlation in the 1.1 Ga Midcontinent Rift

Sarah Sauer

University of Minnesota-Duluth, Department of Geological Sciences

Current degree program: MS Candidate (Advisor: Jim Miller)

The Petrology of the DLS "Chill" – Evidence of Venting of Hydrous Magma from the Layered Series at Duluth?

Nicholas Fedorchuk

University of Wisconsin-Milwaukee, Department of Geosciences

Current degree program: MS Candidate (Advisor: John Isbell)

Biogenicity of Mesoproterozoic Lacustrine Stromatolites from the Copper Harbor Conglomerate

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

Andrew Ware – PolyMet Mining

Prajukti Bhattacharyya – University of Wisconsin-Whitewater

Robert Cundari – Ontario Geological Survey

Board of Directors

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

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

Allan Blaske (2013-2016) – AECOM

Peter Hinz (2012-2015) – Ontario Geological Survey

Tom Fitz (2011-2014) – Northland College

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

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

Local Committee

Chairs

Jim Miller – Program Chair

Department of Geological Sciences and Precambrian Research Center
University of Minnesota Duluth

Mark Jirsa – Field Trip Chair

Minnesota Geological Survey
University of Minnesota

Volume Editors

Jim Miller – Proceedings Volume

Department of Geological Sciences and Precambrian Research Center
University of Minnesota Duluth

Mark Jirsa and Terry Boerboom – Field Trip Guidebook

Minnesota Geological Survey, University of Minnesota

Special Projects

Amy Radakovich – Minnesota Geological Survey, University of Minnesota

Banquet Speaker

Dr. Francis M. Carroll

University of Manitoba - Winnipeg and St. Johns University

"A Line in the Trees:

History of the US-Canadian Boundary from Lake Superior to Lake of the Woods"

Session Chairs

Al MacTavish – Panoramic Resources, Thunder Bay, ON

Joyashish Thakurta – Western Michigan University, Kalamazoo, MI

Geoff Pignotta – University of Wisconsin – Eau Claire

Marcia Bjornerud – Lawrence University, Appleton, WI

Mary Louise Hill – Lakehead University, Thunder Bay, ON

Bernie Saini-Eidukat – North Dakota State University, Fargo, ND

Field Trip Leaders

Field trips have been the mainstay of the ILSG since its inception 60 years ago. We want to give a special thanks to the field trip leaders who volunteered their time and talent in carrying that tradition forward.

1) STRATIGRAPHY, SEDIMENTOLOGY, STRUCTURE AND MINERALIZATION OF THE BIWABIK IRON FORMATION, CENTRAL MESABI IRON RANGE

Phil Larson - Duluth Metals Ltd.

Marsha Patelke - Natural Resources Research Institute, UMD

Jakob Wartman - United Taconite, Cliffs Natural Resources

Michael Totenhagen - Arcelor Mittal

Mark Jirsa - Minnesota Geological Survey

Steven Losh - Minnesota State University – Mankato

Peter K. Jongewaard - Cliffs Natural Resources (retired)

2) A WALK IN THE PARK—NEOARCHEAN GEOLOGY OF LAKE VERMILION STATE PARK

George J. Hudak - Natural Resources Research Institute – UMD

Amy Radakovich - Minnesota Geological Survey

Geoff Pignotta - University of Wisconsin - Eau Claire

Kelly Schwierske - University of Wisconsin - Eau Claire

3) WESTERN MESABI RANGE MINING OPERATIONS

Douglas Halverson - Cliffs Natural Resources, Duluth

Daniel Cervin - Cliffs Natural Resources, Hibbing Taconite

William Everett – Essar Steel

Kevin Kangas - Essar Steel

Joseph Nielsen - Magnetation

5) VISIONS OF MATURI: THE GEOLOGY OF THE SOUTH KAWISHIWI INTRUSION

Dean Peterson - Duluth Metals Ltd.

6) THE ST. LOUIS SUBLOBE AND GLACIAL LAKE UPHAM

Phil Larson - Duluth Metals Ltd.

Alan Knaeble - Minnesota Geological Survey

Howard Mooers - University of Minnesota Duluth

Lisa Marlo - Halcon Resources Corporation

7) GEOLOGY AND GOLD MINERALIZATION OF THE VIRGINIA HORN AREA

Mark Jirsa - Minnesota Geological Survey

William Rowell - Vermillion Gold LLC

Richard Sandri - Vermillion Gold LLC

Jason Richter - Minnesota Department of Transportation

A) STATE DRILL CORE LIBRARY—HIBBING MINNESOTA

Minnesota Department of Natural Resources—Division of Lands and Minerals

Dave Dahl – Minnesota Department of Natural Resources, Div. of Lands and Minerals

Dean Rossell - Kennecott Exploration, Rio Tinto

B) HIBBING’S IRON MINING AND CULTURAL HISTORY

Henry Djerlev - Superior GEO-Services (retired)

Bob Kearney – Hibbing High School (retired)

Erica Larson and other Hibbing Historical Society staff

C) MINNESOTA DISCOVERY CENTER, CHISHOLM, MN

Discovery Center Staff

D) COLERAINE MINERALS RESEARCH LABORATORY

Natural Resources Research Institute, University of Minnesota-Duluth

Dick Kiesel - CMRL Director

Dave Hendrickson - Director Strategic Planning

Matt Mlinar - Program Coordinator Mineral Processing

Basak Anameric - Program Coordinator High Temperature Process)

E) MINEVIEW FROM A CANOE :

Mark Jirsa - Minnesota Geological Survey

Daniel Jordan - Iron Range Resources and Rehabilitation Board

Dale Cartwright - Minnesota Dept. of Natural Resources, Div. of Lands and Minerals

Sponsors

The following organizations and individuals made general contributions to the 60th Annual Meeting. We thank them for their commitment to the Institute on Lake Superior Geology. All of the funds contributed this year go toward travel awards for student registrants.

Eagle Mine

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The Teck logo features a solid blue horizontal bar above the word "Teck" in a large, bold, black sans-serif font.

Midwest Institute of Geosciences and Engineering



INDIVIDUAL CONTRIBUTORS TO STUDENT TRAVEL SCHOLARSHIPS

MARY ARTHUR	JOHN BERKLEY
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Report of the Chairs of the 59th Annual Meeting

Theodore J. Bornhorst and Allan R. Blaske

Houghton, Michigan

The 59th annual meeting of the Institute on Lake Superior Geology (ILSG) was held May 8 to 11, 2013 in Houghton, Michigan, at the Franklin Square Inn. The meeting was hosted by the A. E. Seaman Mineral Museum of Michigan Technological University and was chaired and organized by Ted Bornhorst (A. E. Seaman Mineral Museum) and Allan Blaske (AECOM). The meeting was attended by a total of 228 delegates from 14 U.S. states (Arizona, Colorado, Illinois, Indiana, Iowa, Massachusetts, Michigan, Minnesota, New York, North Dakota, Ohio, Texas, Virginia, Wisconsin) and 4 Canadian provinces (British Columbia, Ontario, Manitoba, Quebec). There were 58 student attendees.

The two-day technical session began on Thursday morning with oral presentations on Archean topics and continued on Friday with presentations on Keweenaw and Quaternary geology. There were a total of 25 oral presentations, 10 of which were presented by students. The technical session included a total of 18 poster presentations, 10 of which were presented by students.

The meeting offered 5 field trips that highlighted the Keweenaw geology of the western Upper Peninsula of Michigan. Two pre-meeting trips were held on Wednesday: *Geologic Overview of the Keweenaw Peninsula, Michigan*, led by Ted Bornhorst (A. E. Seaman Mineral Museum) and *Caledonia Mine, Keweenaw Peninsula Native Copper District, Ontonagon County, MI*, led by Bob Barron (Michigan Tech) and Richard Whiteman (Red Metal Minerals). A third scheduled pre-meeting field trip was cancelled because of the unusual lingering snowpack which prevented access to Silver Mountain. Friday afternoon featured a “field trip” open house at the A. E. Seaman Mineral Museum, with guided tours led by Museum Director, Ted Bornhorst. Two post-meeting trips were held on Saturday: *Geology of the Keweenaw Supergroup, Porcupine Mountains, Ontonagon and Gogebic Counties, MI*, led Laurel Woodruff (USGS), Bill Cannon (USGS), and Robert Wild (Porcupine Mountains Wilderness State Park) and *Geology and Environmental Site Conditions of the Copperwood Deposit, Gogebic County, MI*, led by Ted Bornhorst (A. E. Seaman Mineral Museum), Allan Blaske (AECOM), Dave Anderson (Orvana Resources US Corp) and Tom Repaal (Orvana Resources US Corp.). The field trips were well-attended with each being at maximum capacity (sold out). The unusual snow cover in the Keweenaw and cold weather on Saturday made some shuffling of field trip logistics necessary.

Four Doug Duskin Best Student Paper Awards were given for student paper presentations. Awards were presented for oral and poster presentations, with an award within each category for undergraduate students and for graduate students. The student awardees were Breanne Beh (Lakehead University, graduate student) and Emily Smyk (Lakehead University, undergraduate student) for their oral presentation and Jonathan Dyess (University of Minnesota – Duluth, graduate student) and Brynley Nadziejka (Lawrence University, undergraduate student) for their poster presentation.

Eisenbray Student Travel Awards are funded by ILSG and forty students received a travel award. Thanks to very generous support from ILSG corporate sponsors (AECOM, Coleman Engineering Company, Rio Tinto–Eagle Mine, and Superior Copper Corporation) we were able to award ILSG Corporate Student Registration Awards to all students who attended the meeting. The ILSG Corporate Student Registration Award consisted of the meeting registration fee. In addition, students who were presenting papers received additional monetary support in the form of an ILSG Corporate Presenter Award. We are pleased to report that \$5,325 were awarded to students. Through the support of corporate sponsors, the ILSG can better promote geologic studies of the Lake Superior region to the next generation of professional geoscientists.

The ILSG social and banquet were held at the Franklin Square Inn, Houghton. There were 140 people at the banquet. Jim Ashley of the Lunar Reconnaissance Orbiter Camera Science Operations

Center (LROC) at Arizona State University delivered the banquet address, entitled “*Rusty Metal at the Martian Equator: The Search for Life on the Red Planet*,” which discussed the occurrence and weathering of iron meteorites on the surface of Mars, and the implications these samples have to the history of water on Mars. The highlight of the banquet was the awarding of the 2013 Goldich Medal to Tom Waggoner (retired chief geologist and lands manager for Cleveland-Cliffs and currently a consulting geologist). Ron Seavoy provided a brief summary of Tom’s contributions to the geology of the Lake Superior region and the ILSG. Tom was greeted with warm applause upon receiving the prestigious ILSG award.

The Institute’s Board of Directors met on May 9 to discuss the business of ILSG. The meeting was attended by Ted Bornhorst (Board of Directors meeting Chair), Allan Blaske, Al MacTavish, Tom Fitz, Peter Hinz, Jim Miller, Mark Jirsa and Pete Hollings. ILSG Secretary Hollings took the minutes of the meeting, which are as follows:

1. Accepted report of the Chairs for the 58th ILSG, Thunder Bay, Ontario; as printed in the Proceeding Volume (Hinz), and minutes of last Board meeting, May 17, 2012 (Hollings).
2. Received, discussed, and accepted the 2012-2013 ILSG Financial Summary (Jirsa).
3. Received, discussed, and accepted the 2012-2013 report of the Secretary (Hollings).
4. Approved Allan Blaske as ILSG Board member representing the 2013 meeting.
5. Approved Hibbing as the site for the 60th annual ILSG meeting. The meeting will be hosted by Jim Miller and Mark Jirsa.
6. Discussed and approved renewal of Peter Hollings as Institute Secretary (end of term 2013). This was later approved by a vote of the membership during the technical session.
7. Discussed and approved replacing Laurel Woodruff as the “member from government” on Goldich Committee (end of term 2013) with Mark Smyk.
8. Discussed the possibility of having a short themed session with invited speakers at future meetings.
9. Requested that Secretary Hollings contact past chairs in order to compile statistics on the number of responses to the first circular in relation to attendance at the meeting.
10. Discussed the topic of the level of student participation required to be eligible for an Eisenbrey Student Travel Award. While there was no formal vote, the Board agreed that meeting Chairs should include a statement on the application indicating that full participation in the meeting was required to receive the award. In other words, a student cannot come for ½ day of the technical session or only attend a field trip to pick up the award.

The meeting co-Chairs would like to thank all those who assisted with this year’s meeting either by chairing sessions, judging student papers, leading field trips, driving vehicles for field trips, helping with the registration desk, operating the meeting and banquet projectors, and more. These volunteers made the quality of the meeting better and of course, made the job of the meeting chairs far easier than it may otherwise have been. A special thank you goes to Darlene Comfort, who tirelessly and patiently managed the registration and logistics for the meeting.

We are gratified by all of the positive comments by participants. While chairing and organizing an ILSG meeting involves time and a bit of stress on occasion, we are happy to have had the opportunity to serve the geological community of the Lake Superior region. We look forward to the 2014 meeting when we can be much more relaxed!

Respectfully submitted,

Ted Bornhorst and Allan Blaske
Co-chairs, 59th Institute on Lake Superior Geology

PROGRAM

WEDNESDAY MAY 14, 2014

All trips leave from the northeast entrance of the Hibbing Park Hotel

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

FIELD TRIP 1: STRATIGRAPHY, SEDIMENTOLOGY, STRUCTURE, AND MINERALIZATION OF THE BIWABIK IRON FORMATION, CENTRAL MESABI IRON RANGE

Phil Larson, *Duluth Metals Ltd.*

Marsha Patelke, *Natural Resources Research Institute, UMD*

Jakob Wartman, *United Taconite, Cliffs Natural Resources*

Michael Totenhagen, *Arcelor Mittal*

Mark Jirsa, *Minnesota Geological Survey*

Steven Losh, *Minnesota State University – Mankato*

Peter K. Jongewaard, *Cliffs Natural Resources (retired)*

FIELD TRIP 2: A WALK IN THE PARK - NEOARCHEAN GEOLOGY OF LAKE VERMILION STATE PARK

George J. Hudak, *Natural Resources Research Institute – UMD*

Amy Radakovich, *Minnesota Geological Survey*

Geoff Pignotta and Kelly Schwierske, *University of Wisconsin - Eau Claire*

FIELD TRIP 3: WESTERN MESABI RANGE MINING OPERATIONS

Douglas Halverson, *Cliffs Natural Resources—Duluth*

Daniel Cervin, *Cliffs Natural Resources—Hibbing Taconite*

William Everett and Kevin Kangas, *Essar Steel*

Joseph Nielsen, *Magnetation*

4:00 pm - 10:00 pm **Registration at Hibbing Park Hotel** (hallway outside Arrowhead Ballroom)

7:00 pm - 10:00 pm **Ice Breaker Social** (Arrowhead Ballroom) **and Poster Session** (Whispering Pines Room)

THURSDAY MAY 15, 2014

Asterisk * denotes a student eligible for Best Student Paper Award

7:30 am - noon **REGISTRATION**

8:00 am **OPENING REMARKS**

Jim Miller and Mark Jirsa, Co-Chairs, 2014 ILSG

TECHNICAL SESSION I

Session Chairs:

Al MacTavish – Panoramic Resources

Joyashish Thakurta – Western Michigan University

8:10 **Peter Hollings and Geoff Heggie**

Rethinking the Midcontinent Rift – Puncturing the “Plume Paradigm”

8:30 **Paul Bedrosian**

Electrical resistivity structure of the Midwestern United States from EarthScope magnetotelluric data

8:50 **Elisa Piispa*, Aleksey Smirnov and Lauri Pesonen**

Mesoproterozoic Midcontinent Rift intrusives in Thunder Bay area, Ontario, Canada: a paleomagnetic review

9:10 **Adam Leu* and Jim Miller**

Geology and petrology of the Wilder Lake Intrusion, Duluth Complex, northeastern Minnesota

9:30 **Klaus Schulz, Laurel Woodruff and Suzanne Nicholson**

Midcontinent Rift-related satellite mafic-ultramafic intrusions hosting Fe-Ti-V oxide deposits

9:50 **COFFEE BREAK AND POSTER SESSION**

10:20 **Gabe Sweet, Dean Peterson, Phil Larson, Molly Finnegan, Evan Finnes, Charlie Parent, Bob Nowak, Tyler Boley**

Sulfide highway revisited: New ideas on internal structure and sulfide mineralization of the Nickel Lake Macrodike

10:40 **Molly Finnegan and Phil Larson**

Geochemistry of basalt xenoliths entrained in mineralized troctolitic and anorthositic intrusions, northeastern Minnesota

11:00 **Alex Steiner* and Jim Miller**

Genesis of sulfide mineralization within the footwall granite of the Maturi Cu-Ni-PGE Deposit of the South Kawishiwi Intrusion, Duluth Complex, NE Minnesota

11:20 **Brent Trevisan*, Peter Hollings and Doreen Ames**

The Thunder mafic to ultramafic intrusion: a PGE and precious metal-bearing early rift conduit system in the Midcontinent Rift

11:40 **Jeff Mauk, Laurel Woodruff and Ester Stewart**

Variable copper mineralization in the lower Nonesuch Formation of the Midcontinent Rift System: Constraints on regional controls

Noon **LUNCH BUFFET** (*free to all registrants*)
ILSG BOARD MEETING

TECHNICAL SESSION II

Session Chairs:

Geoff Pignotta – University of Wisconsin – Eau Claire

Marcia Bjornerud – Lawrence University

1:30 **Bill Cannon, Laurel Woodruff, Stacy Saari, and Molly Hagstrom**
A new occurrence of the Sudbury impact layer in the Gogebic Iron Range of Wisconsin

1:50 **Monica Karman* and Philip Fralick**
Sedimentology and paleogeographic reconstruction of the layers in and adjacent to the Subury Impact Layer in the Lake Superior Basin

2:10 **Leif Johnson and Brad Dunn**
An exploration update and mineralogical study of the Emily District Maganese Deposit, Cuyuna Iron Range, Minnesota

2:30 **Adrian Arts* and Philip Fralick**
Nanoscale features within freshwater lacustrine ferromanganese nodules: Nanospheres, nanotubes and nanowires

2:50 **James Walsh**
Strontium isotope study of Mesabi Iron Range groundwater

3:10 **COFFEE BREAK AND POSTER SESSION**

3:40 **Robert Seal**
The danger of “Sulfide Mining” in the Lake Superior Region

4:00 **Tim McIntyre* and Philip W. Fralick**
Sedimentology and geochemistry of the Mesoarchean chemical sediments of Wallace Lake and Red Lake

4:20 **Rob Cundari, Mark Smyk and Peter Hollings**
Geology and geochemistry of the Mesoproterozoic Badwater Intrusive Complex, Ontario: Implications for GEON 15 magmatism

4:40 **Terry Boerboom, Karl Wirth and Joseph Evers**
Five newly acquired high-precision U-Pb ages in Minnesota, and their geologic implications

6:00 **RECEPTION – CASH BAR**

7:00 **ANNUAL BANQUET** (Arrowhead Ballroom)

– Announcement of 61st Annual Meeting Location

– 2014 Goldich Award Presentation to Laurel Woodruff

– Banquet Presentation by **Dr. Francis M. Carroll, Univ. of Manitoba**

A Line in the Trees: History of the US-Canadian Boundary from Lake Superior to Lake of the Woods

FRIDAY MAY 16, 2014

Asterisk * denotes a student eligible for Best Student Paper Award

8:00 OPENING REMARKS, UPDATES

Jim Miller and Mark Jirsa, Co-Chairs, 2014 ILSG

TECHNICAL SESSION III

Session Chairs:

Mary Louise Hill – Lakehead University

Bernie Saini-Eidukat – North Dakota State University

8:10 Jack Berkley

Deer Lake Complex redux: Memories and reflections, 1970 - 1972

8:30. Ben Kuzmich*, Peter Hollings and Michel Houle

Geochemistry and mineralogy of the Fe-Ti-V-P mineralized ferrogabbroic intrusions of the McFaulds greenstone belt, Superior Province, northern Ontario, Canada

8:50 Jordan Quinn*, Peter Hollings and John Biczok

Geochemistry and petrography of a mafic metavolcanic sequence south of Musselwhite Mine

9:10 Lionnel Djon*, Gema Olivo, Jim Miller and Rob Stewart

Petrology of the layered North Lac des Iles Intrusion, Ontario: Part I. Stratigraphy and mineral-chemical evidence for multiple magma injection

9:30 Skylar Schmidt* and Mary Louise Hill

Structural control of mineralization at Lac des Iles Mine

9:50 COFFEE BREAK AND POSTER SESSION

10:20 Amanda Van Lankvelt*, M. Williams, D. Schneider, S. Seaman,

Garnet in the deep crust: The key to linking Archean TTG generation and vertical block motions?

10:40 Jonathan Dyess* and Vicki Hansen

Structural and kinematic analysis of the Shagawa Lake Shear Zone: Implications for Archean tectonic processes in the Southern Superior Province

11:00 Simon Dolega* and Mary Louise Hill

Strain analysis on the Max Lake polymictic conglomerates in the Wabigoon Subprovince, Ontario

11:15 Leah Clapp* and Mary Louise Hill

Evidence of simultaneous brittle and ductile deformation in the Main Break Fault System, Kirkland Lake, Ontario

11:30 Jared Liimu* and Mary Louise Hill

The role of brittle-ductile deformation and competency contrast in gold mineralization in the C-zone at Hemlo

11:45 Daniel LaFontaine* and Mary Louise Hill

Structural control on the Borden Gold Deposit in Chapleau, Ontario

Noon **LUNCH BUFFET** (*free to all registrants*)

1:20 **BEST STUDENT PAPER AWARDS**
STUDENT TRAVEL AWARDS

2:00-6:00 **FRIDAY AFTERNOON FIELD TRIPS**

FIELD TRIP A: STATE DRILL CORE LIBRARY – HIBBING, MINNESOTA (MINNESOTA
DEPARTMENT OF NATURAL RESOURCES –DIVISION OF LANDS AND MINERALS

Dave Dahl, *Minnesota Department of Natural Resources*

Dean Rossel, *Kennecott Exploration, Rio Tinto*

FIELD TRIP B: HIBBING'S IRON MINING AND CULTURAL HISTORY

Henry Djerlev and Staff from the Hibbing Historical Society

FIELD TRIP C: MINNESOTA DISCOVERY CENTER

Discovery Center Staff

FIELD TRIP D: COLERAINE MINERALS RESEARCH LABORATORY, NATURAL
RESOURCES RESEARCH INSTITUTE, UNIVERSITY OF MINNESOTA DULUTH

Dick Kiesel, *Director CMRL*

Dave Hendrickson, *Director Strategic Planning*

Matt Mlinar, *Program Coordinator Mineral Processing*

Basak Anameric, *Program Coordinator High Temperature Process*

FIELD TRIP E: MINEVIEW FROM A CANOE

Mark Jirsa, *Minnesota Geological Survey*

Dan Jordan, *Iron Range Resources and Rehabilitation Board*

Dale Cartwright, *Minnesota Department of Natural Resources*

SATURDAY MAY 17, 2014

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

FIELD TRIP 5: VISIONS OF MATURI: THE GEOLOGY OF THE SOUTH KAWISHIWI
INTRUSION

Dean Peterson, *Duluth Metals Ltd.*

FIELD TRIP 6: THE ST. LOUIS SUBLOBE AND GLACIAL LAKE UPHAM

Phil Larson, *Duluth Metals Ltd.*

Alan Knaeble, *Minnesota Geological Survey*

Howard Mooers, *University of Minnesota Duluth*

Lisa Marlow, *Halcon Resources Corp.*

FIELD TRIP 7: GEOLOGY & GOLD MINERALIZATION OF THE VIRGINIA HORN AREA

Mark Jirsa, *Minnesota Geological Survey*

Bill Rowell, *Vermilion Gold LLC*

Rick Sandri, *Vermilion Gold LLC*

Jason Richter, *Minnesota Department of Transportation*

POSTER PRESENTATIONS

Asterisk * denotes a student eligible for Best Student Paper Award

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

Fault offsetting in the Proterozoic Lorraine Formations along Government Road, south of Echo Bay, Ontario, Canada

Mark Baumgardner, Nathan Brown, Matt Grotte, Alan Jacobson, Jamie Kendall, Claire Ostwald, Nathan Schriener, Justin White, and Dean Peterson

Bedrock geologic map of the Gafvert Lake area, St. Louis County, northeastern Minnesota

Patrick Belshaw* and Mary Louise Hill

Relationship between Microstructure and Rock Mechanics in Shear-Zone-Hosted-Gold Deposits

Terry Boerboom and John Green

Bedrock geologic map of the Marr Island and Hovland 7.5' quadrangles, North Shore of Lake Superior, Minnesota

Anthony Boxleiter*, Joyashish Thakurta, and Thomas Quigley

Geochemical investigation of the origin of the Back Forty volcanogenic massive sulfide deposit, Menominee County, Michigan

Tom Buchholz, A. Falster, and W. Simmons

Zirconium/Hafnium fractionation in some pegmatites of the upper Midwest, USA

Val Chandler and Richard Lively

Continued work on using the horizontal-to-vertical spectral ratio (HVSr) passive seismic method for determining Quaternary sediment thickness in Minnesota

Ben Drenth, Ray Anderson, Klaus Schulz, Val Chandler, Bill Cannon, Ben Bloss, Paul Bedrosian, Josh Feinberg, Rob McKay

Preliminary interpretation of Precambrian lithology and structure from high-resolution, multi-method geophysics, northeast Iowa and southeast Minnesota

Jonathan Dyess* and Vicki Hansen

Determination of Vorticity in Archean Tectonites

Nicholas Fedorchuk*, Stephen Dornbos, John Isbell, Julie Bowles, Frank Corsetti, Dylan Wilmeth, Victoria Petryshyn

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

Kiel Finn* and Julie Bowles

Magnetic Mineralogy of Reversely Magnetized Chengwatana Lava Flows of St. Croix Falls, Wisconsin

Sidney Firmin* and Julie Bartley

An Unusual Mesoproterozoic Carbonate Unit: Relic of a Saline Lake?

Paul Fix, Stephen Ginley, Lauren Schraeder, Aaron Summers, Michael Doyle, Terry Boerboom

Geology of the Brule River area of the Pine Mtn quadrangle, Minnesota: Capstone mapping project for the Precambrian Research Center's 2013 field camp

Marine Foucher*, Renee Curganus, Elisa Piispa, Aleksey Smirnov, and Lauri Pesonen

Evolution of the Midcontinent Rift system: Paleomagnetic, rock magnetic and anisotropy of magnetic susceptibility study of the Mesoproterozoic Baraga - Marquette dike swarm, MI, USA

VJ Grauch, Val Chandler, and Rich Lively

Compilation of existing geophysical models in preparation for 3D modeling of the Midcontinent Rift System in the western Lake Superior region, Minnesota, Wisconsin, and Michigan

Matt Grotte* and George Hudak,

A field and petrographic study of Neoarchean variolitic pillow lavas, Newton Belt, Vermilion District, NE Minnesota.

Ivan Guzman*

Stratigraphic framework and landsystem correlation for deposits of the Saginaw Lobe, Michigan, USA

George Hudak, Stephen Monson Geerts, Larry Zanko, Sara Post, and Bryan Bandli

The Minnesota Taconite Workers Health Study: Environmental Study of Airborne Particulate Matter - 2014 Update

Darcy Jacobson*, Elisa Piispa, Aleksey Smirnov, and Lauri Pesonen

Silica Remobilization in the Biwabik Iron Formation, Minnesota USA

Monica Karman* and Phil Fralick

Impact ejecta features in the Lake Superior basin from the 1850Ma Sudbury Impact Event

Stephen Kissin and Gregory Brumpton

PDFs in Sudbury Ejecta in the Gunflint Formation, Ontario: A Comparison of Methods

Matthew Lamb* and Prajukit Bhattacharyya

Ru-Rh-Pd Mobilization in Flambeau Massive Sulfide Deposit

Gordon Medaris, Jr., Tim Flood, Brian Jicha and Bradley Singer

Composition and $^{40}\text{Ar}/^{39}\text{Ar}$ Age of Pegmatitic Amphibole in the Wausau Syenite Complex, Marathon County, Wisconsin

Jim Miller, Sarah Sauer, Jordan Benningfield, Jackson Graham, Sara Kozmor, and Ann Marie Prue

Geology of the Lake Three Troctolite, Duluth Complex - 2013 Precambrian Field Camp Capstone

Connor Mulcahy, Dan Romanelli, Roger Schulz, Steve Moorhead, Mitchell May, and Mark Jirsa

Geologic mapping of Neoarchean and Paleoproterozoic rocks near Hanson Lake, NE Minnesota, by students of the Precambrian Research Center's 2013 field camp

Brynley Nadziejka* and Marcia Bjornerud

Petrographic characterization of the Penokey Twelvefoot Falls Shear Zone, Marinette County, Wisconsin: Evidence for coeval ductile and seismic behavior

Ainslee Nolan* and Mary Louise Hill

Metamorphism and Deformation at the Wabioon-Quetico subprovince boundary in the Decourcey Lake area

Dean Peterson

Bedrock geologic map of the Twin Metals Minnesota Project, Northern South Kawishiwi Intrusion and adjacent areas

Nadine Piatak, Robert Seal, Perry Jones, and Laurel Woodruff

Potential for copper toxicity caused by surface water and stream sediments in unmined mineralized watersheds of the Duluth Complex

Patrick Quillen* and Jim Miller

Documenting the first lava flows of the Midcontinent Rift by digital mapping and petrographic analysis

Amy Radakovich and Howard Hobbs

The Arrowhead Pilot Project: Mapping of Precambrian and Quaternary geology in two diverse geologic areas of northeastern Minnesota

Bill Rose and Erica Vye

Tools for interpreting Keweenaw geoheritage to a broad public

Kelly Schwierske*, Geoff Pignotta, and George Hudak

The 2.7 billion year old Mt. St. Helens of northern Minnesota: Petrography, geochemistry and economic significance of the Neoarchean Gafvert Lake sequence

Laurel Woodruff, Bill Cannon, Federico Solano, and David Smith

Geochemistry and Mineralogy of Glacial Soils in the Upper Midwest

Chris Yip* and Phil Fralick

The evolution of the atmosphere-hydrosphere: A geochemical comparison of two Paleoproterozoic Gunflint weathering profiles

Abstracts

Nanoscale features within freshwater lacustrine ferromanganese nodules: Nanospheres, nanotubes and nanowires

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Iron-hydroxide and manganese-oxide precipitates, often referred to as ferromanganese nodules (FMN), are common occurrences on lake bottoms worldwide (Sozanski and Cronan, 1978). The nodules form at the sediment-water interface, generally on a sandy substrate, at neutral pH (Kindle, 1932). Detailed studies documenting their morphology and geochemistry have been conducted by several authors (Sommers et al., 2002). FMNs can take varying morphological forms. However, they most typically accrete as disk-shaped precipitates with a concentric growth pattern of alternating Fe- and Mn-rich bands, around a central pebble or small cobble nucleus (Sozanski and Cronan, 1976) (Fig. 1A, 1B). Bacterially mediated precipitation and changes in redox conditions are believed to be a significant factor in their growth (Dean and Greeson, 1979; Boudreau, 1988). These features are environmentally important as the iron hydroxides composing them adsorb arsenic with concentrations up to 4900 ppm. Despite the considerable amount of work conducted on the nodules, no research has been undertaken to explore FMNs at the micro- and nanoscale to investigate the extreme arsenic uptake abilities.

This study was conducted to provide new insights on the micro- and nanoscale features within FMNs and to determine the geochemical composition of these features. The nodules examined were collected from Shebandowan Lake (Ontario), Sowden Lake (Ontario), and Lake Charlotte, (Nova Scotia). The utilization of high resolution field emission scanning electron microscopy (SEM) revealed an intriguing range of nanoscale forms previously undocumented in FMNs.

Coccus bacterial forms were commonly found implanted in extracellular polymeric substance (EPS). Figure 1C illustrates the high concentrations of ovoid to round nanospheres (100-200nm diameter) which are embedded within the EPS. Semi-quantitative analysis (SEM-EDX) indicates the areas containing nanospheres are enriched in iron. It has been postulated that similar structures in carbonates provide nucleation sites for biologically induced mineralization (Aloisi et al., 2006) preventing the cellular membrane from being entombed by the precipitates (Bontognali et al., 2008).

Nanotubes were also documented and appear to be ubiquitous in the FMN samples. The nanotubes appear as a tangled mass of worm like structures, which range in length, from 2-40 μm , with a diameter range of 50-400 nm. Uwins et al. (1998) reported similar structures in Triassic and Jurassic sandstones. Utilizing three different RNA staining techniques they deduced that the structures are biogenic, contain RNA, and have thus referred to them as nanobes.

Finally, nanowires appear to be a common formational constituent of samples from each of the three lakes (Fig. 1E). These wires build together into large sheet-like- masses. SEM-EDX analysis show the wires to be composed of manganese oxides.

This study provides new insight as to how FMNs accrete, and how they are able to accumulate high concentrations of toxic metals. Similar to the environmental goals of artificially produced metal nanotubes, the biogenic iron hydroxide nanotubes greatly increase the reactive area allowing far greater arsenic adsorption.

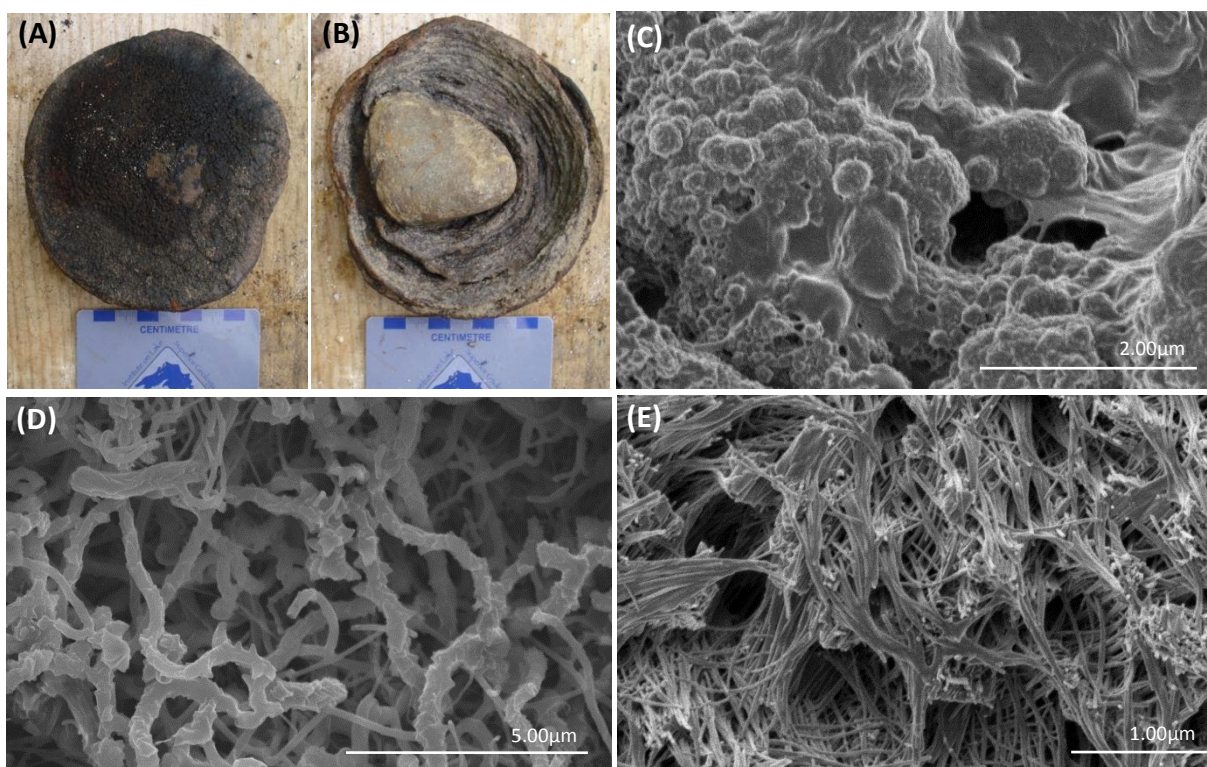


Figure 1. Images of Ferromanganese nodules at different scales. Picture of dorsal (A) and ventral (B) side of a FMN forming around a cobble nucleus, with distinct concentric laminations. (C) SEM image of nanospheres embedded into a smooth layer of extracellular polymeric substance. Mineralization can be seen increasing from the top to bottom of the image. (D) Intertwined mass of nanotubes coated in an iron precipitate. The varying diameters and lengths are evident in the image. (E) Wispy mass of manganese oxide nanowires. They can be seen growing together to form sheet-like layers.

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FAULT OFFSETTING IN THE PROTEROZOIC LORRAINE AND JACOBSTOWN FORMATIONS, ALONG GOVERNMENT ROAD, SOUTH OF ECHO BAY, ONTARIO, CANADA

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Along the east side of Government road (a small road that runs parallel to Trans Canada 17) exists an outcrop about 850 feet long at GPS: 46.46141° -84.05810°. The outcrop is mostly of the Jacobstown Formation, with an approximately 300 foot long outcrop of the Lorraine Formation near the center (see Figure 1). The Lorraine is much more indurated than the Jacobstown. The Lorraine was quarried at this location during sometime in the past. The Lorraine is a nearly white, thinly bedded, crystalline, fine to medium grained, quartz arenite, with minor beds of red jasper and white quartz conglomerate that has been metamorphosed. The Lorraine exposed at the outcrop is probably near the top of the formation. The Jacobstown is dominantly a reddish purple mottled pale yellow brown, cross bedded, fine to medium grained, non-metamorphosed, quartz arenite. Lenses of dark red sandy siltstone with red and green shale breccia are common in the Jacobstown (see Figure 2). The exact stratigraphic position of the Jacobstown is not known at this location.

The outcrop displays a section of the Lorraine “poking up” through the Jacobstown (see Figure 2). There are several ways this relationship could have formed. 1) The Lorraine existed as a paleo-high and the Jacobstown was deposited around it, making the contact depositional in nature. A similar situation exists in the Baraboo Range at the Upper Narrows in Wisconsin, where the Precambrian Baraboo Quartzite is in contact with the Cambrian sandstones and conglomerates. 2) The Jacobstown could have been deposited with some initial dip, and as more sediments accumulated the weight created growth faulting along the Lorraine-Jacobstown contact. 3) The outcrop is a horst structure, where the Jacobstown was originally deposited with little to no initial dip, and later extensional tectonic forces lowered the Jacobstown relative to the Lorraine.

Due to the field relationships of the outcrop, we believe the exposure to be a horst structure (see Figures 1 and 2) for the following reasons. 1) Perhaps the most compelling line of evidence is that no recognizable clasts of Lorraine exist within the Jacobstown at this outcrop, unlike what is seen at the Upper Narrows in Wisconsin, where clasts of Baraboo Quartzite are commonly seen in the local Cambrian sandstones. 2) The brecciated nature of the green and red shale cobbles within the siltstone facies of the Jacobstown appear jumbled. They were probably deposited as clay in stream beds and later brecciated during faulting. This makes sense that the shale and siltstone would have been more susceptible to deformation than the surrounding quartz arenites. 3) The variation in strike and dip between the Jacobstown surrounding the Lorraine. The Lorraine was not deformed during faulting. However, the Jacobstown north of the north fault has a different strike than it does on the south side of the south fault (the south fault may also have some lateral strike-slip movement). 4) There is complex breccia exposed at the north fault (see Figure 4). 5) Slickensides are present on the faces of the Lorraine at both the north and south faults.

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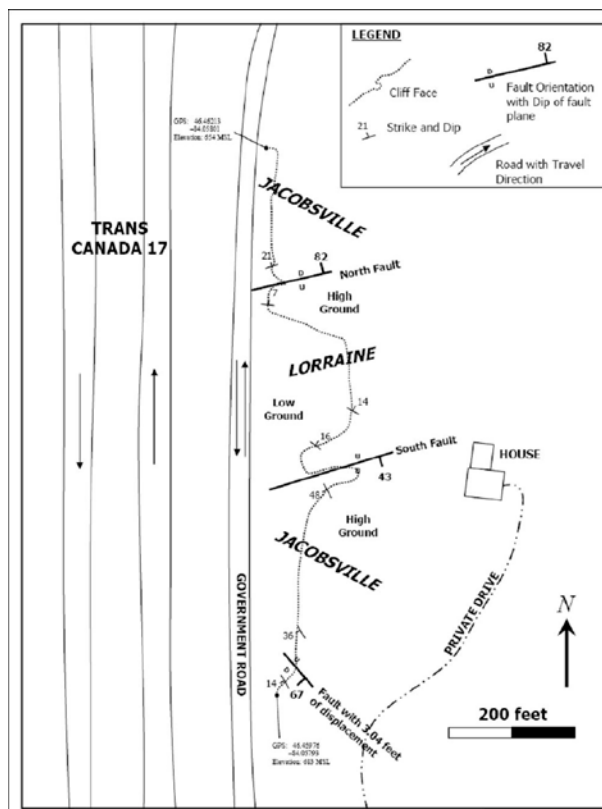


Figure 1: Diagram of the Outcrop and Location Map

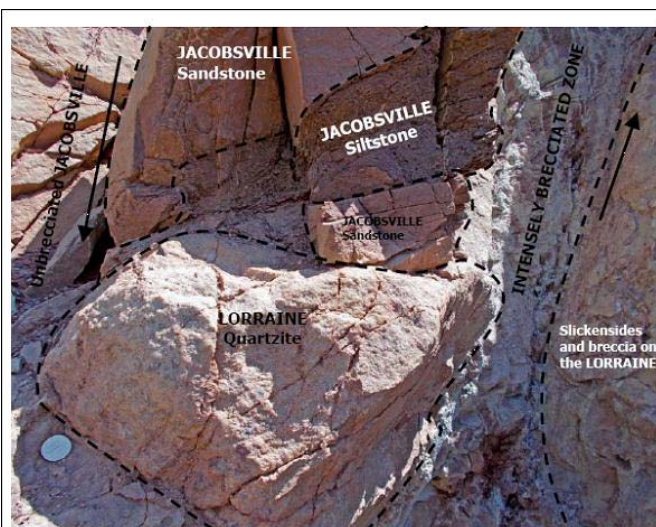


Figure 3: Photo of the Stratigraphic Relationships at the North Fault, U.S. Dollar coin for scale

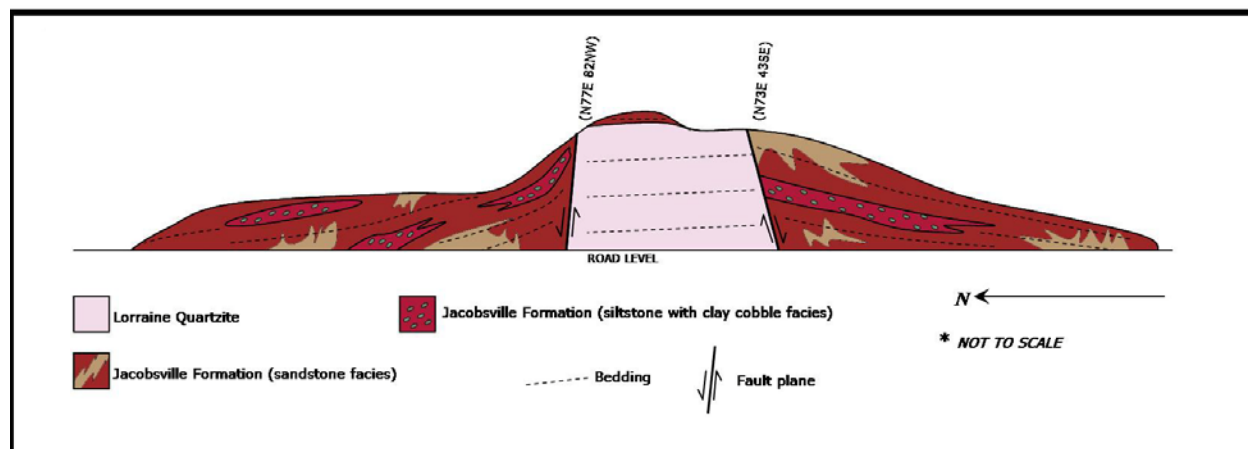


Figure 2: Conceptual Diagram of the Horst Structure along Government Road

BEDROCK GEOLOGIC MAP OF THE GAFVERT LAKE AREA, ST. LOUIS COUNTY, NORTHEASTERN 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 2013 field camp, eight PRC field camp students, under the direction of PRC Assistant Director Dean Peterson, mapped Neoproterozoic rocks of the informally named Gafvert Lake Sequence (Peterson and Jirsa, 1999, Peterson, 2001) between eastern Lake Vermilion’s Mud Creek Bay and Armstrong Lake, 6 miles to the east-southeast (Baumgardner et al., 2013). This capstone mapping project sought to: 1) identify the lithologies and determine the detailed stratigraphy within the Neoproterozoic supracrustal strata in this area; 2) define and characterize the nature of the contacts between various units of the Neoproterozoic 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 of the entire Gafvert Lake sequence stratovolcano.

Mapping was carried out over five days by eight students (**Figure 1**) of PRC field camp and 617 new outcrops were mapped by hiking and lakeshore canoe mapping in the field area. The final map incorporated over 1,500 outcrops from historical work in the area. Emphasis was placed on defining the structure of an Archean stratovolcano within the Vermilion Greenstone Belt.



Figure 1. Students of the Gafvert Lake Capstone.

Mark Severson, while mapping in the area for US Steel in the early 1980's, first recognized that the volcanic rocks in the area around Gafvert Lake represent a proximal facies dacitic to andesitic volcanic edifice. The morphology of the volcanic complex is best seen at map-scale,

which provides an almost perfect cross section through an Archean stratovolcano of dacitic to andesitic composition.

The sequence overlies the Soudan Iron Formation, is overlain by the Upper member of the Ely Greenstone to the east and north, and interfingers with reworked tuff and greywacke of the Lake Vermilion Formation on the west. In simple terms, the complex consists of a core of dacite lava flows that are overlain by coarse fragmental volcanic rocks of dacitic to andesitic composition. The fragmental rocks are in turn overlain by thin- to medium-bedded dacitic lapilli and ash tuffs. The whole complex is cut by multiple intrusions of coarse-grained quartz-feldspar porphyry (with rounded quartz phenocrysts up to 1.5 cm across), which occur as a central plug and thick sills to the east and west.

The presence of pumice and scoriaceous clasts in the fragmental rocks indicates that much of the sequence was erupted in extremely shallow water or subaerially. Two large bodies of quartz-feldspar porphyry intrude pillow basalts of the overlying Upper member of the Ely Greenstone and probably represent the last episode of igneous activity associated with the sequence. Tuffaceous greywacke of the Lake Vermilion Formation is inferred to be derived largely from this dacitic complex, and possibly other felsic complexes developed along this stratigraphic horizon. Capping the Gafvert Lake sequence to the east and north is a distinct horizon of multiple-facies iron-formation.

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ELECTRICAL RESISTIVITY STRUCTURE OF THE MIDWESTERN UNITED STATES FROM EARTHSCOPE MAGNETOTELLURIC DATA

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As part of the EarthScope USArray program, long-period magnetotelluric (MT) data have been collected within the Midwestern United States. From 2011-2013, 237 MT stations were collected with 70 km nominal station spacing over all of Minnesota, Wisconsin, Michigan and Iowa as well as parts of Illinois, Indiana, Missouri, Kansas, Nebraska, and Ohio. This data set is unique in its ability to constrain subsurface electrical resistivity at crustal and lithospheric scales over this broad region. Coupled with advances in three-dimensional (3D) MT inversion, the EarthScope MT data can be used to create 3D resistivity models with coverage and resolution comparable to seismic tomography models.

I will present a preliminary 3D resistivity model derived from these data. The discretized resistivity inverse model has a horizontal cell size of 10 km, with cell thickness starting at 100 m and increasing logarithmically with depth. The full MT impedance tensor was inverted at 11 periods ranging from 10 – 20,000 sec; vertical magnetic-field transfer functions at these same periods were also inverted.

The resulting 3D resistivity model reflects the complex structural collage from the Archean to present. Several zones of high conductivity from the surface to ~5 km depth mimic the distribution of Phanerozoic sediments within the Michigan, Illinois, and Forest City basins. In contrast, structural highs such as the Transcontinental Arch and the Wisconsin and Ozark domes are electrically resistive at these same depths.

At upper- to mid-crustal depths, the resistivity model illuminates the first-order structure of the 1.1 Ga Mid-Continental Rift (MCR) system. Highly resistive rocks coincide spatially with high magnetic-field anomalies, and are attributed to Keweenaw volcanic rocks along the length of the southwest rift arm. In addition, flanking conductive anomalies trace out thick packages of Keweenaw clastic rocks, some of which appear to extend to ~15 km depth. The structure of the MCR system as imaged within the 3D resistivity model is most striking within the Iowa Horst, but can be traced throughout the known extent of the MCR system, including beneath the Michigan Basin within the southeastern rift arm.

Structures predating the MCR system are also reflected in the resistivity model, particularly in the northern half of the model area. One example, the Flambeau anomaly, is imaged as a 300-km long, east-west trending structure through northern Wisconsin and upper Michigan at 46°N. The southern boundary of this high conductivity zone appears coincident with the Niagara Fault.

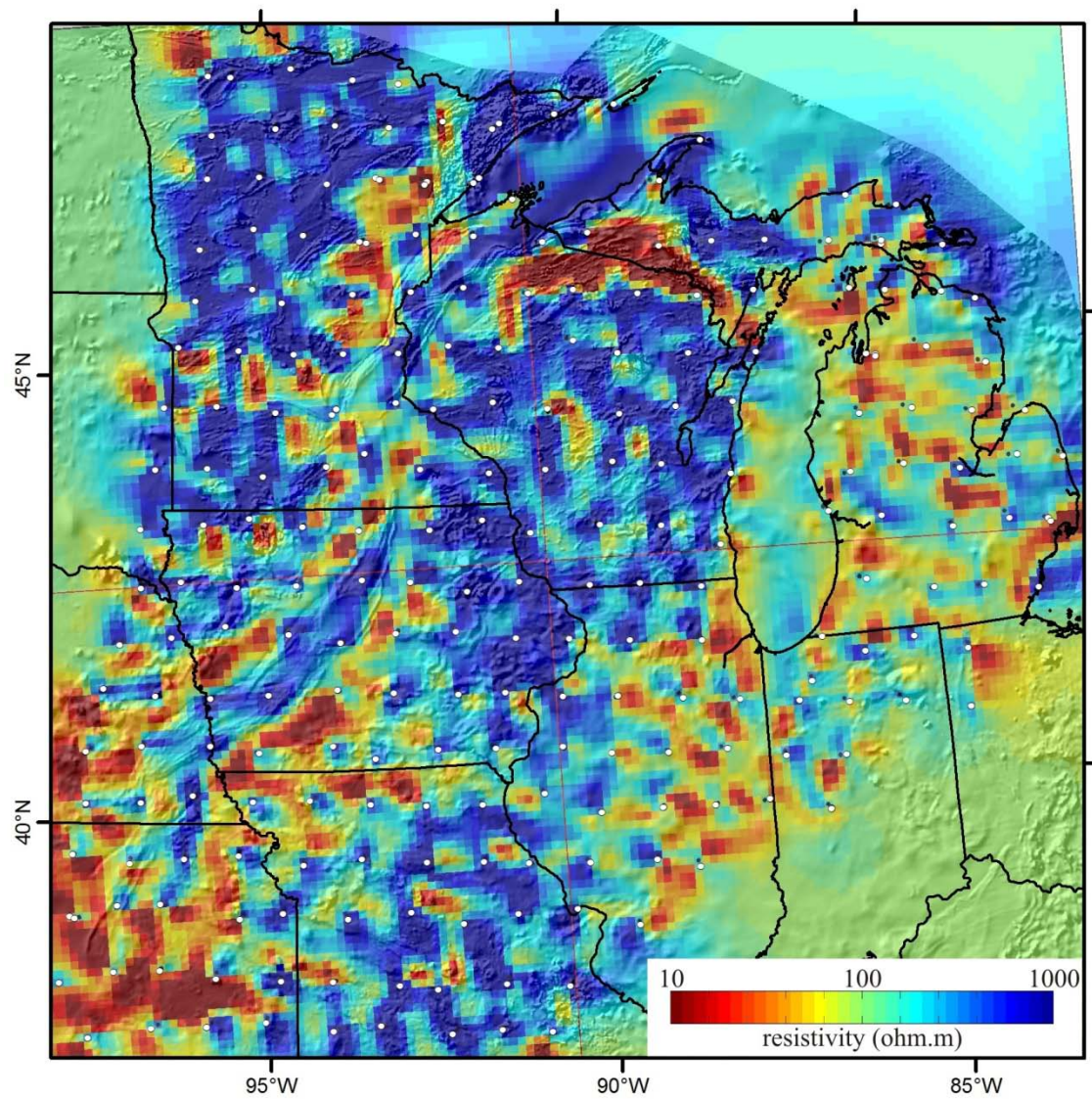


Figure 1: Preliminary resistivity structure at 9 km depth as constrained by 3D inversion of EarthScope magnetotelluric data. Background hillshade shows the total magnetic-field anomaly for comparison.

RELATIONSHIP BETWEEN MICROSTRUCTURE AND ROCK MECHANICS IN SHEAR-ZONE-HOSTED-GOLD DEPOSITS

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Orogenic gold deposits of northern Ontario are often hosted in steeply dipping, mylonitic shear zones. The common challenge of identifying, and mitigating the effects of penetrative planar fabrics with respect to rock mass properties is important in determining the safety of any mining operation. In addition to the relative effect on rock mass behaviour associated with fault planes and joint surfaces, highly ordered flaws in the material can have a significant effect on the orientation, initiation, and propagation of tensile Griffith fractures. In these deposits, where inherent flaws parallel to foliation dip steeply, spalling conditions are often observed in rocks that appear to be adequately competent. Most rocks in these deposits have also undergone grain size reduction during progressive deformation, making the interpretation of penetrative fabrics much more difficult on the outcrop scale. On the microscopic scale however, the morphology and density of grain boundaries and other flaws can be evaluated to develop relationships between the microscopic texture, and macroscopic material properties of the rock mass.

DEER LAKE COMPLEX, REDUX: MEMORIES AND REFLECTIONS, 1970 - 1972

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The Deer Lake Complex (DLC), located between the town of Big Fork and southern tip of Deer Lake in Itasca County, MN, has been the target of precious and industrial metals exploration for over forty years. It was a major Cu-Ni prospect in the early 1970s, but has recently received renewed scrutiny as a gold, PGM, and Cu-Ni prospect. Although written off during the late 60s – early 70s exploration boom as a “dry hole”, application of modern technology and imaginative exploration strategies could conceivably bear positive results in the near future.

The DLC consists of at least two gravity-stratified mafic-ultramafic sills, each roughly 250 meters thick, intruded into an Archean greenstone-meta-sedimentary terrain within the Wawa subprovince of the southern Superior province, Northern Minnesota (Berkley, 1972). Each sill differentiated into a lower wherlite / hornblende peridotite, overlain by distinct layers of clinopyroxenite, poikilitic and non-poikilitic gabbro, topped off by a layer of quartz-hornblende diorite (Berkley and Himmelberg; Ripley, 1978). Upper-most diorite units are commonly transected by thin, randomly dispersed veins of granitic assemblages (mostly microcline + quartz), and also display sheaf-like assemblages of acicular augite (Fig. 2a) plus skeletal plagioclase, the result of extreme undercooling at emplacement contacts (Ripley, 1972). Exposed lower contacts of sills (below peridotite) have chilled margins consisting of fine-grained basalt that – along with quench textures noted above – suggest shallow emplacement. Pyroxene reaction rims on peridotite olivine grains (Fig. 2b) indicate emplacement of less than about 6 km depth (e.g., Longhi and Pan, 1987).

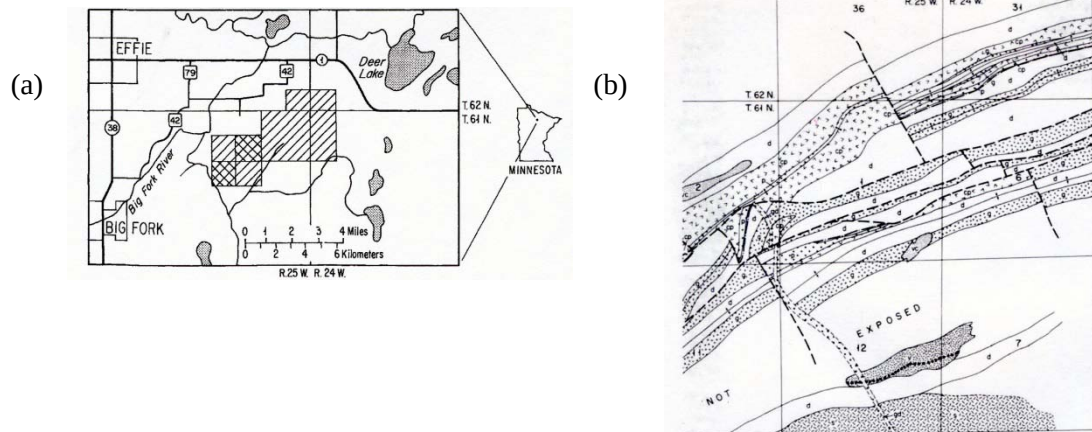


Figure 1: (a) Location map for DLC exposures. Textured squares represent areas mapped 1970-1973 (Berkley & Himmelberg, Ripley, 1978). (b) DLC geologic map from Ripley, 1978.

Initial interest in the area was prompted by 1970 USS Corp. aeromagnetic plots that portrayed pronounced NE-trending, parallel linear patterns. Recent UMD grads, Jack Berkley and David Witt, were dispatched by Sid Iverson to the area to determine the cause of the magnetic anomalies. Upon entering the area using a logging road winding south from highway MN-1, they were eventually rewarded by the discovery of highly sheared black, blue, and blue-

green – *magnetite-rich* serpentine, instantly accounting for the mag anomalies. What followed was a program using techniques and equipment that might seem archaic by today's standards, but that nevertheless demonstrate the value of systematic field work leading to discovery. Subsequent mapping during August, 1970 required using a sun compass to compensate for the Brunton compass' tendency to confuse peridotite exposures for the north magnetic pole. Topographic maps of the area were non-existent (the USGS team arrived the next year), thus geospatial positioning required finding, and using county-installed PLS section posts. Section lines festooned with colorful plastic flagging tape served as base lines for traverses that inevitably crossed insect-infested, soggy high-grass wetlands, waist-high blackberry thickets, and black spruce groves good only for obscuring views of whatever outcrops loomed ahead.

By the end of August 1970 our team had completed a crude map and hand-written report, likely representing the first geological report on the DLC ever produced. It reported the existence of possible layered, mafic-ultramafic igneous intrusions, consisting of – at the very least -- peridotite, pyroxenite, and gabbroic or diorite components.

Berkley returned the next summer (1971) to study and complete a map of the DLC to fulfill the requirements for a master's degree in Geology at the University of Missouri, Columbia under the tutelage of Dr. Glen R. Himmelberg (PhD, 1965 UM, Twin Cities). As he had in 1970, Berkley resided that summer in the cabin on Deer Lake (Fig. 2c) owned by Dave Witt's parents, where they were visited at times by various UMD Geology alums and other friends. One very important visitor was UMD's Dr. Richard Ojakangas, our indefatigable undergraduate instructor who was eager to see the work of his students. We duly escorted him into the depths of the DLC so he could plot the complex on the revised Hibbing Sheet of the Minnesota State Geologic Map. It remains there to this very day!

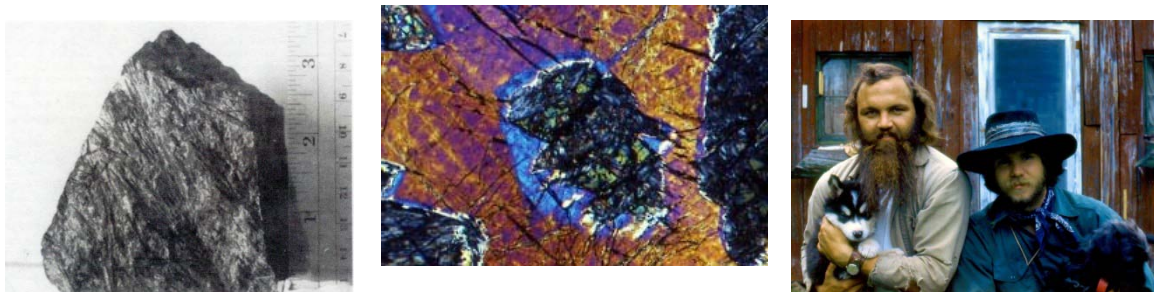


Figure 2. a) Super-cooled pyroxene sheaves, from upper sill contact zone (hand specimen). b) Olivine with augite reaction rim, both enclosed by hornblende (photomicrograph). c) DLC field partners, Dave Witt and Jack Berkley (with “field dogs”) outside the Deer Lake cabin, 1971.

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FIVE NEWLY ACQUIRED HIGH-PRECISION U-PB AGES IN MINNESOTA, AND THEIR GEOLOGIC IMPLICATIONS

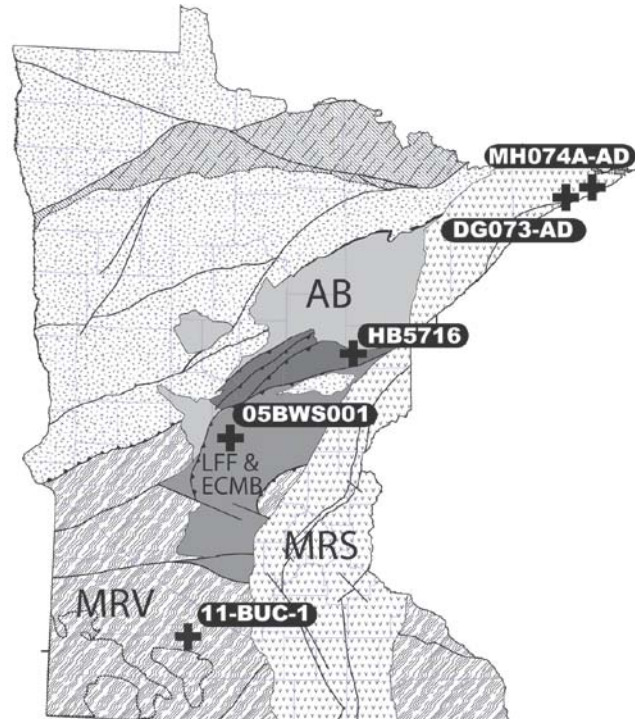
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In the past year, with much appreciated cooperation from Dr. Mark Schmitz, director of the Boise State University isotope geology laboratory, four new high-precision U-Pb ages (three zircon and one baddeleyite) have been acquired for rocks from various geologic terranes throughout Minnesota. We summarize these results and also include the results from a suite of detrital zircon ages obtained as part of a Macalester College student research project. Funding provided by the USGS Statemap program and the MGS County Atlas program. UTM coordinates given below are in NAD '83, Zone 15.

Midcontinent Rift System – Two samples - a porphyritic rhyolite flow (DG073-AD; Grand Marais rhyolite) and a ferromonzonite intrusion (MH047-AD; Hovland sill) were dated as a follow-up to detailed 1:24,000 scale bedrock mapping (Boerboom and Green, 2010; Boerboom and Green, 2013).

Sample DG073-AD – Six zircon crystals were selected for CA-TIMS (*Chemical Abrasion Thermal Ionization Mass Spectrometry*) analysis, from which five grains produced concordant isotopic ratios, with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date of 1095.00 ± 0.33 (MSWD (*Mean Square Weighted Deviation*) = 0.07) and a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1097.26 ± 0.67 (n=5; MSWD 1.47). Using the $^{207}\text{Pb}/^{206}\text{Pb}$ weighted mean date, this age is only slightly younger than the Devil's Kettle rhyolite (1097.7 ± 1.7 ; Davis and Green, 1997), which lies roughly 8,000 feet stratigraphically below and is separated by several thick mafic to felsic volcanic units. The nearly identical ages for these two units indicates rapid and voluminous volcanic activity in the upper part of the northeast limb of the North Shore Volcanic Group. Sample from roadcut at the west edge of Grand Marais. (UTM 698364E, 5291847N)



Sample MH047-AD – Six baddeleyite crystals selected for dissolution were all variably discordant, but gave equivalent $^{207}\text{Pb}/^{206}\text{Pb}$ dates with a weighted mean of 1095.94 ± 0.62 (n=6; MSWD 0.37). This age falls within the range of published ages for various other units of the Beaver Bay Complex, including the Wilson Lake ferrogabbro (1095.75 ± 0.92 ; Hoaglund, 2010), Sonju Lake intrusion (1096.1 ± 0.8 ; Paces and Miller, 1993), Silver Bay ferrogabbro (1095.8 ± 1.2 ; Paces and Miller, 1993), Pine Mountain granophyre (1095.3 ± 3.8 ; Vervoort and others, 2007), as well as others. The Hovland sill occurs near the base of the upper northeast limb of the NSVG. The sample, a coarse prismatic olivine-pyroxene ferromonzonite that forms the upper differentiated cap to the Hovland sill, was collected from a roadcut on Highway 6, 1.3 miles northeast of the Brule River near Hovland. (UTM 722714E, 5301024N)

Yavapai-interval intrusion – **Sample 11-BUC-1-459.5**. Seven zircon grains were selected for CA-TIMS analysis, and five of these seven analyses were concordant and equivalent, with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date of 1779.93 ± 0.56 (MSWD = 0.71), and a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ date of 1782.31 ± 0.64 Ma (MSWD 1.12).

This drill core sample is from the heart of the Minnesota River Valley (MRV) subprovince in southern Minnesota, within a prominent north-south elongate magnetic low about 9 x 1.3 miles in dimension. The age of this granite places it in the Yavapai interval, along with the granites that make up the east-central Minnesota Batholith (1772 – 1800 Ma) and other mafic-intermediate intrusions along the southern Minnesota border emplaced into the MRV subprovince, which have been dated at ca. 1792 Ma (Southwick, 1994) and ca. 1760 Ma (Van Schmus, 2006). (UTM 352525E, 4890299N)

Penokean Orogen – Sample HB5716-AD. Three abraded zircon fragments produced concordant isotopic ratios, with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date of 1882.32 ± 1.21 (MSWD = 0.23), and a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ date of 1882.96 ± 0.67 Ma (MSWD 1.12).

This sample is from a metagabbroic sill encountered in the 7,440' (2,268.3m) – long 'Hattenberger' core (HB-1) located within the Moose Lake-Glen Township panel, in the heart of the Penokean fold-and-thrust belt in east-central Minnesota. The drill hole intersected interlayered mafic volcanic and sedimentary rocks metamorphosed under lower amphibolite-grade conditions, as well as lesser proportions of mafic sills thought to be petrologically related to the mafic volcanic rocks (Southwick and others, 2005). The dated sample is from a coarse-grained, feldspathic zone in the interior of a 500-foot thick mafic sill that has chilled upper and lower margins. This sill mostly retains its primary igneous fabric despite the mafic mineral assemblage being composed almost entirely of blue-green metamorphic hornblende. *UTM 503780E, 5149030N*.

The ca. 1,882 Ma age of this sill clearly predates the geon 17 Yavapai-interval ages of the voluminous east-central Minnesota batholith and the ca. 1858-1877 Ma Bradbury Creek granodiorite (Holm and others, 2005); but it postdates the 2,009 Ma Mille Lacs granite (Holm and others, 2005). It is barely older than the 1878.3 ± 1.3 Ma lapilli tuff in the upper Gunflint Iron Formation (Fralick and others, 2002), and the $1,874 \pm 9$ Ma Hemlock Volcanics interlayered with the Negaunee Iron Formation (Schneider and others, 2002). It overlaps with ages from the Pembine-Wausau portion of the Wisconsin Magmatic Terrane (1,860-1,889; Sims and others, 1989 as reported in Schulz and Cannon, 2007). The sill intruded a carbonate-rich unit tentatively correlated with the Denham Formation, which has a maximum depositional age of $2,072.7 \pm 17.9$ Ma based on detrital zircons, (Vorhies, 2006).

Sample 05BWS001 - Little Falls Formation detrital zircon – A drill core sample of staurolite-garnet schist (Little Falls Formation) yielded abundant detrital zircon grains with U-Pb ages from 1,833 to 2,784 Ma. Most grains have ages from 1,833 - 1,898 Ma; smaller numbers of grains yield clusters (>3 grains each) at 2,420, 2,668, 2,695, and 2,704 Ma. Analysis of the main cluster of ages suggests a separate group with an age of 1,844 Ma, considered to be the maximum depositional age (MDA). The preponderance of ca. 1844 Ma ages (46 of 90 grains analyzed) offers new insights into the long-standing debate about age of the Little Falls Formation. The Little Falls Formation covers a large area of east-central Minnesota, and based on geophysical data is thought to form the upper plate of a thrust sheet that has been ramped west-northwest over rocks correlative with the Penokean Mille Lacs Group. Although it is well known that the Little Falls Formation was affected by the widespread ca. 1760 Ma regional metamorphic event throughout east-central Minnesota (e.g. Holm and others, 2007), the actual depositional age has never gone beyond speculation. If the 1844 Ma maximum depositional age is verified by further studies, this would imply that the Little Falls Formation was deposited synchronous with the much lower grade Animikie basin and that the basin covered a much broader area than previously recognized, necessitating a rethinking of models of the geologic evolution of the Penokean and Yavapai orogens in central Minnesota. Drill hole 05BWS001 *UTM 391454E, 5071884N*.

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BEDROCK GEOLOGIC MAP OF THE MARR ISLAND AND HOVLAND QUADRANGLES, NORTH SHORE OF LAKE SUPERIOR, MINNESOTA

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The Minnesota Geological Survey has continued ongoing mapping of the bedrock geology of 7.5' quadrangles adjacent to Lake Superior as part of the USGS STATEMAP program, resulting to date in twenty published 1:24,000 scale maps from Duluth northeast to beyond Hovland, in addition to 10 quadrangles already published under the former USGS COGEOMAP program. The Marr Island and Hovland quadrangles, (Boerboom and Green, 2013), are the most recent of these maps (Fig. 1). These maps are available at the MGS website (www.mnsgs.umn.edu).

Outcrop mapping was augmented by nearly 60 sets of high-quality water well cutting samples, collected at 10 foot intervals by McKeever Well Drilling of Little Marais, Minnesota. This mapping has refined the volcanic stratigraphy of the North Shore Volcanic Group (NSVG) in this area, as well as details and extents of intrusions. In keeping with prior work, the NSVG is subdivided into informal lithostratigraphic packages (listed below), which on this map follow closely those units identified by Green, 2002.

Most of the rocks in this quadrangle contain typical zeolite mineral assemblages; however in proximity to mafic intrusions the volcanic rocks contain minor garnet and/or epidote.

Volcanic rocks—The volcanic rocks in this map area cross the boundary between the upper (normally-polarized) and lower (reversely-polarized) portions of the northeast limb of the NSVG. The volcanic rocks are intruded by mafic to felsic intrusions inferred to be mostly related to the Beaver Bay Complex in timing. The major lithostratigraphic units are listed below from lowest to highest in the volcanic stratigraphy.

Hovland lavas—Predominantly strongly porphyritic trachyandesite, famous for its abundant and large tabular plagioclase phenocrysts. Also includes a poorly-mapped rhyolite known only from water well cuttings. Only the uppermost of the Hovland lavas are present here, most of the unit being to the northeast.

Brule River lavas—Predominantly rhyolite, interlayered with variably porphyritic intergranular basalts, pigeonitic ferroandesite, ophitic basalt, and minor sandstone. The upper half of this sequence of lavas is made up of the quartz-and feldspar-phyric Devil's Kettle rhyolite ($1,097.7 \pm 1.7$ Ma; Davis and Green, 1997); other rhyolites contain only feldspar phenocrysts, including the Big Bay rhyolite near the base of the upper normally-polarized lavas, which has a U-Pb zircon age of 1100.2 ± 2 Ma (Davis and Green, 1997).

Marr Island lavas—An approximately 1,000 meter thick sequence of dominantly mafic to intermediate lava flows (Green, 2002) that range from ophitic Fe-tholeiite to andesite with minor proportions of icelandite, rhyolite, and sandstone. Pigeonite is present in the basalts and andesites, and some andesites contain fresh glass in the mesostasis.

Kimball Creek felsites—Icelandite and rhyolite; the bulk of this unit occurs to the west in the Kadunce River quadrangle (Boerboom and Green, 2011), and only the very base of the section reaches this map area.

Intrusive rocks—Multiple intrusions range from coarse-grained gabbroic anorthosite, cumulate- differentiated sills, felsic to intermediate intrusions, and small diabase to ferrodiorite dikes and sills. The major intrusions are summarized below from earliest to latest in timing.

Carlson Creek gabbro complex—Anorthositic gabbro with pods of gabbroic pegmatite, and felsic-intermediate rocks that may be related, which locally contain xenoliths of pure anorthosite.

Intrusions tentatively assigned to the Brule-Hovland complex—Mainly ophitic gabbro and diabase but including erromonzodiorite hybrids. Ophitic olivine gabbro contains inclusions of volcanic rocks and interflow sandstone.

Reservation River diabase—A gently dipping sheet-like body of ophitic olivine diabase that is present mainly to the north and east of the map area; intrudes reversely-polarized flows but is normally-polarized.

Horseshoe Bay diabase—Ophitic diabase (normally polarized), troctolitic diabase, and ferromonzonite. Troctolitic phase contains Fe_{62-72} olivine and augite of $Mg\#70$; ophitic diabase contains Fe_{50-58} olivine and augite of $Mg\#70$. Orientations of olivine streaks and sheet joints indicate troctolite is a gently south-dipping sill; this possibly grades into the ophitic diabase. Ophitic diabase contains large inclusions of amygdaloidal basalt, and there are local narrow hybrid melt zones where ophitic diabase intruded rhyolite. Small plug-like bodies of prismatic pyroxene-quartz ferromonzonite may have formed as partial melt segregations from the underlying rhyolite.

Chicago Bay ophitic diabase—Presumably a sill (normally-polarized) beneath the Hovland sill; may be a marginal phase to it. Augite compositions of $Mg\#70$ and partially olivine average Fe_{60} .

Brule River sill—Variably granophyric mafic sill; the lowest part is a cumulate with locally abundant ilmenite and minor poikilitic olivine. Higher parts have layers bearing clots of poikilitic olivine alternating with more coarse-grained granophyric layers. The upper portion may grade into overlying Pine Mountain granodiorite.

Lookout sill—A south-dipping sill, like the Hovland sill in that it contains cumulate plagioclase, augite, olivine (Fo₂₃ near base, Fo₁₅ higher up), apatite, and abundant ilmenite. The upper part is a miarolitic prismatic ferromonzonite that contains fayalitic olivine (Fo₁₀).

Hovland sill—An approximately 15-degree south dipping, subcordant, 300 m-thick sill composed of a basal noncumulate ferrogabbro, a middle cumulate-foliated granophyric ferrogabbro, and an upper coarse-grained felsic cap. Not physically continuous with the Lookout sill but very similar and may be related in timing and paragenesis. Monazite U-Pb age of 1095.94±0.62 (Boerboom and others, this volume).

The lower ferrogabbro contains distinguishing, evenly distributed 3-4mm altered olivine clots (5%), intergranular augite (Mg# 59 to 54), and up to 2% pigeonite (Mg# 41). The middle section is strongly cumulate-foliated and typically coarse-grained; the lowest part of this contains abundant cumulate ilmenite plates but higher in the stratigraphy magnetite becomes dominant over ilmenite; also contains cumulate plagioclase, augite, Fe-Ti oxides, olivine (mostly altered), and minor apatite. Olivine content is generally around 2%, but near the top increases to as much as 13%. Pigeonite (Mg# 49) rims augite, for which average Fe/Mg ratios increase from Mg# 57 at the base to 35 at the top (ferroaugite). Mg numbers for olivine range from Fo₂₉ near the base to Fo₁₇ near the top. The coarse-grained felsic cap contains 8-15% prismatic ferroaugite (Mg#35) and 10-15% fayalitic olivine (Fo₁₀) that is mostly altered and varies in form from irregular coarse clots and prismatic grains to acicular trellises up to 30cm in length.

Pine Mountain Granophyre—Part of a larger body of granophyre and granodiorite located mainly to the west of this map area (e.g. Boerboom and Green, 2011); with a reported U-Pb age of 1,095.3 ± 3.8 Ma (Vervoort and others, 2007). Compositions are gradational from leucogranite into gabbro of the Brule River sill, implying that the Brule River Sill, and by extension, the Lookout sill, may all be close to 1,095 Ma in age.

Miscellaneous intrusions—A wide variety of small intrusions are present throughout the map area. These include small hybrid/contaminated ferromonzonitic dikes with intermingled partially melted rhyolite, fine-grained ferrodiorite dikes, ophitic to intergranular olivine diabase, medium-grained pyroxene granodiorite, and ferromonzodiorite. Most of these are dikes, but some appear to be sills.

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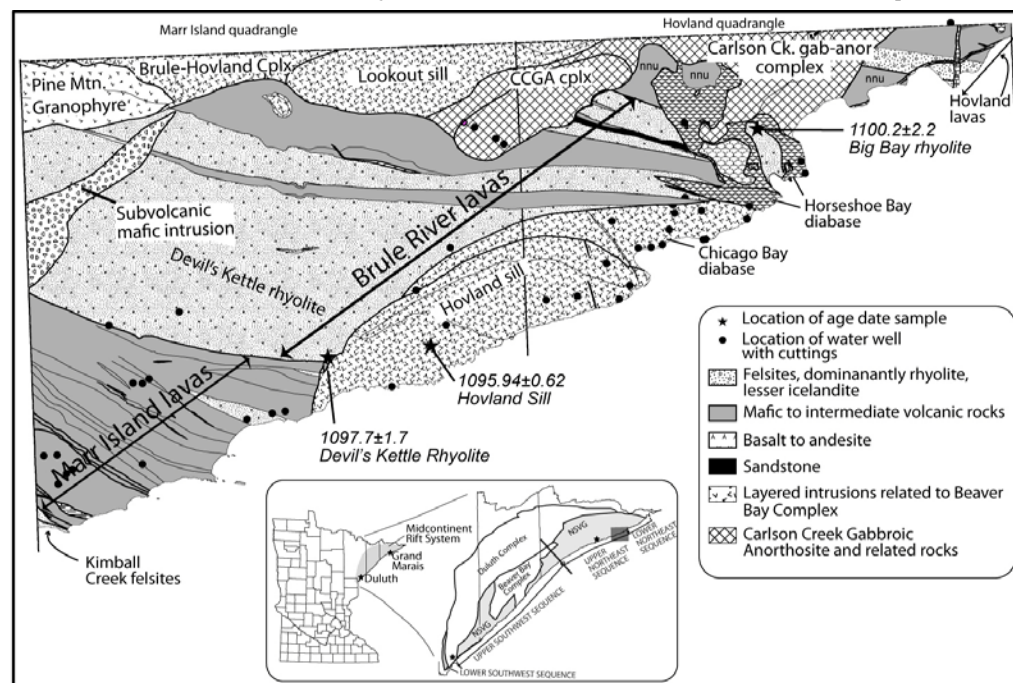


Figure 1. Simplified geologic map of the Marr Island-Hovland quadrangles, showing the major lithostratigraphic units discussed in the text. Inset location map shows the extent of the Keweenawan Midcontinent Rift System in Minnesota, and the locations of the Marr Island-Hovland quadrangles (dark gray box).

GEOCHEMICAL INVESTIGATION OF THE ORIGIN OF THE BACK FORTY VOLCANOGENIC MASSIVE SULFIDE DEPOSIT IN MENOMINEE COUNTY, MI

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The Back Forty Volcanogenic Massive Sulfide deposit is located in Menominee County, Michigan. Several Volcanogenic Massive Sulfide (VMS) deposits can be found trending along the Penokean Volcanic Belt in northern Wisconsin and the Michigan Upper Peninsula (Fig. 1). The Back Forty deposit is a Paleoproterozoic ore deposit which formed during the Penokean Orogeny (1874 ± 4 Ma; Schulz et al., 2007). This deposit is unique because it contains low amounts of copper and high amounts of zinc and gold when compared to other VMS deposits associated with the Penokean Volcanic Belt, such as Crandon and Flambeau. Mineralization of the Back Forty deposit consists of massive, semi-massive, stringer sulfide zones, and sulfide-poor Au and Ag enriched zones (Thakurta and Quigley, 2013). Three chemically distinct varieties of host rhyolite have been identified based upon trace element characteristics, two of which are found to host sulfide mineralization (Quigley et al., 2008).

The relationship between rhyolite geochemistry and VMS mineralization has been proposed by Thurston (1981) and Campbell et al. (1982) as an exploration tool for discerning prospective VMS deposits, based on Archean VMS deposits in the Canadian Shield. From this groundwork, Leshner et al. (1986) and Barrie et al. (1993) developed a formal classification scheme for felsic volcanic rocks based on trace element concentrations and they suggested that certain types of rhyolites are more prospective for sulfide mineralization than others. They classified rhyolites associated with VMS deposits into three types: FI, FII, FIIIa, and FIIIb. Conclusions drawn from Leshner et al. (1986), Lentz (1998), and Hart et al. (2004) are that Archean VMS deposits are hosted mainly by FIII rhyolites, whereas most post-Archean VMS deposits are hosted predominantly by FII rhyolites. Under the classification scheme developed by Leshner et al. (1986) and Barrie et al. (1993), FI and FII type rhyolites are least favorable for VMS mineralization while FIIIa/FIIIb types have been proposed as the most prospective.

FI type rhyolites appear to be particularly associated with gold-rich VMS deposits, such as the world-class Laronde deposit. The FI rhyolites are alkaline to calc-alkaline, with strongly fractionated REE patterns and strongly negative Ta and Nb anomalies. The FII rhyolites are calc-alkaline to transitional, with moderately fractionated REE patterns and moderate Ta and Nb anomalies and considered more favorable than FI rhyolites. The FIIIa and FIIIb rhyolites are tholeiitic and considered to have the greatest potential for hosting VMS deposits. The FIIIa rhyolites show weakly fractionated REE patterns and weak to nonexistent Nb and Ta anomalies. The FIIIb rhyolites are high-temperature rhyolites with flat REE patterns that lack Ta and Nb anomalies. (Gaboury and Pearson, 2008)

Trace element analysis plotted as $[La/Yb]_{CN}$ versus Yb_{CN} for the two rhyolites hosting sulfide mineralization in the Back Forty deposit classifies these rhyolites as FI type under the scheme proposed by Leshner et al. (1986) and Barrie et al. (1993). Trace element analysis plotted as Zr/Y versus Y places these two rhyolites under the FII/FIIIa classification. The elements Zr, Y, La, and Yb are most useful for trace element analysis because they are generally immobile during hydrothermal alteration and are representatives of petrogenetic processes (Gaboury and Pearson, 2008). The FI classification of these rhyolites based upon $[La/Yb]_{CN}$ versus Yb_{CN} and the high amount of gold associated with the Back Forty is consistent with FI type association under this classification scheme. However, the trace element plot of Zr/Y versus Y places these rhyolites under the FII/FIIIa classification scheme. While this classification scheme has demonstrated the usefulness of rhyolite geochemistry for exploration in some areas, more work is required to characterize each type based on actual mineral deposits. For this reason, Gaboury and Person (2008) suggest that a combination of rhyolite geochemistry, volcanic facies, and the style of sulfide mineralization may be more meaningfully applied in exploration than rhyolite type alone. This is particularly important in the case of FI and FII rhyolites associated with VMS deposits of post-Archean age, such as the Back Forty deposit.

This research will explore the use of not only rhyolite classification, but sulfur isotope analysis and petrographic techniques to characterize the Back Forty VMS deposit. This research will investigate the relationship between the pattern of distribution of sulfur isotopes in sulfide minerals of the Back Forty deposit, the mode of occurrence of the ore body, and textural characteristics of the sulfide ore minerals. Sulfur isotope values will help to characterize the distribution of sulfide minerals in the Back Forty deposit and to model the origin of sources. Sulfur isotope analysis may reveal episodic pulses of hydrothermal fluids as well as the source of sulfur (i.e., magmatic sulfur with $\delta^{34}\text{S}$ values of 0 ± 2 per mil, biogenic sulfur with negative $\delta^{34}\text{S}$ values, and surface-derived sulfur with positive $\delta^{34}\text{S}$). Sulfur isotope values measured in VMS deposits in other parts of the world, notably the Archean Kidd Creek VMS deposit in Ontario, Canada, indicate isotopic disequilibrium. In the study conducted on Kid Creek by Hannington et al. (2006), $\delta^{33}\text{S}$ values in conjunction with $\delta^{34}\text{S}$ values were used to model sulfur isotope systematics in Archean ore deposits. A similar study was conducted by the U.S. Geological Survey and U.S. Department of Interior (Taylor et al., 2010) on the Greens Creek VMS deposit located in Admiralty Island, Southeastern Alaska. Sulfur isotope analysis on the Greens Creek VMS produced $\delta^{34}\text{S}$ values of -11 to -16‰ and has been interpreted by Taylor et al. (2010) as resulting locally from the organic reduction of seawater sulfate to H_2S .

Sulfur isotope analysis has never been used on the Back Forty deposit. The relationship of the mode of occurrence of sulfide mineral deposits at Back Forty with sulfur isotope signatures will provide important geochemical constraints on the origin of the deposit. This geochemical dataset will also be useful to model the origins of other VMS deposits in the Penokean Volcanic Belt and to explore for new economic sulfide deposits associated with rhyolitic host rocks.

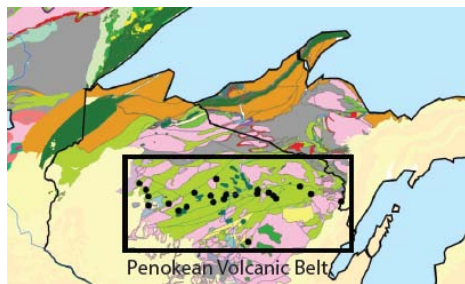


Fig. 1: Locations of VMS deposits along the E-W trend of the Penokean Volcanic Belt in northern Wisconsin. The Back Forty is the easternmost deposit of this trend and is the only VMS deposit found in the Michigan Upper Peninsula.

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ZIRCONIUM/HAFNIUM FRACTIONATION IN SOME PEGMATITES OF THE UPPER MIDWEST, USA

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Zirconium and hafnium form a coherent pair, being of similar radius and chemistry, and mutually substitute in various Zr minerals. Zircon, nominally ZrSiO_4 , incorporates Hf levels reflecting the relative Hf contents of the crystalizing melt, which in turn reflects the degree of fractionation or evolution of the melt, rarely culminating (in highly evolved pegmatites) in the very rare Hf dominant analog hafnon. In the course of our studies of pegmatites in Wisconsin, Michigan and Minnesota, considerable data have been developed regarding chemistry of zircons from these pegmatites, in particular regarding Hf, which will be discussed below.

HfO₂ contents in zircons from source granites are generally low, in the range of 1-2 wt% (Fleischer, 1955, Wang et al, 2000), though higher levels have been reported in evolved granites (e.g. Wang, et al 2000). For local comparisons, a zircon from typical Nine Mile granite, Marathon Co, WI was analyzed, and found to contain 1.0-1.2wt% HfO₂, zircons from the Zunker property (site of a former zircon mining attempt) in the Stettin Complex, Marathon Co, WI contained 1.8 to 2.2wt% HfO₂, and zircons from the Bell Creek Granite (Marquette Co, MI) contained 3.8 to 4.3wt% HfO₂. Results from Midwest pegmatite zircons are summarized below. The lists of associated minerals are not intended to be complete, but rather to suggest the degree of fractionation achieved, with emphasis on Mn/Fe, Nb/Ta, W, Sn and F.

Waterloo Quarry, Jefferson Co, WI: (Small fractionated pegmatites emplaced in quartzites/metapelites, associated minerals: columbite-(Mn), tantalite-(Mn), microlite, gahnite, Bi): 8.1 to 10.9 wt% HfO₂.

Wimmer Pit #3, Marathon Co, WI: (Small fractionated pegmatite emplaced in Nine Mile Granite, associated minerals: cassiterite, tantalite cassiterite, columbite-group minerals, U-rich pyrochlore, and a U-niobate phase): 1.6 to 4.9 wt% HfO₂, Hf-rich rims on zircon.

Maguire Pit, Marathon Co, WI: (Greisenized pegmatites and aplites emplaced in Nine Mile Granite, associated minerals: huebnerite/ferberite, cassiterite, topaz, W-rich columbite-group minerals, zinnwaldite, fluorite, prosopite, cryolite): 1.8 to 10.4wt% HfO₂, Hf enriched cores in and rims on zircon.

Pegmatite #22, Koss Pit, Marathon Co, WI: (Small fractionated pegmatite emplaced in aplite body in Nine Mile Granite, associated minerals: columbite-group minerals, tapiolite-(Fe), cassiterite, microlite, monazite, xenotime-(Y), xenotime-(Yb), fluorite): 7.4 to 14.6 wt% HfO₂, Hf-rich rims on U-rich zircon.

Woodland Drive Pegmatite, Marathon Co, WI: (Small unusually fractionated silica-saturated REE & Th-poor pegmatite emplaced in tabular syenite phase of the Stettin Complex, associated minerals: Ta-rich columbite-Fe, Ta-rich pyrochlore, cassiterite, ilmenite, unidentified phases): 3.9 to 8.5 wt% HfO₂.

Hoskin Lake pegmatite field (Florence Co, WI): (Moderate sized highly fractionated LCT pegmatites, associated minerals: elbaite tourmaline, tantalite-Mn, stibiotantalite, tantite, pegmatite phosphates, pollucite, rhyersonite, behierite): 6.1 to 19.8wt% HfO₂.

Groveland Pegmatite, Dickinson Co, MI: (Small fractionated pegmatite emplaced in metasediments adjacent to the old Groveland Mine, associated minerals: columbite-(Fe), tantalite-(Fe), tapiolite-(Fe), microlite, gahnite, beryl): 1.7 to 6.5wt% HfO₂.

Black River Pegmatite, Marquette Co, MI: (Small pegmatite emplaced in Archean Bell Creek Gneiss, associated minerals: columbite-(Fe), late microlite, monazite-(Ce), synchysite-(Ce), synchysite-(Y), topaz, fluorite): 3.9 to 5.3wt% HfO₂.

Orr Pegmatite, St Louis Co, MN: (Moderate sized pegmatite emplaced in biotite schist-rich migmatite, associated minerals: Mn-rich almandine garnet, magnetite, Th-rich monazite, possible chevkinite-(Ce), columbite-Fe, allanite-(Ce), titanite): 2.1 to 5.3wt% HfO₂.

Substantial enrichment in Hf is evident in many of the above pegmatites and is in accordance with observations made by Fleischer (1955) and Linnen & Kepler (2002). The enrichment present in the Woodland Drive pegmatite, emplaced in the alkalic Stettin Pluton, is particularly interesting as in all other Stettin zircon samples Hf contents are quite low.

The highest HfO₂ levels, from pegmatites in the Proterozoic Nine Mile Granite, are closely associated with highly fractionated Nb-Ta minerals, as well as high to very high F levels (as evidenced by late fluorite and other F-rich minerals). It is likely that high Hf levels in the evolved zircons are related to the relatively greater stability of Hf-F vs Zr-F complexes (Linnen & Kepler, 2002). Break down of Hf-F complexes triggered by the formation of F-rich minerals released Hf which was then incorporated into the outer zones of growing zircon crystals.

The high levels of enrichment in HfO₂ observed in the Florence County pegmatites can be attributed to the extreme level of fractionation achieved in these LCT pegmatites. F is present in various phases, but does not approach the high levels observed in the Nine Mile Granite and the Stettin Complex, and is unlikely to be the driving factor in this fractionation.

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A NEW OCCURRENCE OF THE SUDBURY IMPACT LAYER IN THE GOGEBIC IRON RANGE OF WISCONSIN

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Exploration drilling in 2014 by Gogebic Taconite, LLC in the western Gogebic Iron Range in northern Wisconsin provides seven new intersections of the Sudbury impact layer (SIL) (Fig. 1). Together with a hole drilled previously, they reveal features of the SIL along 6 km of strike length. Data presented here are observations of drill core and preliminary microscopic examination. The SIL lies at the expected stratigraphic position- at or very near the contact of the underlying Ironwood Iron-formation and Tyler Formation. The Ironwood-Tyler contact appears transitional as evenly bedded magnetic iron-formation of the Pence Member of the Ironwood grades upward into nonmagnetic laminated argillite of the lower Tyler Formation. The precise location of the contact is generally arbitrary; we have seen no indications of a hiatus in sedimentation between the Ironwood and Tyler. Although the Pence Member is predominantly evenly- and thinly-bedded at this locality, it contains a few interbeds of wavy bedded granular iron-formation suggesting that at the time of deposition of the SIL the area was submerged to depths only slightly below the maximum depth of surface wave agitation.

The SIL here consists of ejecta having similarities to many other SIL localities reported previously in the Lake Superior region. The most definitive features are accretionary lapilli (Fig. 2), altered glass spherules and fragments of diverse character (Fig. 3), and a very sparse suite of quartz grains showing relict planar deformation features (Fig. 4). The rocks are somewhat metamorphosed so that biotite, chlorite, and sericite are common in the matrix. Secondary carbonate is widespread and obscures much of the original texture. Fragments of argillite are also common. Together, these lithologies vary in total thickness from about 20 m to only 0.1 m along the 6 km strike length studied to date. In some drill cores, a zone of seismically disrupted sediments underlies the ejecta.

Several features suggest that the SIL is largely, or entirely, reworked ejecta mixed with more local sediments. One drill hole contains several clasts of lapillistone at least 5 cm diameter about 15 cm above the base of a 1.2 m thick ejecta layer (Fig. 2). The clasts appear to be original lapilli-bearing material that was lithified (or frozen?), fragmented, and redeposited in its present position. Many clasts of Tyler-like laminated argillite are included within ejecta and vary from thin wisps of apparently soft sediments to much thicker intervals. The thickest of the SIL drilled sections contains four intervals of distorted laminated argillite from 3 m to less than 1 m thick. A second drill core contains a 4 m interval composed of lapilli-bearing ejecta interlayered with five intervals of laminated argillite as much as 1.5 m thick. We interpret the argillite to be clasts of semiconsolidated Tyler Formation that were incorporated into debris flows composed originally of ejecta. This implies that a nearby elevated area existed onto which ejecta originally was deposited and subsequently slumped into the deeper water of this area. Such an elevated area probably existed only a few tens of kilometers to the east. The classic five-fold stratigraphy of the Ironwood, defined in the central and eastern Gogebic Range, includes the Anvil Member, a

shallow water granular iron-formation that overlies the Pence Member in that area. Deposition of the Anvil was probably followed by uplift that raised the Anvil above sea level. The base of the Tyler in that area is a basal conglomerate (Pabst Member of the Tyler Formation) that marks a short-lived erosion interval between the Tyler and Ironwood (see Cannon and others, 2008 for a summary of previous publications on stratigraphic details). Our preliminary model, therefore, begins with deposition of the Sudbury ejecta, in part in a terrestrial setting, to the east of our study area. The ejecta deposit was partly lithified before being remobilized and traveling as debris flows that incorporated newly deposited argillite to the current depositional site. Thus, at least part of the SIL in the western Gogebic Range may not record the instant of impact, but rather is a younger deposit whose deposition was delayed sufficiently to allow partial lithification of the ejecta and deposition of at least a thin layer of Tyler argillite.

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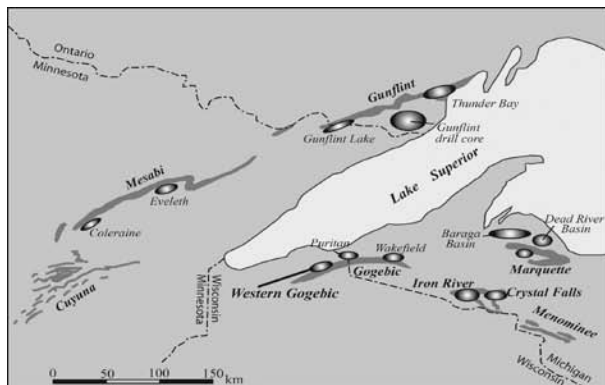


Figure 1. Location of western Gogebic Range locality.

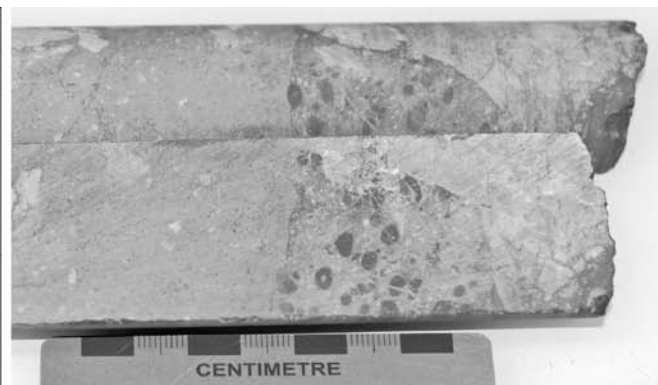


Figure 2. Accretionary lapilli. Note that these lapilli are within a fragment of lapillistone.

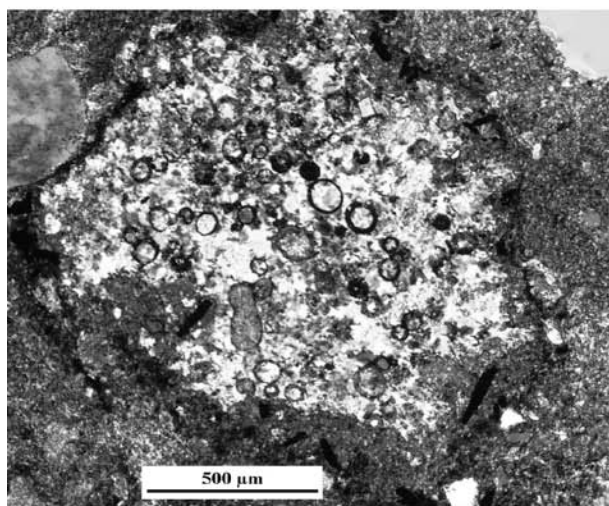


Figure 3. Glass particle. Now a matrix of microcline with relict internal spherical structures.

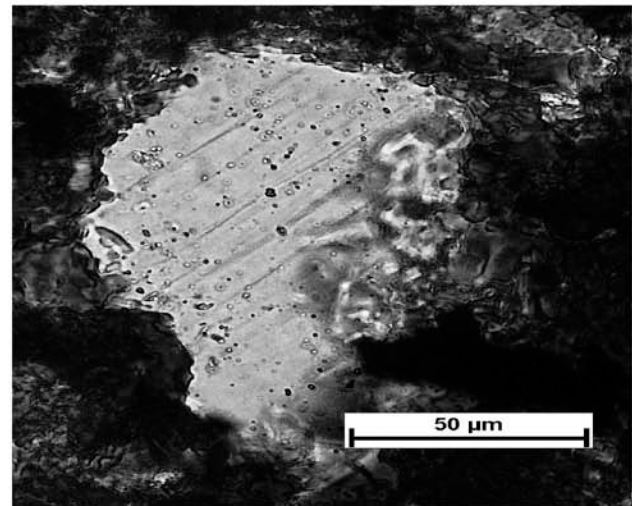


Figure 4. Quartz grain with relict planar deformation features.

CONTINUED WORK ON USING THE HORIZONTAL-TO-VERTICAL SPECTRAL RATIO (HVSr) PASSIVE SEISMIC METHOD FOR DETERMINING QUATERNARY SEDIMENT THICKNESS IN MINNESOTA

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Work has continued on using the horizontal-to-vertical-spectral ratio (HVSr or sometimes H/V) passive seismic method for determining the thickness of Quaternary sediments in Minnesota, which consist chiefly of Pleistocene glacial deposits. The HVSr method is used to estimate the primary resonant frequency (shear wave) of unconsolidated sediments. If the acoustic impedance (density*seismic velocity) at the sediment-bedrock contact differs by a factor of at least 2, and if this surface is reasonably flat, the thickness (z) of the unconsolidated materials can be estimated by the relationship:

$$z = a f_0^b$$

Where f_0 is the estimated primary resonant frequency, and a and b are parameters that are calibrated empirically for a given area from control points where a wide range of bedrock depths are known. Once calibrated, the relationship can be used to estimate depths at points lacking control. Due to the pronounced variations in shear-wave velocities for glacial deposits, calibrated parameters are reliable only within fairly localized areas, and multiple calibrations may have to be conducted for larger regions. At control points where z is known, the average shear-wave velocity (V_s) of the unconsolidated sediments can also be estimated.

During the spring and summer of 2013 more than 425 passive seismic stations were acquired, bringing the total to over 1100 passive seismic stations in Minnesota and adjacent parts of Wisconsin (Figure 1). The most recent work has been focused in the “Arrowhead” area in northeastern Minnesota, in Kanabec County in east-central Minnesota, and along profiles that traversed parts of Becker, Clay, Hubbard, Todd and Wadena Counties in northwestern Minnesota (Figure 1)

Considerable scatter is observed in the f_0 vs z relationships at control points in the new study areas, implying that V_s values vary significantly, both laterally and vertically, and more than one depth calibration may be needed for each area. In addition, HVSr results were commonly poor in parts of the Arrowhead area where unconsolidated sediment was thin (<15 meters), most likely reflecting an irregular bedrock surface. In spite of these limitations, the HVSr method was nonetheless useful in mapping the thickness of Quaternary sediments in both the Arrowhead and Kanabec County areas. In Kanabec County the HVSr-results were combined with drillhole and gravity data to produce residual gravity data that further helped in mapping the thickness of Quaternary sediments. Preliminary analysis of HVSr data in northwestern Minnesota indicates good results in Clay County, and in western Becker, northern Hubbard, northern Todd, and southern Wadena Counties, whereas generally poor results were observed elsewhere. Further work is being planned for the northwestern part of the state this summer.

In summary the HVSR passive seismic method continues to be a very useful tool for estimating the thickness of Quaternary sediments in Minnesota and adjacent areas, provided the appropriate cautions are heeded. In some situations the HVSR methods will provide a suitable and much cheaper alternative to conventional seismic sounding, and when not, it will at least help in prioritizing and targeting areas where conventional seismic sounding is necessary.

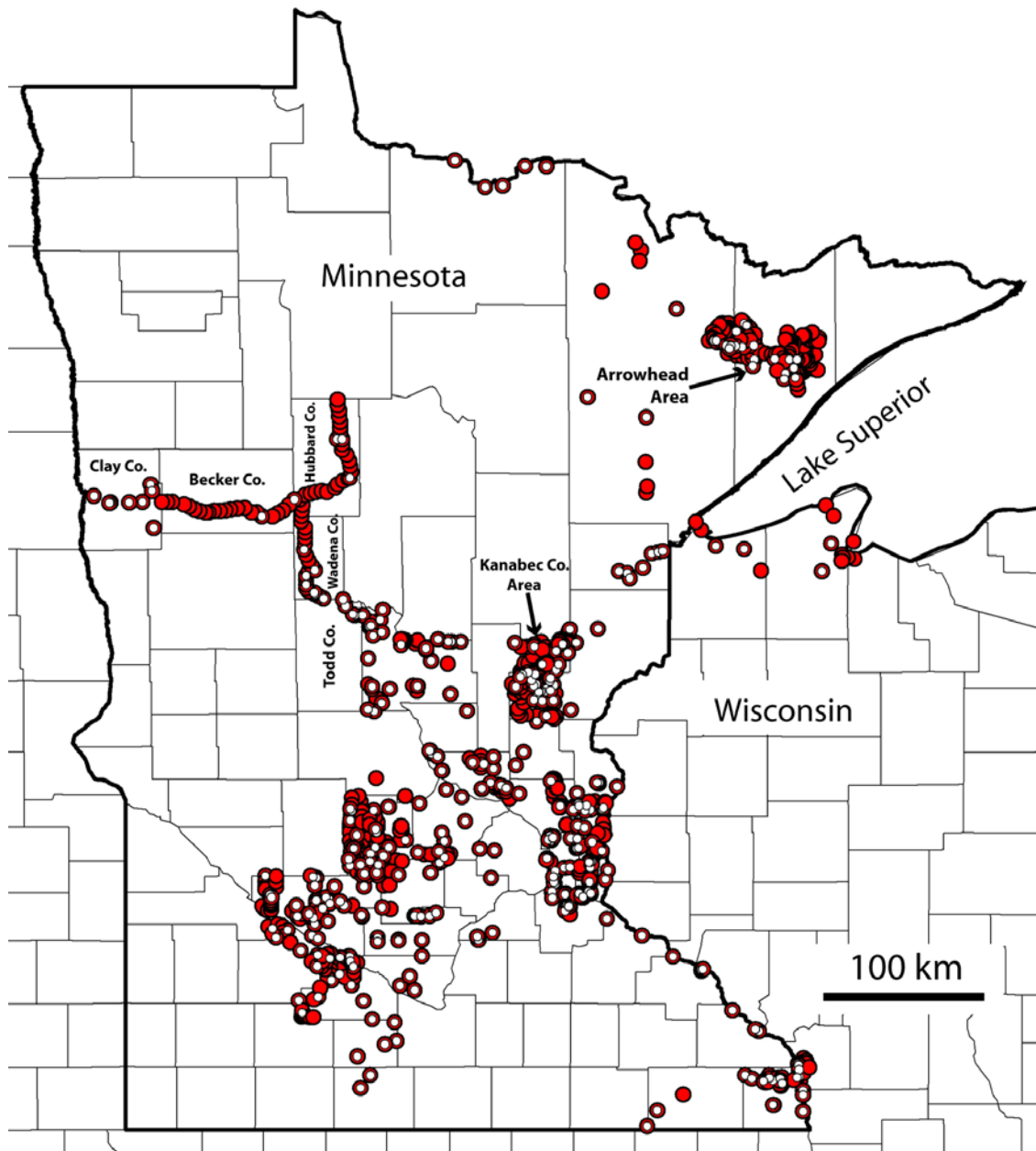


Figure 1. Map showing all passive seismic stations that have been acquired in Minnesota and adjacent parts of Wisconsin through the summer of 2013 (red circles). Stations highlighted in white represent control points where bedrock depth is known through either drillholes or seismic soundings.

EVIDENCE OF SIMULTANEOUS BRITTLE AND DUCTILE DEFORMATION IN THE MAIN BREAK FAULT SYSTEM IN KIRKLAND LAKE, ON

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Microstructural analysis provides evidence of significant ductile deformation concentrated along the main break, in Kirkland Lake, ON. The Main Break is an east-west striking mineralized fault system that has sustained multiple gold mines since its discovery in 1911. It is found in the southern Abitibi gold belt on Kirkland Lake Gold Inc.'s Lakeshore Mine property, which is a structurally controlled orogenic gold deposit.

Oriented samples for microstructural analysis were collected from two new 1-meter long channels across the main break spaced eight meters apart (Fig.1). Samples were examined in transmitted and reflected light microscopy. Evidence of ductile deformation by dislocation creep to produce mylonite includes porphyroclasts of potassium feldspar in an extremely fine-grained matrix, mineral alignment, undulatory extinction and subgrains in potassium feldspar, as well as lenticular aggregates of feldspar and muscovite showing dextral shear sense (Fig.2). Dislocation creep occurs in feldspar during ductile deformation at temperatures in the amphibolite facies of metamorphism or higher which puts deformation of the Main Break at temperatures above 400°C.

Sericite aggregates replacing potassium feldspar likely enhanced grain softening during this ductile deformation process. Sericite as well as evidence of pressure solution along grain boundaries indicate the presence of a hydrous fluid during deformation.

The most significant evidence of simultaneous brittle-ductile deformation is a potassium feldspar porphyroclast with strong undulatory extinction and subgrains in one half of the grain and microfractures in the other half (Fig.3).

We conclude that the main break is a narrow ductile shear zone with minor brittle deformation.

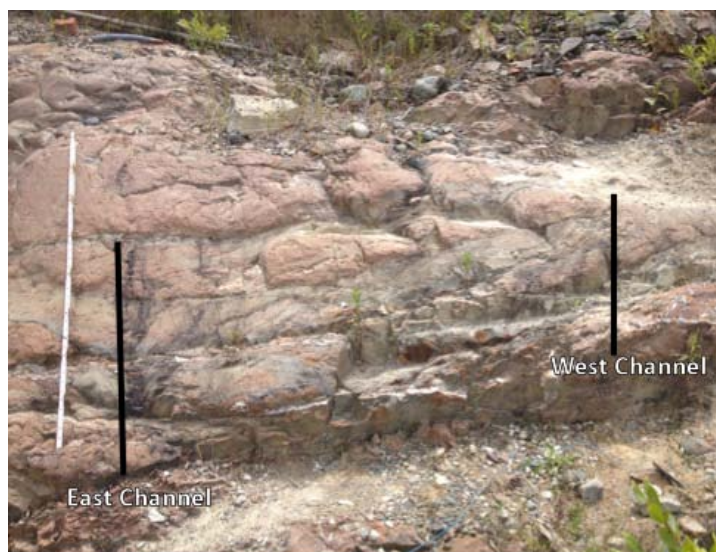


Figure 1. Main Break outcrop with channel samples shown in black lines

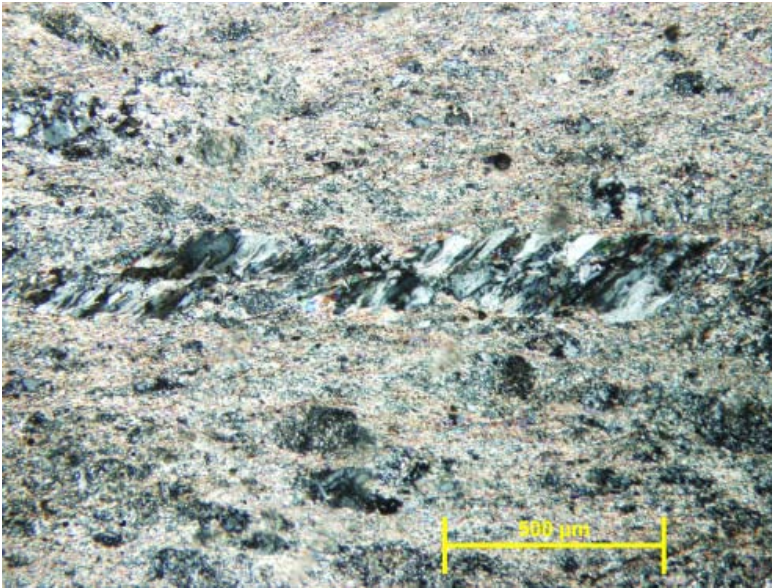


Figure 2. Lenticular aggregates of feldspar and muscovite showing dextral shear sense

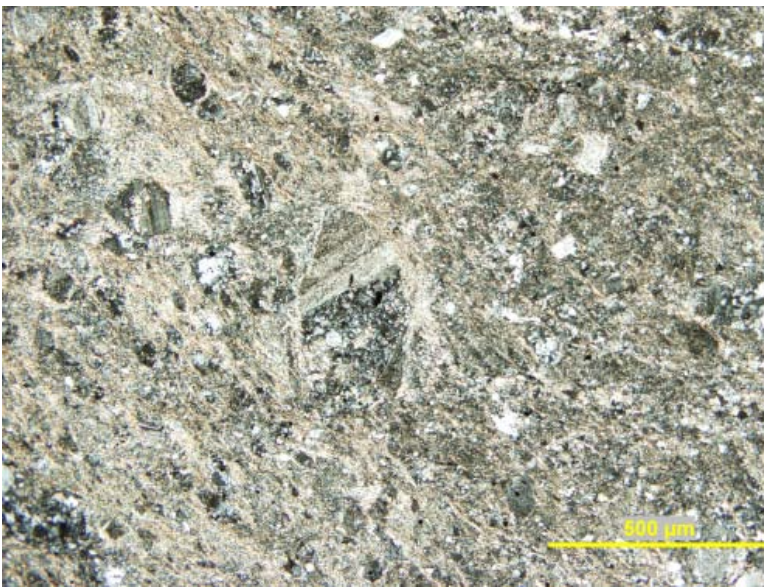


Figure 3. K-spar porphyroblast showing mutually overprinting brittle and ductile deformation

GEOLOGY AND GEOCHEMISTRY OF THE MESOPROTEROZOIC BADWATER INTRUSIVE COMPLEX, ONTARIO: IMPLICATIONS FOR GEON 15 MAGMATISM

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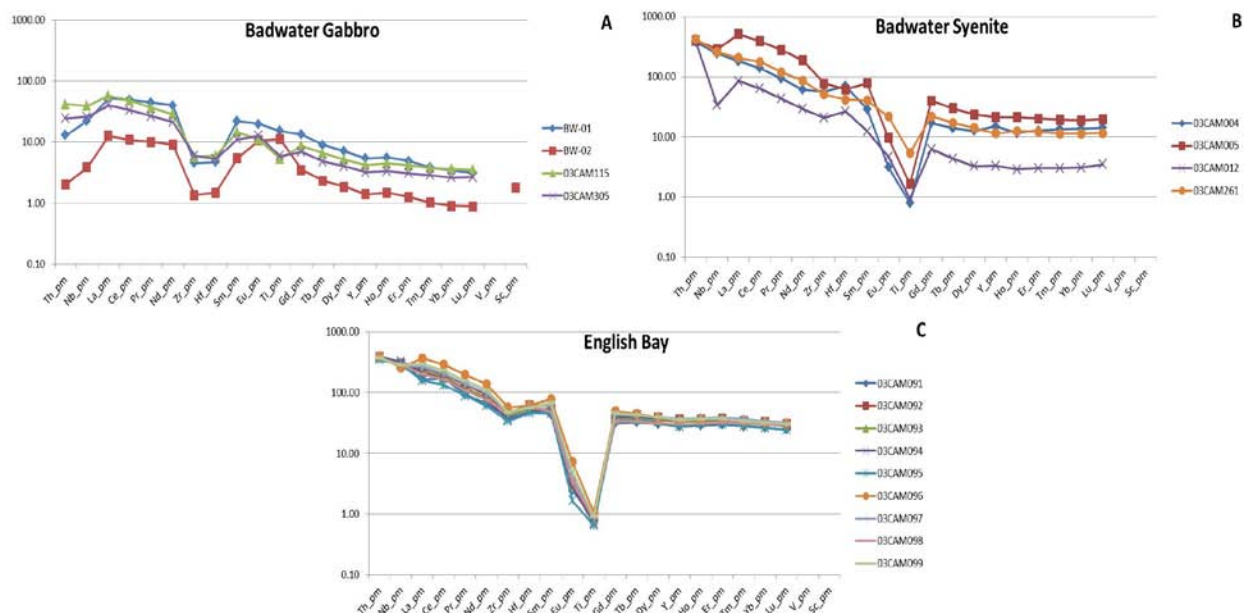
The Mesoproterozoic Badwater Intrusive Complex (a.k.a. Waweig Troctolite Complex; *cf.* Borradaile and Middleton, 2006) intrudes Archean Wabigoon Subprovince country rocks, 13 km southwest of Armstrong, Ontario. This proposed complex comprises the Badwater Gabbro (BG) and the Badwater Syenite (BS). It is believed to form a multi-phase, intrusive complex which is expressed by a circular magnetic anomaly 12 km in diameter (Borradaile and Bennett, 2008). Initial mapping by MacDonald (2004) identified a variety of intrusive rocks, ranging from gabbro to quartz monzonite and syenite. They are unconformably overlain and largely obscured by Pillar Lake volcanic rocks which were possibly erupted at 1129 ± 4.6 Ma (U-Pb age from titanite) which would then likely represent early Midcontinent Rift magmatism (Heaman et al., 2007; Smyk et al., 2011).

The poorly exposed BG was first recognized in 2000 by East West Resources Corp. (Middleton 2004) and was tested for PGE mineralization in drilling campaigns carried out in 2004 and 2008. The BG is described as a layered troctolite-gabbro complex consisting of olivine gabbro, anorthosite, troctolite, glomeroporphyritic rocks and layers of magnetite with sulphides (Middleton and Bennett, 2008). Magmatic layering dips $\sim 45^\circ$ to $\sim 55^\circ$ southeast. Modal mineralogy for typical olivine gabbro is listed as: plagioclase (labradorite/bytownite) 55%; clinopyroxene (augite?) 25%; biotite 10%; olivine (partly relict) 3%; talc/sericite (after olivine) 2%; amphibole (secondary actinolite) 2%; opaque (magnetite? pyrrhotite?) 2%; clay?/sericite (after plagioclase) trace (Middleton and Bennett, 2008). The BG is undeformed and displays generally fresh plagioclase and relatively unaltered olivine.

The Badwater Syenite likely represents a multi-phase intrusion, characterized by intrusive breccias and hybrid rocks resulting from assimilation and contamination. Syenite dykes crosscut BG and BG xenoliths occur in syenite. High-precision U-Pb dating of baddeleyite yielded an emplacement age of 1598.7 ± 1.1 Ma for the BG and a U-Pb zircon age of 1590.1 ± 0.8 Ma for the BS, which supports observed cross-cutting relationships (Heaman et al., 2007).

A possible genetic relationship between the BG and the BS can be tested using geochemistry. The BG is geochemically distinct from the BS on primitive mantle-normalized diagrams. The BG shows a flatter REE pattern with slight LREE enrichment, moderate HREE fractionation ($Gd/Yb_n = 2.4$ to 3.9) and pronounced negative Zr and Hf anomalies (Fig. 1A). The BS shows a steeper REE pattern characterized by strong LREE enrichment, weak HREE fractionation ($Gd/Yb_n = 1.3$ to 2.2) and pronounced negative Eu and Ti anomalies (Fig. 1B). It should be noted that two BG samples (03CAM115 and 03CAM305) were taken from mafic phases within the BS on the shore of Pillar Lake (not from within the main body of the BG) and display lower Gd/Yb_n ratios than those taken from the two BG outcrops north of Pillar Lake (BW-01 and BW-02) which display Gd/Yb_n ratios of 3.88 and 3.90, respectively. The trace element patterns for the BS show distinct similarities to those for the nearby 1546.5 ± 3.9 Ma (Heaman et al., 2007) English Bay granite-rhyolite complex (EBC) (Fig. 1C).

Based on similar trace element geochemistry, it would appear that the BS was derived from a similar source to the EBC, despite the 50 m.y. gap between the two units, whereas the BG appears to be sourced from a deeper source region. Hollings et al. (2004) suggested that the anorogenic EBC was derived from a mantle plume and it recorded the northern portion of a Mesoproterozoic plume track which produced anorogenic granites throughout North America. If the BS and the EBC are genetically related, the plume would have been attached to the base of the lithosphere for ~50 m.y. before detaching to create the anorogenic granites to the south in the United States. The BG could represent an early expression of the plume emplaced through a lithospheric-scale structure allowing for the tapping of a deeper-seated source. Alternatively, it may represent an earlier, unrelated plume that exploited the same structures as the EBC. Further work will elucidate intrusive relationships and possible regional associations.



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PETROLOGY OF THE LAYERED NORTH LAC DES ILES INTRUSION, ONTARIO; PART I. STRATIGRAPHY AND MINERAL-CHEMICAL EVIDENCE FOR MULTIPLE MAGMA INJECTION

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The North Lac Des Iles Intrusion (NLDI-I) is a large, multi-phase, layered ultramafic intrusive component of the Lac des Iles Complex located in the northwest Ontario, which also includes the mafic Mine Block intrusion that has been extensively studied because of the palladium mining over two decades. The NLDI-I is an extensive (~25km²) well-layered tadpole-shaped complex, characterized by a series of nested bodies emplaced into the Archean tonalitic basement rocks of the Central Wabigoon Subprovince (McCracken et al., 2014). Two major intrusive centres, the Northern Ultramafic Centre (NUC) and the Southern Ultramafic Centre (SUC), are distinguishable based on dominant lithologies and attitudes of layering (Sutcliffe and Sweeney, 1986; Brugmann et al., 1989; Gupta et al., 1990; Brugmann et al., 1997).

The focus of this study is the eastern limb of the NUC, which is a nearly circular funnel-shaped body with a mean diameter of approximately 4 km (Stone et al., 2003). Gravity modelling indicates that the NUC body thickens southward from a thickness of 1 km at the north end of NLDI to 3 km at the contact with the SUC (Gupta et al., 1990). North American Palladium's integration of historical geological data with recent geophysical surveys shows that the magmatic layering is concentric and is preserved in the eastern part of northern centre but, is disrupted in the west by several smaller bodies of irregular to semi-elliptical shape.

Bedrock mapping and reconstruction of 1.5 km long stratigraphic traverse of the eastern flank of the NUC show that it consists of a shallow, west- to northwest-dipping, layered sequences of ultramafic cumulate assemblages composed of olivine, chromite, clinopyroxene (augite) and orthopyroxene (bronzite). These sequences are characterized by regular repetitions of cumulate assemblage that define cyclic units that range from 50 to 250 meters in thickness. The upward progression of a typical cyclic unit is a basal olivine-chromite cumulate (dunite) grading into an olivine-bronzite-augite ± chromite cumulate (olivine websterite) and capped by a locally feldspathic augite-bronzite cumulate (websterite). In some cyclic units, however, the olivine websterite cumulate is absent. Contacts between cumulate assemblages within cyclical units are gradational over 0.5 to 3m to less commonly sharp. Minor plagioclase commonly occurs as an intercumulus phase in the websterite, but locally is abundant (up to 70 modal %) and can display cumulus texture in thin lenticular intervals.

Although cyclic units appear throughout the NLDI-I, cyclic units in the lower part of layered sequence are dominated by websterite assemblages and are thus designated as the Pyroxenite Zone. This zone is composed of three, thick (200-250m) cyclic units that have websterite/dunite unit thickness ratios averaging 3:1. The upper cyclic units, in contrast, tend to be thinner (20-175m) and are dominated by olivine-bearing intervals (websterite:dunite unit thickness ratios average 2:3. This sequence is designated as the Peridotite Zone.

Electron-microprobe analyses of cumulus olivine, chromite, and pyroxene compositions from drill core NL12-100, which profiles the two zones, are shown in Figure 1. The total ranges of compositions are not significantly different between the two zones, implying that the composition of the parent magma was likely the same for both sequences. Although a cyclical cryptic variation is evident throughout the core and consistent among the different cumulus phases, the breaks in mineral composition (dashed lines in Fig. 1) do not consistently correlate with cyclical boundaries. If this cryptic variation was due to repeated magma recharge pulses followed by fractional crystallization, the mineralogically most primitive dunite cumulate units would be expected to have the highest mg# ($=\text{MgO}/(\text{MgO}+\text{FeO})$, mole%) and the upper websterites to be the most evolved. However, this type of cryptic variation is clearly evident only in the

upper (third) cycle of the Pyroxenite Zone. The cryptic break at the boundaries of cyclic units 1-2 and 3-4 is displaced upward from the lithologic contact. The density of data in the Peridotite Zone cycle is not sufficient to evaluate a correlation between cumulus phase layering and cryptic layering.

The cause of the deviations from expected correlations between cumulus phase layering and cryptic layering and other petrologic aspect of the NLDI-I stratigraphy are still under investigation. Some possible processes being evaluated include: 1) variations in trapped liquid shift wherein primitive cumulus compositions are reset to lower mg#s by reequilibration with intercumulus liquid; 2) differences in the partitioning of MgO and FeO between cumulus olivine, clinopyroxene, and orthopyroxene (MgO is more compatible in pyroxenes than olivine); 3) changes from eutectic to peritectic relations between olivine and orthopyroxene, which could explain why olivine websterite cumulates are not always present;; and 4) contrasting densities of hot, primitive recharging magma and cooler, evolved resident magmas. If the recharging magma is denser than the resident magma, it should intrude beneath the resident magma and produce a sharp phase and cryptic change. If the recharging magma density is lower than the resident magma, it will plume into the chamber and would result an abrupt phase change and a more gradual cryptic shift to more primitive compositions. The relative volumes of recharging and resident magmas will also control the phase and mineral chemical effects.

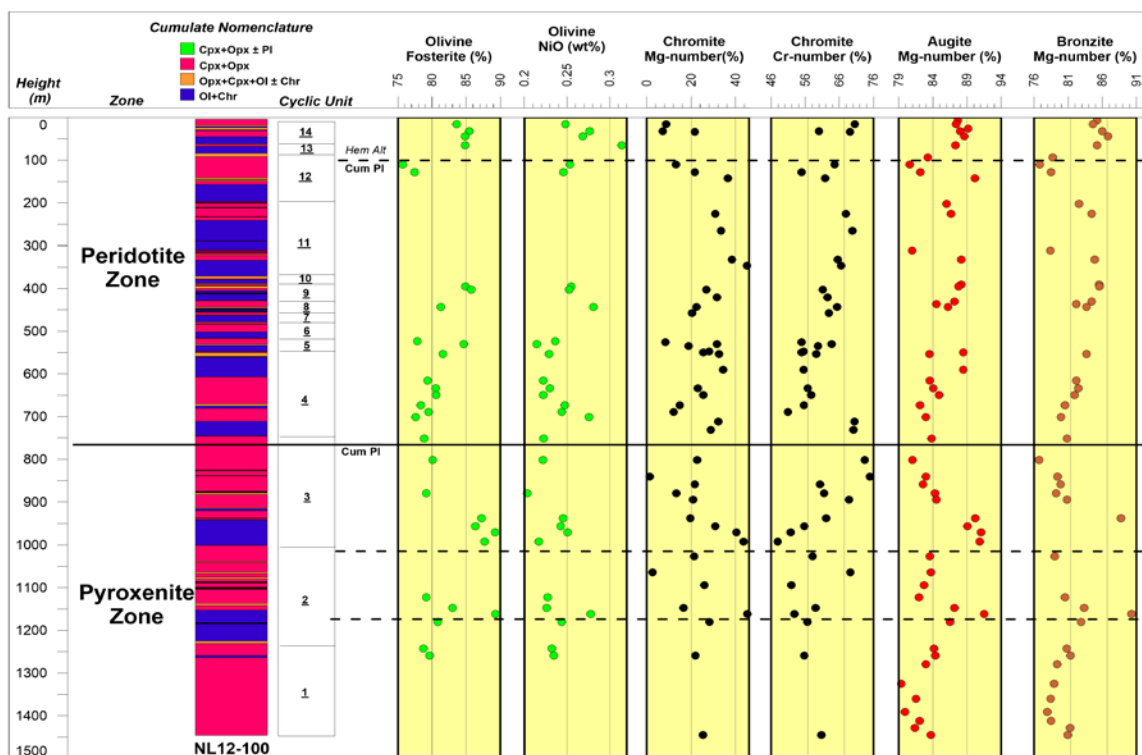


Figure 1: Cryptic variation shown by olivine, chromite, clinopyroxene, and orthopyroxene in the Peridotite and Pyroxenite zones of the Northern Ultramafic Center of the North Lac des Iles Complex.

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STRAIN ANALYSIS ON THE MAX LAKE POLYMICTIC CONGLOMERATES IN THE WABIGOON SUBPROVINCE, ONTARIO, CANADA

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The Max Lake polymictic conglomerates are exposed near Highway 527, about 88 km north of the intersection with Highway 11-17. The conglomerates are part of the Beardmore-Geraldton belt in the Wabigoon Subprovince, Superior Province of Ontario, Canada. The R_f/Φ method for initially elliptical objects was used to estimate the amount strain on the conglomerates. In the Max Lake conglomerates, chlorite-actinolite clasts are more deformed than amphibolite clasts, which are more deformed than granitoid clasts. Heterogeneous strain also occurs among different outcrops. The overall amount of strain is lower where larger, more abundant and more competent clasts are found. Petrographic and microstructural analyses were used to determine the peak metamorphic grade preserved by each clast in the polymictic conglomerate. The matrix of the conglomerate and the chlorite-actinolite clasts preserve a peak metamorphic mineral assemblage stable in the greenschist facies. The amphibolite clasts preserve a peak metamorphic mineral assemblage stable in the amphibolite facies. The preservation of the amphibolite facies metamorphic mineral assemblage in the amphibolite clasts indicates that these clasts were derived from a metamorphic terrane.

PRELIMINARY INTERPRETATION OF PRECAMBRIAN LITHOLOGY AND STRUCTURE FROM HIGH-RESOLUTION, MULTI-METHOD GEOPHYSICS, NORTHEAST IOWA AND SOUTHEAST MINNESOTA

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Large amplitude gravity and magnetic highs over northeast Iowa are interpreted to reflect a buried intrusive complex composed of mafic/ultramafic rocks, the northeast Iowa Intrusive Complex (NEIC), intruding Yavapai Province (1.8-1.72 Ga) rocks. The age of the complex is unproven, although it has been considered to be Keweenawan (~1.1 Ga). Because only four boreholes reach the complex, which is thought to be covered by 200-700 m of Paleozoic sedimentary rocks, geophysical methods are critical to developing a better understanding of the nature and mineral resource potential of the NEIC. An initial airborne data collection campaign in the region of Decorah, Iowa, included high-resolution magnetic, gravity gradient (AGG), and time-domain electromagnetic (TDEM) data.

Geophysical interpretations are presented in the form of a preliminary geologic map of the basement Precambrian rocks (Fig. 1), largely constructed by interpreting lithologies and cross cutting relationships expressed in magnetic and AGG anomalies. Numerous magnetic anomalies are coincident with AGG highs, indicating widespread strongly magnetized and dense rocks of likely mafic/ultramafic composition. A Yavapai age (Van Schmus et al., 2007) metagabbro unit (Ymg) is interpreted to be part of a layered intrusion with subvertical dip, and is thought to be among the oldest rocks present in the survey area. Another presumed Yavapai-age unit (Ysp) has low density and weak magnetization, observations consistent with granitic plutons. Northeast-trending, linear magnetic lows are interpreted to reflect reversely magnetized diabase dikes, and modeling shows that the anomalies are consistent with Keweenawan magnetization. The interpreted dikes are cut in places by normally magnetized mafic/ultramafic rocks (mi), suggesting that the latter represent younger Keweenawan rocks. Large magnetic highs without coincident AGG highs are interpreted to reflect intermediate or silicic intrusive rocks (ii). Distinctive horseshoe-shaped magnetic and AGG highs correspond with a known gabbro (dg, undated), and surround rocks with weaker magnetization and lower density (dwm). Here called the Decorah Complex, the source body has notable geophysical similarities to Keweenawan alkaline ring complexes, such as the Coldwell and Killala Lake Complexes, and Mesoproterozoic anorogenic complexes, such as the Kiglapait, Hettasch, and Voisey's Bay intrusions in Labrador. Most units are cut by suspected northwest-trending faults imaged as magnetic lineaments, and one produces apparent sinistral fault separation of a dike in the eastern part of the survey area. The location, trend, and apparent sinistral sense of motion are consistent with the suspected faults being part of the Belle Plaine fault system, a complex transform fault zone within the Midcontinent Rift System.

The TDEM data fail to directly image Precambrian rocks, due to their large burial depth. However, most of the overlying sedimentary section is well imaged, and depths to Precambrian rocks are estimated at 400-600 m based on preliminary TDEM interpretations and downward extrapolation of known stratigraphy. This interpretation is consistent with the limited borehole data.

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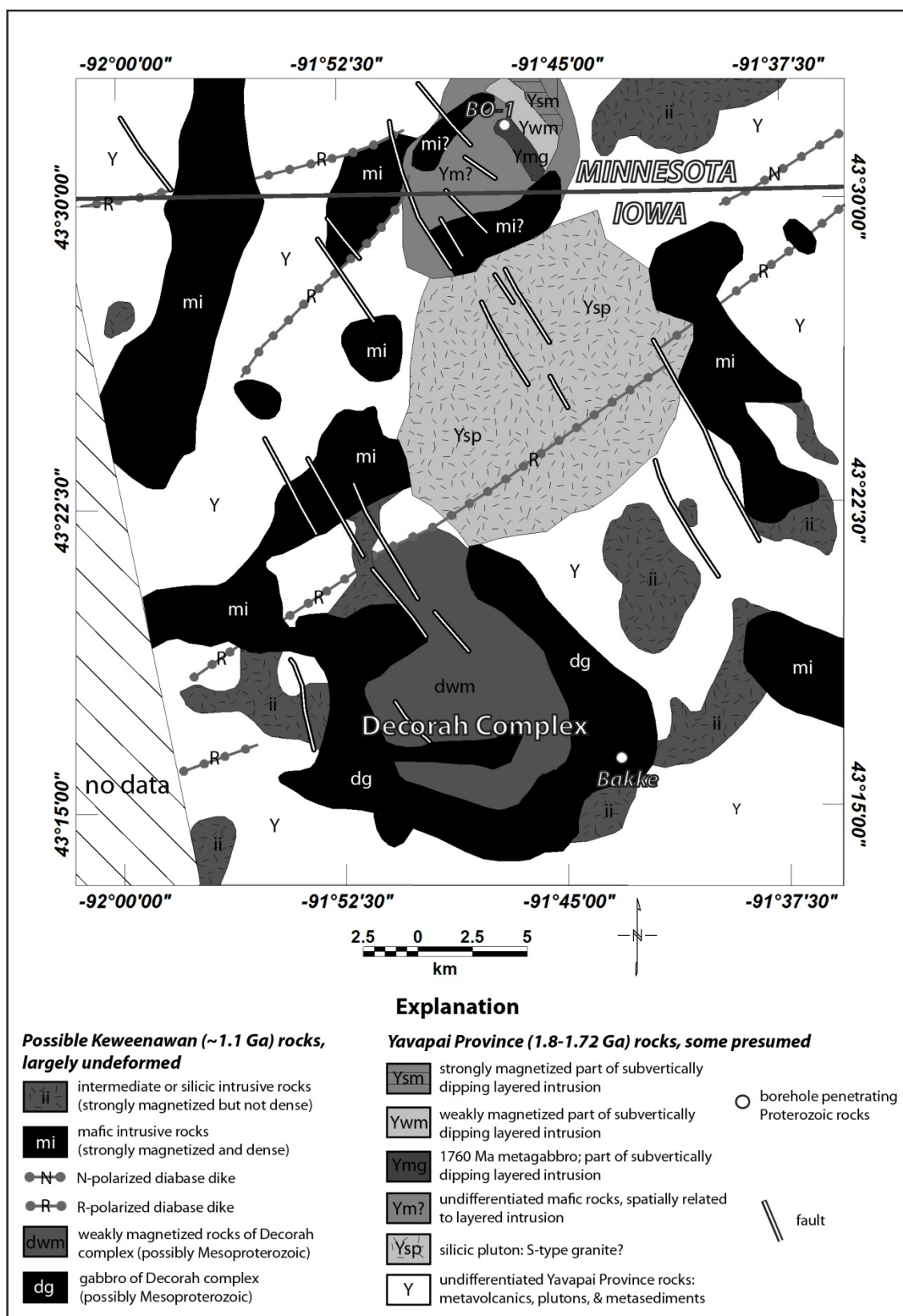


Figure 1: Preliminary geologic map of Precambrian crystalline rocks, interpreted from limited boreholes and high-resolution airborne gravity gradient and magnetic data.

Structural and Kinematic Analysis of the Shagawa Lake Shear Zone: Implications for Archean Tectonic Processes in the Southern Superior Province (Part 2 of 2)

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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 (e.g., Percival et al., 2007, and references therein). The Wawa Subprovince, southern Superior Province, is widely interpreted as a transpressional margin with shear zones recording unidirectional dextral strike-slip along the subprovince boundary (Hudleston et al., 1988; Bauer and Bidwell, 1990; Schultz-Ela and Hudleston, 1991), an interpretation held up as fundamental evidence for Archean plate-tectonic processes (Sleep, 1992). Others interpret these shear zones as recording 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 invoke different assumptions about non-coaxial shear direction. Due to the proximity of the Shagawa Lake shear zone to the Wawa subprovince boundary, structural and kinematics fabrics recorded within the Shagawa Lake shear zone have direct implications for crustal assembly of the southern Superior Province. If the Shagawa Lake shear zone records significant unidirectional strike-slip, then supported plate-tectonic models for Wawa Subprovince formation will be further constrained. If the Shagawa Lake shear zone does not record significant unidirectional strike-slip, then existing plate-tectonic and structural models of terrane amalgamation along the Southern Superior Province 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) thin-section kinematic analysis. The Shagawa Lake shear zone contains a regional subvertical metamorphic foliation with an average strike of 065 but varies locally from 065 to 100. Two types of elongation lineation occur within the Shagawa Lake shear zone. These include ridge-in-groove striations on C-foliation surfaces (Lc) and stretching lineations on S-surfaces (Ls) (Lin and Williams, 1992; Lin et al., 2007). Lc and Ls plunge steeply to obliquely, with local zones of shallow plunge, and non-coaxial shear direction is sub-parallel to elongation lineation (Dyess et al., 2014). Thus non-coaxial shear was dominantly dip- to oblique-slip with localized strike-slip. Microstructures, within foliation-normal, lineation-parallel sections, record both north-side-up and south-side-up shear in different samples. Samples with oblique lineation commonly 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 as required by accepted plate tectonic models.

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Determination of Vorticity in Archean Tectonites (Part 1 of 2)

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There is no consensus about the processes responsible for the formation of Archean crust. The Superior Province of North America is widely interpreted as a series of accreted terranes with subprovinces representing individual terranes (Talbot, 1973; Goodwin and Ridler, 1970; Langford and Morin, 1976; Dimroth et al., 1983a, b; Ludden et al., 1986; Sylvester et al., 1987). The Neoarchean (2.7-2.5 Ga) Wawa Subprovince (Fig. Location) forms a NE-trending belt of sub-greenschist to greenschist facies supracrustal rocks cut by multiple shear zones marked by a well-developed metamorphic foliation (Fm) and elongation lineation (Le). The Wawa is interpreted as a transpressional plate-margin with significant dextral strike-slip displacement (Hudleston et al., 1988; Schultz-Ela and Hudleston, 1991). This interpretation is held up as evidence for Archean plate-tectonic processes based on plate-tectonic models that require strike-slip shear zones more than 1200 km of long (Sleep, 1992). Despite apparent broad acceptance of this interpretation, the nature of shear zone deformation within the Wawa remains poorly constrained.

Displacement direction and magnitude is genetically linked to vorticity, marked by the vorticity-normal-section (VNS) and vorticity axis (pole to VNS), within L-S tectonites (Passchier, 1998; Xypolias, 2010 and references therein). However, geometric relationships between displacement direction and macroscopic structures, such as Le, can vary depending on shear zone kinematics (Passchier, 1998). Le can form parallel, perpendicular, or oblique to displacement direction during L-S tectonite formation. Therefore determination of L-S tectonite vorticity requires careful consideration before interpretation of displacement direction. A determination of the vorticity axis and observation of the geometric relationships between the VNS and Le can allow for the use of Le as a reference to non-coaxial shear direction.

In this contribution, we determine the vorticity for seven samples from two Neoarchean shear zones from the Wawa subprovince. We use a combination of thin-section, X-Ray Computed Tomography, and quartz petrofabric data. We demonstrate that the vorticity axis lies approximately within the Fm and is normal to Le and that the VNS lies approximately within Fm-normal, Le-parallel planes for all seven samples. Thus non-coaxial displacement direction is sub-parallel to Le. Regional Le orientation varies within the two shear zones ranging from steeply to obliquely plunging, with local zones of shallow plunge (Hudleston, 1976; Hudleston et al, 1988; Bauer and Bidwell, 1990; Jirsa, et al., 1992; Goodman, 2008; Erickson, 2010; Johnson, 2009; Karberg, 2009). Data indicate that non-coaxial shear direction is sub-parallel to Le regardless of Le geographic orientation.

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EVALUATING THE BIOGENICITY OF FLUVIAL-LACUSTRINE STROMATOLITES FROM THE MESOPROTEROZOIC COPPER HARBOR CONGLOMERATE, UPPER PENINSULA OF MICHIGAN, USA

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The Mesoproterozoic (1.09 Ga) Copper Harbor Conglomerate represents alluvial fan, fluvial and lacustrine deposition into the Midcontinent Rift System. The formation outcrops in the Upper Peninsula of Michigan where it contains carbonate stromatolites preserved within both siltstone and conglomerate facies. The purpose of this study is to evaluate the biogenicity of these stromatolites, which lack direct microfossil evidence. The stromatolites were placed into their depositional context, their macro-scale features and thin section microfabrics were analyzed, and growth angles were measured of cobble-draping samples to determine if a phototrophic response existed. A methodology that uses magnetic susceptibility as a biosignature was also performed on these stromatolites. The result of these analyses reveals two distinct types of stromatolites. Stromatolites from the siltstone facies are interpreted as biogenic. They contain detrital laminae, hematite-rich micritic laminae, and fenestral fabrics. The stromatolites formed as microbial mats grew over a mudflat or sandflat with carbonate filled dessication cracks and an eroded topography. Stromatolites from the conglomerate facies are interpreted to have formed by a mix of chemical and biological processes. They are microdigitate and have abiogenic features such as isopachous laminae with radial fibrous calcite fans and botryoids. They also lack a phototrophic response, suggesting that growth was not controlled by cyanobacteria. These stromatolites also have some biogenic signatures such as conical wavy laminae that have been separated by gas build-ups. These stromatolites are interpreted as having formed in a flooded braidplain setting with restricted circulation. Magnetic susceptibility tests yielded inconclusive results in this case because the stromatolites in question contain secondary hematite. This study supports previous studies of these stromatolites, as well as microbial structures and organic-rich paleosols that have suggested freshwater microbial communities were abundant in the Midcontinent Rift during the Mesoproterozoic. It also highlights how variable environmental factors can influence stromatolite growth, even in similar depositional settings and with a consistent microbial presence.

GEOCHEMISTRY OF BASALT XENOLITHS ENTRAINED IN MINERALIZED TROCTOLITIC AND ANORTHOSITIC INTRUSIONS, NORTHEASTERN MINNESOTA

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Troctolites of the Nickel Lake Macrodiike (NLM), South Kawishiwi (SKI) and Partridge River (PRI) Intrusions, as well as the varying lithologies of the Anorthositic Series (An-series), within the 1.1 Ga Duluth Complex, host numerous basaltic xenoliths. These xenoliths provide evidence that these intrusive bodies originally emplaced within the basalts and other accompanying lithologies of the North Shore Volcanic Group (NSVG; Miller and Weiblen, 1990). These xenolith packages, which include Biwabik Iron Formation, Virginia Formation and Colvin Creek metasediment, and An-series material, in addition to both magnetic and non-magnetic basalts, are often associated with sulfide-mineralized troctolitic and anorthositic lithologies. Lithogeochemical data suggests these basalt xenoliths can be grouped into three distinct categories, correlating with different mineralization styles in the host rock lithologies. This study aims to determine the nature of the apparent correlation between the presence of basalt xenoliths and Cu-Ni-PGE mineralization as well as attempt to correlate the basalt compositions with possible sources.

Samples were collected from drill holes and outcrop from the NLM, eastern margin of the SKI (East Shore), and the northeast corner of the PRI (Rook)(Fig. 1). Three groups of basalt are distinguished by relative abundances of MgO, Al₂O₃, Fe₂O₃, TiO₂, Zr, and Mg# (calculated as $Mg/(Mg+Fe^{3+}) \cdot 100$), using factor analysis (which identifies trends between multiple variables) to provide a more robust classification. Type 1 basalt xenoliths are characterized by Mg#s which range from 42-52 accompanied by elevated MgO and Al₂O₃, and low TiO₂ and Zr. Type 2 has a range of Mg#s from 19-33, along with elevated Al₂O₃, TiO₂, and Zr, and low MgO. Type 3 has a mid-range Mg# with respect to the other two types (27-36), accompanied by low MgO and Al₂O₃, and high TiO₂, Zr, and Fe₂O₃^{*}. An Mg# vs. Zr plot clearly discriminates the three different basalt xenoliths types (Fig. 2). Comparing these basalt xenoliths to basalt compositions from the NSVG using an MgO vs. TiO₂ plot demonstrates Type 2 and Type 3 basalts correlate well with compositions of basalts within the NSVG, whereas the composition of the Type 1 basalt is particularly anomalous (Fig. 3). The nearest compositional correlation to Type 1 comes from sample KEW-6, collected from the Laramont basalts of the NSVG near Knife River, MN (Boerboom et al., 2002). A closer match appears to be the P-Magma of Miller and Weiblen (1990) (Mg# 48), their representative primitive high-Al olivine tholeiitic basalt composition, which plots within the range of the Type 1 basalt xenoliths (Fig. 3).

Type 1 basalts are spatially associated with the lower contact of a Cu-Ni mineralized zone at the southwest end of the NLM. Other xenolith lithologies occurring with Type 1 basalts include Virginia Formation and Biwabik Iron Formation. Type 2 basalts are spatially associated with high-grade PGM mineralization along the SKI-An-series contact, occurring with Colvin Creek and An-series xenoliths. Type 3 basalts are spatially associated with high-grade Cu-Ni-PGE mineralization in the PRI. They are the most variable in composition, as well as geographically widespread, occurring along the eastern margin of the SKI and within the NLM as well. Xenolith lithologies associated with Type 3 basalt include Colvin Creek, Virginia Formation, and An-series.

Basalt xenolith populations can potentially be used as an indicator of the prospectivity of heterolithic mafic rocks. Correlating these xenoliths with their source areas potentially allows reconstruction of the sources and pathways of mineralized troctolitic and anorthositic magmas in the Duluth Complex.

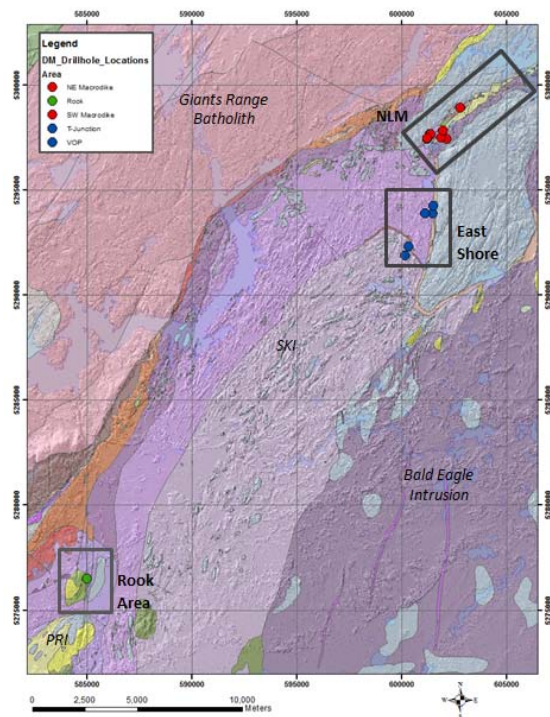


Figure 1: Map indicating spatial relationships between the intrusions and showing the xenolith rich areas of the NLM, SKI, and PRI.

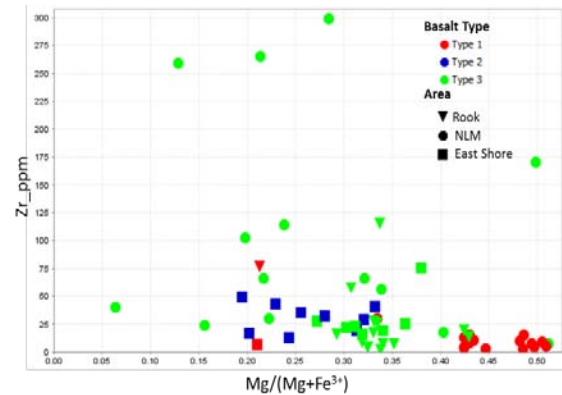


Figure 2: Plot of $Mg\# (=Mg/(Mg+Fe^{3+}))$ versus Zr (ppm). Type 1 has clustered around higher $Mg\#$ values, while Type 2 and 3 have lower and more variable $Mg\#$ ranges in conjunction with higher Zr content.

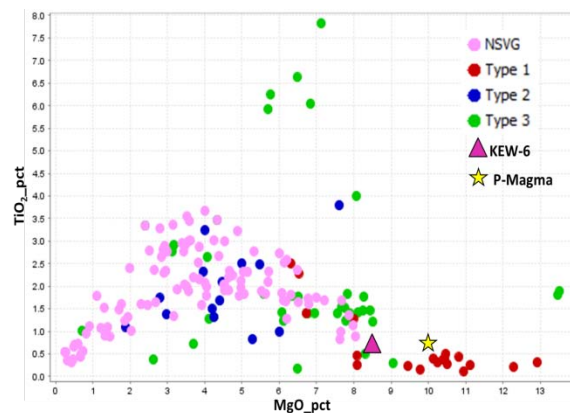


Figure 3: Plot of TiO_2 versus MgO for the three differentiated types of basalt as well as known compositions within the NSVG. Sample KEW-6 (Boerboom et al, 2002) is the sample plotted closest to the Type 1 basalt xenolith trend. The composition of P-Magma (Miller and Weiblen, 1990) is also shown.

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MAGNETIC MINERALOGY OF REVERSELY MAGNETIZED CHENGWATANA LAVA FLOWS OF ST. CROIX FALLS, WISCONSIN

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Previous paleomagnetic studies on the 1.1 billion year old Chengwatana Volcanic lava flows, located near St. Croix Falls, Wisconsin, found a period of reversed polarity within a predominantly normal sequence that was very similar to that found at another location within the Keeweenawan Rift at Mamainse Point in Ontario. Based on this observation, the two sequences were correlated with each other. However, new research at Mamainse Point (Swanson-Hysell et al., 2011) has discovered that some of the lava flows there carry a self-reversed magnetization. This means that the magnetization is opposite in direction to the Earth's field in which the rocks originally cooled. Further, data from some of the Chengwatana samples reported by Kean et al. (1997) also showed two components of magnetization approximately antiparallel to each other.

The goal of this study was to further investigate the magnetic mineralogy of the Chengwatana Volcanic lava flows in order to test that reversely-magnetized samples from Chengwatana indeed reflect a period of reversed field polarity and not a self-reversed magnetization. Thirty samples were collected in two different locations at Interstate State Park in St. Croix Falls, Wisconsin. The natural remanent magnetization was demagnetized both by alternating field (AF) and thermal demagnetization at the University of Wisconsin – Milwaukee (UWM). Also at UWM, Curie temperature was measured via temperature-dependent susceptibility using an MFK1 Kappabridge susceptibility bridge with furnace insert. Hysteresis measurements to determine grain size were carried out on a vibrating sample magnetometer at the Institute for Rock Magnetism at University of Minnesota.

Results indicate that the magnetic remanence held by both normal and reverse polarity flows, as defined previously by Kean et al. (1997), is held by multi-domain to pseudo-single-domain magnetite. Individual samples that carry two anti-parallel components of magnetization are also dominated by magnetite, and the high-coercivity or high-temperature component is similar in direction and polarity to single-component samples from the same flow. It is likely that the antiparallel component was acquired by partial remagnetization during a reheating event during a later period of opposite polarity. It does not completely overprint the primary magnetization, and the polarity sequence identified Kean et al. (1997) remains unchanged. This is in contrast to the self-reversed magnetization found in some of the Mamainse Point basalts by Swanson-Hysell et.al (2011). In those samples, the antiparallel component was controlled by fine grained hematite that acquired its magnetization during the formation of martite within the rocks. There is no indication that the Chengwatana flows share this mineralogy and the conclusions of Kean et al. remain valid.

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AN UNUSUAL MESOPROTEROZOIC CARBONATE UNIT: RELIC OF A SALINE LAKE?

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The Mesoproterozoic Rosspoint Formation of Ontario, Canada is primarily made up of sandstone and shale. The Rosspoint Formation is approximately 1.4 billion years old (Franklin et al., 1980) and is generally interpreted to have been deposited in an intracratonic basin, most likely a rift-related lake (Rogala et al., 2005). The Middlebrun Bay Member, in the middle of the formation, consists of cherty limestone containing stromatolites. While examining outcrops of the Middlebrun Bay Member on the Channel Islands of Lake Superior, we discovered an unusual limestone bed on Copper Island. This calcite does not contain stromatolites; it has an unusual bright white color and lacks internal structure (Fig. 1).



Previous work on the Rosspoint Formation suggests that the stromatolites formed when lake levels were low and not much sand was making it to the basin (Rogala et al., 2007). In this model, stromatolites would have formed in a hypersaline lake environment during intervals of low clastic influx. If this interpretation is correct, the non-stromatolitic “white-bed” could have formed as an evaporite bed, now replaced by calcite. In this study, we investigate the hypothesis that the massive white limestone unit is calcitized evaporite.



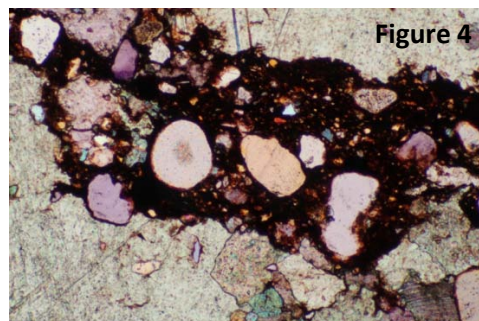
At the outcrop level, the massive white carbonate is approximately 1.1 m thick and occurs between layers of sandstone. The carbonate unit contains sandstone clasts (Fig. 2). This outcrop relationship is consistent with either collapse of sandstone during evaporite dissolution, or upward growth of evaporite rock, causing sandstone to wedge, split, and form clasts surrounded by evaporite.



The macroscopic texture of the carbonate unit is both massive and coarsely crystalline, with a texture reminiscent of chicken-wire evaporite (Fig. 3). Chicken-wire texture forms when nodules of gypsum crystals grow and push other material to their edges, forming a coarsely crystalline structure with a network of residuum outlining large crystal domains.

Thin-sections of the massive white carbonate were compared to those from Middlebrun Bay Member Stromatolites from Channel Island. The stromatolitic thin sections show relatively small crystals and fine lamination, consistent with their macroscopic texture. In contrast, the “white-bed” rock had large subhedral to euhedral crystals, with zonation apparent by

cathodoluminescence. “White-bed” samples also had a large number of stylolites, indicating substantial dissolution along crystal boundaries. Both stylolites and large crystal edges contain accumulations of insoluble residue (Fig. 4), indicating that dissolution and reprecipitation processes were important in generating the final texture of the white bed.



Chemical evidence is consistent with an evaporite origin of the “white-bed” carbonate. Trace element concentrations, measured by ICP-MS, were generally highly elevated in stromatolite samples and moderately elevated in the massive carbonate unit, compared to average Proterozoic carbonate compositions. Taken together, geochemistry suggests that both the stromatolites and the white bed were deposited in a hypersaline lake environment. Trace elements were concentrated in carbonate during precipitation of stromatolites. Primary evaporite phases would also have been highly concentrated in trace elements, but these concentrations would have decreased during dissolution of evaporites and precipitation of secondary calcite. Similar patterns of trace element enrichment are observed in hypothesized calcitized evaporites from the Mesoproterozoic Atar Group, Mauritania (Manning-Berg and Kah, 2013).

Based on the evidence collected both in the field and lab, it seems likely that the “white bed” carbonate possesses a unique texture because it was originally precipitated as gypsum. The massive, coarsely crystalline texture indicated pervasive recrystallization, consistent with a primary evaporite mineral, like gypsum, which was secondarily replaced by calcite, resulting in coarse, featureless carbonate and collapse of overlying sandstone layers. Geochemical results are consistent with deposition under hypersaline conditions. In further research we will look at sulfate concentrations, both as total S and as carbonate associated sulfate (CAS). Other calcitized evaporites have shown elevated CAS concentrations (Manning-Berg and Kah, 2013). A depositional environment where gypsum formed would indicate a saline lake, consistent with previously proposed environmental conditions for the Rossport Formation.

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GEOLOGY OF THE BRULE RIVER AREA OF THE PINE MOUNTAIN QUADRANGLE, MINNESOTA: CAPSTONE MAPPING PROJECT FOR THE PRECAMBRIAN RESEARCH CENTER'S 2013 FIELD CAMP

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The Precambrian Research Center at the University of Minnesota Duluth conducted its seventh annual Precambrian Field Camp during the summer of 2013. This presentation is one of a series that detail the results of the 2013 Capstone Mapping Projects which represent the culmination of activities at the field camp. The Capstone projects, conducted during the final two weeks of the field camp, are meant to test the skills obtained by the camp participants by conducting field studies and creating geological maps of areas of poorly understood geology. This Capstone Project involved mapping near Brule River area, in the Pine Mountain 7.5' Quadrangle, approximately 25 miles north-northwest of Grand Marais, MN.

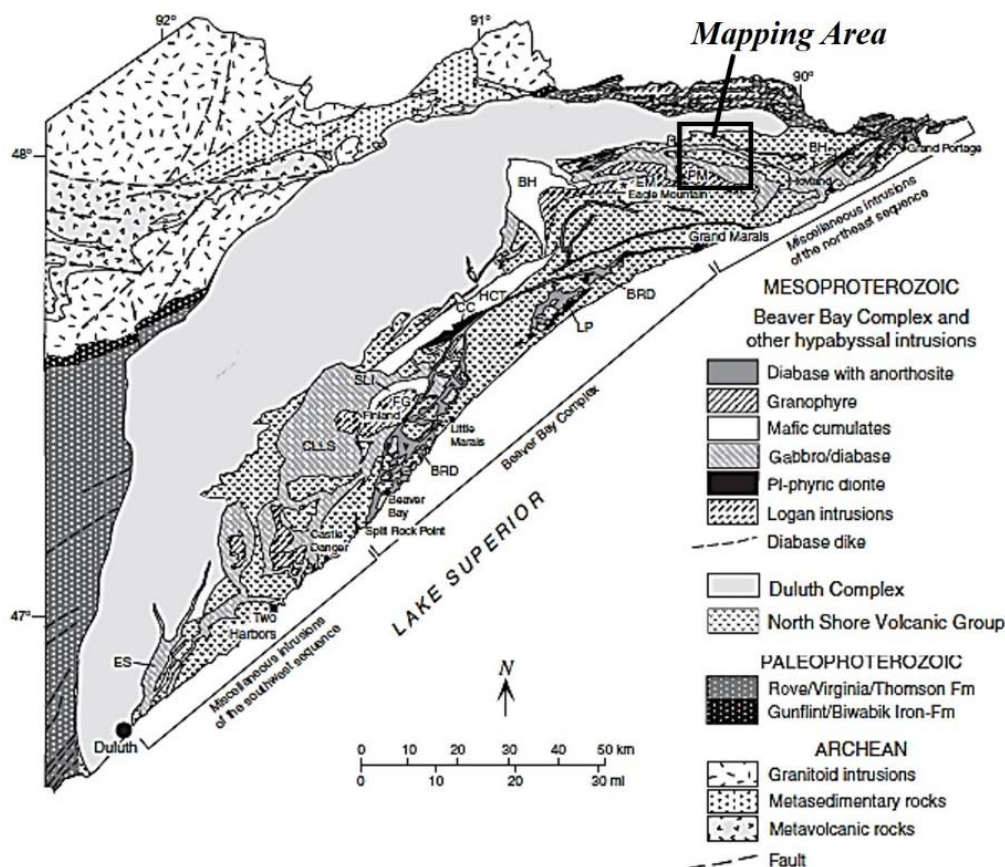


Figure 1. Geology of northeastern Minnesota showing the area of the Pine Mountain capstone mapping project. From Miller and Green, 2002

Prior to this work, the area had only been mapped in a reconnaissance fashion, and consequently the geologic detail was poorly understood and interpretations were largely derived from only geophysical data. The map area is in a geologically complex Mesoproterozoic terrane comprised largely of mafic to

felsic lavas of the Keweenaw North Shore Volcanic Group (NSVG), and later mafic to felsic intrusions related largely to the Beaver Bay Complex.

The map area lies along the western extension of the reversely-polarized Hovland lavas (1107.7 ± 1.9 Ma; Davis and Green, 1997), shown only as a single unit of undivided volcanic rocks on published maps (e.g. Miller and others, 2001). The area is bordered on the south by the Brule-Hovland gabbro complex, and is cut by roughly east-west trending diabase dikes inferred to also be related to the Brule-Hovland gabbro. Geophysical evidence implies that the latter dikes form a forked dike set which cuts the middle of the mapping area.

Our mapping has shown that multiple east-west striking, southeast-dipping, lava flows composed of alternating rhyolite and andesite are present within the map area. The rhyolites are generally quartz- and plagioclase-phyric but local aphyric varieties with large (5-10 cm) pumice inclusions were noted. Contorted flow banding and flow-aligned plagioclase laths in the rhyolites give evidence of viscous flow. The andesites are generally plagioclase phyric to glomeroporphyritic, with plagioclase phenocrysts as large as 1-5 cm. Some of the flows contain abundant pyroxene and ilmenite, and may be basaltic in composition, but no thin sections or geochemical analyses were obtained to verify this. The orientations of the lava flows in the andesites were determined by measuring the orientations of oxidation-lamination. Flow contacts were noted via the presence of amygdaloidal flow tops, and amygdules in both the rhyolites and andesites contain quartz, epidote, and chlorite, indicating that they experienced low grade contact metamorphism due to emplacement of the surrounding mafic intrusions.

The volcanic rocks are cut by a series of mafic intrusions related in timing to the Beaver Bay Complex (~1096 Ma; Miller and Chandler, 1997). Based on field relationships the oldest intrusive unit is a medium-grained, variably porphyritic, slightly granophyric, poorly- to moderately-foliated anorthositic gabbro. This is intruded by medium-grained ophitic olivine gabbro, which is much more extensive throughout the map area than was recognized prior to this work. Hybrid ferrodioritic rocks are common along the margins of this ophitic gabbro, especially where in contact with felsic volcanic rocks. This hybrid unit contains abundant rhyolite inclusions and felsic stringers mixed with light to dark gray, fine-grained chilled mafic phases. The shape and textures of these felsic stringers implies that they were formed from partial melting of the rhyolite inclusions, and that these melts commingled with mafic magma. Sparse inclusions of meter to outcrop scale hornfels basalt are also found in this unit.

Two narrow and parallel, high-amplitude linear aeromagnetic anomalies, formerly interpreted as two parallel east-west trending diabase dikes, instead may be caused by the magnetic margins of a single, thick dike of ophitic olivine gabbro. However the ophitic gabbro also covers a large area that is characterized by lower amplitude magnetic anomalies; in order to resolve this further petrographic and rock property studies would need to be completed.

In summary, although not all outcrops in the capstone field map area were examined due to time constraints, we have shown that there is much more geologic complexity than had been documented by previous reconnaissance mapping. This small map window should lay the groundwork for and encourage future mapping endeavors in this poorly mapped area.

This and other capstone maps produced by the Precambrian Research Center can be viewed at www.d.umn.edu/prc.

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EVOLUTION OF THE MIDCONTINENT RIFT SYSTEM: PALEOMAGNETIC, ROCK MAGNETIC AND ANISOTROPY OF MAGNETIC SUSCEPTIBILITY INVESTIGATION OF THE MESOPROTEROZOIC BARAGA - MARQUETTE DIKE SWARM (MICHIGAN, USA)

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The Midcontinent Rift System (MRS) is characterized by multiple diabase dike swarms parallel to sub-parallel to the rift axis (e.g. Green et al. 1987). The dikes are generally considered to be feeders to now eroded lava flows once deposited on the flanks of the rift. We report the results of a detailed investigation of rock magnetism, paleomagnetism, and anisotropy of magnetic susceptibility (AMS) from 24 dikes of the east-west trending Baraga-Marquette (BM) dike swarm exposed in the Upper Peninsula of Michigan. In addition, preliminary rock magnetic and paleomagnetic data from five dikes of the Central Wisconsin (CW) dike swarm are presented. Thermomagnetic and magnetic hysteresis analyses indicate that the principal magnetic carrier in the studied dikes is single- to pseudo-single domain low-titanium titanomagnetite. Approximately a third of the dikes contain minor amounts of hematite. In addition, several dikes from highly mineralized areas exhibit an additional magnetic phase likely pyrrhotite or maghemite.

Twelve of the investigated BM dikes yielded well-defined characteristic remanent magnetization (ChRM) directions similar to the typical directions observed from other reversely magnetized MRS rocks and the directions observed in a prior study of the BM swarm by Pesonen and Halls (1979). The new data from reversely magnetized dikes are combined with the prior study data and the combined dataset (20 dikes) is subjected to paleosecular variation analysis. The results are also compared with the paleomagnetic data obtained from other nearly coeval dike swarms of MRS. Three BM dikes yielded normal ChRM directions with steep inclinations, significantly different from the direction exhibited by other normally magnetized MRS sequences. The normal and reversed polarity dikes are also distinguishable with respect to their magnetic grain size. While the statistical significance of these observations requires further investigation, taken at face value it suggests that the BM swarm may represent at least two emplacement episodes with normally magnetized dikes being older. Three CW dikes yielded stable ChRM directions (two normal and one reversed) typical for the MRS time.

The anisotropy of magnetic susceptibility analyses yielded well-constrained magma flow directions in most of the studied dikes. The magma flow directions of the BM dike swarm are discussed in the context of the tectonic evolution of MRS.

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Compilation of existing geophysical models in preparation for 3D modeling of the Midcontinent Rift System in the western Lake Superior region, Minnesota, Wisconsin, and Michigan

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Over the past several decades, both 2D and 3D geophysical models have played a large part in developing our understanding of the subsurface structure and composition of the Midcontinent Rift System (MRS). The overall configuration of the MRS is prominently expressed in regional gravity and magnetic maps. Details of the subsurface configuration of volcanic layers and structures are evident in high-resolution aeromagnetic data and published seismic-reflection sections.

Improvements in the resolution and coverage of gravity and magnetic data and technical advances in modeling capabilities in the last decade provide the motivation for new attempts at 3D modeling of the MRS. In particular, the MRS has complex structure in the western Lake Superior region that is appropriate for 3D modeling. In this area, bounding faults of the NNE-trending St. Croix horst abruptly turn more easterly at White's Ridge and transition into the ENE-striking Lake Owen and Keweenaw faults (Fig. 1). Gravity data west of White's Ridge suggest that relations between the St. Croix Horst and the Duluth Complex are also 3D in nature (Fig. 2). Thus, we are developing a new 3D model of the MRS for the area surrounding White's Ridge (Figs. 1 and 2). We start with the 3D gravity models of Allen (1994), who constrained his modeling using seismic-reflection lines (Fig. 1). Refinements are made by incorporating new 2D geophysical models and constraints from analysis of more recent geophysical and geologic data sets. We also plan to re-evaluate the gravity effects of the lower crust and mantle, as interpretations of new deep-looking geophysical data become publically available. As the model develops, the generalized rock units can be subdivided and additional structure added.

The first step in the modeling process is to compile existing models and information into the 3D model space so that discrepancies or other issues can be easily recognized. Images captured from published 2D geophysical models, interpreted seismic-reflection sections, and geologic cross-sections (Fig. 1) were input as displays along section lines. The two 3D gravity models of the MRS constructed by Allen (1994) for western Lake Superior and the Minnesota-Wisconsin section (Figure 2) were recently combined by Chandler and Lively (2011) into a 3D visualization of surfaces, where each surface represents the base of a generalized rock package. Grid points from these surfaces were input into the 3D model space, then projected onto the section displays to quickly discover discrepancies between models. The discrepancies found are mostly explained by how rock units are generalized and what rock properties are assigned to which rock units. After consideration of updated rock property information, we chose the following model units and associated densities (in kg/m³) for the 3D modeling, which generally follows those of Allen (1994): Bayfield Group—2,450; Oronto Group—2,650; volcanic rocks—2,950; Duluth Complex—3,000; pre-rift upper crust (<20 km depth)—2,750; and lower crust (>20 km depth)—2,900.

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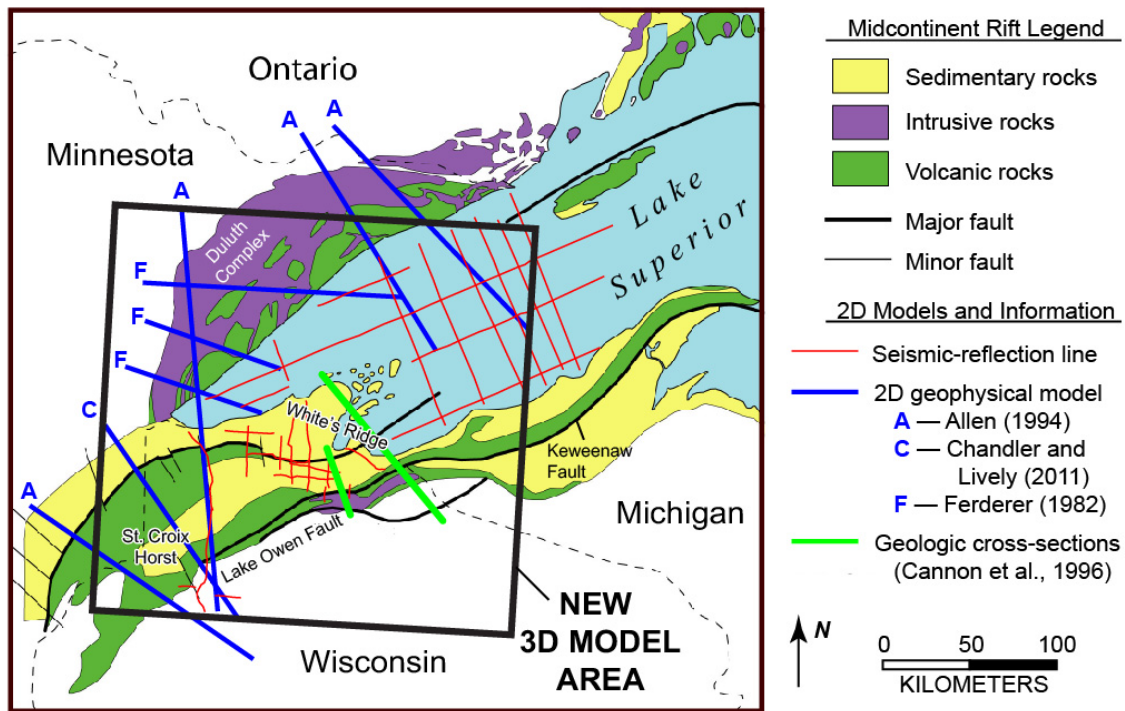


Figure 1: Rock units of the Midcontinent rift in the western Lake Superior region, area covered by the new 3D model, and locations of previous 2D geophysical models and seismic lines. Geographic boundaries are shown by dashed lines.

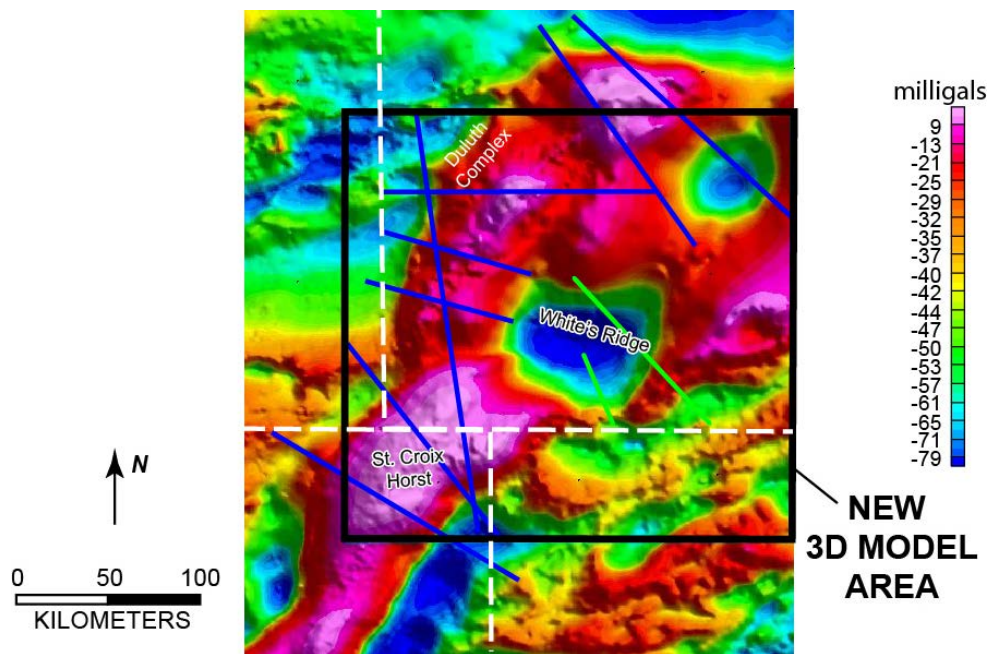


Figure 2: Color shaded-relief image of Bouguer gravity, showing the new 3D model area (bold black outline). Sections are as in Fig. 1. The white dashed lines outline the two 3D model areas of Allen (1994).

A Field and Petrographic Study of Neoproterozoic Variolitic Pillow Lavas, Newton Belt, Vermilion District, Northeastern Minnesota

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The Newton Lake Formation, located northeast of Ely, Minnesota, comprises a series of tholeiitic to komatiitic lava flows, mafic to ultramafic intrusions, and associated clastic sedimentary rocks. Approximately one-half mile north of CR-88 on the Echo Trail, a sequence of exceptionally well-preserved, steeply dipping, south-topping, lower greenschist-facies metamorphosed variolitic pillow lavas are exposed on the northwest side of the road. This outcrop was recently visited during the 55th Annual Institute of Lake Superior Geology Field Trip 7 and was described as “spherulitic pillow basalt” (Peterson et al., 2009).

Although mapped on a regional scale (Peterson et al., 2005), to date no detailed geological sketches or petrographic analyses of these variolitic pillowed flows have been completed for the purpose of understanding the genesis of these variolites. As varioles may be the result of blotchy alteration, magma mingling, or quench crystallization (Arndt and Fowler, 2004; Fowler et al., 2002), a detailed petrographic study was conducted to evaluate the genesis of the variolites that exist at this location. Scanning electron microscopy will be utilized to better understand the compositional characteristics of the variolites.

A series of hand samples from this exposure of Newton Lake Formation pillow lavas was collected during fall, 2013. Samples were chosen at different distances from the crusts of individual pillows, as well as from areas where both pillow selveges and associated pillow hyaloclastite occurred. All sample locations were documented using a hand-held GPS unit in the UTM NAD 83 Zone 15 North coordinate system. A series of photographs was taken, and a panorama of these photos was constructed to assist in the mapping of this exceptional outcrop. Samples were prepared into standard and polished thin sections for analysis on a Leica DM EP polarizing microscope and by energy dispersive spectroscopy using a JEOL JSM-6490LV scanning electron microscope, both at the University of Minnesota Duluth.

In outcrop, the pillow lavas vary from bun- to mattress-shaped (Dimroth et al., 1978) and range from <1 m to >2.5 m in diameter. A typical cross-section through these pillow lavas is shown in Figure 1. Pillow cores tend to be dark green to pale yellow-green in color depending on the degree of secondary epidote alteration present. Locally, quartz-filled vacuoles are present near the stratigraphic tops of individual pillows. Variolitic textures are most common in the border zone of individual pillows within 0.5 m of the crust of individual pillows, shown in Figure 2. Here, 5-15% individual rounded to spherical variolites up to 1 cm in diameter, as well as nearly massive, globular, coalescing variolites oriented sub-parallel to pillow margins are present.

Petrographic studies indicate exceptional preservation of hyaloclastite adjacent to the crusts of individual pillows (Figure 3). The hyaloclastite comprises shard-shaped, jigsaw-puzzle fit lapilli composed of light brown to light green altered glass similar to that comprising the pillow crusts. Small (<5 mm) spherical plagioclase variolites are commonly present in the hyaloclastite shards. Variolites in the border region are zoned moving inward toward the pillow core, with an outer zone comprising of individual, small (2-5 mm), spherical to oval plagioclase spherulites with minor (<20%) fan-shaped to bow-tie shaped inclusions of altered mafic minerals. A secondary zone comprising larger (5-10 mm), round plagioclase spherulites in a matrix composed of fine-grained, chaotically-oriented skeletal amphibole that may be pseudomorphs of original pyroxene. A third zone composed of semi-massive to massive, globular, coalescing spherical plagioclase spherulites that contain 30-55% fan-shaped to bow-tie inclusions of mafic minerals, and a fourth zone containing <10% rounded plagioclase spherulites up to 15 mm in

diameter in a matrix of coarser grained, chaotically oriented skeletal amphibole. The cores of the pillow lavas are composed of fine-grained tabular to acicular plagioclase intergrown with fine-grained tabular to prismatic amphibole pseudomorphs of pyroxene. Scanning electron microscopy studies are currently in progress to evaluate compositional differences between the variolites and groundmass minerals in the various variolite zones and pillow cores.

Based on the results of this study, variolites in this exceptional exposure of Newton Lake Formation pillow lavas are dominantly composed of rounded to oval, radiating plagioclase spherulites with rare, axiolitic plagioclase spherulites locally present. The presence of needle-like to acicular skeletal plagioclase crystals and absence of phenocrysts suggest that lavas responsible for the pillow lava flows at this location were erupted at temperatures above the liquidus and experienced relatively large degrees of undercooling before undergoing rapid crystallization on the Neoarchean seafloor.

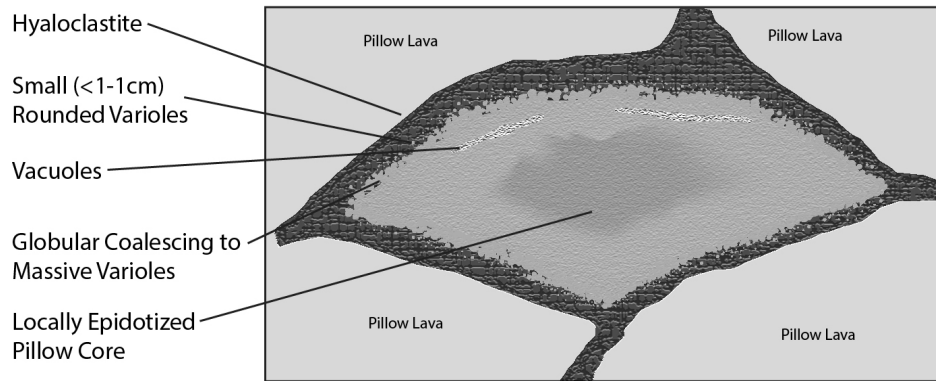


Figure 1. Typical pillow lava cross-section.

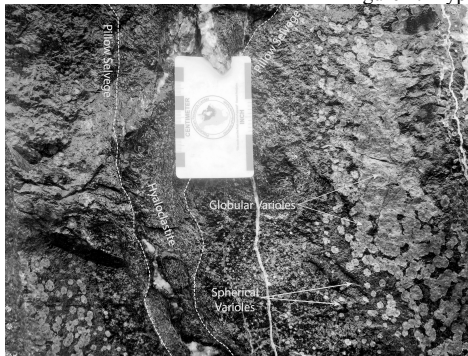


Figure 2. Outcrop photo of pillow margin, variolites transitioning into hyaloclastite (from right to left).



Figure 3. Thin section of pillow margin containing small variolites and well preserved hyaloclastite.

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STRATIGRAPHIC FRAMEWORK AND LANDSYSTEM CORRELATION FOR DEPOSITS OF THE SAGINAW LOBE, MICHIGAN, USA

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Since the time of the Last Glacial Maximum (LGM) the south-central portion of the Lower Michigan Peninsula has been subject to several glacial advances and retreats by the Saginaw lobe. As part of the U.S Geological Survey Great Lakes Geological Mapping Coalition projects, several rotasonic borings were drilled between 2006 and 2013 in Barry, Kalamazoo and Calhoun Counties. Gamma ray logs and textural analyses were completed for each core. Five of these borings were selected according to their diamicton (till) content and correlated using water well logs and surficial geology maps. Glacial deposits such as diamicton serve as evidence of glacial advance/retreat, and are usually present as nearly continuous layers of sediments. Analysis of these layers affords the ability to accurately correlate these types of sediments across an area. Three cores, BA-10-02 and BA-09-02, KA-12-02 were drilled along the Kalamazoo moraine, each one containing 1 to 3 diamicton units separated by lacustrine sediments. The last two cores, CA-11-01 and KA-13-01 were drilled on a drumlinized till plain; both contain 2 to 4 diamicton units separated by outwash sediments. These diamicton units indicate the presence of at least one major and two minor advances/retreats of the Saginaw Lobe.

RETHINKING THE MIDCONTINENT RIFT – PUNCTURING THE “PLUME PARADIGM”

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The mantle plume origin for the Midcontinent Rift (MCR) is widely accepted in the literature (e.g., Hutchinson et al., 1990; Nicholson and Shirey, 1990; Nicholson et al., 1997). However, recent geochronological, geochemical and mineralogical data suggest that the simple plume model should no longer be applied and it is necessary to evaluate alternate models. So, why do we need to rethink the rift?

Geochronology – The majority of plume-related Large Igneous Provinces (LIPs) are characterized by a short-duration magmatic pulse or pulses (less than 1–5 My; Ernst et al., 2013a). Recent geochronology has shown that MCR magmatism spans at least 20 million years (Heaman et al., 2007, Hollings et al., 2010 and Dunlop, 2013) and possibly as much as 60 million years.

Ultramafic rocks – One argument often put forward in favour of a plume origin for the rift is the presence of ultramafic rocks. Although there are, indeed, ultramafic rocks in the MCR, all of which are hosted in intrusions, mineral chemistry analyses from these intrusions shows that they have maximum olivine forsterite compositions not in equilibrium with the mantle: Seagull (Fo₈₅), Thunder Bay North (Fo₈₂), Eagle (Fo₈₅; Ding et al., 2010) and Tamarack (Fo₈₈; Goldner, 2011). Numerical models of these olivine compositions suggest a parental magma with 8-10 wt% MgO. Even the most primitive Tamarack intrusion suggests a primary magma with a composition of 12wt% MgO and 11wt% FeO (Goldner, 2011).

Dyke swarms – The majority of plume-related LIPs are associated with, or even recognized by, the presence of giant, radiating dike swarms up to 3000 km long which project for long distances into cratonic hinterlands and provide evidence for paleo-stress regimes consistent with a central piercing point, likely a plume (Ernst et al., 2013a). To date, no radiating dike swarm has been recognized nor associated with the MCR. Rather, the majority of MCR-related dikes occupy extensional, rift arm-parallel structures (e.g. Hollings et al., 2010).

Hanson et al. (1998, 2004, 2006) recognized ~1100 Ma magmatism in the Kalahari Craton, termed the Umkondo event. Ernst et al. (2013b) have recently proposed that this magmatic event may be considerably more widespread, with the recognition of ~1100 Ma magmatism in the Congo, the Amazon and India. They proposed that paleogeographic reconstructions are permissive of these events representing a single LIP that, based on paleomagnetic reconstructions, was distinct from Keweenaw magmatism (Ernst et al., 2013b). The presence of multiple, broadly contemporaneous LIP events suggests that the Mesoproterozoic may have been a period of significant mantle overturn (Stein and Hofmann, 1994) and atypically increased magmatic activity.

The long duration of MCR magmatism, absence of primary ultramafic magmas and lack of a radiating dike swarm all suggest that a passive rifting model may be more appropriate for the rift. According to this model, rifting of the Superior Craton, possibly a response to the Umkondo LIP event, allowed for upwelling of material underplated by earlier plume events thought to have been centered in the vicinity of the present-day Lake Superior (e.g. the Marathon LIP, Halls et al., 2008).

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THE MINNESOTA TACONITE WORKERS HEALTH STUDY: ENVIRONMENTAL STUDY OF AIRBORNE PARTICULATE MATTER - 2014 UPDATE

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

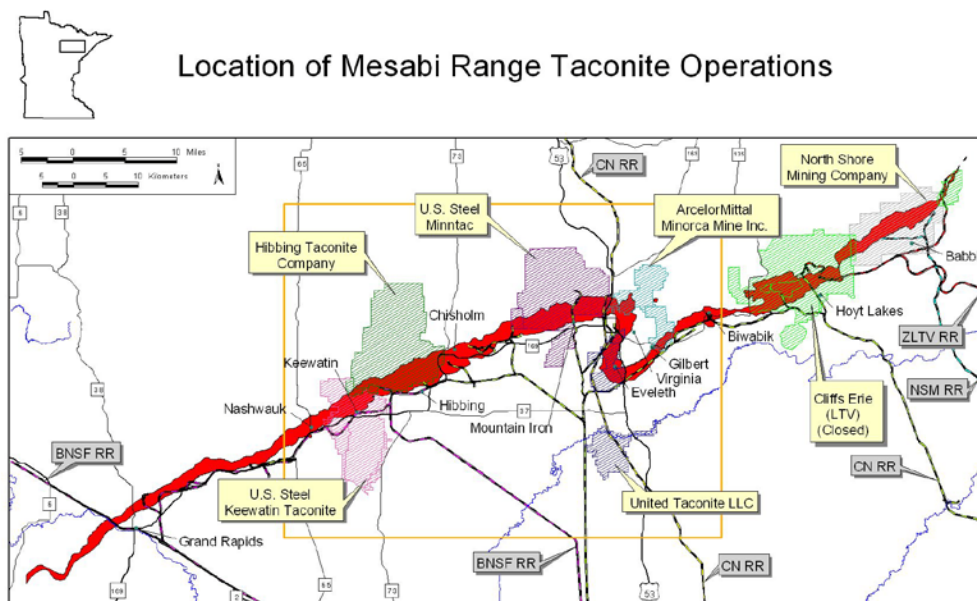


Figure 1. Locations of taconite processing plants on the Mesabi Iron Range being sampled during this study (after Oreskovich and Patelke, 2006)

Air sampling was performed within taconite operations, MIR communities, and non-MIR communities by NRRI scientists during both winter and summer seasons from 2009-2012. Sampling was conducted at four process locations within taconite operations, including: 1) secondary crushers; 2) magnetic separators/concentrators; 3) agglomerators/ball drums; and 4) kiln/pellet discharge areas. Sampling within the MIR communities took place on centrally-located rooftops of public buildings, whereas sampling in non-MIR communities occurred on either rooftops, or in remote sampling locations,

so that background air quality away from the MIR could be evaluated. Airborne particles were collected using: 1) a micro orifice uniform deposit impactor (MOUDI) (Marple et al., 1991, 2014), which enables size-fractionated particulate matter collection; and 2) a Total Filter Sampler (TFS). Particulate matter was evaluated via gravimetric analysis and was subsequently subjected to comprehensive particulate matter characterization that included: 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 Standardization Organization's Indirect Method 13794 for Ambient air – Determination of Asbestos Fibers. NRRI's research methods do not produce exposure data, and are not meant to provide data for regulatory purposes.

During the past year, the NRRI has been evaluating the physical (gravimetric, morphology, concentration), mineralogical, and chemical characteristics of the particulate matter obtained from sampling at the taconite operations and MIR/non-MIR communities. This includes analysis of samples obtained during 14 sampling events at taconite operations and 79 sampling events at locations within communities and sites in northeastern Minnesota (73) and Minneapolis (6). Lake sediment analysis continues, and will provide important historical 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.

Community results to date are as follows:

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

In-plant results to date are as follows:

- plant environments can be very dusty, with the most dusty environments associated with the agglomerator and kiln discharge areas;
- particulate levels (PM₁, PM_{2.5}, PM₁₀, and total PM) show a slight increase in the five MIR communities during plant/mine activity, but this increase is not statistically significant compared to when the plants were not operating.

The NRRI plans to complete this work in 2014.

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ROCK MAGNETISM AND PALEOMAGNETISM OF THE ~1144 MA LAMPROPHYRE DYKES, THE EASTERN LAKE SUPERIOR REGION, ONTARIO, CANADA

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Despite several decades of intensive research, the origin of the formation of the ~1.1 Ga Midcontinent Rift system (MRS) remains an open question. The proposed hypotheses vary from active rifting due to a mantle plume or plumes (e.g. Nicholson et al., 1997; Hollings et al., 2010), to passive rifting related to the Grenville Orogeny (Gordon and Hempton, 1986), or separation of the Amazon craton from Laurentia (Stein et al., 2014). Abundant ~1144 Ma lamprophyre dykes in the Eastern Lake Superior region (Ontario, Canada) (Queen et al., 1996) are coeval with the ~1141 Ma Abitibi diabase dyke swarm (Krogh et al. 1987) in the same area. In addition, both dyke suites share similar alcalic composition and appear to fan out from a locus in the present-day Lake Superior. These observations hint that the lamprophyre dykes and Abitibi dykes may form a single radiating dyke swarm representing the earliest magmatic stage of MRS. The existence of such a swarm is consistent with the arrival of a mantle plume, hence supporting the active rifting hypothesis.

In order to test this hypothesis, we sampled 173 independently oriented samples from 22 lamprophyre dykes. In addition, at three sites, samples for the baked contact test were collected from the presumably baked and unbaked host rocks. The dependence of low-field magnetic susceptibility versus temperature indicates low titanium titanomagnetite as the dominant magnetic mineral. Subordinate hematite was observed in several samples. Magnetic hysteresis measurements reveal single to pseudo-single domain behavior in most dykes except for four dykes that show multidomain behavior. Both alternating field (AF) and thermal demagnetization were used to determine the paleomagnetic directions. In general, the AF demagnetization technique proved to be more effective in revealing the characteristic paleomagnetic directions. For several dykes, temperature treatment resulted in unstable demagnetization behavior due to alteration. Preliminary measurements of the anisotropy of magnetic susceptibility were also conducted on selected dykes in order to test whether the flow directions are consistent with the potential plume center. The paleomagnetic results of this study will be compared with the results obtained from the Abitibi dykes by Ernst and Buchan (1993) and the possible implications related to the formation of the MRS will be discussed.

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AN EXPLORATION UPDATE AND MINERALOGICAL STUDY OF THE EMILY-DISTRICT MANGANESE DEPOSIT, CUYUNA IRON RANGE, MINNESOTA

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The Cuyuna Range in east-central Minnesota produced in excess of 100 million tons of manganiferous iron ore from initial discovery in 1904 to the final mine closing in 1984. The presence of higher percentages of manganese (greater than 10 percent) is the main component that distinguishes the Cuyuna Range from other Early Proterozoic iron mining districts in the Lake Superior Region. Similar to the Mesabi Iron Range, The Cuyuna Range has been documented as part of the Animikie Group, containing the Virginia Formation, "Unit A" iron formation (similar to the Biwabik Iron-Formation), and the Pokegma Quartzite (Morey and Southwick, 1993)

Numerous works have studied the manganese deposits of the Emily-District. Summaries of the regional structural setting by Southwick et al. (1988) and Morey et al. (1981) show that deformation within the Emily-district is associated the Penokean Orogeny. Regionally, rocks within the Emily district form a broad synclinorium that plunges to the east. Morey and Southwick (1993) presented an in-depth summary of the stratigraphic and sedimentology characteristics that show possible geologic controls of manganese distribution. Dahl et. al. (1994) characterized the mineralogy for the purposes of utilizing in-situ mining techniques using two holes drilled in 1990. Other studies have utilized historic drill core obtained from the Minnesota Department of Natural Resources core library in Hibbing.

Cooperative Mineral Resources (CMR) controls 80 acres within the Emily-District. Historic resource estimates for this district showed one to two million tons of manganese resource. On their controlled property, thirteen historic drill holes were drilled, which indicated a sizeable manganese resource. In 2011 and 2012, CMR commissioned an expanded exploration drilling program with seven additional holes. This drilling confirmed the historic resource, which is divided into upper and lower manganese-rich zones. Assays from these modern drill holes showed stratigraphically continuous manganese grades of 15 to 20 percent.

Further work has continued on the CMR Emily deposit. In 2013, metallurgical studies included a mineral liberation analyses (MLA). The MLA report analyzed fourteen core samples from the 2011 and 2012 drill holes using an automated scanning electron microscope equipped with energy dispersive detectors (SEM-EDS) and MLA software. The MLA technique analyzes X-ray spectrometry (XRF) from individual grains, assigns an elemental composition based on the geometric center of each grain, and assigns the most likely mineralogy based on a database of XRF.

The results of the MLA confirmed the mineralogy described by past studies on the Emily-District. Predominant iron mineralogy was assumed to be hematite. Manganese mineralogy occurred in several manganese oxide (MnO) phases. Most notably, MnO was assumed to be the composition of manganite. Several manganese-iron (FeO-Mn) phases were found, which were not assigned a specific mineralogy. Cryptomelane ($K_{12}Mn_8O_{16}$), hollandite ($BaMn_8O_{16}$), stilpnomelane ($K(Fe,Mg)_8(Si,Al)_{12}(O,OH)_{27}$), and calcite_Mn ($(Ca,Mn)CO_3$) were secondary manganese minerals. Quartz is the principal gangue mineral.

Past metallurgical work on the manganese resource has shown that primary and secondary grinding, associated with flotation is insufficient in separating individual manganese-oxide from iron-oxide grains

and quartz. The MLA report showed the mineral liberation at various grind meshes. These results will be further refined to develop an alternative processing technique for the manganese resource.

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SEDIMENTOLOGY AND PALEO GEOGRAPHIC RECONSTRUCTION OF THE LAYERS IN AND ADJACENT TO THE SUDBURY IMPACT LAYER IN THE LAKE SUPERIOR BASIN

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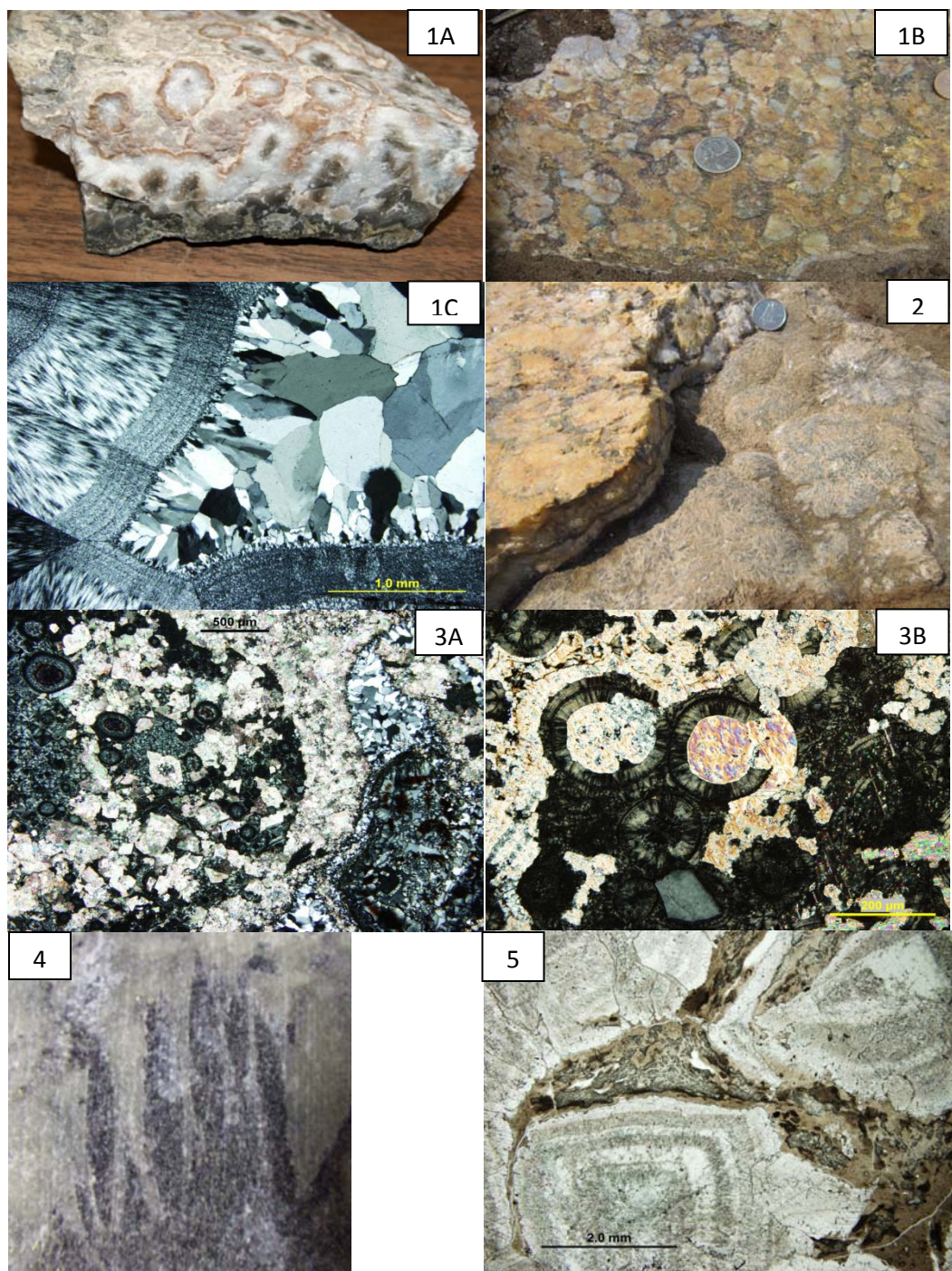
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Various locations around the area of the Lake Superior Basin reveal stratified layers of the 1878.3±1.3 Ma (Fralick et al., 2002) Gunflint Formation, the 1850 Ma (Krogh et al., 1984) Sudbury Impact Layer, and the overlying 1832±3 Ma (Addison et al., 2005) Rove Formation. Samples were collected and tested, and stratigraphic logs were drawn from these locations to determine the sedimentology of the lithologic units in an attempt to reconstruct the paleogeographic setting at the time of deposition, along with diagenesis. Focus is given to two units, one above and one below the Sudbury Impact Layer (S.I.L.), which display time gaps in the stratigraphic record. The units below and above the S.I.L. display a ~28 Ma, and an ~18 Ma year time gap respectively (Addison et al., 2010), indicating a period of subaerial exposure and ultimately, erosion; during this time the Rove Sea had regressed back to the southern edge of the continent.

Samples collected below the S.I.L. near the Terry Fox monument and the Harbour Expressway in Thunder Bay, ON, indicate that subaerial exposure was present in this unit. The Terry Fox site displays stalactite-like structures (Figure 1A) composed of silica, indicating growth above the water table. The Harbour Expressway site reveals the same stalactite-like features, except that only a very small, eroded outcrop was found, showing plan-view stalactites termed by the author as silica flowerettes (Figures 1B, 1C). In addition, the Harbour Expressway site reveals botryoidal gypsum-like rosettes (Figure 2), indicative of an arid environment. Although these rosettes were most likely comprised of gypsum at one point in time, XRD and geochemical analysis show that this feature has been overprinted by calcite.

Samples collected from the S.I.L. indicate that subaerial exposure affected this ejecta unit, made evident by silica invasion, carbonate crystal and cement growth or replacement. Ejecta features such as sphere-in-sphere structures (Figure 3A), and vesicular glass bubbles (Figure 3B) have been infilled, overprinted/replaced, and/or broken because of subaerial exposure.

Samples collected above the S.I.L. display formation in subaerial conditions exemplified by a unit resembling gypsum laths sampled from drill core BDQ (Figure 4), collected near Hwy 588, Thunder Bay, ON. As with the gypsum-like rosettes found near the Harbour Expressway site, these gypsum laths had to have precipitated in an arid, subaerial environment. Another sample taken from drill core BDQ displays a chicken-wire texture of zoned carbonate crystals (Figure 5). SEM-EDX analysis of the crystals displays Mg and Fe zonation, indicating that formation occurred in a sabhka environment with access to meteoric water, rather than being covered by the Rove Sea. Although these zoned crystals were formed through the percolation of meteoric waters, the Rove Sea seems to have abruptly transgressed into the Animikie Basin, as seen by the silt and shale unit situated directly on top of the carbonate unit, seemingly choking it out.



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IMPACT EJECTA FEATURES IN THE LAKE SUPERIOR BASIN FROM THE 1850 MA SUDBURY IMPACT EVENT

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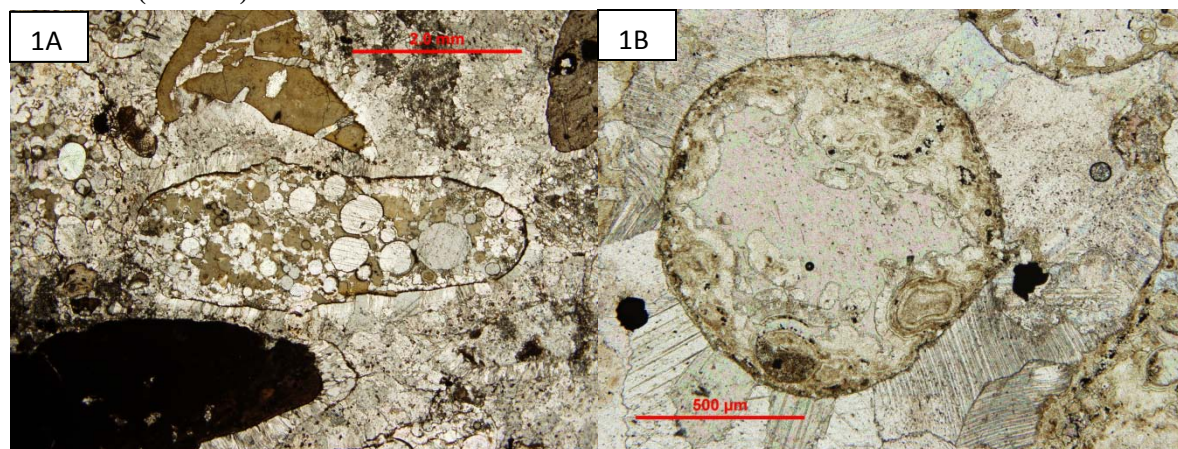
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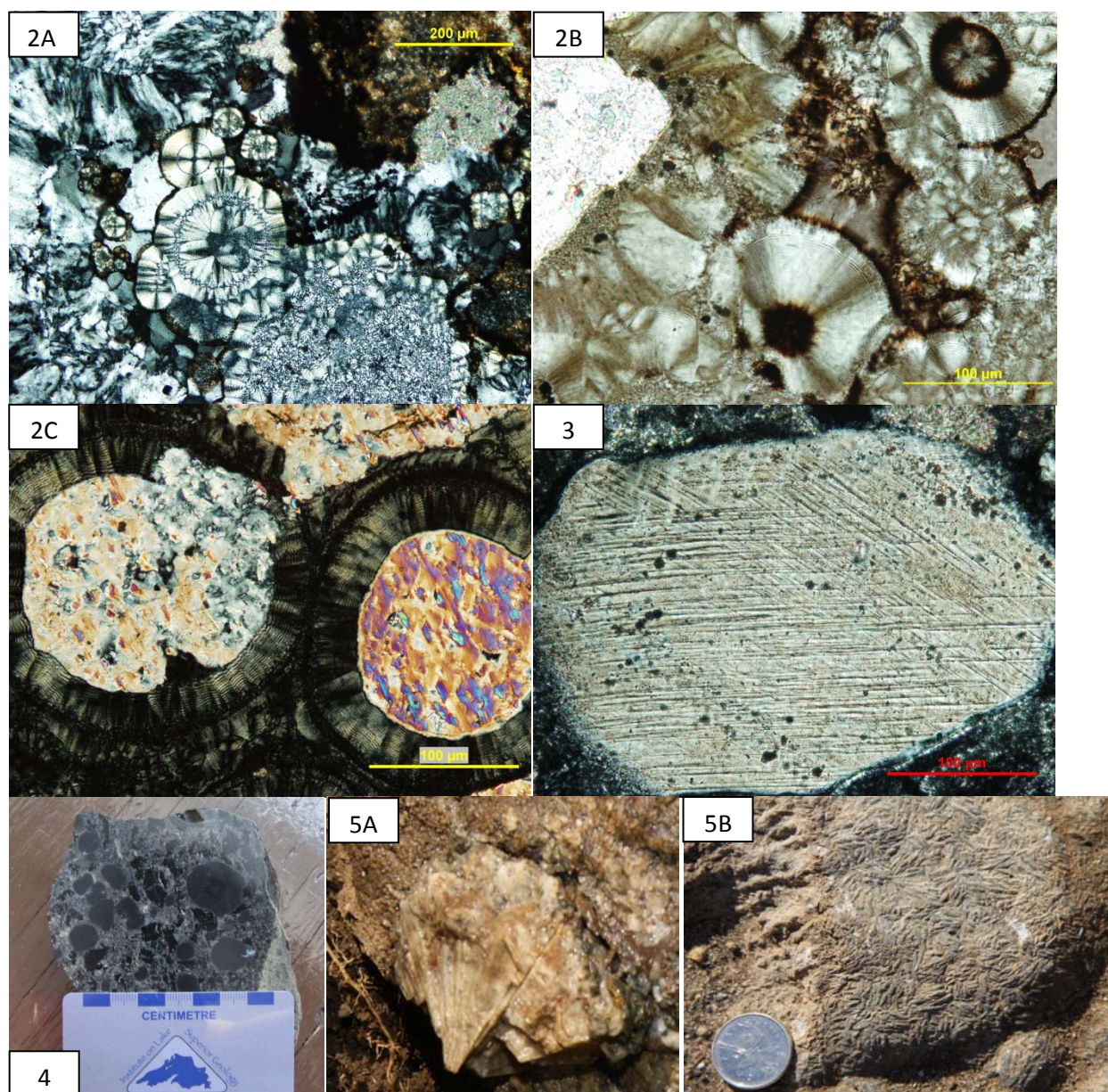
Between the 1878.3±1.3 Ma (Fralick et al., 2002) Gunflint Formation, and the overlying 1832±3 Ma (Addison et al., 2005) Rove Formation, unconformably lies the 1850 Ma (Krogh et al., 1984) impact ejecta unit from the Sudbury Impact Event. These distal ejecta sites that have been discovered in the Lake Superior basin, extend approximately 600-800 kilometers, or ~5-7 crater radii (Spray et al. 2004), from the Sudbury impact crater.

The Sudbury Impact Layer (S.I.L.) is composed of two constituents: 1) A chaotic debrisite portion that includes clasts and rip-ups of carbonate grainstone, along with blocks of chert and stromatolite that have been sheared from the underlying Gunflint Formation; 2) The ejected material from the impact event (Addison et al., 2010). Ejecta features of the S.I.L. unit include devitrified glass (Figures 1A, 1B), spherules (Figures 2A, 2B, 2C), planar features (Figure 3), and lapilli (Figure 4).

During deposition of the 1850 Ma Sudbury Impact Layer, it is assumed that deposition took place in a subaerial environment (Fralick and Burton, 2008). Samples taken from two locations in the field directly below and above the S.I.L. unit display what seems to be gypsum rosettes (Figures 5A, 5B) indicating an arid environment (Karman and Fralick, 2014). Because of subaerial exposure, many ejecta features have been affected by carbonate replacement/alteration and silicification, either overprinting, or destroying them.

Figures: Devitrified vesicular impact glass (DVIG); 1A: Oval DVIG with carbonate-filled vesicles (plane polarized light HEW site), 1B: Spherical DVIG with carbonate-filled void (plane polarized light BC site); 2 - Spherules replaced by chalcedony; 2A: Spherule cluster with irregular intricate banding (crossed polarized light HCP site), 2B: “LP record” spherules (plane polarized light BM site), 2C: Fibrous radial rimmed spherules with carbonate-filled previously hollow centers (crossed polarized light HEW site); 3 - Planar Deformation Feature (PDF) (crossed polarized light JN34 slide); Two sets of PDFs in quartz grain decorated with inclusions; 4 - Lapilli; Accretionary lapilli ~2.5cm width (588 site); 5 - Replaced gypsum rosettes; 5A: Cross section of radially banded gypsum rosette replaced by carbonate directly under ejecta (HCP site), 5B: Cluster of botryoidal gypsum rosettes replaced by calcite growing in mat-like form overlying the S.I.L. (HEW site).





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PDFS IN SUDBURY EJECTA IN THE GUNFLINT FORMATION, ONTARIO: A COMPARISON OF METHODS

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Planar deformation features (PDFs) in quartz are considered to be definitive evidence, along with other features, of large terrestrial impact (French 1998). The ejecta from the 1850 Ma Sudbury impact structure has been described in the Animike Group and correlative units in the western Lake Superior area in Michigan, Minnesota and Ontario (Cannon and Addison 2007). PDFs are known to develop in response to shock pressures greater than those developed by terrestrial events (e.g. volcanic eruptions) and form on rational planes in the quartz crystal (von Engelhardt and Bertsch 1969). Indexed planes of PDFs from the Baraga Group and correlative units from Michigan have been reported by Pufahl et al. (2007) and Cannon et al. (2010); however, although PDFs in Gunflint Formation of Ontario have been described (Addison et al. 2005), they have not been indexed.

In this study, we have indexed 22 PDFs in 11 thin sections of ejecta from drill holes BP99-2 and MC95-1, which have been described by Addison et al. (2005). The conventional method for indexing of PDFs, as described by von Engelhardt and Bertsch (1969), utilizes the universal stage to determine the pole of a PDF and the orientation of the c-axis of the quartz grain. Based on the polar angle between the c-axis and the pole of the PDF, the results are then compared to a template of the projection of known indices of PDFs in a stereographic projection. The standard template devised by von Engelhardt and Bertsch (1969) allows a margin of error of 5° in the stereographic projection.

The conventional method described above suffers from some imprecision in the plotting and manipulations of measurements on a Wulff net, which must be done manually. In order to overcome errors of this sort, Huber et al. (2011) created the Automated Numerical Index Executor program (ANIE), which is based on angular calculations from spherical trigonometry. They demonstrated the apparent superiority of use of the program over manual methods in indexing of PDFs. In our study, we have compared the application of the conventional method with that of the ANIE program, as well as presenting results from the Gunflint Formation, which lies approximately 200 km west of the Baraga Group and hence, more distally from the Sudbury structure.

Quartz grains examined in this study in most cases contained only one orientation of PDF in the thin section examined. An example of an exceptional grain with a high density of PDFs in two orientations is shown in the figure. The Miller-Bravais indices of PDEs examined, according to the ANIE program, with numbers determined in parentheses are as follows in order of increasing polar angle: {1014} (1 set); {1013} (1 set); {1012} (1 set); {1122} (1 set); {1011} (1 set); {1121} (4 sets); {2131} (2 sets); {2241} (1 set); {3141} (2 sets); {5161} (6 sets); {5160} (1 set); unindexed (1 set). There is good agreement with the planes recorded by Cannon et al. (2010); however, they found most planes to be of low index, whereas the high index planes, e.g. {5161}, of this study are indicative of high shock intensity. Pufahl et al. (2007) found most of the planes seen in this study with a fairly uniform number of occurrences.

Using the conventional method with the Wulff net, a number of planes were "near misses" on the template and thus would appear to be unindexed. This a result similar to that found by Huber et al. (2011), which indicates that the ANIE program is superior to the conventional method. As well, the format for input of measurements from the universal stage accepts an error of $\pm 1^\circ$, providing for a more realistic accounting of error of measurement. The program also can provide output in tabular form for ease of recording of data.

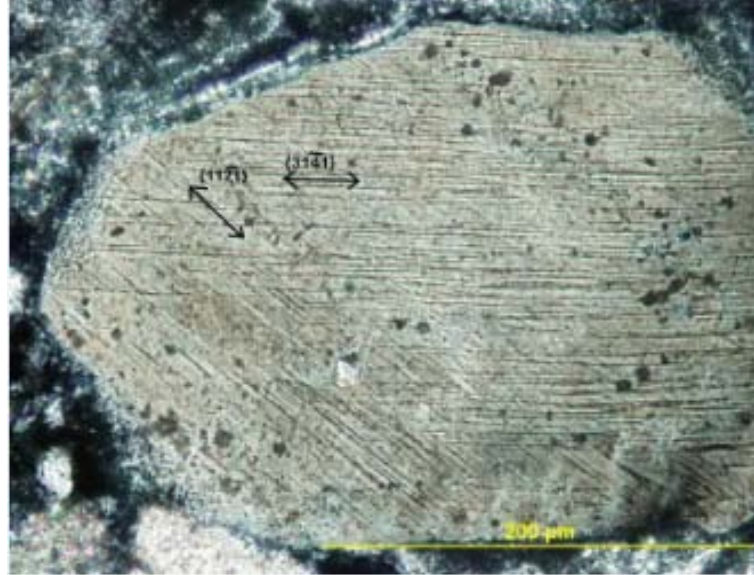


Figure 1. A "toasted" quartz grain from section JN34 with two indexed directions of PDFs.

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GEOCHEMISTRY AND MINERALOGY OF FE-TI-V-P MINERALIZED FERROGABBROIC INTRUSIONS OF 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 exploration leading to the discovery of several mineralization types including chromite and nickel sulfide deposits. Although the majority of exploration has been focused on chromium, the area also contains significant Fe-Ti-V-P mineralization associated with gabbroic intrusions, of which the Thunderbird and Butler occurrences are the best defined.

The study has been focused on the geochemical and petrographic characterization of the intrusions to investigate their petrogenesis. The intrusions are widely distributed throughout the McFaulds Lake area and can be grouped into two main types: (1) large mafic-dominated intrusions and (2) subconcordant to slightly discordant mafic-dominated sills/dikes characteristic of the Thunderbird and the Butler intrusions respectively. Both types are composed of an evolved mafic suite termed the ‘Ferrogabbro’ characterized by the presence of Fe-Ti oxides. Detailed core logging has shown that both intrusions are largely composed of very similar lithologies including iron-rich gabbros, leucogabbros, and anorthosites. Two types of Fe-Ti oxide mineralization occur within these intrusions: (1) Fe-Ti-V and (2) Fe-Ti-P mineralization. Fe-Ti-V mineralization has been intersected within both intrusions, whereas the Fe-Ti-P mineralization has only been identified within the Thunderbird intrusion. The mineralization occurs dominantly as disseminated magnetite and ilmenite (1-10%), but is also present as semi-massive (50-80%), to massive layers (>80%: Fig. 1). These layers typically contain distinct sharp, stratigraphically lower contacts and gradational upper contacts typical of primary igneous layering (Fig. 2). The ilmenite and magnetite occurs as anhedral to subhedral crystals and to a lesser extent, as very fine-grained exsolutions within anhedral magnetite grains.



Figure 1. Massive magnetite from Butler East intrusion (BP11-V01).



Figure 2. Magmatic layering within the Thunderbird intrusion (NOT09-2G25).

This research project has also addressed the use of $\text{TiO}_2/\text{V}_2\text{O}_5$ ratio as a potential vector towards vanadium and/or phosphorous mineralized horizons within the ferrogabbroic intrusions of the McFaulds Lake area. Preliminary data in the Butler intrusions, strongly suggest that the ratio $\text{TiO}_2/\text{V}_2\text{O}_5$ ratio values are independent of rock type, abundance of magnetite-ilmenite, and/or alteration and could be useful in determining favorable horizons for further vanadium mineralization. Furthermore, the samples from this intrusion that exhibit significant vanadium contents (>0.50 weight % V_2O_5) are restricted to a narrow range of $\text{TiO}_2/\text{V}_2\text{O}_5$ values (between 8 and 12). This ratio has the potential to be a significant exploration tool to target magmatic Fe-Ti-V-P mineralization and it has also been an instrumental tool interpretation of stratigraphy of the Butler and Thunderbird intrusions.

The ferrogabbroic intrusions may be petrogenetically related to the abundant ultramafic rocks within the McFaulds Lake area, and could possibly represent the late stage end member of a magmatic sequence as has been suggested for the Bushveld complex. However, the rare or absent ultramafic components spatially associated with these ferrogabbroic intrusions, combined with some ultramafic units cross-cutting the ferrogabbroic units within the Butler intrusion, may suggest that they could represent two distinct magmatic events rather than a dismembered layered intrusion, as proposed by previous workers.

STRUCTURAL CONTROL ON THE BORDEN GOLD DEPOSIT IN CHAPLEAU, ONTARIO

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The Borden gold deposit is located 20 km east of Chapleau, 180 km southwest of Timmins, within the Kapuskasing Structural Zone and Wawa subprovince of the Superior Province. The deposit is a low grade, bulk tonnage style hosting 4.3 million ounces at 1.03 g/t Au in upper amphibolite to granulite facies metamorphic rocks. The metamorphic minerals at Borden include biotite, muscovite, hornblende, sillimanite, garnet, kyanite, cordierite and pyroxene. Based on the abundance of aluminous metamorphic minerals, the protolith is inferred to be pelitic. At such high metamorphic temperatures, deformation is dominantly by ductile mechanisms although microfracturing of competent minerals is also possible. On the macroscopic scale, gold mineralization seems to be controlled by strain heterogeneity related to metamorphic grade and competency. Competent lithons (boudins?) of granulite facies rock appear to be surrounded by more ductile amphibolite facies gneisses and schists, suggesting polymetamorphism with retrograde amphibolite facies metamorphism after granulite facies metamorphism. Gold is typically observed in low strain rocks with weakly developed foliation and also in low strain rocks that are bordered by strongly foliated units. Gold mineralization has been observed at grain boundaries of quartz, within cleavage planes of biotite and associated with euhedral pyrite and anhedral pyrrhotite. This project will provide specific structural and microstructural parameters to guide further exploration and development of the mineralized zone at the Borden gold deposit.

RU-RH-PD MOBILIZATION IN FLAMBEAU MASSIVE SULFIDE DEPOSIT

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The Flambeau deposit located in Rusk county Wisconsin is a Volcanogenic Massive Sulfide (VMS) deposit that plays host to large amounts of copper (chalcopyrite) and zinc (sphalerite). The Flambeau deposit is located in the Ladysmith-Rhineland volcanic complex and has a felsic center which is a steeply dipping section of interlayered fragmental quartz-sericite, andalusite-biotite, quartz-eye, chlorite-garnet, actinolite, and chlorite schist (DeMatties, 1994). The deposit has gone through major alteration due to preliminary sulfide mineralization, regional metamorphism, and supergene alteration near the surface (May and Dinkowitz 1996). However, the characteristics of hydrothermal alterations associated with sulfide mineralization at deeper levels of Flambeau deposit have not been well studied.

The goal of this research project is to study how hydrothermal fluids at Flambeau deposit concentrated Cu, Zn, and Fe sulfides, and mobilized other metals such as Ru, Rh, Pd, Ti, and Cr in the process. In order to accomplish this goal I am analyzing a core sample from the Flambeau deposit using a Bruker handheld X-Ray Fluorescence (XRF) analyzer. I am collecting data from primary bedrock layers (sericite-rich layers with little or no sulfide), discrete, thin (1-2 cm thick) sulfide bands within the host rock, bedrock with visible amounts of sulfide minerals (mixed layers), sharp boundary layers between bedrock and massive sulfide layers, and massive sulfide layers with no visible bedrock. Preliminary data collected from the depths of 620 feet to 640 feet (which is within the hypogene massive sulfide deposit) show that Ru and Pd concentrations are lower within the massive sulfide layers, and progressively increase towards the sericite-rich bedrock layers, while Rh concentration progressively decreases going from massive sulfide layers towards bedrock (Figure 1). Besides Ru, Rh, and Pd, no other PGE, or common “pathfinder” elements like Ba, Co, Ni, etc. are present in the samples in detectable quantities. Ti concentrations are higher in bedrock layers compared to the sulfide layers, but Cr concentrations stay relatively constant in all the layers.

The distribution patterns of Ru, Rh, and Pd associated with Flambeau VMS deposit might provide important insights regarding how sulfide mineralization may affect the distribution of trace elements already present in host rocks. Results from this research can potentially help in future explorations for other, similarly formed VMS deposits around the world.

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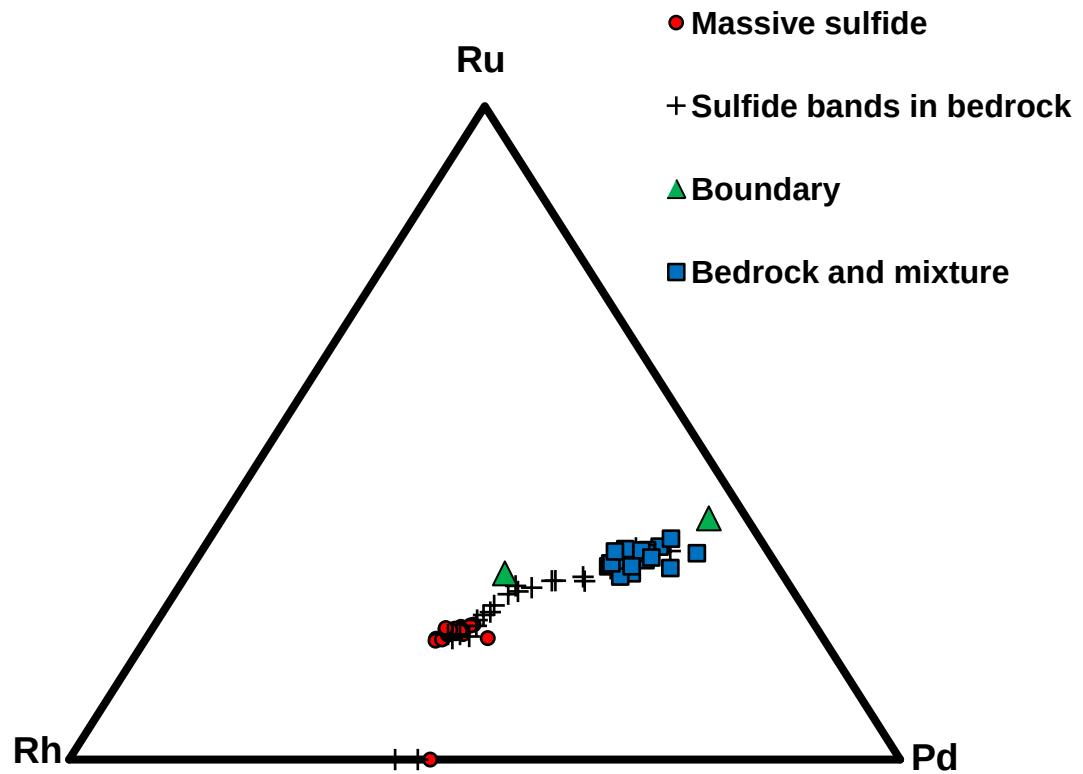


Figure 1. Change in Ru, Rh, and Pd within Massive Sulfide, Boundary Layers, and Sericite-Rich Bedrock Layers (620-640 Ft).

GEOLOGY AND PETROLOGY OF THE WILDER LAKE INTRUSION, DULUTH COMPLEX, NORTHEASTERN MINNESOTA

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In a massive forest fire in the autumn of 2011, 160 square miles of dense forest in the Boundary Waters Canoe Area Wilderness (BWCAW) was intensely burned. Underlying what was termed Pagami Creek burn area are mafic intrusive rocks of the 1.1 Ga Duluth Complex - a large, arcuate-shaped, multiple intrusive igneous complex that underlies most of northeastern Minnesota and that constitutes the largest exposed plutonic component of the 1.1 Ga Midcontinent Rift. Situated in the center of the burn area is the Wilder Lake Intrusion (WLI), an incompletely studied, northward-dipping sheet-like mafic layered intrusion known only from reconnaissance mapping of its lake-accessible western extent. The intense burn created a time-sensitive opportunity to access freshly exposed outcrops along the entirety of its 10 km strike length.

The WLI is part of the Layered Series – a collection of mafic layered intrusions within the Duluth Complex emplaced near the base of a comagmatic volcanic edifice (North Shore Volcanic Group). While most Layered Series intrusions were emplaced beneath an earlier intrusive suite of anorthositic rocks (Anorthositic Series; Fig. 1), the WLI was intruded entirely within Anorthositic Series rocks (Miller et al., 2002),

The overall objective of this study is to document the igneous stratigraphy along its entire strike-length with the goal of better understanding the composition and emplacement and crystallization history of its parental magma(s) that produced its unique petrologic attributes. These attributes, noted by others and confirmed here, include 1) its unique cumulate stratigraphy where Fe-Ti oxide becomes a cumulus phase before augite; 2) the cumulus reversal indicated by the change from a four-phase cumulate of Pl+Cpx+Ox+Ol abruptly giving way up section to a troctolitic (Pl+Ol) cumulate; and 3) its reversed cryptic variation of Fo in olivine and En' in clinopyroxene (Miller and Ripley, 1996). Detailed field mapping (1:12,000), petrographic observations, and geochemical analyses were conducted to accomplish these goals and objectives.

WLI was first discovered 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 to northeast between 15° and 35°, which contrasts with the southerly to easterly (riftward) dip of most layered series intrusions of the Duluth Complex. Reconnaissance mapping and follow-up petrologic studies were conducted by Jim Miller who noted a distinct cumulate reversal (Pl+Cpx+Ox+Ol → Pl + Ol) in the upper section of the western portion of the intrusion, as well as identifying a reversed cryptic variation of upwardly increasing En' and Fo content of pyroxene and olivine, respectively (Miller, 1986; Miller and Ripley, 1997). Unpublished field, petrographic and geochemical data also collected in the western WLI by Joy Turnbull in 2004 verified the reversed cryptic variation and phase layering in the western part of the WLI.

Detailed mapping conducted in 2012 and 2013 for this study shows that most cumulate units of the WLI can be followed along the entire 10km strike length of the WLI, but with some notable exceptions. Remapping in the western part of the WLI has confirmed that the 2km-thick igneous stratigraphy exposed here starts with a basal unit of heterogeneous, intergranular olivine oxide gabbro that is in sharp contact with Anorthositic Series rocks. This marginal gabbro is overlain by a troctolitic unit of Pl+Ol cumulates, which can be subdivided into a heterogeneous subunit, a layered subunit and an anorthosite inclusion subunit. The troctolite unit is overlain by a thin (20-100m thick) oxide troctolite unit of Pl+Ol+ Ox cumulates which abruptly gives way to an olivine oxide gabbro unit of Pl+Cpx+Ox+Ol cumulates. Above the gabbro, an upper troctolitic unit occurs marking a cumulus reversal back to Pl+Ol cumulates. Mapping of the excellent exposures created by the burn reveal that the upper troctolite unit cross-cuts and locally scours out the four-phase gabbro. Thus it is interpreted as a recharge of more primitive magma into the upper part of the WLI chamber rather than a downward crystallizing roof zone unit as proposed by Miller (1986).

Detailed mapping by overland traverses in the central and eastern extents of the WLI show it to thin from 2 km in the west to 1 km in the east. Moreover, several units pinch out in the eastern section of the intrusion. The oxide troctolite pinches out just east of center, but swells back to about 20 meters in thickness before pinching out again with the upper gabbro farther east. The lower gabbro also pinches out around the same place and is replaced by a taxitic unit that dominates at the eastern margin; a similar heterogeneous unit also can be found at the western margin.

Petrographic studies of 223 thin sections collected along three profiles across the intrusion at its western, east central and eastern extents helped to confirm and refine the mineralogy and textures described from field observations. In addition, olivine and pyroxenes from many of the thin section samples were analyzed by UMD's SEM-EDS to document cryptic variation of Mg/Fe ratios. This mineral chemical data was acquired to verify the reversed cryptic variation previously documented in the west and to determine if this variation persists along strike to the east. Reversed cryptic variation of upwardly increasing magnesium number ($mg\# = MgO/(MgO+FeO)$, mole%) in olivine (Fo) and pyroxene (En') was confirmed in the west and in the eastern profiles. However, the data also reveal that the $mg\#$ tends to decrease at a particular stratigraphic horizon from west to east. We interpret the reversed cryptic variation up section to be due to a reduced trapped liquid shift within the oxide troctolite and olivine oxide gabbro units. Trapped liquid shift occurs where high $mg\#$ cumulus olivine re-equilibrates with low $mg\#$ intercumulus liquid. As evidenced by their strong foliation, these rocks are adcumulates with very little intercumulus minerals (i.e., trapped liquid component) and thus retain their high- $mg\#$ cumulus compositions. The lateral decrease in $mg\#$ to the east as well as the disappearance of the oxide troctolite unit is thought to be caused by the thinning of the intrusion causing the eastern portion of the intrusion to cool more rapidly than the west. This more rapid cooling would have caused more trapping of intercumulus liquid (and thus a stronger trapped liquid shift) and would have promoted oxide and pyroxene to crystallize more synchronously since their liquidus temperatures are not very different. We are currently evaluating whole rock analyses of the basal intergranular gabbro samples to determine if they may be representative of a parental liquid composition. We are using a MELTS-based modeling program, Pele (Boudreau, 2006), to evaluate the phase equilibrium of these compositions and to see if fractional crystallization of these compositions under different conditions of oxygen fugacity and cooling rate can replicate the cumulate stratigraphy observed in the WLI.

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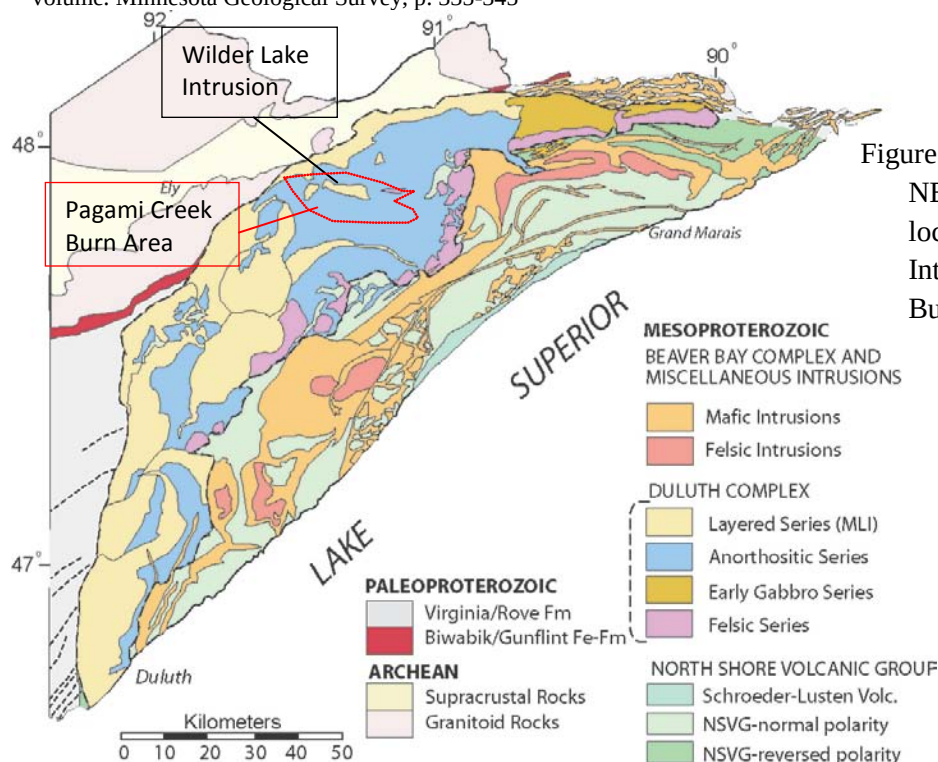


Figure 1. Generalized geology of NE Minnesota showing the location of the Wilder Lake Intrusion and the Pagami Creek Burn Area.

THE ROLE OF BRITTLE-DUCTILE DEFORMATION AND COMPETENCY CONTRAST IN GOLD MINERALIZATION IN THE C-ZONE AT HEMLO

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The Hemlo gold mine is located along the Hemlo shear zone within the Hemlo-Schreiber greenstone belt (Muir, 2002). This greenstone belt lies within the Archean Wawa subprovince of the Superior province (Muir, 2002). The characteristics of an active mineralized stope in the C-zone were studied. The area was interpreted to be under amphibolite facies metamorphism, based on ductile deformation of feldspar, and the presence of sillimanite. This is consistent with findings by Powell et al. (1999), who also noted a peak kyanite phase followed by a decrease in pressure but a relatively minor decrease in temperature. Lingering high temperatures are supported by our observation of annealed grain boundaries.

Brittle-ductile deformation is present throughout the C-zone, on all scales of measure. Figure 1 shows evidence of this on a microstructural scale, where quartz shows evidence of ductile deformation (undulose extinction and subgrains), as well as fracturing. Different minerals show evidence for different behaviours; for example, clinozoisite deformed in a purely brittle manner. Mutually overprinting brittle and ductile deformation, as well as competency contrasts are also evident on outcrop scale.

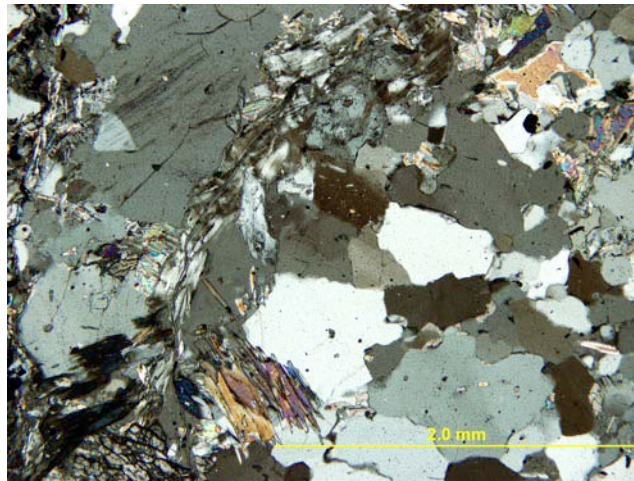


Figure 1: Photomicrograph of a microshear zone with evidence for brittle and ductile deformation within quartz.

Competency contrast within the area of study is most obviously seen between the more competent metavolcanics and more ductile biotite schist. Quartz veins within the metavolcanics tend to have relatively straight contacts with the host rock, whereas quartz veins in the biotite-schist tend to exhibit boudinage or pinch and swell textures. Quartz veins in the metavolcanics are localized within this unit and do not extend into the surrounding biotite-schist (Fig. 2).

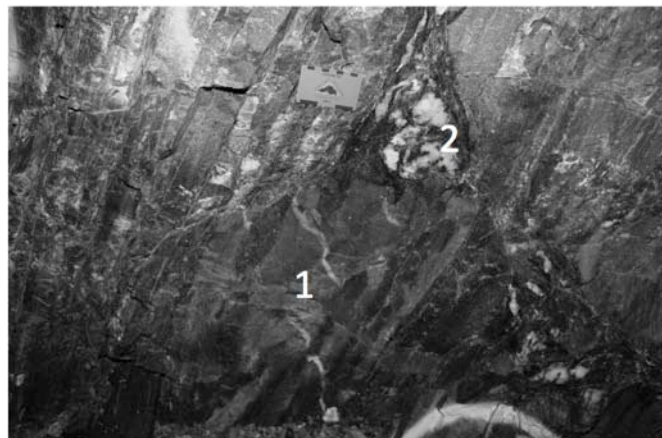


Figure 2: More competent metavolcanic unit (1) and the less competent biotite-schist (2).

Greenschist facies pressure and temperature are considered by many to be the perfect conditions for simultaneous brittle-ductile deformation due to competency contrasts (Weinberg et al., 2012), which in turn provides an ideal

setting for gold mineralization. Results from this project show that similar mineralization can occur under amphibolite facies conditions where ductile deformation dominates. There are three modes of mineralization observed within the C-zone. The first two include mineralization of gold along competence contrast boundaries. The third involves mineralization of gold within metavolcanic hosted fractures.

The role competency plays in gold mineralization is two-fold. The first is that competent bodies tend to fail via brittle deformation. This allows pore space for gold-hosting fluids to infiltrate. This may be the basis for mineralization within the metavolcanic hosted fractures.

The second role competency plays involves high-temperature diffusion of gold-hosting fluids along boundaries between competent and ductile lithologies. This causes mineralization, a) within the biotite-schist along the boundary of quartz boudins, and b) within the metavolcanics along the boundary with the biotite-schist.

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VARIABLE COPPER MINERALIZATION IN THE LOWER NONESUCH FORMATION OF THE MIDCONTINENT RIFT SYSTEM: CONSTRAINTS ON REGIONAL CONTROLS

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The lower Nonesuch Formation in the Lake Superior portion of the Midcontinent Rift System is a host of major sediment-hosted stratiform Cu mineralization, including the White Pine mine, which produced more than 2 Mt Cu, and the Copperwood deposit, which has measured, indicated, and inferred resources of 0.5 Mt Cu. However, the lower Nonesuch Formation is not uniformly mineralized; instead some areas are relatively well-endowed with Cu mineralization, whereas other areas, such as the Ashland syncline in northern Wisconsin, contain only trace quantities of Cu. These variations in Cu content lead to questions on the possible first-order controls of regional to local mineralization, and we critically evaluate new and preexisting data to help identify possible controls on Cu mineralization.

The western Lake Superior portion of the Midcontinent Rift contains clastic sedimentary rocks of the Oronto Group. The basal unit is the conglomerate, sandstone, and siltstone that form red beds of the Copper Harbor Conglomerate. This is overlain by gray siltstone, shale, and fine-grained sandstone of the Nonesuch Formation, which is overlain by reddish brown sandstone of the Freda Formation.

Sediment-hosted stratiform Cu deposits such as White Pine and Copperwood occur in the lowest gray beds, which contain organic matter and diagenetic pyrite that can serve as a reductant for cupriferous brines that are introduced from red beds of the underlying stratigraphy. Previous work on the lower Nonesuch has documented that the total organic carbon and sulfur contents are similar in the Ashland syncline and the White Pine-Copperwood area, suggesting that the sedimentary rocks in both places had similar reduction potential for trapping metallic minerals. The hydrothermal fluid that transported metals to the reduction site is widely accepted to be oxidized cupriferous brines. Neither the Ashland syncline nor the White Pine-Copperwood area have abundant evaporite minerals, but both contain evidence for local to minor evaporite minerals in the lower Nonesuch Formation, and the red beds of the Copper Harbor Conglomerate underlie the Nonesuch Formation in both areas, so we infer that the carrying capacity of the diagenetic basinal fluids was similar in both areas. The ultimate source of the Cu is typically interpreted to be the basalt that underlies the Oronto Group, and because both areas are underlain by extensive basalt, we infer that a source of Cu was not the greatest limitation. The sedimentary facies in each of the main formations of the Oronto Group are similar in both areas; this suggests that first-order control of fluid flow by major facies variations was not a likely control on different Cu endowments. However, the detailed stratigraphy of the lower Nonesuch Formation, which shows remarkable continuity in the White Pine-Copperwood area, differs in the Ashland syncline: most of the marker beds in the White Pine-Copperwood area are poorly developed and rarely occur in the Ashland syncline. This observation is consistent with previous interpretations that the Ashland syncline lies within a different subbasin that was either partially or completely separated from the large rift basin that hosts the White Pine and Copperwood deposits.

Taken together, these results suggest that one major constraint on the Cu endowment of favorable strata in the Nonesuch may have been the size of the available mineralizing diagenetic fluid source. The White Pine-Copperwood deposits are on the margin of a large rift basin that would have been able to contribute significant quantities of mineralizing fluid. In contrast, the presumably smaller size and restricted connectivity of the rift sub-basin in the Ashland syncline area would have had a smaller fluid source thereby limiting the potential metal endowment in that area.

SEDIMENTOLOGY AND GEOCHEMISTRY OF THE MESOARCHEAN CHEMICAL SEDIMENTS OF WALLACE LAKE AND RED LAKE

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In the western Superior Province, Mesoarchean (~2.93Ga) carbonates and iron formation of the Uchi Subprovince represent a large carbonate platform that extended between the Wallace Lake and Red Lake greenstone belts. The aerial extent, sedimentary structures, and geochemistry of the platform indicate that significant changes in oceanic processes were occurring in the Mesoarchean. These changes include the precipitation of aerial extensive platform carbonates and evidence for the addition of free oxygen to limited areas of the hydrosphere by its initial production on semi-restricted platforms. Paleoproterozoic marine carbonates consisted of thin bedded units precipitating from anoxic water basins (ex. Strelley Pool Chert (Allwood et al., 2010)). Geographically scattered large Neoproterozoic carbonate platforms show evidence for the gradual build-up of oxygen during this time and leading to a relatively oxygenated atmosphere by 2.4Ga (ex. Steep Rock platform (Fralick and Riding, in press) and the Campbellrand-Malmani platform (Kendall et al., 2010)). The occurrence of this large carbonate platform in the earliest transitional period of this change and its similarities to younger Neoproterozoic platforms is significant in that the information gathered has significant import to processes responsible for the change in carbonate deposition through the Paleoproterozoic to Paleoproterozoic.

The lithofacies of the Wallace Lake and Red Lake carbonate platform represent deposition from peritidal to basinal environments, with many of the structures being present in younger Neoproterozoic and Proterozoic carbonate platforms. The peritidal lithofacies assemblage consists of herringbone calcite, pseudomorph fans, and tufa. The sub-tidal environment is characterized by large pseudomorph fans (Figure 1A) and laterally linked domal stromatolites (Figure 1B). Upper slope environments consisted of slumps, ribbon rock, and carbonate associated oxide-facies iron formation. Chert-oxide facies iron formation defines the basinal environment. These lithofacies typify younger Neoproterozoic carbonate platforms contributing to the gradual oxidation of the atmosphere (cf. Sumner and Grotzinger, 2004; Kendall et al., 2010; Fralick and Riding, in press).

The rare earth element (REE) geochemistry of the Wallace Lake and Red Lake chemical sediments (Figure 2) can significantly contribute to our understanding the changing early oceans. The PAAS normalised REE patterns ($REE_{(PAAS)}$) of the basin lithofacies (oxide-facies iron formation) is characterized by LREE depletion and positive Eu anomalies (Figure 2). This pattern mirrors REE geochemistry of Paleoproterozoic oceans (cf. Allwood et al., 2010). However, the carbonates show very little LREE/HREE fractionation, positive La, Eu, and Y anomalies, and negative Ce anomalies. This implies a significant change

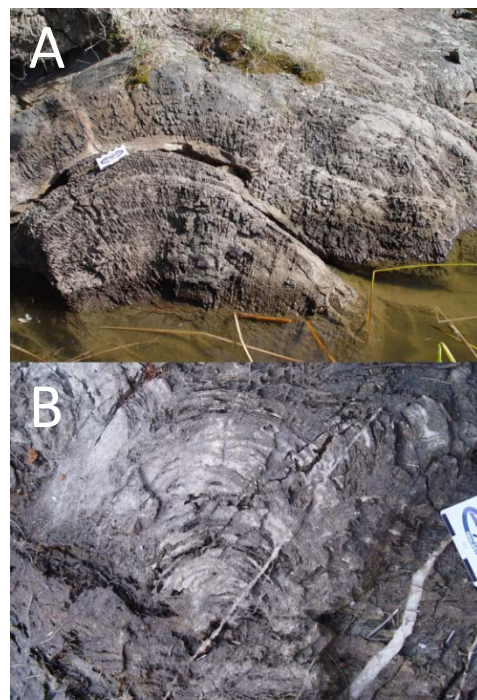


Figure 1. A) Pseudomorph fans after aragonite. B) Laterally linked domal stromatolites.

in ocean chemistry from basin to the shallow carbonate platform. The transitional facies between basin and peritidal platform (upper slope) is characterized by a $REE_{(PAAS)}$ pattern similar to that of the platform carbonates. The significant difference in basin and platform $REE_{(PAAS)}$ patterns and the $REE_{(PAAS)}$ pattern of the upper slope suggests that the platform was semi-restricted and evaporitic. This would lead to density contrasts between the shallow platform and basin waters allowing for seeping and down-welling of platform waters to the basin and imparting the shallow carbonate $REE_{(PAAS)}$ pattern to the upper slope environment.

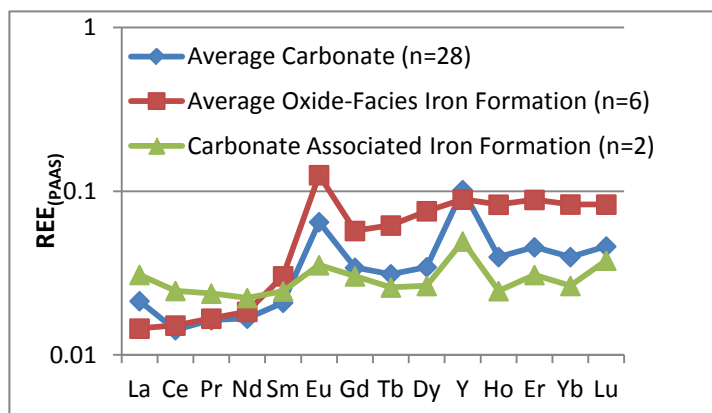


Figure 2. REE plot normalized to Taylor and McLennan's (1989) Post Archean Australian Shale (PAAS) (n refers to the number of samples analyzed).

The presence of Ce anomalies in the carbonates and lack thereof in the basin iron formation is indicative of a redox boundary separating the basin and peritidal environments. The negative Ce anomalies are the largest and most consistent in the pseudomorph fan facies. These pseudomorph fans are common structures found in Precambrian carbonate platforms, range in depositional environments from

peritidal to sub-tidal, and are thought to be pseudomorphs after aragonite (Sumner and Grotzinger, 2004). The fans of the Wallace Lake and Red Lake carbonate platform are also characterized by increased Ba, Sr, P, and K concentrations. The presence of the negative Ce anomalies in the fans and lack thereof in most of the rest of the platform indicate that the fans precipitated from relatively oxygenated water. It is suggested here that the fans are not indicative of a particular environment of deposition, but limited to periods of relative oxygenation of the platform and, when occur, are a platform wide occurrence.

To summarize: the Wallace Lake and Red Lake carbonate platform is the oldest known carbonate platform in a series of geographically scattered platforms contributing to a gradual change in oceanic processes in the Mesoarchean and Neoarchean that led to an extensively oxygenated atmosphere by 2.4Ga.

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COMPOSITION AND $^{40}\text{Ar}/^{39}\text{Ar}$ AGE OF PEGMATITIC AMPHIBOLE IN THE WAUSAU SYENITE COMPLEX, MARATHON COUNTY, WISCONSIN

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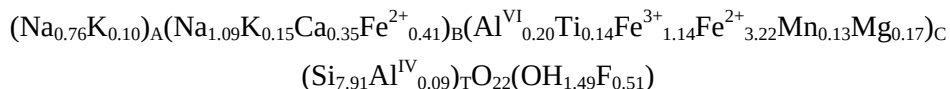
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Granitic pegmatites are of great interest for their unusual and exotic minerals. Because they are highly differentiated chemically, they may also contain silicate minerals of end-member compositions, such as arfvedsonite, aegirine, and albite. End-member amphibole crystals ≤ 30 cm in length occur in an NYF (niobium-yttrium-fluorine) granitic pegmatite that intrudes quartz syenite of the Wausau Complex (Fig. 1).

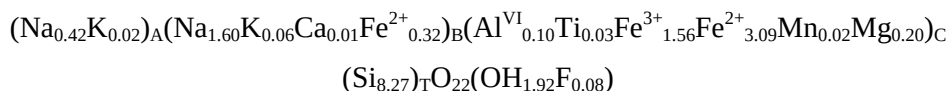
The Wausau Complex is one of four, alkaline syenitic to granitic concentric complexes proximate to Wausau in Marathon County. The igneous complexes decrease in age from 1565 Ma in the north (Stettin) to 1506 Ma in the south (Nine Mile) and precede the Wolf River batholith in intrusive age by 30 to 90 m.y. (Van Wyck *et al.*, 1984; Dewayne and Van Schmus, 2007). The granitic pegmatite in the Wausau Complex is ~6m long $\times$ ~1m wide and consists of 35% euhedral amphibole, 40% subhedral microcline, 25% anhedral quartz, and accessory pyroxene, albite (Ab 99.7), fluorite, ilmenite, and magnetite.

The amphibole is mainly arfvedsonite (Table 1; Fig. 2), with a mean atomic composition of:



A-site occupancy varies from 0.73 to 0.97, and F contents vary from 0.51 to 1.26 wt.%.

In contrast, the rims of amphibole and fine-grained amphibole associated with aegirine are intermediate arfvedsonite-riebeckite, with a mean atomic composition of:



A-site occupancy varies from 0.35 to 0.48, and F contents vary from 0.13 to 0.43 wt.%.

The intermediate arfvedsonite-riebeckite contains less TiO_2 , Al_2O_3 , MnO , CaO , and K_2O than the predominant arfvedsonite and is closer to a Na-Fe-Si end-member composition. However, the Si content of arfvedsonite-riebeckite exceeds 8.0 apfu, which may indicate the presence of a pyribole component, which is under further investigation.

The pyroxene is very close to end-member aegirine, with a mean atomic composition of:

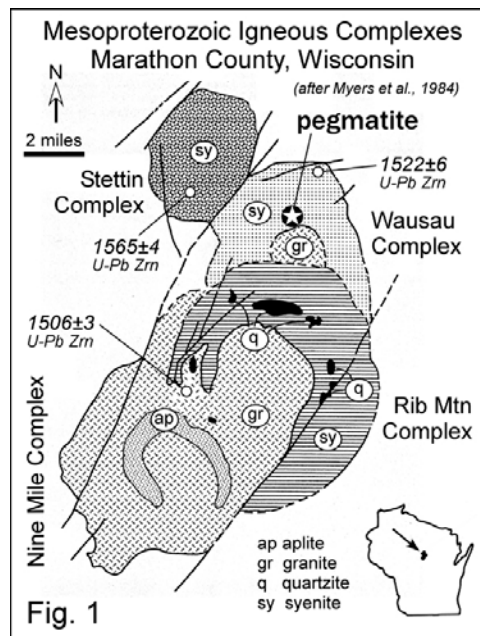
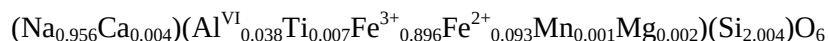
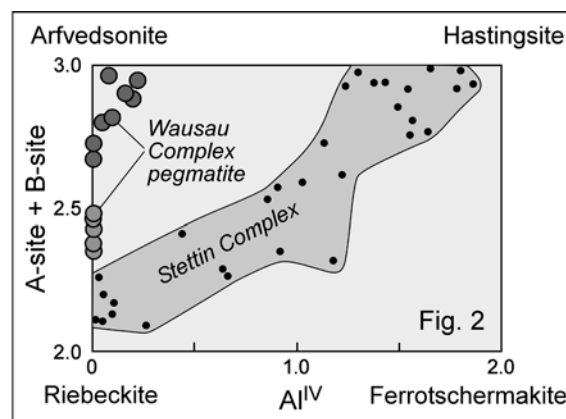


Fig. 1

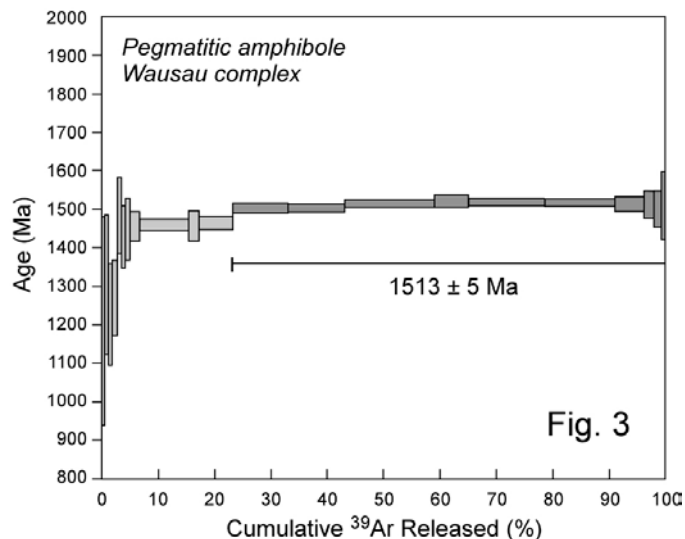
	Arf mean n = 27	1σ	Arf-Rbk mean n = 23	1σ	Aeg mean n = 23	1σ
wt%						
SiO ₂	48.50	0.67	51.18	0.40	52.26	0.33
TiO ₂	1.11	0.28	0.22	0.17	0.23	0.10
Al ₂ O ₃	1.51	0.16	0.52	0.24	0.84	0.48
FeO _{total}	34.93	0.85	36.88	0.60	30.85	0.51
MnO	0.97	0.44	0.14	0.04	0.01	0.01
MgO	0.71	0.14	0.82	0.14	0.03	0.04
CaO	2.01	0.70	0.08	0.25	0.09	0.05
Na ₂ O	5.85	0.21	6.45	0.19	12.86	0.10
K ₂ O	1.21	0.16	0.37	0.24	na	
F	0.72	0.31	0.16	0.13	na	
Sum	97.54		96.81		97.15	
-O=F	0.31		0.07			
Total	97.23		96.74			



Aegirine occurs interstitially and intergrown with arfvedsonite-riebeckite at the rims of arfvedsonite crystals. Such textural and compositional relations are likely the result of increasing oxygen fugacity during crystallization, which stabilizes riebeckite at the expense of arfvedsonite and stabilizes aegirine at the expense of alkali amphibole (Ernst, 1962; Scaillet & MacDonald, 2001). The presence of ilmenite inclusions in arfvedsonite and an association of magnetite with interstitial aegirine are consistent with this interpretation.

Ar analysis of a single arfvedsonite crystal was performed by step heating using a CO₂ laser, which yielded a well-defined plateau at 1513 ± 5 Ma (Fig. 3), representing ~75% of the ³⁹Ar released. This age is slightly younger than, but within error of, the 1522 ± 6 Ma U-Pb zircon age for syenite in the Wausau Complex (Dewayne and Van Schmus, 2007).

The geon 15 igneous intrusions near Wausau are classic examples of alkaline granitic to syenitic concentric complexes, the differentiated parts of which, such as the NYF pegmatite in the Wausau Complex, contain end-member silicate mineral compositions. These igneous intrusions represent an important magmatic event in the Precambrian evolution of the southern Lake Superior region, appearing somewhat earlier than the more voluminous and slightly less alkaline geon 14 Wolf River batholith.



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GEOLOGY OF THE LAKE THREE TROCTOLITE, DULUTH COMPLEX - 2013 PRECAMBRIAN FIELD CAMP CAPSTONE MAPPING

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Ann Marie Prue**

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As a capstone mapping project for the 2013 Precambrian field camp, a crew of four students, a teaching assistant (Sauer) and an instructor (Miller) conducted five days of field mapping bedrock geology in the southern area of Lake Three in the Boundary Waters Canoe Area. The field area was affected by the Fall 2011 Pagami Creek Fire, which burned an area of approximately 93,000 acres. The area immediately south of Lake Three experienced moderate fire intensity such that significant amounts of deadfall still existed on the forest floor. Moreover, in the second summer after the burn, a thick cover of shrubs and vines covered the forest floor creating difficult conditions for inland traverses. Despite these less than ideal conditions, three crews of field partners conducted multiple inland traverses that ultimately extended detailed mapping over a mile south of the Lake Three shoreline.

The Lake Three Troctolite (L3T) is a sub-circular body of troctolitic cumulates exposed along the southern shore of Lake Three and intruded into Anorthositic Series rocks. Both the troctolitic and anorthositic rocks are parts of the extensive Duluth Complex, which is the largest exposed intrusive component of the 1.1Ga Midcontinent Rift. Shoreline exposures of the L3T were first mapped by Phinney (1972) and Miller (1986). Additional reconnaissance mapping to south of Lake Three by Miller (1986) and more recent post-fire mapping by Jirsa (2013) suggests that the L3T may extend to as far as 3 miles south of the Lake Three shoreline.

This study sought to extend detailed mapping of the L3T south of the shoreline into the area burned by the Pagami Creek Fire. This detailed mapping shows the L3T to have broad asymmetrical synformal structure that trends NNE-SSW with a thinner eastern limb dipping NW and thicker western limb dipping SE. Moreover, the capstone mapping distinguished two distinct map units – an outer (lower) zone of vari-textured troctolitic cumulates rich in anorthositic inclusions, and an interior (upper) zone of homogeneous ophitic augite troctolite.

More specifically, the outer troctolite unit is composed of light to dark gray, commonly vari-textured (medium- to coarse-grained), locally layered, poorly to well foliated, subophitic to ophitic, Pl-phyrlic troctolitic rock types that are locally rich in irregular masses of anorthositic lithologies. Modal variants include melatroctolite, leucotroctolite and augite troctolite. The unit typically contains 2%-15% plagioclase phenocrysts typically about 1cm diameter. Modal layering is typically defined by variable olivine:plagioclase concentrations. Contacts with anorthositic series rocks are not exposed, but near inferred contacts, the troctolite becomes vari-textured, generally finer grained, and contains numerous anorthosite inclusions from cm to several meters. Contacts with the interior ophitic augite troctolite are broadly gradational over several to tens of meters.

Rocks of the inner augite troctolite unit are typically light gray to dark gray, medium-grained, poor to moderately foliated, homogeneous, ophitic, Pl-phyrlic augite troctolite. Plagioclase phenocrysts are typically 1-2 cm in diameter, but some are up to 4 cm. Augite oikocryst range from 2-5 cm in diameter and iron oxide commonly occur as subpoikilitic clots less than 1 cm across. Contacts with the troctolite unit are gradational over several to tens of meters.

Anorthositic Series rocks are composed of various anorthositic to leucogabbroic rock types including anorthosite, troctolitic anorthosite, olivine gabbroic anorthosite, leucotroctolite, and augite leucotroctolite.. All lithologies have greater than 75% plagioclase with less than 25% olivine, augite, and Fe-Ti oxides. Augite and oxide always occur as poikilitic to subpoikilitic crystal relative to lathy plagioclase, whereas olivine ranges in habit from subhedral granular to poikilitic. Oikocrysts of olivine up to 20 cm diameter have been observed and commonly recessively weather to create a pocked surface. Most anorthositic lithologies have a well- developed igneous foliation defined by plagioclase alignment, but modal and textural layering are rare. Locally anorthositic series rocks occur as inclusions into both the troctolite and augite troctolite units of the L3T.

A previously unrecognized lithology was found along the eastern margin of the L3T and as a large xenolith at the western troctolite-augite troctolite contact during the capstone mapping. It is typically a fine- to medium fine-grained, equigranular (granoblastic) olivine gabbro to augite troctolite. It is typically homogenous, but locally contains abundant coarse-grained clots and stringers rich in oxides and olivine. In some areas, a swirly mixture of medium fine-grained olivine oxide gabbro, fine-grained augite leucotroctolite, and fine grained leucotroctolite with 1cm oikocrysts of olivine is observed. Subtle modal layering with hints of crossbedding have been observed in a few locations. These masses are similar to other areas of the Duluth Complex that have been interpreted to be intensely metamorphosed inclusions of mafic volcanics of the North Shore Volcanic Group.

Abundant unburned blowdown trees and thick forest floor vegetation prevented traverses to reach south much more than a mile. Confirmation of the southern extent of the L3T will require additional mapping north of the Isabella River.

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GEOLOGIC MAPPING OF NEOARCHEAN AND PALEOPROTEROZOIC ROCKS NEAR HANSON LAKE, NE MINNESOTA, BY STUDENTS OF THE PRECAMBRIAN RESEARCH CENTER'S 2013 FIELD CAMP

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The University of Minnesota-Duluth's Precambrian Research Center conducted its seventh annual field camp in 2013, 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 (Fig. 1) accessed by 20 lakes, with Hanson Lake at its center. 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.

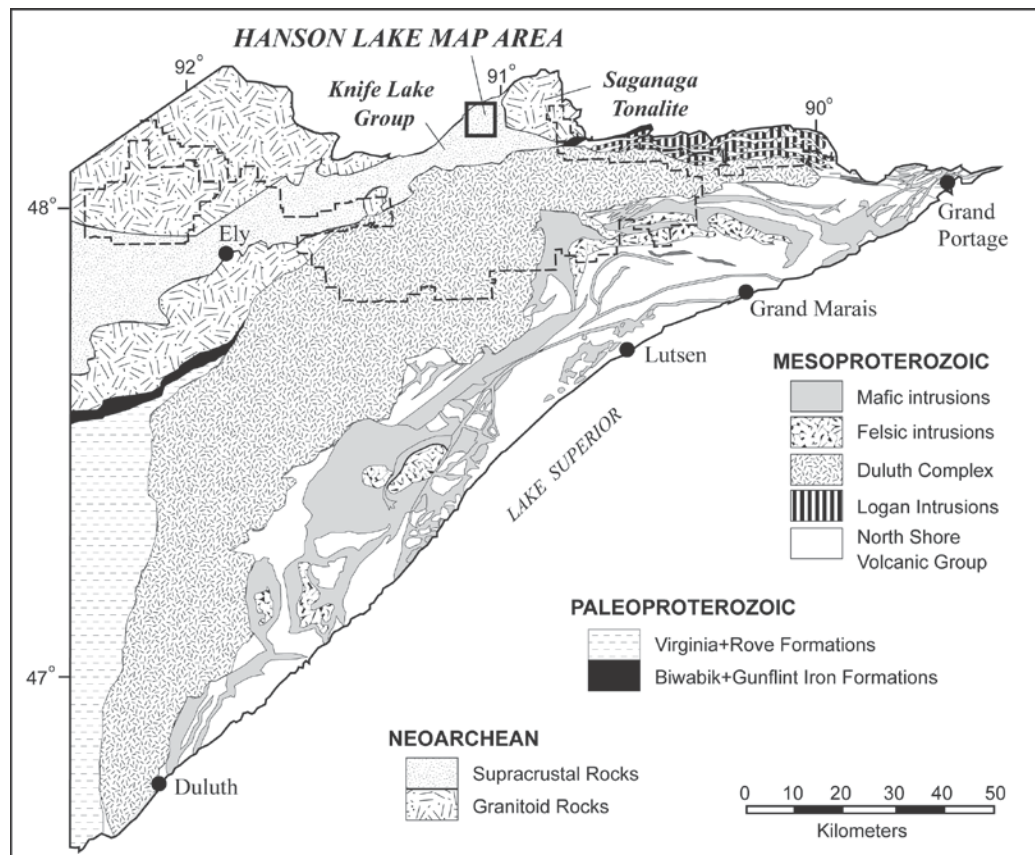


Figure 1. Generalized bedrock geologic map of northeastern Minnesota showing the Hanson Lake capstone area. The unit labeled "Knife Lake Group" also encloses older volcanic sequences that are not delineated separately at this scale. Dashed line is the border of the Boundary Waters Canoe Area Wilderness.

The Hanson Lake map area lies west of the boundary between the Saganaga Tonalite (ca. 2690 Ma), and superjacent sedimentary strata of the Knife Lake Group that are inferred to have been derived in part from it. Both rock units were variably tilted, folded, faulted, and metamorphosed to low greenschist facies during a regional deformation event at about 2680 Ma, which brackets deposition of the Knife Lake Group between ca. 2690-2680 Ma.

Our mapping demonstrated that strata of the Knife Lake Group in this area form a broad, northeast-trending synclinorium, bounded by the Saganaga Tonalite on the east, and an apparently uplifted fault-block of metabasalt on the west. The limbs of this large structure are marked by smaller sympathetic folds, and are dissected by faults and shear zones. Several major faults enclose what appear to be discrete blocks that were uplifted, tilted, and eroded to expose different crustal levels of the stratigraphic succession. As a result, some of the blocks contain older metavolcanic and meta-intrusive rocks that are unconformably overlain by Knife Lake strata. The dominant rock types are interbedded graywacke and slate, which were subdivided into eastern and western sections having somewhat different attributes. The eastern section contains sandstone, graywacke, and mudstone that is locally interlayered with several types of conglomerate and one thin unit of banded iron-formation, and intruded by rare peperite. A conglomerate near Nawaska Lake contains rounded, cobble-to-boulder sized clasts of tonalite, metabasalt, and metagabbro, implying fluvial deposition from streams draining a lithologically diverse terrane. Conglomeratic strata near Gift Lake contain amoeboid and diffuse-edged clasts of dacitic rock, inferred to have been weathered to saprolite before incorporation. Shreds of mafic peperite occur in chaotically bedded gritstone that contains angular grains of feldspar and mafic minerals identical with those in the peperite, indicating synchronous magmatism and sediment deposition. The western section consists of graywacke and slate, together with localized occurrences of more enigmatic strata. At Lake of the Clouds, a trachybasaltic crystal-lapilli tuff and breccias, containing clasts as large as 25cm occurs within an overall package of gray wacke. This implies episodic explosive calc-alkalic volcanism was synchronous with or just predated deposition of graywacke. At least macroscopically, this rock and the peperite appear magmatically-related. In the South Arm of Knife Lake, a unit of metabasalt is capped by basaltic conglomerate having both angular and amoeboid clasts. Presence of the latter implies the basaltic substrate was weathered prior to erosion, which is consistent with the inference that the sedimentary sequence lies unconformably on older basaltic substrate within the fault-bounded block.

Taken together, these attributes portray deposition in a largely fault- and unconformity-bounded, Timiskaming-type extensional basin. We infer that after the Saganaga Tonalite intruded older basaltic strata, the terrane was uplifted, weathered, and eroded to contribute detritus from both source rocks into the developing Knife Lake basin. The abundant 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 iron-formation that are associated with graywacke and slate are inferred to represent chemical precipitation into what may have been a shallow marine environment during periods of relative quiescence. These attributes, together with the association of syn-sedimentation magmatism, are consistent with the model of a Timiskaming-type basin assemblage.

Several N20°W-trending, vertically dipping diabasic dikes were also encountered in the area. They are locally as thick as 30m, coarse-grained, subophitic, and have chilled margins. The dikes are inferred to be part of the Paleoproterozoic Kenora-Kabetogama dike swarm on the basis of similarities in trend, thickness, and macromineralogy.

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

PETROGRAPHIC CHARACTERIZATION OF THE PENOKEAN TWELVEFOOT FALLS SHEAR ZONE, MARINETTE COUNTY, WI: EVIDENCE FOR COEVAL DUCTILE AND SEISMIC BEHAVIOR

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The Twelvefoot Falls Shear Zone in northeastern-most Wisconsin lies 25 km south of, and approximately parallel to, the NW-SE-striking Niagara Fault, which is thought to represent the ca. 1.88 Ga Penocean suture between the Archean-Paleoproterozoic Superior Craton and Paleoproterozoic island arc rocks of the Pembine-Wausau terrane (Schulz & Cannon, 2006). The shear zone is well exposed along the Pike River at Twelvefoot and Eightfoot Falls, where it cuts through quartz diorite with a U-Pb zircon crystallization age of 1889 $\pm$ 6 Ma (Schulz & Schneider, 2005). This intrusive body was emplaced into the Quinnesec Formation, a metavolcanic unit interpreted to be part of a pre-collisional suprasubduction zone ophiolite-island arc complex (LaBerge et al., 2003). The Twelvefoot Falls Quartz Diorite lies on the southern flank of the Dunbar Gneiss Dome, a younger, post-collisional composite intrusion dated at 1862 $\pm$ 5 Ma (Sims et al., 1985; Sims, 1990).

Detailed petrographic study of samples from outcrops at Twelvefoot and Eightfoot Falls reveals a complex, multistage deformational history. The rocks have a pervasive, though heterogeneously developed, subvertical NW-striking foliation defined by the preferred orientation of relatively large (2-5 mm) hornblende porphyroclasts and planar quartz-rich domains. The quartz in these bands is typically fine grained (<0.1 mm), with undulose extinction, irregular grain boundaries, and in places ‘core and mantle’ structure. These textures record ductile deformation, dynamic recrystallization and subsequent partial annealing. The hornblende grains have ragged grain boundaries and are commonly dismembered or boudinaged. In many cases, once-joined grain fragments can be recognized through their optical continuity (simultaneous extinction). Alteration of hornblende to chlorite is common.

Narrow (<1 cm wide) mylonite zones transect the foliation at oblique angles. Within these bands, both the hornblende and quartz grains are finer than they are in the rest of the rock, but their microstructural characteristics are similar: the hornblende is fragmented in a quasi-brittle manner, while the quartz forms narrow, high-strain bands. This suggests that both the foliation and mylonite zones developed under similar temperature conditions, namely between ca. 300°C (threshold for quartz ductility) and 600°C (onset of hornblende ductility under hydrous conditions; Hacker & Christie, 1999). This is consistent with the upper greenschist- to amphibolite-facies metamorphic conditions in the area surrounding the Dunbar Gneiss Dome (Sims et al., 1985) and also with temperature estimates for rocks with similar compositions and textures from mylonite zones in the Grenville Province (Babaie & LaTour, 1994).

At Eightfoot Falls, dark, branching discordant veins 0.3-0.5 cm wide and 10-15 cm long cut across the foliation in the rocks. In thin section, these are found to contain a mesh of fine hornblende crystals with high aspect ratio, arranged with no preferred orientation in a non-crystalline matrix that is dark in plane light. These macro- and micro-scale characteristics suggest that the veins represent devitrified pseudotachylyte – frictional melt glass generated on a fault plane during seismic slip, and injected as ‘hydro’-fractures into the surrounding rock. Significantly, the pseudotachylyte material can be seen in thin section to have been cut by, and in places incorporated into, the mylonitic bands, indicating that brittle seismic failure occurred at least once while the rocks were still at depths and temperatures where crystal plastic deformation was predominant. Such mutually cross-cutting relationships between mylonites and pseudotachylytes have been reported from a small number of sites around the world (e.g., Sibson, 1975; Hobbs et al., 1986) and are interpreted as records of large earthquake ruptures,

usually in convergent tectonic settings, that propagated downward from the fully brittle upper crust into the upper part of the ductile regime.

We interpret the fabrics in the rocks from the Twelvefoot Falls Shear Zone to be of mid-late Penokean age, based on the proximity and parallelism of the Zone with the Niagara Fault and on the regional evidence that intrusion, deformation and metamorphism of the Dunbar Gneiss Dome coincided with later Penokean (ca. 1.85 Ga) crustal shortening at the time of the collision of the Marshfield terrane with the Pembine-Wausau terrane (Schulz & Cannon, 2006; Sims, et al., 1985). If so, our results provide insight in the rheology of the middle crust in the heart of a growing mountain belt.

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METAMORPHISM AND DEFORMATION AT THE WABIGOOON-QUETICO SUBPROVINCE BOUNDARY IN THE DECOURCEY LAKE AREA

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The Wabigoon and Quetico subprovinces are east-west trending belts of metasedimentary and metavolcanic rocks located within the Superior province, the world's largest preserved Archean craton. The Wabigoon-Quetico subprovince boundary in the Decourcey Lake area is complex and several kilometers wide. The 130m-long roadcut on Hwy 527 near Decourcey Lake is composed of a garnet-biotite to biotite schist with three intrusions, a pegmatitic intrusion, a felsic intrusion and a mafic dyke. There are also several quartz-carbonate veins that have been folded and boudinaged; the folded veins crosscut the boudinaged veins that are parallel to foliation.

In the southern portion of the outcrop, mats of fibrolite in the schist indicate peak metamorphism at amphibolite facies or higher. However, some parts of the outcrop show evidence of overprinting retrograde metamorphism. The amount of retrograde metamorphism increases from south to north in the outcrop. In the southern part of the outcrop there are minimal amounts of chlorite (~1%) and the amount increases to about 30% in the north. The chlorite replaces biotite, the main mica in the southern portion of the roadcut. Chlorite replacing biotite is indicative of retrograde metamorphism.

Other evidence for this retrograde metamorphism is the presence of stable garnet in the southern portion of the outcrop and metastable garnet in the northern portion, indicated by euhedral unfractured crystals in the south and anhedral, fractured and separated grains in the north (fig. 1).

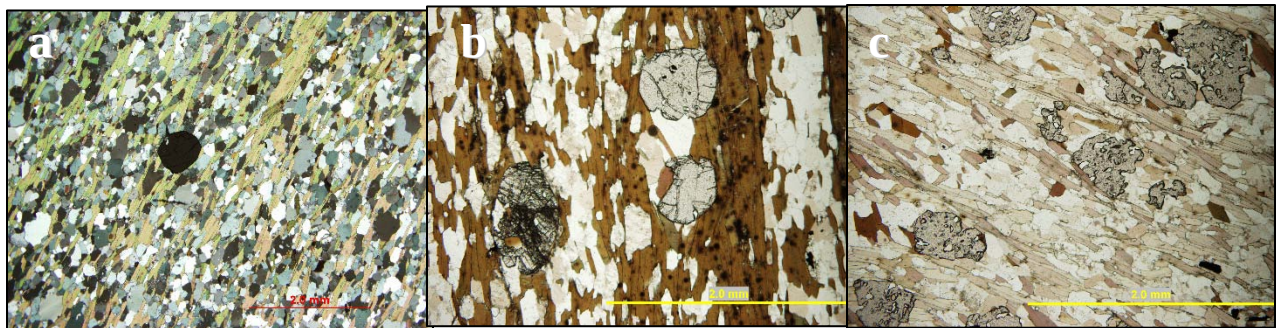


Figure 1. a) Garnet from southern portion of the outcrop (stable), b) garnet from middle portion of the outcrop (metastable), c) garnet from northern portion of the outcrop (metastable)

Throughout the schist, quartz with undulose extinction, irregular grain boundaries and subgrains provides evidence for deformation by dislocation creep. In the southern portion of the outcrop, undulose extinction in feldspar indicates deformation at amphibolite facies temperatures or higher. This higher temperature deformation of feldspar is not evident in the northern portion of the outcrop where retrograde metamorphism is more pervasive. The pegmatite and felsic

intrusions preserve evidence of deformation at the amphibolite facies or higher, including undulose extinction in feldspar and bent mica grains (Fig. 2).

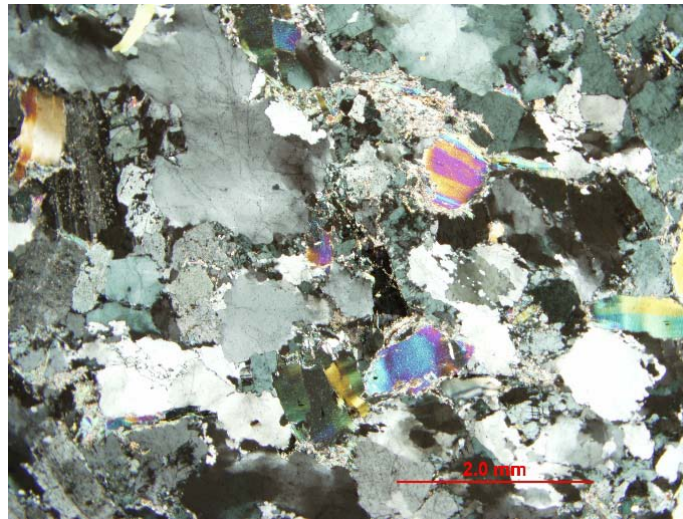


Figure 2. Photomicrograph of the felsic intrusion showing evidence for dislocation creep

The preservation of evidence for amphibolite facies metamorphism and high temperature deformation in schist in the southern portion of the outcrop as well as in the pegmatite and felsic intrusions suggests that the Decourcey Lake roadcut is composed of metamorphosed Quetico lithologies. Therefore, the Quetico-Wabigoon subprovince boundary lies to the north of this roadcut. The increase in retrograde metamorphism toward the northern portion of the outcrop (in the direction of the subprovince boundary) suggests that this lower temperature metamorphism may be associated with the boundary.

BEDROCK GEOLOGIC MAP OF THE TWIN METALS MINNESOTA PROJECT, NORTHERN SOUTH KAWISHIWI INTRUSION AND ADJACENT AREAS

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Twin Metals Minnesota LLC (TMM), is the joint venture company between Duluth Metals Limited (60% ownership interest) and Antofagasta plc (40% ownership interest). TMM is currently in the process of completing a prefeasibility study of the Maturi Cu-Ni-PGE deposit in the northern South Kawishiwi intrusion (SKI) of the Duluth Complex, northeastern Minnesota. Assuming a favorable outcome of the prefeasibility study, TMM will embark on a bankable feasibility study that will include extensive study of groundwater within and around the facilities (the proposed underground mine at Maturi, a concentrator facility, and a tailings storage facility). All of these studies would be incorporated into an environmental review of the project and would be open for comment and review by the general public. As the joint venture looks to the immediate future, Duluth Metals Limited believes that it is imperative that this process be as transparent as can be possible, especially on the publication of confidential geological data that could possibly be linked to water issues in an environmental review process.

The bedrock geological map presented in this poster is the result of nearly two decades of geological work by the author integrated with data from seemingly innumerable government (Minnesota Geological Survey, U.S. Geological Survey, Natural Resources Research Institute, Minnesota Department of Natural Resources), academic (Minnesota-Duluth, Indiana, Minnesota, Wisconsin), and industry (Duluth Metals, Twin Metals, Franconia, INCO, Hanna, Bear Creek, Kennecott, Newmont, Duval, Encampment, etc...).

POTENTIAL FOR COPPER TOXICITY CAUSED BY SURFACE WATER AND STREAM SEDIMENTS IN UNMINED MINERALIZED WATERSHEDS OF THE DULUTH COMPLEX.

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The characterization of baseline conditions in unmined mineralized watersheds of the Mesoproterozoic Duluth Complex, northeastern Minnesota, is essential to understanding how to responsibly extract minerals in one of the most prospective mining areas in the United States. Mining could release metals into watersheds that already contain ecologically-significant naturally-occurring amounts of some elements such as Cu and Ni. The potential for metals to be toxic to aquatic organisms is influenced by the amount of organic carbon in the aquatic environment, the cumulative effects of multiple metals, cation competition for biologic binding sites, and speciation of metals. We estimated toxicity in mineralized watersheds using approaches that incorporate these water and sediment quality parameters.

Surface-water and streambed-sediment samples were collected from sites along three geologically distinct watersheds in the Duluth Complex: 1. Filson Creek where Cu-Ni-PGM mineralization occurs at the bedrock surface along the basal Duluth Complex; 2. Keeley Creek where Cu-Ni-PGM mineralization occurs only at great depth; and 3. the St. Louis River in the vicinity of Fe-Ti oxide ultramafic intrusions, which occur at the subcrop beneath glacial cover. Samples were collected in September 2012 near base-flow conditions in watersheds dominated by lakes, wetlands, and streams.

The geochemistry of the surface waters and stream sediments reflects underlying rock types, glacially transported unconsolidated materials, mineralization style within each watershed, and geochemical processes occurring in the streams. The surface water is oxic, near neutral to slightly acidic (pH 5.9 to 7.6), has low total dissolved solids (41 – 94 mg/L), and is characterized by moderate hardness (18 – 50 mg/L CaCO₃), moderate carbonate species concentrations (11 – 38 mg/L CaCO₃ as bicarbonate), low sulfate (<0.8 – 3 mg/L), and high dissolved organic carbon (DOC) concentrations (18 – 47 mg/L). The dominant dissolved trace elements are Fe (472 – 3,950 µg/L), Al (54 – 228 µg/L), Cu (0.8 – 8 µg/L), Ni (1 – 5 µg/L), and Co (0.4 – 3 µg/L). Stream sediments contain significant Al (7 – 11 wt. %), Ca (1.5 – 6 wt. %), Fe (1 – 7 wt. %), and Na (2 – 4 wt. %). Sulfur is very low (<0.05 wt. %). Organic carbon reaches 4.7 wt. % in one sample but is ≤1.5 wt. % in all the other samples. Trace metals are dominated by Cr (14 – 346 mg/kg), Cu (10 – 179 mg/kg), Ni (13 – 127 mg/kg), and Zn (23 – 95 mg/kg). On average, Cu and Ni are highest in Filson Creek surface waters and sediments where Ni-Cu-PGM mineralization occurs at the surface. Samples collected from the St. Louis River watershed, where Fe-Ti oxide-bearing ultramafic rocks and a Paleoproterozoic shale/greywacke unit (Virginia Formation) occur, contain the highest average concentrations of As, Fe, and Pb in both surface water and sediments, Cr and Zn in sediment, and sulfate in waters.

In water, the toxicity of most metals is assessed on the basis of hardness-based criteria that adjust for the protective effects of Ca and Mg ions, which compete with metal ions for binding sites on organisms. For sediment, consensus-based total-metal guidelines are routinely used and rely on laboratory toxicity tests that document increased toxicity caused by increased metal concentrations (McDonald and others, 2000). However, new guidelines that rely on the Biotic Ligand Model (BLM) utilize a more sophisticated approach incorporating more water and sediment quality parameters including the cumulative effects of multiple metals in sediment, metal speciation in water, and organic carbon complexes in both water and sediment (Di Toro and others, 2005; Paquin and others, 2001).

The baseline surface-water and sediment metal concentrations can be compared to aquatic guidelines using the hazard quotient (HQ), which is the ratio of the concentration of a metal in the sample to the guideline. Values above 1 imply toxic conditions, whereas those below do not. In water, HQs for Cu are greater than 1 for several sites in the Filson Creek watershed when calculated using hardness-based criteria (Figure 1). However, as shown in Figure 1, HQs for Cu in water calculated based on the BLM model are significantly less than 1, suggesting a lack of toxicity from all samples. The radically different results from the hardness-based and BLM-based approaches suggest that the former may be inadequate to describe metal toxicity in these watersheds because it is based on a more limited set of parameters (i.e., only hardness). The complexation of Cu with DOC likely significantly affects the bioavailability of dissolved Cu, helping mitigate its toxicity.

The sediment BLM approach also suggests a different level of predicted toxicity from sediments than predicted from consensus-based guidelines. Several HQs for Ni and one HQ for Cu are greater than 1 when calculated using the consensus-based guidelines, which suggests toxic conditions (Figure 2A). In comparison, no toxicity to uncertain toxicity is predicted based on Equilibrium Partitioning Sediment Benchmark (ESB) (USEPA, 2005) (Figure 2B).

Specific considerations of this approach include:

1. determining extractable (a proxy for bioaccessible) metal concentrations (i.e., combined simultaneously extracted metals, Σ SEM);
2. adjusting them for potential incorporation into less bioaccessible sulfides (i.e., acid volatile sulfide, AVS);
3. and adjusting for complexation with organic carbon (i.e., fraction of organic carbon, f_{oc}).

The high organic carbon in some of the sediments could sequester significant amounts of trace elements; however, the low AVS suggest trace elements bound to sulfides are not significant components in these sediments.

Applying these more sophisticated and holistic approaches enhances our capability to predict metal toxicity. This improved understanding will be advantageous when developing successful strategies to help minimize future mining impacts and develop appropriate restoration goals.

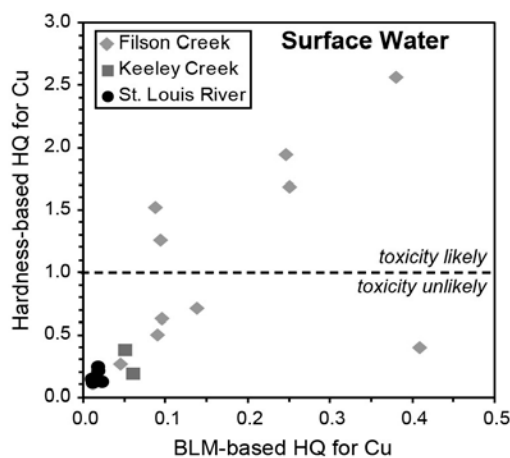


Figure 1. Hardness-based and BLM-based Hazard Quotients (HQ) of chronic toxicity for dissolved Cu in surface waters in mineralized watersheds of the Duluth Complex.

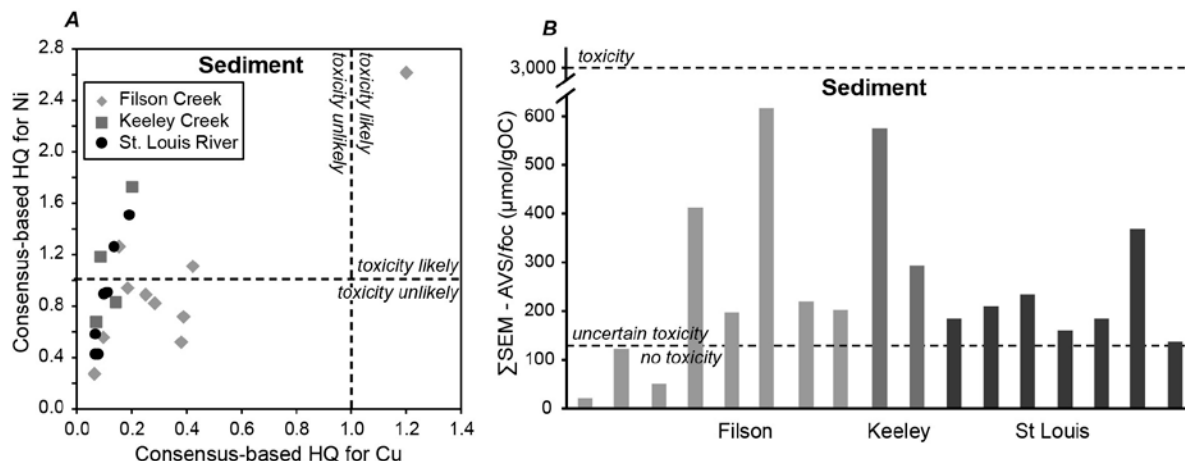


Figure 2. (A) Consensus-based Hazard Quotients for Ni and Cu in sediment in mineralized watershed of the Duluth Complex. Probable Effect Concentrations from MacDonald and others (2000) were used as the criteria in the calculation. (B) Equilibrium Partitioning Sediment Benchmarks for sediment samples by watershed and plotted from upstream to downstream (right to left for each watershed). See text and USEPA (2005) for further explanation of terms.

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MESOPROTEROZOIC MIDCONTINENT RIFT INTRUSIVES IN THE THUNDER BAY AREA (ONTARIO, CANADA): A PALEOMAGNETIC REVIEW

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Mafic sills and dykes extend over 300 km from south of Thunder Bay to northeast of Lake Nipigon, representing the northern expression of the ~1.1 Ga Midcontinent Rift System (MRS). Recent geochemical and geochronological studies have significantly improved our understanding of the area geology. The Logan sills, south of Thunder Bay, are geochemically similar but not identical to the sills exposed in the vicinity of Lake Nipigon, which in turn can be divided into three separate groups based on their geochemical signatures (e.g. Hollings et al., 2010, 2012). In addition, several discrete mafic/ultramafic intrusions and dyke swarms that represent both the earliest and the latest stages of the Midcontinent Rift magmatism are exposed along the north shore of Lake Superior (Heaman et al. 2007; Hollings et al., 2010). The dykes within the Thunder Bay area are currently grouped into four lithological units based on their orientation, petrology and geochemical differences: the Mount Mollie dyke and the Sibley, Pigeon River and Cloud River dykes (Hollings et al. 2010, 2012; Cundari et al., 2012).

In general, the magnetostratigraphy of the MRS can be summarized as follows:

- a) The earliest rock sequences (~1115-1105 Ma) are reversely magnetized;
- b) A polarity reversal (or reversals) occurred between 1105-1102 Ma;
- c) The rocks emplaced after ~1102 Ma are normally magnetized.

Withstanding the age uncertainty, this geomagnetic polarity sequence allows for an approximate correlation within and between the MRS rock sequences. When combined with high quality geochronological and petrographical observations as well as detailed geochemical and isotope data, paleomagnetic data can provide valuable information of the development of the MRS.

We present the new results of our rock magnetic and paleomagnetic investigation of several MRS intrusives exposed in the vicinity of Thunder Bay (Ontario, Canada). We also re-evaluate the previously published paleomagnetic data based on the newly published geochronological and geochemical data from the sills and dykes of the Thunder Bay area. Finally, we will critically address the observed inconsistencies between the field observations

and paleomagnetic and geochronological data. This study contributes to better understanding of the MCR magnetostratigraphy and further improvement of the late Mesoproterozoic apparent polar wander path for North America.

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DOCUMENTING THE FIRST LAVA FLOWS OF THE MIDCONTINENT RIFT BY DIGITAL MAPPING AND PETROGRAPHIC ANALYSIS

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The Ely's Peak basalts (EPB) located west of Duluth represent the first lava flows to be erupted from the Midcontinent Rift. The EPB lie conformably on siltstones, sandstones, and conglomerates of the Nopeming sandstone, which in turn unconformably overlies the Paleoproterozoic Thomson Formation. This classic outcrop area (Jirsa and Morey, 1979; Green, 1999; Jirsa and Green, 2011) has been a popular field trip location for many years, and today it's used as a field mapping exercise for a Geologic Maps course at UMD (GEOL 3000) and the Precambrian Research Center's field camp (GEOL 4500).

The area was initially mapped by J.A. Kilburg as part of his MS thesis at UMD (Kilburg, 1972) with a reconnaissance map later produced by Kilburg and Morey (1977). Kilburg (1972) noted that the Duluth Complex thermally metamorphosed the EPB flows and made them difficult to distinguish.

The focus of this project is exposure of the EPB north of Interstate 35 (Fig. 1). The research questions for this project were to determine the number of lava flows represented in the area, their petrographic characteristics and their geographical distribution of exposure. The data collected from several years of mapping and new mapping conducted for this study were also compiled and digitized with ArcMAP 10. For this study, 17 new were collected and made into thin sections and combined with 17 samples collected previously. A petrographic analysis of this suite of sections were made, noting textures and mineral assemblages comprising the groundmass, phenocrysts, and amygdulites that might be useful for distinguishing individual lava flows and revealing the nature and intensity of thermal metamorphism.

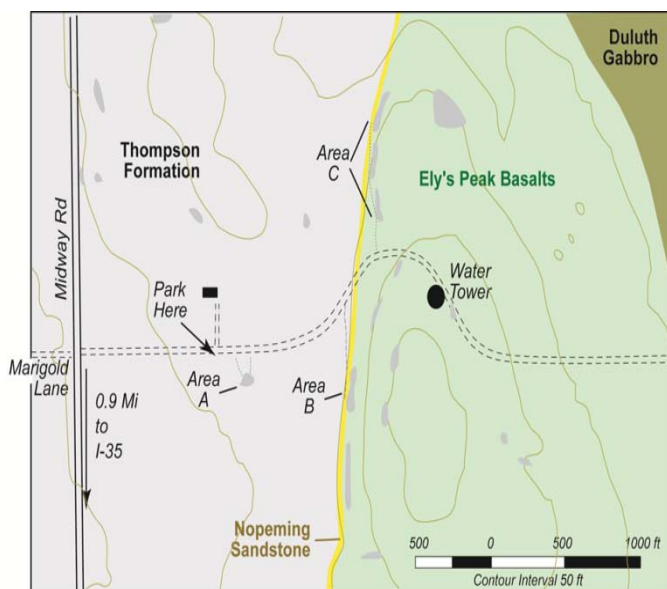


Figure 1. Bedrock geology of the field area based on previous mapping by Kilburg (1972). Significantly more outcrops have been discovered by mapping conducted for the UMD geology courses.

Prior mapping by Kilburg (1972) and UMD classes concluded that there were two main types of flows. The first is a lower sequence of variably amygdaloidal, dense, pyroxene-phyric basalts overlying the Nopeming sandstone. Pyroxene phenocrysts up to 1 cm in diameter appear to compose between 10 and 40 vol.% of these flows, but up to 90% pyroxene phenocrysts have been locally observed. Amygdaloidal zones composed of chlorite, quartz and epidote amygdulites are locally observed, but flow contacts are difficult to recognize, presumably due to annealing by thermal metamorphism. In the eastern third of the EPB exposure area (Fig. 1), a distinctly aphyric basalt is recognized. It is also distinguishable from the pyroxene-phyric flow by being moderately magnetic. The contact

with the Duluth Complex on the east side of the field area is somewhat ambiguous by being marked by a fine-grained, massive gabbro that has been variably interpreted to be intensely metamorphosed basalt or chilled gabbro.

Petrographic observations from this study reveal several interesting and unexpected results. Most notable is that the previous interpretation of pyroxene-phyric basalt overlain by aphyric basalt is a significant oversimplification of the area. Several samples collected from the porphyritic basalt area are actually aphyric. Also, what have been assumed to be pyroxene phenocrysts are actually clusters of pyroxene that may be glomerphenocrysts or perhaps xenoliths of pyroxenite. Curiously, they commonly have amphibolitic reaction rims, suggesting that they may be out of equilibrium with the enclosing basaltic groundmass and thus be xenoliths. The few exposures that have been mapped as comprising an area of aphyric basalt instead appear to be more related to the Duluth Complex. They are subophitic, olivine gabbro and could potentially be the chilled contact zone of the Duluth gabbro. Another surprising observation is that given the density of these basalts, granoblastic recrystallization textures are rarely noted. Instead, original intergranular igneous textures dominate the sections observed.

This poster presentation will show a revised geological map and of the area and display photomicrographs of the textures and mineral assemblages observed.

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GEOCHEMISTRY AND PETROGRAPHY OF A MAFIC METAVOLCANIC SEQUENCE SOUTH OF MUSSELWHITE MINE

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The North Caribou Greenstone Belt (NCGB), within the North Caribou Terrane of the Archean Superior Province, is host to multiple ~3.0Ga metavolcanic and metasedimentary assemblages. The assemblages have been metamorphosed from greenschist to upper-amphibolite grade and are bounded by ~2.7-3.0 Ga granitoids and gneisses (Biczok et al., 2012). The study area is located approximately 5km south of Musselwhite Mine within what was previously thought to be the Opapimiskan-Markop metavolcanic assemblage. There were three lithologies identified within the study area (basaltic, komatiitic, and felsic volcanic flows) which have been subdivided into four separate volcanic suites: Volcanic Suite A, Volcanic Suite B, Volcanic Suite C, and Felsic Volcanic Suite.

Volcanic Suite A is comprised of a succession of massive and pillowed basaltic flows that were metamorphosed to amphibolites. These flows exhibit a mineral assemblage of amphibole, chlorite, and plagioclase with minor quartz, muscovite, titanite and epidote. Major element geochemistry reveals that this suite is compositionally similar to that of a high-Mg tholeiitic basalt. Primitive mantle normalized plots for this volcanic suite are characterized by a flat rare-earth element (REE) pattern comparable to tholeiites from the South Rim Unit (SRU) (Fig. 1), which have been interpreted to represent oceanic island plateau basalts formed from a mantle plume (Hollings et al., 1999).

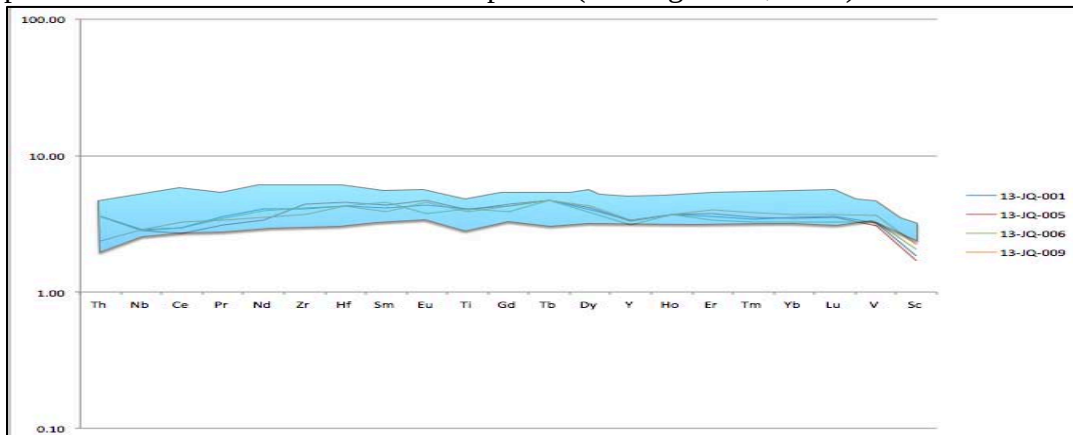


Figure 1: Comparison of primitive mantle plots from Volcanic Suite A versus tholeiites from the South Rim Unit (Blue trace).

Volcanic Suite B was comprised of pillowed and massive basaltic flows that have been metamorphosed to amphibolites. The main mineral assemblage observed in this suite was amphibole and chlorite with minor plagioclase, clinozoisite, quartz, titanite and dolomite. Major element geochemistry indicates that this suite is comprised of high-Mg tholeiitic basalts, komatiitic basalts, and a komatiite. Primitive mantle normalized plots display a relatively flat REE pattern but with a negative Nb anomaly (Fig. 2). The similar

trace element geochemistry of Volcanic Suites A and B suggests that they are both derived from a plume source, however, the negative Nb anomaly in Volcanic Suite B indicates that it has undergone crustal contamination during emplacement.

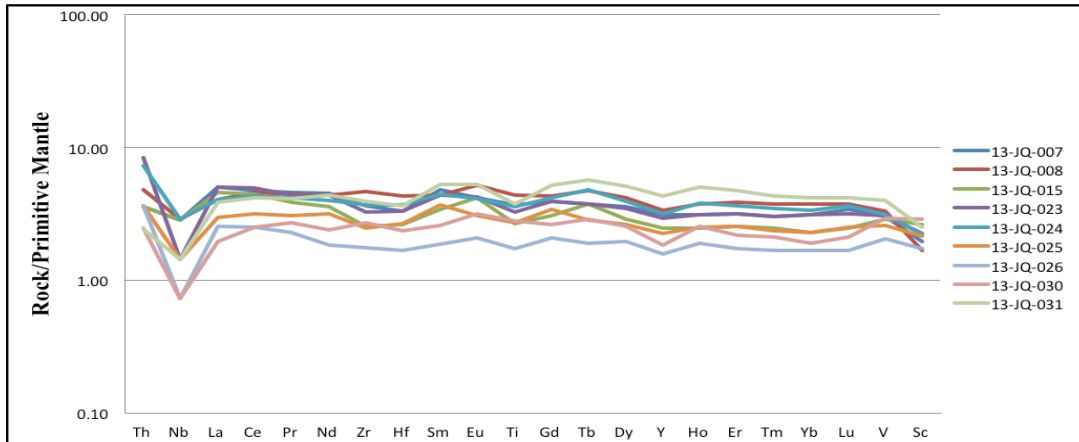


Figure 2: Primitive mantle normalized plot of the samples from Volcanic Suite B.

Volcanic Suite C was also comprised of massive and pillowed basaltic flows with a main mineral assemblage of amphibole and chlorite. A single sample was taken from this suite and it was determined to be a high-Fe tholeiitic basalt based on major element geochemistry. Primitive mantle plots of this suite are light rare-earth element (LREE) enriched with a negative Nb anomaly and positive Zr and Hf anomalies. A similar REE pattern was observed in the tholeiitic basalts from the Opapimiskan-Markop Unit (OMU) (Hollings and Kerrich, 1999).

The felsic volcanic suite overlies the mafic volcanic suites and is comprised of rhyolitic flows. This suite was LREE enriched with a relatively flat heavy rare-earth element (HREE) pattern and negative Nb and Ti anomalies in conjunction with positive Zr and Hf anomalies. Similar REE patterns were observed in the SRU and interpreted to be derived from a subduction tectonic setting (Hollings et al., 1999).

The results of this study are consistent with previous work in the region and suggest that the early history of the area preserved the interaction of a mantle plume with pre-existing continental crust. In addition this study has refined the boundaries of the various assemblages within the NCGB.

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THE ARROWHEAD PILOT PROJECT: MAPPING OF PRECAMBRIAN AND QUATERNARY GEOLOGY IN TWO DIVERSE GEOLOGIC AREAS OF NORTHEASTERN MINNESOTA

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The Arrowhead Pilot Project was undertaken by the Minnesota Geological Survey (MGS) to explore the feasibility of County Geologic Atlas-style mapping in NE Minnesota. It integrates new field mapping by the authors with archived data to provide both Precambrian and Quaternary geologic interpretations of two areas of interest in northeastern Minnesota (Fig. 1). Two distinct areas were mapped: the western one contains significant exposure of Archean, Paleoproterozoic and Mesoproterozoic bedrock, and relatively thin and patchy Quaternary deposits; the eastern area has limited bedrock exposure of Mesoproterozoic rocks, and thick Quaternary glacial cover. Together these areas cover part or all of fifteen 7.5' quadrangles.

The intent of this study was multi-faceted: (1) to compile previous maps (both Precambrian and Quaternary) of these areas into single, coherent maps; (2) to augment gaps in data with new mapping; (3) to assess the usefulness of LiDAR (Light Detection And Ranging altimetry) imagery in identifying bedrock outcrop and surficial features; and (4) to assess the costs and feasibility of a mapping project at a similar level of detail over a much larger area, such as that typical of a County Geologic Atlas produced by the MGS. The motivation to produce large scale, comprehensive regional map products is in part driven by increased interest in extracting mineral resources, as well as management of ground and surface water resources. Further, the area's complex bedrock geology provides insight into more than 1.5 billion years of earth's history in three distinct terranes: the Archean Giants Range batholith, the Paleoproterozoic Animikie Group, and the Mesoproterozoic Duluth Complex. This study area is also key to understanding the glacial history of the region, as it includes the interlobate junction between the Rainy and Superior lobes, and spans the transition in the provenance of Rainy lobe clasts from the Duluth Complex-dominated eastern portion to the granite-dominated western part.

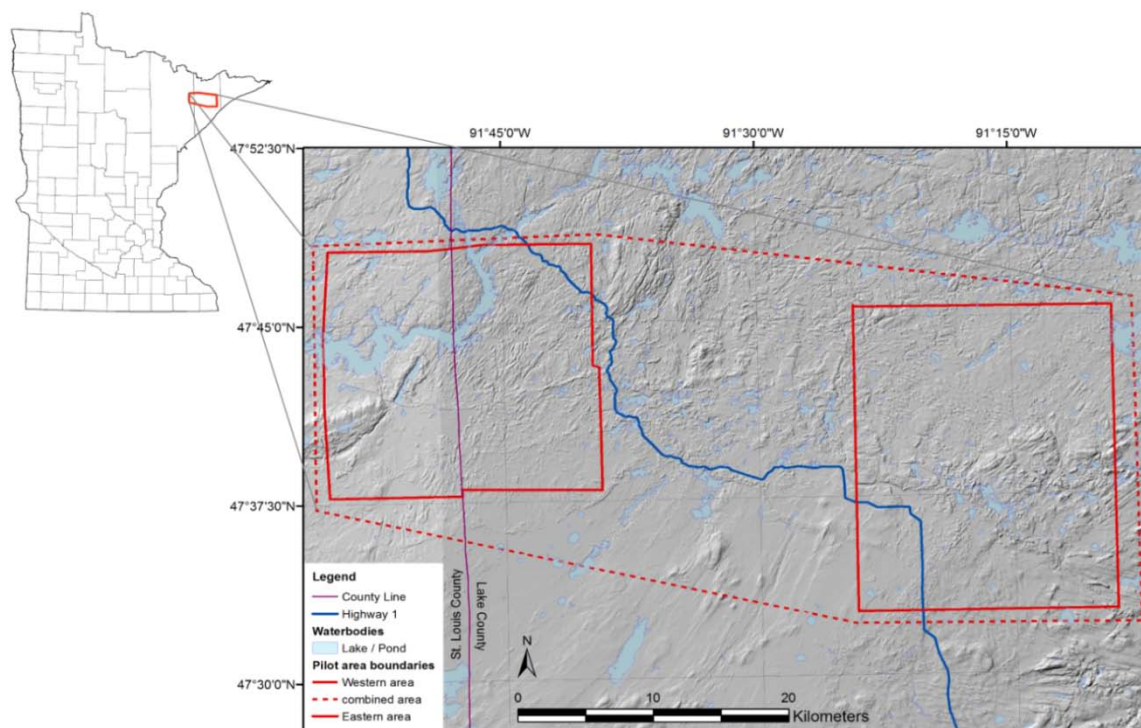


Figure 1. Location of study areas showing 1-meter LiDAR (Light Detection and Ranging Altimetry) imagery.

The bedrock portion of the study resulted in creation of modified bedrock geologic and bedrock topographic maps, and a detailed fault and lineament analysis. In the western area, new mapping north of the Mesabi Iron Range helped provide a more complete characterization of the Archean Giants Range batholith. Mapping south of the Iron Range also helped better define layers of the Mesoproterozoic South Kawishiwi Intrusion in the Duluth Complex. In the eastern area, new outcrop data combined with improved aeromagnetic and gravity data helped modify and extend unit contacts within Mesoproterozoic volcanic sequences. LiDAR analysis combined with field mapping and structural analysis identified significant bedrock-controlled linear topographic features which were classified as faults, lineaments, or igneous foliations. Such features are known to potentially play significant roles in the hydrogeologic system. Finally, mapping of the bedrock surface incorporated data from County Well Index (CWI) records, passive seismic data, outcrop elevations, and LiDAR; It revealed that depth to bedrock varies considerably across the area: from zero to as much as 250 feet (~75m).

The Quaternary portion of the study revealed the Highland moraine of the Superior lobe to be highly collapsed and strewn with ice-walled lake plains, indicating widespread stagnant ice. The overall texture of the unsorted material of the Highland moraine is rocky sandy loam. The lake plains are composed of sorted material, typically sand and gravel on the raised rims, grading vertically down to fine sand and silt. The center of the plains are presumably composed of silt and clay, but were not investigated. Subglacial meltwater from two large esker systems coalesced and spewed large volumes of meltwater, which deposited outwash that followed the edge of the retreating Rainy lobe. The meltwater was ponded for a time in glacial Lake Dunka, and ultimately flowed through a gap in the Giant's Range into a lake indirectly connected to glacial Lake Agassiz. The Rainy lobe built several distinct recessional moraines in the mapping area; the Vermilion moraine is the last Rainy lobe moraine south of the International Border. The ice deposited a relatively thin, extremely coarse till between the moraines, and did not discharge copious amounts of meltwater. Rogen moraine ridges are common north of the Vermilion moraine; these ridges formed under the ice, and do not represent ice margins.

The Arrowhead Pilot Project demonstrates that successful products can result from regional mapping in areas of northeast Minnesota given appropriate time, funding, and creativity. However, areas of especially sparse data and remote settings will necessarily result in diminished mapping detail, particularly in the depiction of the subsurface distribution of Quaternary materials, compared to other parts of the state where the MGS has produced County Geologic Atlas maps. Nevertheless, even with that limitation, County Geologic Atlas map products for the region would provide a markedly improved geologic framework that would facilitate resource management decisions.

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TOOLS FOR INTERPRETING KEWEENAW GEOHERITAGE TO A BROAD PUBLIC

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In the United States, the public is seemingly isolated from *geoheritage*, perhaps due to a disconnect between the geoscience academic community and how we communicate what we know. Recently retired, and with nearly 45 years in Houghton, a place with a strong geoheritage, the first author has begun to focus on communicating Earth Science to the a broader public with vital help from his co-author. This has generated new interpretive activities and tools paramount for engaging the public in learning about how and why their place has come to be the way it is.



Boulder Gardens. Around Lake Superior we have an abundant teaching resource of glacial erratics. We moved some of the most exemplary ones in our region (some with difficulty!) to a public square in the center of campus to serve as an educational and cultural focus (**Rose, 2011**). The boulders have fresh, glacially polished surfaces and are an assemblage of dozens of outcrops representing all the lithologies of the Keweenaw Rift in one succinct location. The site has drawn educational attention, and is especially useful as an introduction to field trips of the area.

GPS, smart phones, QR codes, EarthCaches. We have embraced treasure hunting and technology-based tools to engage people in learning about geolocations, fundamental to 3D visualization and “reading the landscape”. We have identified more than 150 field sites in the Keweenaw and linked them to .kmz file information, Google Maps, and QR codes to be accessed via smartphones. We have also very successfully contributed to GSA’s EarthCache efforts and database (**Gochis *et al.* 2013**).



Community geotours - bike/walk and trolley. We fashioned a geotour of our local town (Houghton) which can be done on foot or bike. The tour identifies and interprets a variety of features such as mines, large lava flows, faults, veins, aa and pahoehoe flows, amygdaloids, glacial features, river deltas, kame terraces and Anthropocene features in the town (**Rose *et al.* 2013**). The Geotour is integrated with other heritage tours and has been successfully used as a fundraiser that uses the local trolley to access a wider range of sites.

Grassroots Partnership. We work with local groups who share common goals of conservation and public access to field sites. Partners include the local Chamber of Commerce, Copper Country Trail

National Byway, the Keweenaw Land Trust, the Michigan Nature Association, the Nature Conservancy, national and state parks, local towns and villages, historical societies, museums, and local businesses all wishing to disseminate geoheritage information. A demonstration of geotours with a broad audience (ex. “elderhostal” format) is being done this summer with five two-day geotours which use combined van and boat transport to visit many remote sites of the Keweenaw. The goal is to facilitate public geotours of greater depth which last for several days. We have built our network to engage Earth science teachers, who can replicate geointerpretation efforts and transfer them to their students. This, in turn, helps us find more geosites as they are in everyone’s own yards!

International Geoheritage links. We have a strong partnership with colleagues at European Geoheritage sites who are teaching us successful strategies for international geoheritage status; common in Europe, China and other parts of the world, but so far unknown in the US (**VanWyk deVries, 2013**).

All of these efforts are found on a single Keweenaw Geoheritage website (<http://www.geo.mtu.edu/~raman/SilverI/KeweenawGeoheritage>), which broadly links shared technical, geographic and heritage information. We invite public input about this process; how can we improve geoheritage outreach?

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STRUCTURAL CONTROL OF MINERALIZATION AT LAC DES ILES MINE

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North American Palladium Ltd.'s Lac des Iles mine is located approximately 90km north of Thunder Bay, ON and is the only mine in Canada that is a primary producer of palladium. The mafic Mine Block intrusion that hosts the ore is located in the Wabigoon subprovince north of the regional boundary with the Quetico subprovince, within the Superior province. The property yields evidence for high-temperature deformation in the solid state, indicating that the intrusion is pre- and/or syntectonic, rather than post-tectonic as commonly presumed. The purpose of this MSc thesis project is to discover and examine evidence for high-temperature deformation and assess any controls this deformation may have on the mineralization. Evidence for high-temperature deformation is documented in the North Varitextured rim, Baker zone, Sheriff zone, and Creek zone. From the analysis of structural measurements and field relationships in these areas, two populations of narrow ductile shear zones have been recognized in the North Varitextured rim (NVT), Baker zone, Sheriff zone, and Creek zone. One population has an average orientation of 319/85 (n=30) with a dextral sense of shear, the other population has an average orientation of 058/83 (n=44) with a sinistral shear sense. The NW-striking dextral shear zones are commonly parallel to intrusive features and are variably foliated. The NE-striking sinistral shear zones are discordant to intrusive features. The presence of quartz-carbonate veins within the NE-striking sinistral shear zones may indicate reactivation and/or a local tensile component to stress. The orientation of the intersection lineation between the two populations of ductile shear zones is 81/108. A mutually cross-cutting relationship has been found indicating conjugate formation under the same stress field.

MIDCONTINENT RIFT-RELATED SATELLITE MAFIC-ULTRAMAFIC INTRUSIONS HOSTING FE-TI-V OXIDE DEPOSITS

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The best known Fe-Ti-V oxide deposits in the Midcontinent Rift are in the Duluth Complex, northeastern Minnesota, in two types of deposits: 1) titanomagnetite/ilmenite-rich layers in the early (1107 Ma) Poplar Lake intrusion (formerly Nathan's Layered Series), and 2) late discordant Oxide-bearing Ultramafic Intrusions (OUI) such as the Longnose and Water Hen intrusions. Less well known are Fe-Ti-V oxide deposits that occur in relatively small (<10 km) mafic-ultramafic intrusions emplaced in country rocks surrounding the Midcontinent Rift. These intrusions are currently known to extend from northwestern Wisconsin into southeastern Minnesota and northeastern Iowa based on geophysics and limited drill core (Fig. 1).

The Round Lake intrusion in northwestern Wisconsin is characterized by a large amplitude negative aeromagnetic anomaly; the other intrusions (Clam Lake, WI; Fillmore B1, MN; and Osborne, IA) are characterized by large positive amplitude aeromagnetic anomalies. The Clam Lake intrusion appears to be a plug-like body (Mudrey and others, 2003); the other intrusions appear as linear, northeast-trending dike-like bodies. All the intrusions show variable modal silicate-oxide mineral layering at scales ranging from centimeters to meters; oxide mineral content (Ti-magnetite with variable ilmenite) varies from a few percent to locally massive layers and from intercumulus to cumulus in texture. Strong to moderate igneous flow foliation, defined by aligned plagioclase crystals, is common in all the intrusions. The Clam Lake intrusion is composed of oxide gabbro (plag+cpx+oxide) with some clinopyroxenite layers. Round Lake is dominantly composed of oxide troctolite and melatroctolite (plag+ol+oxide). Both the Clam Lake and Round Lake intrusions are cut by diabase dikes. The Fillmore B1 and Osborne intrusions show greater variability particularly with respect to olivine content and contain oxide dunite and peridotite (ol+oxide) as well as oxide troctolite and melatroctolite (plag+ol+oxide). The Osborne intrusion is oxide- and olivine-rich in the upper portion and becomes more plagioclase-rich with depth; it also contains oxide-rich noritic anorthosite layers (plag+opx+oxide).

The major element compositions of these intrusions largely reflect their cumulate mineralogy but are dominated by their oxide mineral content. Phosphorous contents are uniformly low (<0.5 wt.%) in all samples and not correlated with TiO₂ content. Overall trace element abundances are mostly low as would be expected of dominantly cumulate rocks with low interstitial melt contents. Cobalt, Ni, Sc, and V generally show positive correlations with TiO₂ content suggesting that their concentrations are controlled by oxide mineral content. Samples from Round Lake have V contents considerably higher than samples from the other intrusions (up to ~4,500 ppm); the differences in V content may reflect differences in oxygen fugacity between intrusions as V partitioning is strongly dependent on oxygen fugacity. High field strength element (HFSE) covariations within and between intrusions are variable. Samples with high TiO₂ mostly show positive Nb-Ta anomalies on primitive mantle-normalized (PMN) trace element plots. However, positive Nb-Ta anomalies are highest in samples from the Clam Lake and Osborne intrusions and weak to absent in samples from Round Lake. In contrast, samples show varying Zr-Hf anomalies on PMN trace element plots ranging from positive anomalies in samples from the Iowa intrusion to no or negative anomalies in samples from Round Lake and Clam Lake. Given the general correlation between HFSE and TiO₂ content, it is likely that the HFSE variations are controlled by oxide minerals with different partition coefficients controlled by changing oxygen fugacity.

The REE data show that the intrusions are related to more than one magma type. The Round Lake intrusion has relatively steep REE patterns with enriched light REE and depleted heavy REE. The REE patterns match those of the basal, magnetically reversed basaltic lavas from Pigeon Point and Ely's Peak. The Fillmore B1 and Osborne intrusions have similar slightly enriched light REE and flat heavy REE patterns. They are likely related to Portage Lake-Chengwatana-equivalent high-TiO₂ basalt. The REE patterns for the Clam Lake intrusion have flat light REE and depleted heavy REE; they overlap REE patterns from the BIC intrusion and Eagle Deep dikes in the Baraga basin of Michigan.

The Midcontinent Rift-related satellite mafic-ultramafic intrusions and their Fe-Ti-V oxide deposits are very similar to the intrusions hosting Fe-Ti-V oxide deposits in the Permian Emeishan large igneous province of southwest China (Pang and others, 2010). Like the China examples, the Midcontinent Rift intrusions likely formed as conduits experiencing frequent replenishment of fractionated, crystal-rich high-Ti mafic magmas.

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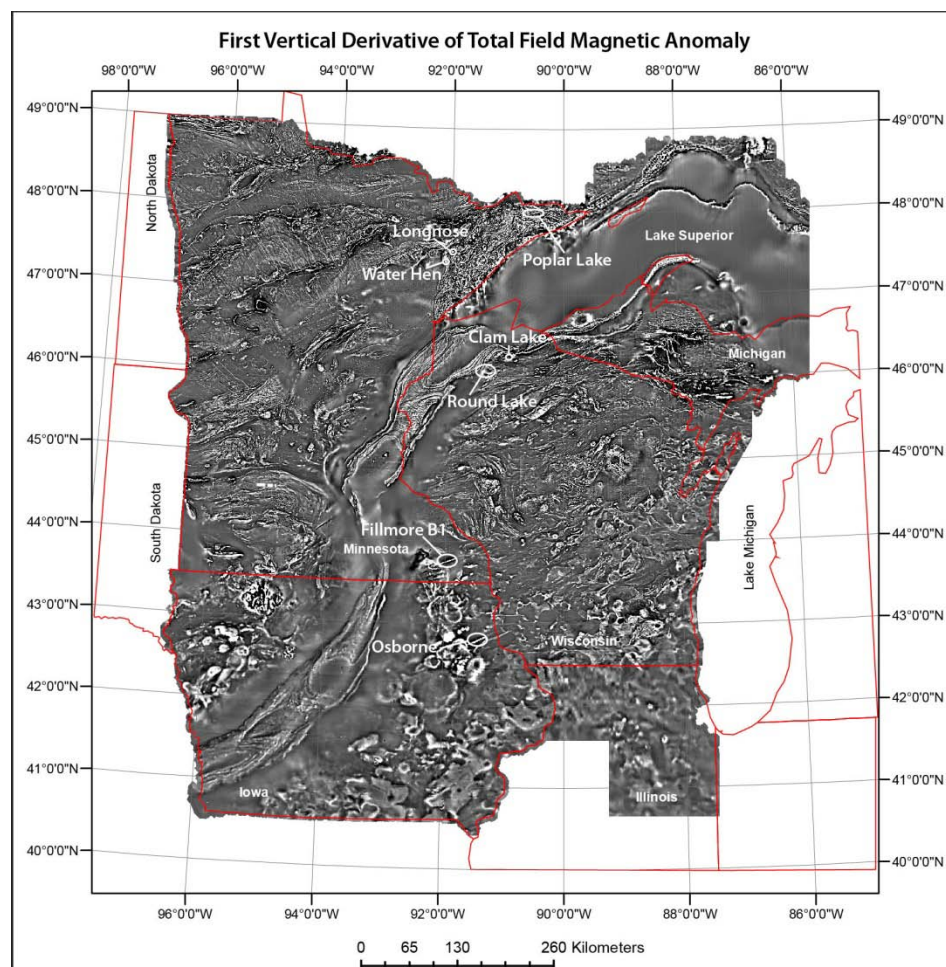


Figure 1. Location of Midcontinent Rift-related satellite mafic-ultramafic intrusions hosting Fe-Ti-V oxide deposits.

THE 2.7 BILLION YEAR OLD MT. ST. HELENS OF NORTHERN MINNESOTA: PETROGRAPHY, GEOCHEMISTRY AND ECONOMIC SIGNIFICANCE OF THE NEOARCHEAN GAFVERT LAKE SEQUENCE

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The Neoarchean Gafvert Lake sequence comprises part of the Vermilion District in the Wawa-Abitibi Terrane in northeastern Minnesota and is located in Minnesota's newest state park, Lake Vermilion State Park (Fig. 1). The Wawa-Abitibi Terrane is the most economically important granite-greenstone belt in the Superior Province, and hosts a wide variety of mineral deposits (including but not limited to shear zone hosted gold deposits, volcanogenic massive sulfide deposits, komatiite-hosted copper-nickel-platinum group element deposits, rare earth element deposits, diamond deposits) in its extents from Minnesota to northeastern Quebec. There has been minimal historic economic mineral exploration in this region despite the striking similarities between the Vermilion District and prolific metal (e.g., Au, Cu, Zn) producing regions across the border in Ontario, Canada.

The Gafvert Lake sequence was initially recognized by Peterson and Jirsa (1999) and appeared to represent a stratovolcano complex located immediately up-section from the Soudan Iron Formation, an Algoma-type iron formation unit that hosted Minnesota's first iron mine, the Soudan Mine. Recent mapping in the Vermilion District, northeast of Ely, MN has documented the regional distribution of rocks associated with the Gafvert Lake sequence which consists of intermediate to felsic volcanic and volcanoclastic rocks intruded by intermediate plutons that are likely age equivalent (Hudak et al., 2004). A dacitic tuff breccia from the Gafvert Lake sequence yielded a 2689.7 ± 0.8 Ma U-Pb age indicating that these deposits lie unconformably on Lower Ely and Soudan members of the Soudan belt (Fig. 1; Lodge et al., 2013).

This project examines the petrographic, geochemical and structural characteristics of the Gafvert Lake sequence. In the field, this package of volcanics and associated plutons is strikingly similar to other arc volcano-plutonic complexes found in more recent, Mesozoic and Cenozoic subduction zone related arc systems, like those exposed along the western margin of North America. Field, petrologic, and structural relationships suggest that the Gafvert Lake sequence volcanic rocks are dominantly intermediate in composition and comprised of a series of flows, welded tuffs, and volcanoclastic breccias. Petrographic analyses also show that primary textures are generally well preserved in the volcanics. Preliminary geochemistry indicates that the sequence is dominantly rhyodacite to dacite. Trace element chemistry suggest that the sequence formed in a volcanic arc setting. The volcanics are intruded by a very coarse crystalline to porphyritic tonalite to granite complex called the Gafvert Lake intrusive complex that is geochemically identical to the volcanic package. The volcano-plutonic complex is cut by several steeply dipping, east-west trending, dextral shear zones with stretching lineations that are shallowly east plunging. The tectonic and structural setting of the Gafvert Lake sequence suggests that there is economic potential in this package of rocks due to its strikingly similar characteristics to other economically viable volcano-plutonic systems in the Wawa-Abitibi Terrane.

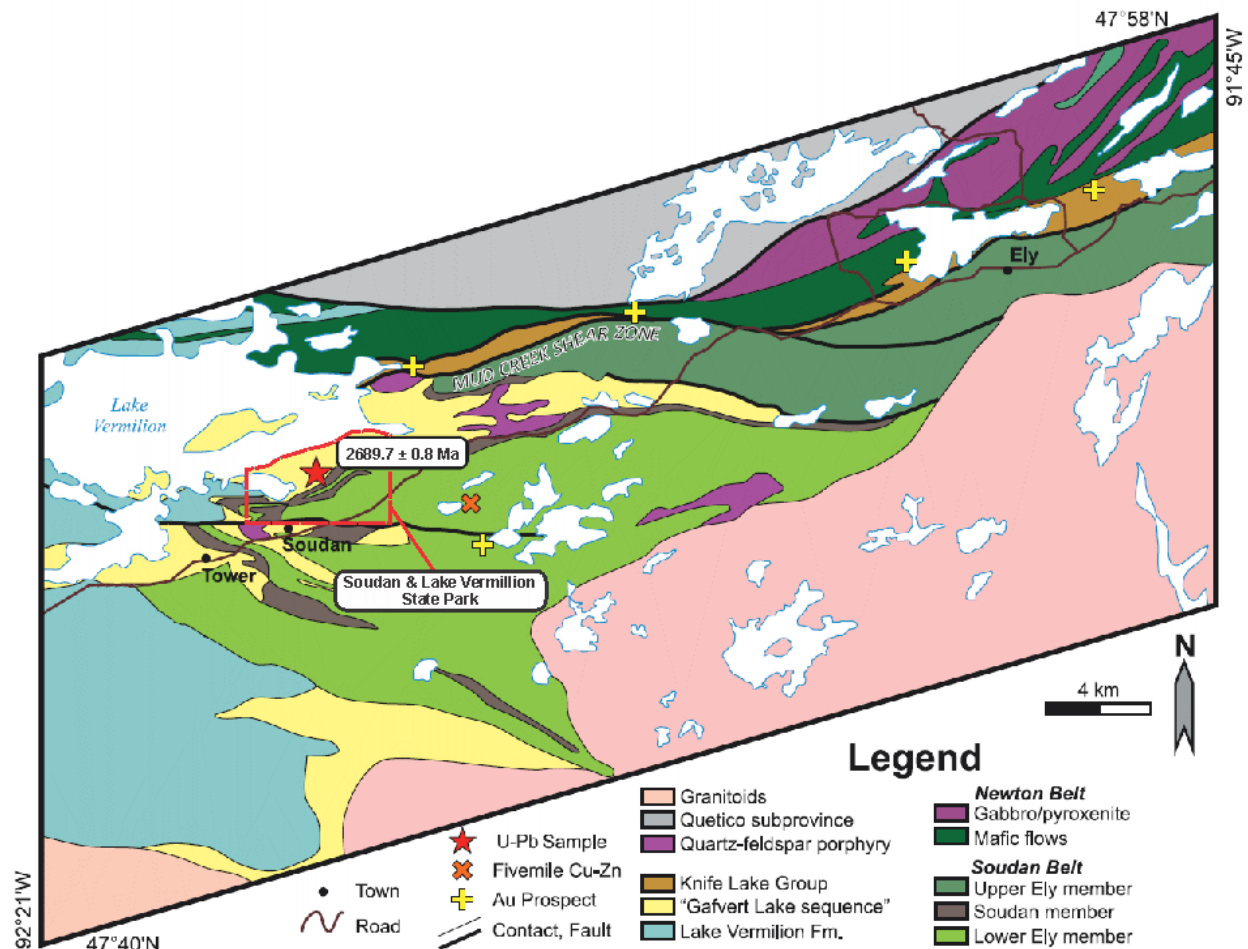


Figure 1. The Gafvert Lake sequence is exposed in the Vermilion District between Soudan Mine and the Mud Creek shear zone (modified from Lodge et al., 2013).

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THE DANGER OF “SULFIDE MINING” IN THE LAKE SUPERIOR REGION

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The danger of “sulfide mining” is in the term itself. The term “sulfide mining” undermines meaningful evaluation of environmental risks associated with metal mining because it fails to recognize important influences that geology, hydrology, climate, mining methods, ore-processing methods, and continued evolution of environmental management practices have on environmental risks specific to prospective deposit types. It also places an over-emphasis on a single environmental risk – acid generation from the weathering of sulfide minerals – when other risks, such as trace elements in water and solids warrant thorough consideration as well. The mineral deposits in the Lake Superior region, especially the Cu-Ni-PGM ores, highlight the importance of a geologically-based context for assessing environmental risk and designing sound environmental management practices for mining.

Acid-mine drainage results from the oxidative weathering of sulfide minerals, principally pyrite or pyrrhotite, in the presence of oxygen or other oxidant, such as dissolved ferric iron. The risk of acid generation from waste rock or mill tailings is directly proportional to the amount of these sulfide minerals present, and inversely proportional to the amount of acid-neutralizing potential available. In the case of the Cu-Ni-PGM ores in the Lake Superior region, the deposits anchor both ends of a wide spectrum in terms of sulfide abundance and therefore acid-generating potential. At one end of the spectrum are the magmatic disseminated sulfide deposits of the Duluth Complex, northern Minnesota; at the other end is the Eagle magmatic massive sulfide deposit in Upper Peninsula of Michigan. Drill core from along the strike of the basal mineralized zone in the Partridge River and South Kawishiwi intrusions of the Duluth Complex, sampled from the Minnesota Department of Natural Resources Core Library, average 0.4 ± 0.7 weight percent S (range $<0.05 - 2.6$ wt. %), whereas semi-massive to massive sulfide ore at the Eagle mine has sulfur contents ranging from 13 to 36 weight percent (Kennecott Eagle Minerals, 2006). Further, the hydrometallurgical technique likely to be used on the disseminated Duluth Complex ores uses a bulk sulfide concentrate, effectively removing most of the sulfide from the solid waste, whereas the Eagle mine plans to use traditional froth flotation to produce separate copper and nickel concentrates with the pyrrhotite left in the solid waste. These mineralogical, geochemical, and ore-processing features of the proposed ores all affect the acid-generating potential of solid waste and associated waste management approaches. The acid-generating potential of mine waste is commonly evaluated through a technique known as “acid-base accounting” that compares the acid-generating potential (AP) of the material to its acid-neutralizing potential (NP). The AP is inferred from the sulfide content of the material and the NP is typically inferred from its carbonate content. The acid-generating potentials of the disseminated and massive sulfide ores vary dramatically, although neither has significant carbonate acid-neutralizing potential (Figure 1). From a mine waste management perspective, NP:AP ratios below 1 are considered to be “probably acid-generating waste”, those above 2 are considered to be “non-probably acid-generating waste”, and those between 1 and 2 are considered to have uncertain potential. Silicate minerals are generally not considered because of their limited NP and slow reaction rates; however, two silicate minerals that have some of the highest NP values are olivine and calcic plagioclase (Jambor et al., 2002), which are important constituents of the host rocks of the Lake Superior Cu-Ni-PGM ores, especially the troctolites of the mineralized basal portion of the Duluth Complex.

Trace metals, especially Cu and Ni, in mine waste warrant consideration relative to human health and aquatic ecosystem risks. Both Cu and Ni show strong correlations with sulfur concentrations in drill core from the basal mineralized zone (Figure 2), similar to variations found by Ripley (2014). Metallurgical testing on ore from the NorthMet deposit resulted in 88 to 91 percent recovery of Cu and 67 to 73 percent recovery of Ni; this yielded tailings material with Cu concentrations ranging between 320 and 390 mg/kg and Ni concentrations between 280 and 350 mg/kg (Dreisinger, 2009). The difference in recovery between Cu and Ni suggests that approximately 20 percent of the Ni is hosted by a non-sulfide phase such as olivine. Ripley (2014) found Ni concentrations up to 1,800 mg/kg in olivine from the Partridge River intrusion, which is consistent with this interpretation. Nickel in olivine in mill tailings is less likely to be labile and bioavailable than Ni in residual sulfides.

The concentrations of Cu and Ni in the experimental tailings are well below both residential and industrial soil screening levels for human health protection (US Environmental Protection Agency, 2013). However, these ranges

are above probable effects concentrations for sediments relative to aquatic ecosystem protection (MacDonald et al., 2000), indicating that waste management practices must be designed to guard against accidental release of tailings to nearby waterways. The potential release of Cu and Ni from mine waste to surface water and groundwater will depend upon hydrologic setting and chemical setting (factors such as the availability of oxygen or other oxidants) of mine waste in the context of waste management practices.

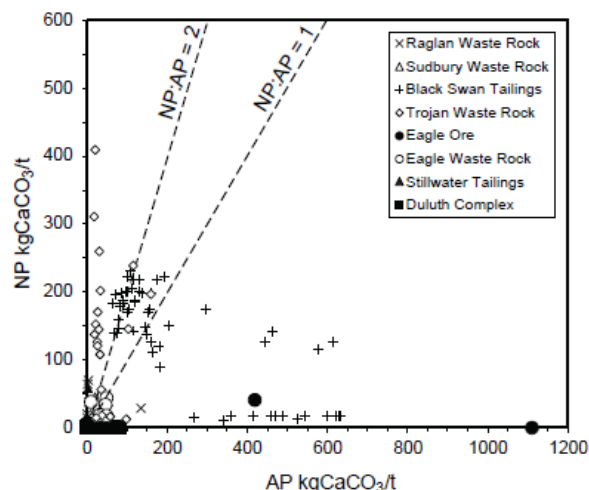


Figure 1. Plot of acid-generating potential (AP) and acid-neutralizing potential (NP) of various magmatic Ni-Cu-PGM deposits, modified from Schulz et al. (2010).

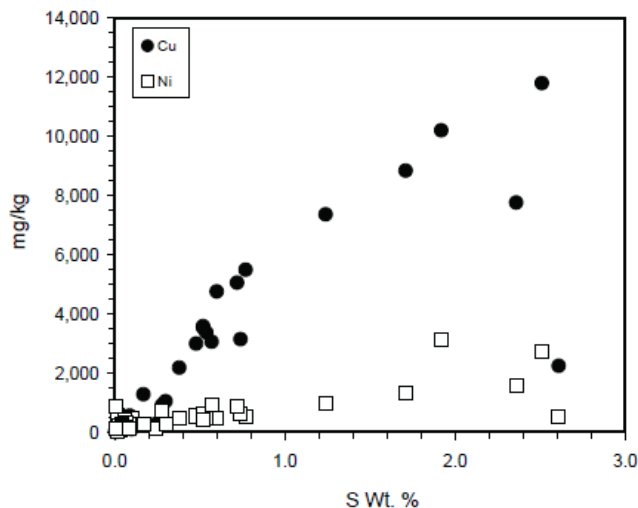


Figure 2. Plot of bulk sulfur, copper, and nickel concentrations of drill core from the basal mineralized zone of the Duluth Complex.

Consideration of the geologic, mineralogical, and ore-processing characteristics of magmatic mineral deposits in the Lake Superior region provides greater insights into environmental challenges associated with mining and mineral extraction than those from the oversimplified perspective of “sulfide mining”. These insights extend beyond acid-generating potential and include the assessment of potential risks to human health and aquatic ecosystems from trace metals. The identification of environmental risks enables effective mine planning for environmental protection.

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GENESIS OF SULFIDE MINERALIZATION WITHIN THE FOOTWALL GRANITE OF THE MATURI CU-NI-PGE DEPOSIT OF THE SOUTH KAWISHIWI INTRUSION, DULUTH COMPLEX, NE MINNESOTA

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The development of the 1.1 Ga Midcontinent Rift (MCR) generated voluminous magmatism resulting in the extensive flood basalts and sub-volcanic intrusions exposed along the flanks of Lake Superior (Miller et al., 2002). In northeastern Minnesota, two intrusions of the Layered Series, the Partridge River Intrusion (PRI) and South Kawishiwi Intrusion (SKI), are known to hosts significant Cu-Ni-PGE sulfide mineralization (Miller et al., 2002).

The Maturi Cu-Ni-PGE deposit occurs along the basal zone of the SKI where it is in contact with granitic rocks of the Archean Giants Range Batholith (GRB). Generally Cu-Ni-PGE-enriched sulfides are disseminated throughout a 50-150m-thick basal mineralized zone (BMZ) and locally may be semi-massive to massive sulfide (Bonnichsen, 1974). Several researchers (Severson, 1993; Peterson, 1997; Sawyer, 2002; Hovis, 2003) have noted significant sulfide mineralization in the dominantly granitic footwall. Extensive drilling by Twin Metals Minnesota since 2006 has shown that the mineralization within the footwall is typically disseminated sulfide, to locally massive sulfide veins, that is dominantly composed of chalcopyrite, pyrrhotite, pentlandite, as found in the BMZ. The mineralization extends as deep as 100 meters below the basal contact with the SKI (Kevin Boerst, 2013, personal comm.). While sulfur isotope data show that the sulfide in the mineralized granite originated from the same source as that in the overlying gabbro (Ripley, 1986; Molnar, 2009), the mechanism by which footwall mineralization occurred is unconfirmed.

The purpose of this study is to evaluate evidence for possible mechanisms by which the Giants Range Batholith may have become mineralized. Two hypotheses will be evaluated:

1. Partial melting of the GRB resulting in buoyant exchange of dense magmatic sulfide fluid and less dense anatectic melts rising from the GRB.
2. Hydrothermal fluids mobilizing sulfide from the mineralized gabbro into the granitoid rocks.

These two hypotheses are being tested by acquiring petrographic and geochemical data from four drill cores from the Maturi deposit that penetrate the gabbro-footwall contact and reach below the mineralized zone in the granite. Three of the drill cores represent variations in different styles of mineralization in the gabbro and the granite recognized in recent exploration drilling (Peterson, 2012). A fourth core was selected for the extensive occurrence of mineralization into a large biotite schist enclave within the batholith.

Preliminary results suggest a relationship between the degree of partial melting of the GRB and sulfide mineralization. Core logging and subsequent petrographic observations indicate that the footwall experienced pyroxene hornfels grade metamorphism producing orthopyroxene and clinopyroxene at the expense of biotite and amphibole that extends in excess of 30 meters from of the SKI-GRB contact. The volatiles produced by recrystallization of biotite and amphibole likely played a role in promoting anatectic melting of the granite as well. Petrographic evidence of partial melting of the GRB recognized in this and previous studies (Sawyer, 1999 2002; Hovis, 2003) included mylonitic textures, pockets of polygonal quartz-orthoclase-plagioclase aggregates, and lattice-dislocation textures in plagioclase. Leucosome patches have been observed to contain massive to semi-massive sulfide suggesting a relationship between escaping partial melts and sulfide liquid.

A retrograde alteration of metamorphic pyroxene to biotite, cummingtonite/actinolite, and chlorite is evidence of post-metamorphic hydrothermal alteration. This late hydrothermal alteration assemblage, which is recognized throughout the granite, typically does not contain significant sulfide. Additionally, where sulfides are present they appear largely unaffected by hydrothermal alteration indicating that this event did not cause significant sulfide remobilization or recrystallization. The presence of rare, late gypsum may indicate that the hydrothermal fluids were strongly oxidized and that any remobilized sulfur was crystallized as sulfate.

Petrographic observations implying exchange of anatectic melts and sulfide liquid are also supported by geochemical analyses. All REE became increasingly depleted with increased proximity to the gabbro

contact except for Eu which appears as a peak on the diagrams. During partial melting, Eu is likely being retained in plagioclase whereas other REE will be partitioned into partial melts which are able to escape the system. Plotting S concentration against Eu/Ce (Fig. 1A) shows a positive correlation indicating that the amount of anatectic melt escaped generally correlates with an increase in sulfide mineralization. Another proxy of increased escape of anatectic melt is an increase in plagioclase relative to quartz and alkali feldspar. A plot of CIPW norm values of Ab/(Or+Qtz) vs. wt% S (Fig. 1B) shows a similar, though broader, positive correlation.

Research is ongoing to further test these hypotheses by evaluating isocon plots (Grant, 1986) of whole rock geochemistry and by acquiring SEM-EDS analyses of pyroxene and amphibole compositions. The isocon method will be applied to determine element mobility through the system in order to better identify the mechanism of mineralization. Partial melting or hydrothermal alteration have distinct elemental signatures that can be identified in isocon modeling. Mineral chemistry acquired by SEM-EDS analyses will be used to trace changes in mineral composition relative to distance from the SKI-GRB contact.

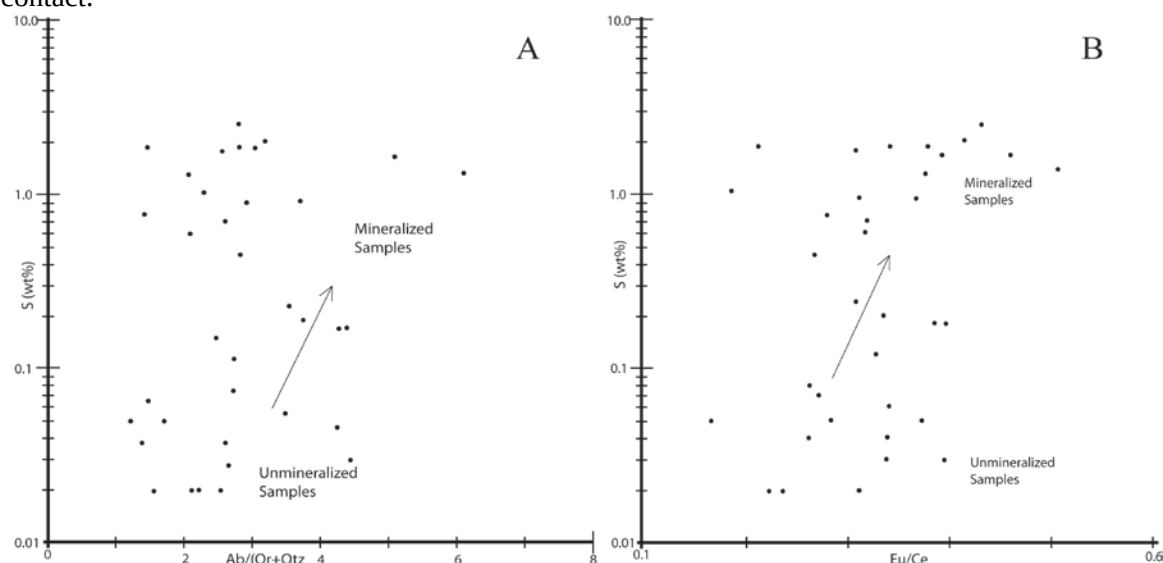


Figure 1 – Plot of GRB samples comparing sulfur concentration (wt% S) to two different proxies for increasing anatectic melt escape – Eu/Ce (A) and CIPW normative values of Ab/(Or+Qtz) (B). Arrows show general trends reflecting increasing anatectic melt escape and sulfide liquid infiltration.

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SULFIDE HIGHWAY REVISITED: NEW IDEAS ON INTERNAL STRUCTURE AND SULFIDE MINERALIZATION OF THE NICKEL LAKE MACRODIKE

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Recent exploratory drilling within the Nickel Lake Macrodiike (NLM) by Duluth Metals has facilitated the first subsurface investigations of the magma conduit into the prolifically mineralized South Kawishiwi Intrusion (SKI). Seventeen holes were drilled in late 2012 and early 2013 along 6500' feet of strike length of the NLM, with 4 holes reaching depths of over 4000'. Intercepts of the primary surface lithologies suggests that the youngest units of the NLM (the variably pegmatoidal oxide gabbro (N-xG) and layered troctolite (N-Tl)) are dipping irregularly (~30°) towards the northwest anorthositic sidewall of the NLM. Based on limited pierce points through this internal stratigraphy, the oxide gabbro appears to extend into the anorthosite series wall rocks beyond the surface-mapped northwestern sidewall contact of the NLM. At depth, the top of the N-xG truncates the xenolith-bearing (dominantly hornfelsed North Shore Volcanic Basalt and Biwabik Iron Formation) heterogeneous troctolite (N-Th) and sulfide-bearing troctolite (N-Ts) packages emplaced along the southeast-dipping (60°) northwest margin of the NLM. Below the N-xG and N-Tl units is a second package of heterogeneous troctolite (Th). Unlike the heavily xenolith-bearing N-Th unit present at and near surface, this troctolite is sparsely populated by small (~10') hornfelsed basalt xenoliths. This same heterogeneous troctolite hosts a series of large (100' thick) rafts of Virginia Formation argillite and greywacke at depth (~3000') in the south-central portion of the NLM.

Sulfide mineralization was encountered along the northwestern margin of the NLM both as the down-dip extension of outcropping and subcropping mineralization, as well as at greater depths. Three distinct types of mineralization were defined with respect to overall sample grades, interval thicknesses and lithological associations:

- Type 1* - long intervals (~50'-200'+) of moderate grade disseminated to blebby chalcopyrite and pyrrhotite (broadly 0.4%Cu, 0.1%Ni and 0.15g/t Pt+Pd+Au) associated with variably hornfelsed basalt xenolith-bearing Th,
- Type 2* - short intervals (~5'-35') of higher grade disseminated to blebby chalcopyrite and pyrrhotite (upwards of 0.55%Cu, 0.11%Ni and from 0.25g/t to over 2.0g/t Pt+Pd+Au) generally intercepted deeper than the larger, moderate grade intervals, and
- Type 3* - variable-length intervals (~25'-400') of low grade, disseminated to coarse-grained pyrrhotite and minor chalcopyrite (generally < 0.25%Cu, <0.10%Ni and <0.10g/t Pt+Pd+Au) hosted by a variably oxide-rich pyroxenite.

Mineralization Type 1 and Type 2 tend to occur at shallow depths in the majority of drill holes along the western margin of the NLM. However, the Type 3 mineralization is confined to the shallow southwestern NLM, where it is found in close proximity to a large iron-formation xenolith (~1300' strike length as mapped at surface).

Comparison of the geochemical signature of NLM sulfide mineralization types to basal SKI mineralization suggests a distinctly different fractional history for the NLM sulfide populations. Copper-nickel ratios for Types 1 and 2 tend to fall between 4:1 to 5:1, and 5:1 to 6:1, respectively. Coupled with low to moderate TPM tenors, NLM mineralization is distinct from the broadly 3:1 Cu:Ni ratio and propensity towards elevated precious metal tenors of the basal SKI mineralization. At this time, no direct analogue to basal SKI mineralization has been identified in the NLM. The deviations in precious metal tenor between Type1 and Type 2 mineralization, and the SKI may speak more directly to processes operating "downstream" of the NLM.

With Cu:Ni ratios of 1:1 to 3:1, Type 3 mineralization is distinctly more Ni-rich than Types 1 and 2, and the basal SKI mineralization. Type 3 mineralization is further distinguished by its unique pyroxenite host rock, and highly elevated P (up to 1%) and Zn (generally >175ppm), respectively up

to two orders of magnitude and double that of the vast majority of basal SKI mineralization. However, the Type 3 lithological association and distinct geochemical signature shows affinity with reported rock types and whole rock compositions of apatite-bearing, mineralized oxide-rich ultramafic intrusions (OUIs; Ripley et al., 1998). The spatial association with a large xenolith of metamorphosed iron formation is also in line with the observations of Severson (1995), who noted that OUIs in the basal central Duluth Complex occur in close proximity to metamorphosed Biwabik Iron Formation.

The lithological relationships noted in the drilling confirm the intrusive sequence of the NLM as suggested by Peterson et al. (2006), but imply a slightly different geometry for the youngest intrusive phases internal to the NLM. The difference between the xenolith populations in the near surface N-Th unit and the Th at depth may indicate origination from different pulses of troctolitic magma through the conduit. The long intervals of xenolith-poor Th (up to 2500' +) at depth within the central NLM may represent areas of high magma flow through the conduit.

The existence of multiple types of mineralization along the margins of the NLM magma conduit indicates sulfide mineralized magmas passed through the conduit. Variation of the NLM mineralization grade and tenor from that of basal SKI mineralization may be the result of fractionation processes that occurred down-stream of the NLM conduit (e.g., sulfide dissolution upgrading; Kerr and Leitch, 2005), or it may ultimately correlate with undiscovered mineralization with the SKI-NLM system.

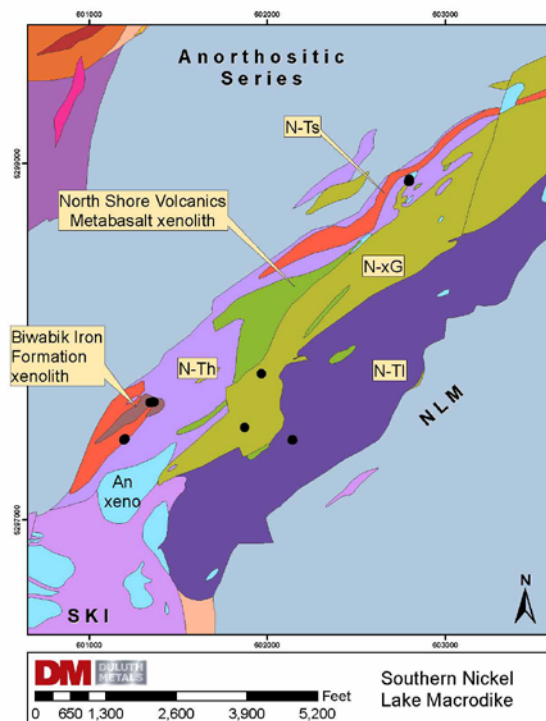


Figure 1 – Geological map of the southern Nickel Lake Macrodike with major lithological units and Duluth Metals' drill pads (black dots).

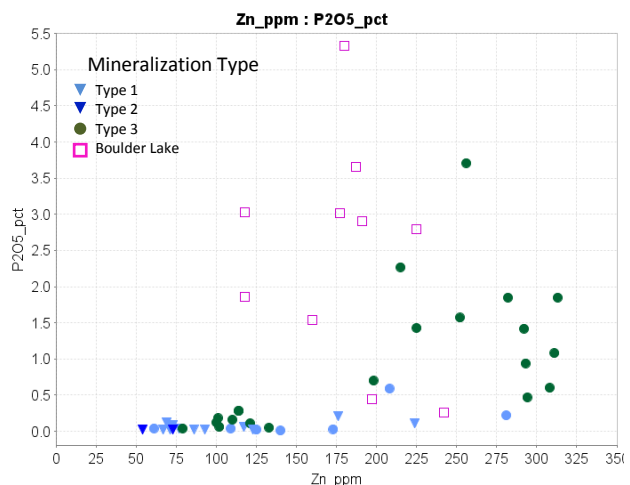


Figure 2 – Zn vs P_2O_5 comparison of NLM mineralization types with oxide-apatite- rich samples from DDH IV-2 from the Boulder Lake Intrusion in the southwestern Duluth Complex, from Ripley et al., 1998.

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THE THUNDER MAFIC TO ULTRAMAFIC INTRUSION: A PGE AND PRECIOUS METAL BEARING EARLY-RIFT CONDUIT SYSTEM IN THE MIDCONTINENT RIFT

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In 2002, high grade massive Ni-Cu-PGE sulphide mineralization at the Eagle deposit near Marquette, Michigan was discovered stimulating exploration programs in search of small mafic to ultramafic intrusions hosting “conduit-type” magmatic sulphide mineralization associated with the early stages of the Mesoproterozoic Midcontinent Rift (MCR; Miller and Nicholson, 2013; Ripley, 2014). Since the Eagle discovery over a half-dozen poorly exposed mineralized early-rift mafic to ultramafic intrusions have been discovered within the Lake Superior region, prompting active petrological research (e.g., Ding et al., 2010) and re-evaluation of the current MCR tectono-magmatic model (e.g., Miller and Nicholson, 2013). However, from an exploration stand point the small size of these buried mineralized mafic to ultramafic intrusions makes them difficult to locate both on the ground and on regional magnetic survey maps (Ames et al., 2012).

This study is a collaborative project between the Geological Survey of Canada, the Ontario Geological Survey, and Lakehead University as part of the Ni-Cu-PGE-Cr project, Targeted Geoscience Initiative-4 (TGI-4; Ames et al., 2012). The objective is to characterise the petrology, mineralization, and alteration footprint of the Thunder intrusion within the context of the MCR as a whole, in order to identify criteria for targeting buried mineralization.

The Thunder intrusion is a small, layered mafic to ultramafic intrusion located on the outskirts of Thunder Bay, ON, which has been explored by Rio Tinto (formerly Kennecott Canada Exploration Inc.) in 2005 and 2007 (Bidwell and Marino, 2007). The intrusion is interpreted to be associated with the early magmatic stages of the MCR based on geochemical similarities to mafic and ultramafic rocks of the Nipigon Embayment (Hollings et al., 2007) and an unpublished ²⁰⁷Pb/²⁰⁶Pb baddeleyite age of 1110.33±0.92 Ma (Ames, pers. comm., 2014). This intrusion is distinct from the other known mineralized early-rift intrusions as it is the only known occurrence hosted by the Archean Shebandowan greenstone belt. The intrusion is approximately 800 by 1000m by < 500 m thick and dips steeply to the south. Major textural and geochemical differences can be used to divide the lithostratigraphy into a lower mafic to ultramafic basal unit and an upper gabbroic unit, however, similar trace and rare earth element ratios of the two units suggests they formed from a single magmatic pulse that has undergone subsequent fractionation.

Ni-Cu-PGE mineralization is hosted by clinopyroxenite in the lower mafic to ultramafic unit adjacent to the basal wall rock, including 20 m of 0.22% Cu, 0.06% Ni, 0.25ppm Pt, 0.29ppm Pd (Bidwell and Marino, 2007). Sulphides rarely comprise up to 30% by volume but more typically 1-5%, with textures ranging from medium- to fine-grained disseminated, globular and rarely net-textured. Pyrrhotite, chalcopyrite and rare pentlandite with common secondary marcasite-pyrite replacement are present along with trace kotulskite, naldrettite, merenskyite, sperrylite, electrum and native silver.

The $\delta^{34}\text{S}$ values of sulphide minerals from the Thunder intrusion are similar to the adjacent wall rock forming a tight range between +3.8 and -3.1‰. Although $\delta^{34}\text{S}$ values are broadly consistent with a

mantle origin ($0 \pm 2\%$) the involvement of crustal sulphur during the mineralization process remains a possibility. Radiogenic isotopes were measured from select samples to investigate possible contamination of the Thunder intrusion. The ϵ_{Nd} values from the intrusion range between -0.74 and +0.99, with no trends towards wall rock compositions, whereas the $^{87}\text{Sr}/^{86}\text{Sr}$ values range from 0.7031 and 0.7061 and trend towards wall rock values of 0.7071 and 0.7087. The decoupling of the two radiogenic isotope signatures is consistent with crustal contamination at depth and local contamination during the emplacement of the Thunder intrusion.

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GARNET IN THE DEEP CRUST: THE KEY TO LINKING ARCHEAN TTG GENERATION AND VERTICAL BLOCK MOTIONS?

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There is substantial debate about the differences between geologic processes that operated during the Archean and those operating today (e.g. Percival et al., 2006; Van Kranendonk, 2010). Two notable differences between modern terranes and Archean cratons are the presence of very large volumes of TTGs (tonalite-trondhjemite-granodiorite) and tectonic structures suggesting that locally, TTG blocks moved up relative to adjacent mafic greenstone belts.

Explanations for the structural differences between modern and early Earth vary between two end-member models: density-driven (vertical) and modern-style (horizontal) tectonics. Many field-based structural studies of Archean rocks contain evidence for both vertical and horizontal tectonics (e.g. Lin, 2006). When the spatial scales of vertical and horizontal structures are considered, horizontal structures seem to dominate the large-scale province framework and are more prevalent in high-grade rocks, whereas low-grade and local (greenstone belt-scale) structures exhibit more evidence for vertical processes (Van Kranendonk, 2010).

Current interpretations for the origins of TTGs favor partial melting of a mafic, hydrous, garnet-bearing source rock. TTGs are chemically similar to modern arc rocks, so the suprasubduction-zone setting of modern arcs is commonly invoked for the generation of TTGs as well (see Moyen & Martin, 2012, and references therein). Other suggestions invoke plume-related process for generating larger volumes of TTGs than are found in modern arc settings (e.g. Moyen & Martin, 2012). Below, we attempt to integrate geodynamic and petrogenetic models for Archean tectonics.

One approach to better understand geodynamic and petrogenetic processes operating in the Archean is to compare rocks from different crustal levels. The North Caribou Terrane is located in the central Superior Province, and it is dominated by Meso- to Neoarchean TTGs. Lin (2006) studied the structures within and adjacent to greenstone belts in the North Caribou and concluded that these rocks preserve structures consistent with synchronous vertical and horizontal tectonism. Several studies of the TTGs in the North Caribou show that their compositions are consistent with typical Archean TTGs (e.g. Wyman et al., 2011). The thermobarometric and geochemical data we present from TTGs in the North Caribou are consistent with Wyman et al.'s (2013) data and indicate that the TTGs were emplaced in the mid-crust and later metamorphosed at shallower levels.

The Athabasca granulite triangle is an exposure of deep-crustal rocks that straddles the Snowbird Tectonic Zone north of Lake Athabasca. The granulite-facies (0.9-1.9 GPa, 700-950 °C; Baldwin et al., 2003) terrane contains several generations of mafic rocks, two of which, Neoarchean gabbros and Paleoproterozoic mafic dikes, are possible analogues to TTG source rocks, as both preserve primary hornblende and contain garnet. Although the source for the older gabbros is not fully understood, the dikes are not associated with arc magmatic rocks (Flowers et al., 2006). Some of the mafic dikes have undergone anatexis due to dehydration melting of hornblende, resulting in tonalitic melt and peritectic garnet (Williams et al., 1995).

Implications

The rocks in the Athabasca provide an interesting option for the generation of TTGs. The mafic dikes, which are not related to subduction, indicate the potential for long-term storage of water in the

lithospheric mantle, so concurrent subduction and melting are not necessarily required. Their anatectic textures also suggest the possibility for melting through underplating or mantle upwelling (Williams et al., 1995).

Regardless of the melting mechanism, extraction of significant volumes of TTG parent magma from mafic rocks would leave a garnet-rich restite, similar to what has been postulated by Saleeby et al. (2003) to exist below the Sierra Nevada batholith. Foundering of this gravitationally unstable lithospheric root may be the cause of the uplift of the Sierra Nevada (Saleeby et al., 2003), and a similar delamination scenario in the Archean may explain relative uplift of TTGs compared to adjacent greenstone belts. This is observed in the North Caribou, and a higher frequency of delamination events in the Archean due to widespread extraction of melt could explain the evidence for vertical tectonics. Delamination of dense restite and subsequent mantle upwelling could also trigger additional melting, creating a positive feedback mechanism that could produce significant amounts of tonalitic magma, like the large batholiths that are common in the North Caribou.

This scenario would require a wet mantle, either through the release of primordial water or an earlier introduction of volatiles. Structural evidence for horizontal tectonics preserved in large-scale structures suggests that subduction may have operated during the Archean, but not all TTG-type magmas need to have been derived at subduction zones. Instead, TTGs could be generated in several non-unique tectonic settings, and garnet-driven delamination of the lower crust can explain both evidence for vertical tectonics and large volumes of TTGs.

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STRONTIUM ISOTOPE STUDY OF MESABI IRON RANGE GROUNDWATER

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On the Mesabi Iron Range, significant differences in $^{87}\text{Sr}/^{86}\text{Sr}$ exist between long residence time groundwater from wells completed in the Biwabik Iron Formation, especially where covered by the Virginia Formation, and short residence time groundwater from wells completed in overlying glacial aquifers and in surface waters. The relatively low $^{87}\text{Sr}/^{86}\text{Sr}$ observed at the iron formation wells falls within the range commonly observed for weathering of Phanerozoic marine carbonates, whereas the higher values observed at the drift wells and surface waters are more characteristic of weathering of Archean silicate minerals. Short residence time water from Biwabik Iron Formation wells situated in the subcrop of the formation span a wide range of $^{87}\text{Sr}/^{86}\text{Sr}$ and in some cases is more radiogenic than that observed at the glacial drift wells and surface water bodies.

These results likely reflect the impact of glacial provenance on the distribution of strontium-bearing minerals within their groundwater flow pathways. The glacial deposits on the Mesabi Range are dominated by northeast-sourced glaciers of the Rainy Lobe, whose sediments are characterized by an abundance of Archean granitic material and scarcity of Phanerozoic marine sediments. However, northwest-sourced glacial sediments are recognized locally and have contributed sediments relatively rich in Phanerozoic marine carbonate and shale, especially along the west-central Mesabi Range. It is likely that water samples with high $^{87}\text{Sr}/^{86}\text{Sr}$ and low strontium concentrations are predominantly influenced by recharge through Rainy Lobe glacial sediments. In contrast, those that are relatively low in $^{87}\text{Sr}/^{86}\text{Sr}$ but high in strontium concentration are predominantly reflecting dissolution of carbonate minerals from northwest-sourced glacial deposits or from the iron formation itself.

GEOCHEMISTRY AND MINERALOGY OF GLACIAL SOILS IN THE UPPER MIDWEST

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The U.S. Geological Survey has recently completed a low-density (1 site per 1,600 square kilometers, 4,857 sites) geochemical and mineralogical survey of soils of the conterminous United States (Smith et al., 2013). Three samples were collected, if possible, from each site; (1) a sample from a depth of 0 to 5 centimeters, (2) a composite of the soil A horizon, and (3) a deeper sample from the soil C horizon or, if the top of the C horizon was at a depth greater than 1 meter, from a depth of approximately 80–100 centimeters. The <2-millimeter fraction of each sample was analyzed by a combined inductively coupled plasma-atomic emission spectrometry/mass spectrometry method for a suite of 45 major and trace elements following near-total multi-acid digestion. The major mineralogical components in samples from the soil A and C horizons were determined by a quantitative X-ray diffraction method. Regional- and national-scale element and mineral patterns can be related to (1) soil parent materials, (2) climate factors, (3) soil age, and (4) possible anthropogenic loading to surface soils. This presentation will describe the influence of source provenance and soil age factors on the geochemistry and mineralogy of the soil A and C horizons in the upper Midwest.

In the upper Midwest, melting of glacial ice left the region mantled with a blanket of mixed, immature sediments from which present day soils developed. Individual ice lobes of the late Wisconsinan glaciation created distinct patterns in soil geochemistry and mineralogy because of varying provenance and transport paths. Carbonate- and shale-rich ‘gray’ tills in Minnesota, North Dakota, South Dakota, and Iowa, deposited by the Des Moines and James lobes were derived from Cretaceous sedimentary rocks (dolostone, limestone, shale); glaciolacustrine sediments of Glacial Lake Agassiz along the North Dakota/Minnesota border have a similar provenance (Wright, 1972). Gray tills were transported significant distances to the south and southeast from their source and deposited on Precambrian bedrock that is largely devoid of carbonate minerals. ‘Red’ tills were deposited in northeastern Minnesota and northern Michigan and Wisconsin by the Rainy and Superior lobes. The Rainy lobe provenance is mainly Precambrian crystalline rocks of the Canadian Shield and the Superior lobe provenance is mainly basalts and sediments of the Precambrian Keweenawan Supergroup (Wright, 1972). In the lower Great Lakes region, carbonate- and shale-bearing tills sourced from the Cambrian to Devonian sedimentary bedrock units that rim the Michigan basin were deposited by the Green Bay and Lake Michigan lobes in western Wisconsin and northern Illinois, by the Saginaw lobe in central Michigan, and by the Huron-Erie lobe in eastern Indiana and western Ohio (Johnson, 1986; Hofer and Szabo, 1993).

Soils developed on glacial sediments are relatively young and often retain easily weathered minerals and mobile elements, such as carbonates and related elements (e.g., Ca and Mg), typically leached from older, more mature soils beyond the southern extent of the last glaciation. As expected from their differing provenance, soils developed on red tills have much lower clay contents and much higher quartz and feldspar contents compared to soils developed on gray tills. This divergent mineralogy creates striking contrasts in element concentrations. Soils on gray tills have higher Ca contents from carbonate as well as higher As, Cd, Mo, Sb, and U concentrations, likely contributed by the shale component, compared to soils on red tills, which have higher Na and K contents from the higher feldspar content. Soils developed on the James lobe have somewhat higher Mn contents than soils developed on the Des Moines lobe, perhaps related to local redox conditions. Soils developed on Lake Agassiz clays have relatively higher Li, Sc, Ti, V, and Zn contents compared to soils developed on surrounding gray tills.

One of the more dramatic characteristics of some glacial soils in the upper Midwest is a high concentration of primary dolomite. Tills of the Green Bay and Lake Michigan lobes are characterized by an especially high content of dolomite relative to calcite, and as a consequence, these soils have some of the

highest soil Mg concentrations in the conterminous United States. The Green Bay and adjacent Lake Michigan lobes, as well as the Saginaw and adjacent Huron-Erie lobes are all largely sourced from similar rocks (dominantly dolostone, limestone, and black shale). However, a strong contrast in Mo contents in the soil C horizon between the Green Bay and Lake Michigan lobes and between the Saginaw and Huron-Erie lobes is an indication of the proportion of black shale incorporated into their respective glacial sediments by the individual lobes (Figure 1). The higher the percentage of black shale, the higher Mo content of soils, as well as a number of other elements such as As, Cd, Co, K, Sb, Tl, U, and Zn, all of which may be enriched in black shale. Because of this shale influence, large areas of northern Ohio and Indiana have some of the higher soil Mo concentrations in the conterminous United States. Thus, glacial dispersal of materials sourced from different bedrock sources, especially relatively thin shale units, had a widespread effect on soil geochemistry and mineralogy throughout the glaciated upper Midwest.

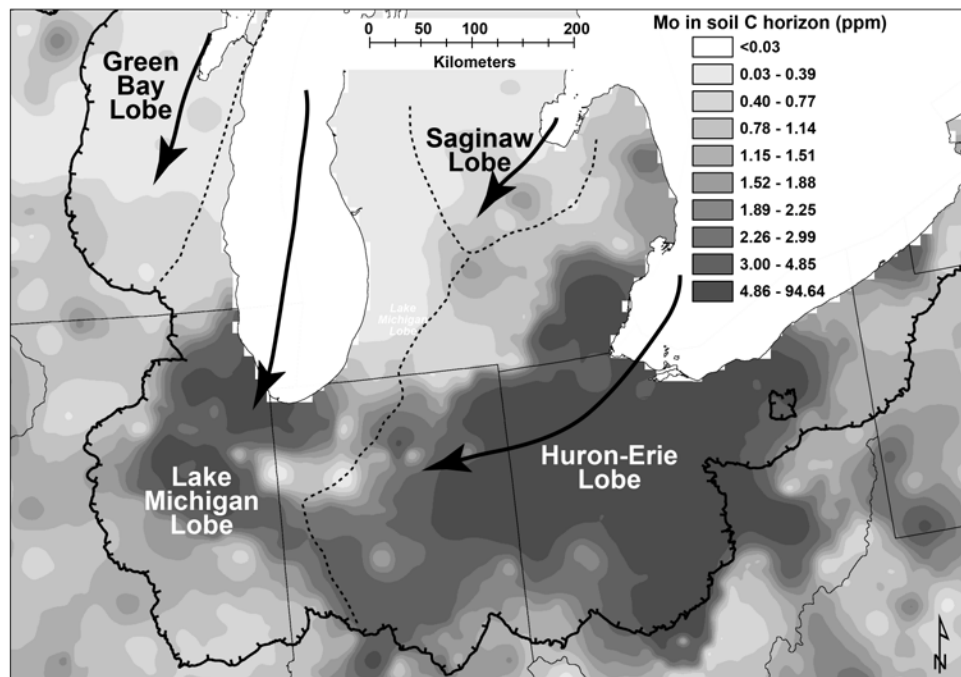


Figure 1. Interpolated concentration map depicting molybdenum (Mo) in the soil C horizon in the lower Great Lakes region. The hachured black line is the maximum southern extent of Wisconsinian glaciation; dotted lines are the approximate margins of named individual ice lobes, with arrows indicating major ice flow direction (after Grimley, 2000; Hofer and Szabo, 1993).

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THE EVOLUTION OF THE ATMOSPHERE-HYDROSPHERE: A GEOCHEMICAL COMPARISON OF TWO PALEOPROTEROZOIC GUNFLINT WEATHERING PROFILES

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The 1878±1 Ma year old Gunflint Iron Formation is a chemical sedimentary unit that forms one of the members of the Animike Group. It is well known that the Gunflint Formation is made up of a transgressive-regressive-transgressive sequence, which represent the advance and retreat of the ancient sea that filled the Animike basin. This sequence traps a unique point in the evolution of the atmosphere-hydrosphere during the Precambrian. This interaction with the atmosphere should be seen in the rock record at the point where the water depth was at its shallowest, such as the initial transgression or the regressive surfaces. If oxygen was present, the rocks underlying the transgression, as well as the initial transgressive strata that were precipitated in the shallow ocean should contain geochemical markers such as Ce anomalies.

The newly created two-lane Highway 11/17 outside of Thunder Bay, shows a clean example of the basal section of the Gunflint Formation (Figure 1a). This section of the Gunflint overlies an Archean granodiorite unit. The overlying Gunflint carbonate grainstones show no unique features. What is important is the underlying granodiorite unit. The granodiorite shows a very clear example of spheroidal weathering that should occur if joints in the bedrock were the site of intense chemical weathering. Samples were collected starting from the base of the granodiorite where it is the freshest and least weathered up through the increasingly altered portions of the weathering profile into the Gunflint grainstone. Samples were prepared and analysed for major oxides as well as trace and rare earth elements. Another prime example of the basal section of the Gunflint Formation can be seen at Schreiber Beach outside of Schreiber ON, which was studied by Polat et al. (2012) (Figure 1b). This area differs from the 11/17 site in that the Gunflint strata sits above a Neoarchean pillow basalt sequence that shows the well preserved basaltic pillows overlain by hyaloclastites made up of shattered pillow breccias and flows. Directly below the contact with the Gunflint, the pillow sequence has been weathered and exfoliated creating red to brown highly fractured pillows topped off by brown to green pillow basalt soils. A geochemical comparison of these two sample locations was performed. When plotted on Nesbitt (2003) A-CN-K feldspar diagrams the 11/17 outcrop shows an enrichment in Al_2O_3 (Figure 2a), whereas the A-CN-K diagram plotted by Polat et al. (2012) shows that the weathered layer is enriched in K_2O and Al_2O_3 (Figure 2b). The difference in the parent material of the two weathered profiles and possibly potassic metasomatism in the basaltic material is controlling these weathering trends. The spheroidal weathering granodiorite also has an intense enrichment in Fe, Mn and Mg, probably the result of interactions with Gunflint derived fluids, which overprinted the effects of weathering. This period of alteration by Gunflint fluids also resulted in intense leaching of rare earth elements.

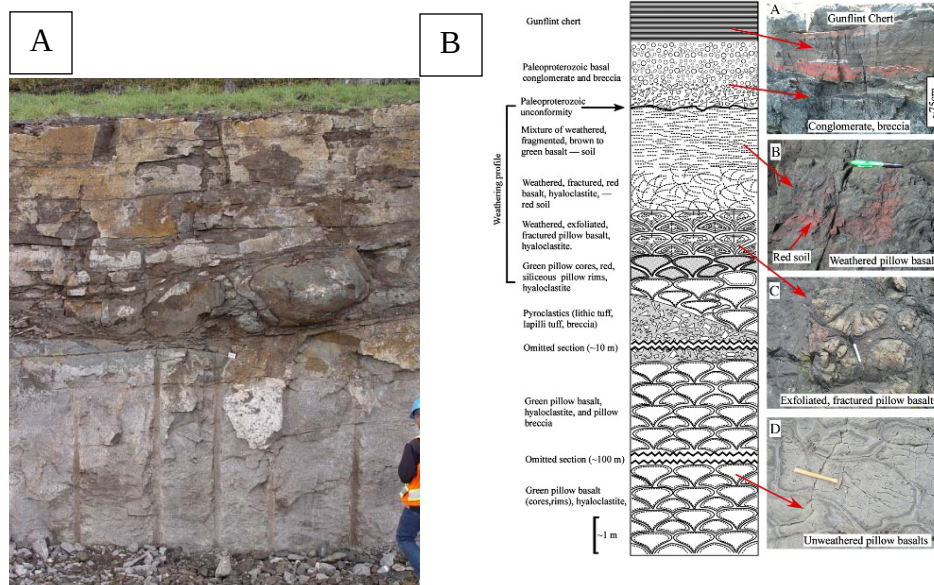


Figure 1. a) the outcrop on the side of Highway 11/17, showing the weathering profile starting with the granodiorite and working up through the weathered section eventually capped by Gunflint grainstone. B) The stratigraphic sequence of the Schreiber beach outcrop modified from Polat et al., (2012).

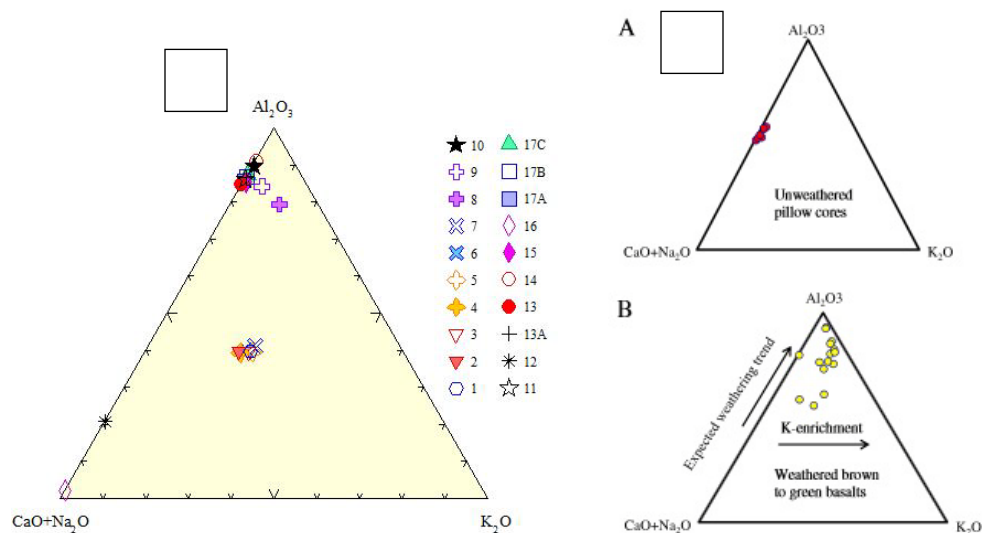


Figure 2. a) A-CN-K diagram for the data collected from the Highway 11/17 outcrop outside of Thunder Bay, ON. The fresh granodiorite samples plot in the middle and the weathered samples plot at the top showing CaO , Na_2O and K_2O depletion. B) The A-CN-K diagram from Polat et al.(2012) showing the enrichment of K from the unweathered pillows to the weathered brown to green basalts.

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