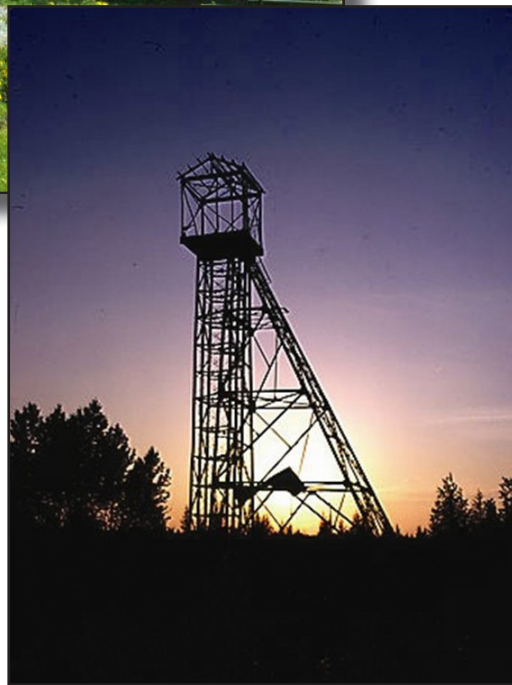
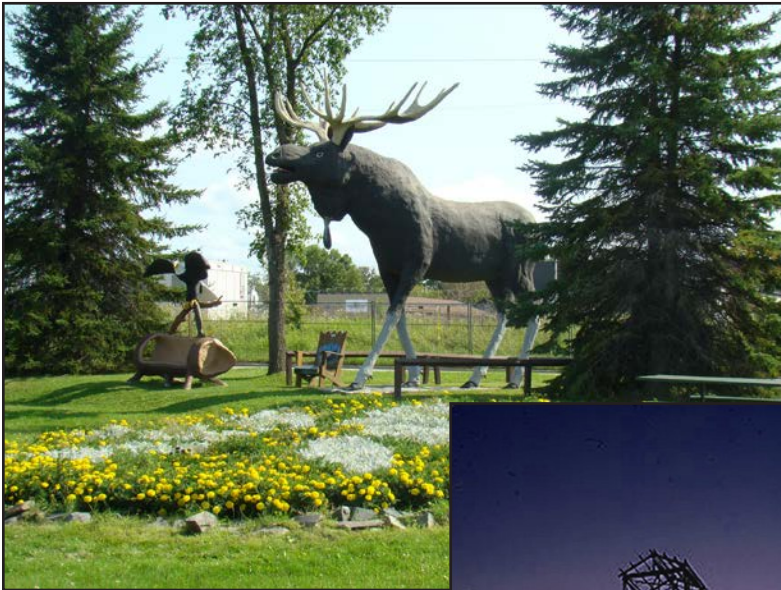


61st ANNUAL MEETING
INSTITUTE ON LAKE SUPERIOR GEOLOGY
Dryden, Ontario - May 20-24, 2015
Part 1 – Proceedings and Abstracts



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The following organizations made generous contributions to the 61st 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. For the past 60 years this organization has thrived as a result of the interest of individuals, corporations, universities and government agencies. The dedication to an exchange of scientific ideas and a passion for field trips has enabled the Institute to provide one of its primary objectives – to promote better understanding of the geology of the Lake Superior Region.

Mary Arthur

Steve Baumann

Leonard Espinosa

Gordon Medaris Jr.

Allan MacTavish

Jim Miller

Paul Weiblen



**Canadian Institute of Mining and Metallurgy
Thunder Bay Branch**



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61st ANNUAL MEETING

INSTITUTE ON LAKE SUPERIOR GEOLOGY

Supported by
ONTARIO MINISTRY OF NORTHERN DEVELOPMENT AND MINES

May 20-24, 2015

Dryden, Ontario

HOSTED BY:

Rob Cundari & Peter Hinz

Co-Chairs

Ontario Geological Survey

Proceedings - Volume 61

Part 1 – Proceedings and Abstracts

Edited by Mark Smyk

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61st INSTITUTE ON LAKE SUPERIOR GEOLOGY

VOLUME 61 CONSISTS OF:

PART 1: PROGRAM AND ABSTRACTS

PART 2: FIELD TRIP GUIDEBOOK

TRIP 1: THE CENTRAL RED LAKE GOLD BELT

TRIP 2: WESTERN WABIGOON SUBPROVINCE TRANSECT, DRYDEN TO MEGGISI LAKE

TRIP 3: *CANCELLED*

TRIP 4: THUNDER LAKE (GOLIATH) PROJECT

TRIP 5: CLASSIC OUTCROPS OF THE DRYDEN AREA

TRIP 6: GOLD OCCURRENCES OF VAN HORNE TOWNSHIP, VAN HORNE GOLD PROPERTY -
FLAMBEAU EXPLOSURES

TRIP 7: UNIQUE MINERALIZING EVENT AT THE PIDGEON MOLYBDENUM DEPOSIT STRIPPED
SURFACE EXPOSURE

TRIP 8: GEOLOGY AND MINERAL DEPOSITS OF THE PICKLE LAKE GREENSTONE BELT

TRIP 9: THE GHOST LAKE BATHOLITH AND RELATED PEGMATITES

TRIP 10: MATATABI/STURGEON LAKE HISTORIC VMS CAMP

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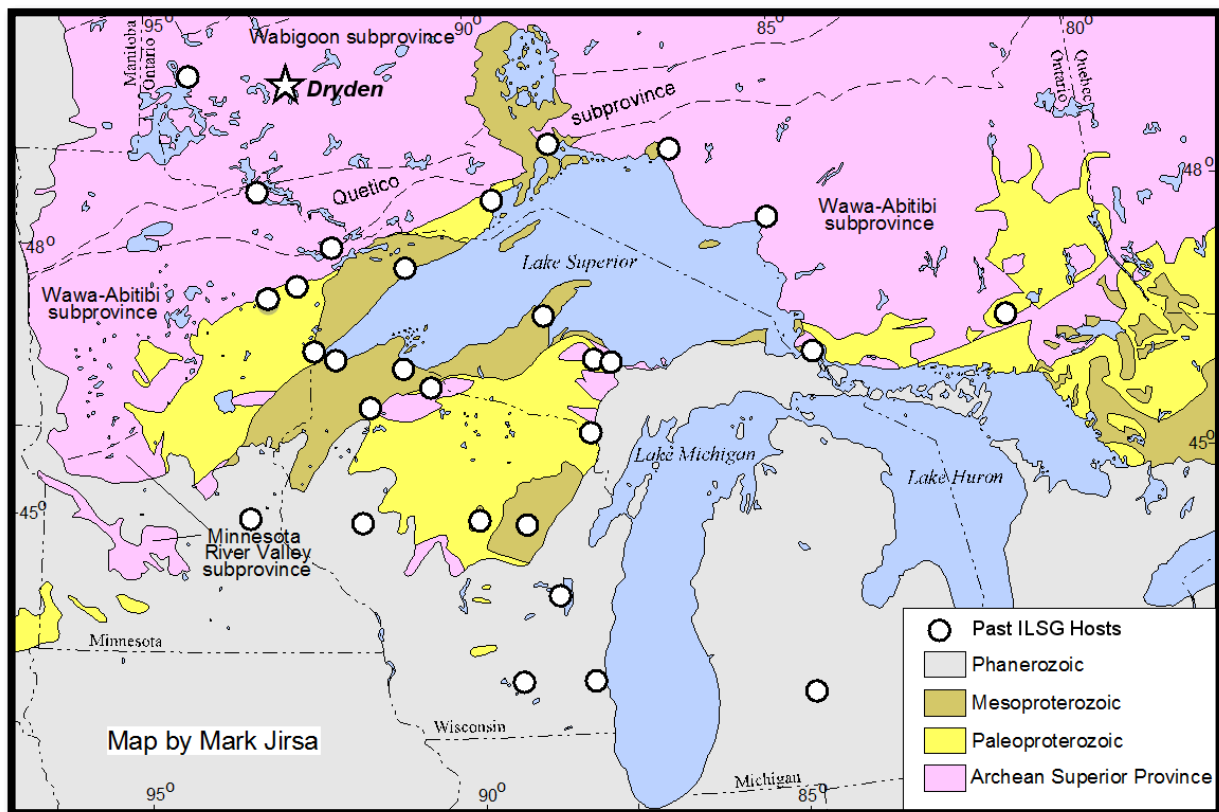
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Some figures in this volume were submitted by authors in color, but are printed grayscale to conserve printing costs. Full color imagery will appear in the digital version of the volume when it is available on-line at <http://www.lakesuperiorgeology.org>.

Institutes on Lake Superior Geology, 1955-2015



#	Date	Place	Chairs
1	1955	Minneapolis, Minnesota	C.E. Dutton
2	1956	Houghton, Michigan	A.K. Snelgrove
3	1957	East Lansing, Michigan	B.T. Sandefur
4	1958	Duluth, Minnesota	R.W. Marsden
5	1959	Minneapolis, Minnesota	G.M. Schwartz & C. Craddock
6	1960	Madison, Wisconsin	E.N. Cameron
7	1961	Port Arthur, Ontario	E.G. Pye
8	1962	Houghton, Michigan	A.K. Snelgrove
9	1963	Duluth, Minnesota	H. Lepp
10	1964	Ishpeming, Michigan	A.T. Broderick
11	1965	St. Paul, Minnesota	P.K. Sims & R.K. Hogberg
12	1966	Sault Ste. Marie, Michigan	R.W. White
13	1967	East Lansing, Michigan	W.J. Hinze

14	1968	Superior, Wisconsin	A.B. Dickas
15	1969	Oshkosh, Wisconsin	G.L. LaBerge
16	1970	Thunder Bay, Ontario	M.W. Bartley & E. Mercy
17	1971	Duluth, Minnesota	D.M. Davidson
18	1972	Houghton, Michigan	J. Kalliokoski
19	1973	Madison, Wisconsin	M.E. Ostrom
20	1974	Sault Ste. Marie, Ontario	P.E. Giblin
21	1975	Marquette, Michigan	J.D. Hughes
22	1976	St. Paul, Minnesota	M. Walton
23	1977	Thunder Bay, Ontario	M.M. Kehlenbeck
24	1978	Milwaukee, Wisconsin	G. Mursky
25	1979	Duluth, Minnesota	D.M. Davidson
26	1980	Eau Claire, Wisconsin	P.E. Myers
27	1981	East Lansing, Michigan	W.C. Cambray
28	1982	International Falls, Minnesota	D.L. Southwick
29	1983	Houghton, Michigan	T.J. Bornhorst
30	1984	Wausau, Wisconsin	G.L. LaBerge
31	1985	Kenora, Ontario	C.E. Blackburn
32	1986	Wisconsin Rapids, Wisconsin	J.K. Greenberg
33	1987	Wawa, Ontario	E.D. Frey & R.P. Sage
34	1988	Marquette, Michigan	J. S. Klasner
35	1989	Duluth, Minnesota	J.C. Green
36	1990	Thunder Bay, Ontario	M.M. Kehlenbeck
37	1991	Eau Claire, Wisconsin	P.E. Myers
38	1992	Hurley, Wisconsin	A.B. Dickas
39	1993	Eveleth, Minnesota	D.L. Southwick
40	1994	Houghton, Michigan	T.J. Bornhorst
41	1995	Marathon, Ontario	M.C. Smyk
42	1996	Cable, Wisconsin	L.G. Woodruff
43	1997	Sudbury, Ontario	R.P. Sage & W. Meyer
44	1998	Minneapolis, Minnesota	J.D. Miller & M.A. Jirsa
45	1999	Marquette, Michigan	T.J. Bornhorst & R.S. Regis
46	2000	Thunder Bay, Ontario	S.A. Kissin & P. Fralick
47	2001	Madison, Wisconsin	M.G. Mudrey & Jr., B.A. Brown

48	2002	Kenora, Ontario	P. Hinz & R.C. Beard
49	2003	Iron Mountain, Michigan	L. Woodruff & W.F. Cannon
50	2004	Duluth, Minnesota	S. Hauck & M. Severson
51	2005	Nipigon, Ontario	M. Smyk & P. Hollings
52	2006	Sault Ste. Marie, Ontario	A. Wilson & R. Sage
53	2007	Lutsen, Minnesota	L. Woodruff & J. Miller
54	2008	Marquette, Michigan	T. Bornhorst & J. Klasner
55	2009	Ely, Minnesota	J. Miller, G. Hudak, & D. Peterson
56	2010	International Falls, Minnesota	M. Jirsa, P. Hollings, & T. Boerboom, P. Hinz & M.Smyk
57	2011	Ashland, Wisconsin	T. Fitz
58	2012	Thunder Bay, Ontario	P. Hollings
59	2013	Houghton, Michigan	T. Bornhorst & A. Blaske
60	2014	Hibbing, Minnesota	J. Miller & M. Jirsa
61	2015	Dryden, Ontario	P. Hinz & R. Cundari

Sam Goldich and the Goldich Medal

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

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

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

Reference:

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

Prepared by various Goldich Medal Awardees, 2007



INSTITUTE ON LAKE SUPERIOR GEOLOGY GOLDICH MEDAL

Goldich Medal Guidelines

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

Preamble

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

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

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

Award Guidelines

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

Nominating Procedures

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

Selection Guidelines

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

Goldich Medalists

1979	Samuel S. Goldich	1997	Ronald P. Sage
1980	<i>not awarded</i>	1998	Zell Peterman
1981	Carl E. Dutton, Jr.	1999	Tsu-Ming Han
1982	Ralph W. Marsden	2000	John C. Green
1983	Burton Boyum	2001	John S. Klasner
1984	Richard W. Ojakangas	2002	Ernest K. Lehmann
1985	Paul K. Sims	2003	Klaus J. Schulz
1986	G.B. Morey	2004	Paul Weiblen
1987	Henry H. Halls	2005	Mark C. Smyk
1988	Walter S. White	2006	Michael G. Mudrey
1989	Jorma Kalliokoski	2007	Joseph Mancuso
1990	Kenneth C. Card	2008	Theodore J. Bornhorst
1991	William Hinze	2009	L. Gordon Medaris, Jr.
1992	William F. Cannon	2010	William D. Addison & Gregory R. Brumpton
1993	Donald W. Davis	2011	Dean M. Rossell
1994	Cedric Iverson	2012	James D. Miller
1995	Gene La Berge	2013	Tom Waggoner
1996	David L. Southwick	2014	Laurel Woodruff

2015 GOLDICH MEDAL RECIPIENT

RODNEY J. IKOLA

Goldich Medal Committee

Serving through the meeting year shown in parentheses.

Bernhardt Saini-Eidukat (2015)	North Dakota State University
Mark Smyk (2016)	Ontario Geological Survey
Hélène Lukey (2017)	Cliffs Natural Resources

Citation for the Goldich Medal Award to **Rodney J. Ikola**



Rodney J. (Rod) Ikola was born and raised in the Finnish community of Esko, Minnesota. As he puts it, he had learned his first “foreign language” (ENGLISH) by the end of his first year in school. He has continued to be active in Finnish organizations throughout his life, such as Festival Finlandia at Ironworld in Chisholm, MN, and FinnfestUSA in Duluth in 2008. He has dual citizenship in the U.S. and Finland and served as a member of the Expatriate Parliament of the Republic of Finland for a number of years. Rod has a list of accomplishments in the field of geophysics that would make any Finnish Mother proud, and we suggest that they are worthy of adding Rodney Ikola’s name to the list of Goldich Medal recipients.

He did his undergraduate studies at the University of Minnesota Duluth, with a major in geology and a minor in mathematics. He continued his education at the University of Utah on a scholarship in geophysics from the Continental Oil Company, during which time he obtained sufficient math credits to fulfill the requirements for a degree in mathematics. After one year he transferred to the University of Minnesota to complete his Masters degree. During his time at the University of Minnesota, Professor Hal Mooney knew that Rod had been doing gravity work around the southern end of the Duluth Complex and west into Carlton County, simply out of personal curiosity, using a gravimeter made available to him compliments of U. S. Steel. Mooney suggested that Rod should write up the gravity work he had already done and he would accept that as a Master’s thesis. This gravity survey showed several gravity anomalies at the western edge of Carlton County, which became known as the Tamarack Intrusion; this is currently being drilled for copper, nickel and PGE by Rio Tinto-Kennecott.

During his days at the U of M, Rod worked on several geophysical projects. In 1959 he conducted his first geophysical survey; a magnetic study of the Barden’s Peak Intrusive of the Duluth Complex. During the summers of 1960 and 1962 he worked on field geophysical exploration for U.S. Steel under the supervision of their geophysicist, George Durfee. The 1960 project consisted of running magnetometer lines across every dip needle anomaly in northwestern Wisconsin (most of which were located in swamps). In 1962 he conducted an extensive gravity survey of Jackson County in central Wisconsin, for the Jackson County Iron Company, a subsidiary of Inland Steel; a taconite mine was developed a decade later in the Archean rocks in Jackson County.

In 1965 Director Paul Sims obtained funding to significantly expand the activities of the Minnesota Geological Survey and asked Rod if he would join the Survey to start a systematic gravity survey of the State. Rod accepted the offer and he and G. B. Morey started working for the Survey on the same day. Most of Rod’s time with the Survey was consumed with the gravity survey of the state. This resulted in the publication of several Bouguer gravity maps at a scale of

1:250,000. During this time he produced the first gravity map of the entire Duluth Complex. He was also periodically on loan to the U.S. Army Topographic Command to establish geodetic control over the central U.S. At the AIME meeting in Duluth in 1970, Fred Chase, chief geologist of the Hanna Mining Co., asked Rod if he would be interested in joining Hanna. They had started a large exploration program in the greenstone belts of Minnesota and needed a geophysicist for the project. Rod accepted the offer, eventually was appointed chief geophysicist for Hanna in 1974, and became responsible for world-wide exploration, a position he held until 1982.

Initially his work with Hanna was mainly involved with geophysical exploration in support of Hanna's geological activities in Minnesota's greenstone belts and the Duluth Complex. However, he soon began working on all of Hanna's projects around the world. The list of projects is too long to list here, but demonstrates a wide range of geophysical techniques that Rod mastered.

With the downturn of the iron ore market in 1982, Hanna eliminated their entire exploration program as the first step in the eventual demise of the entire company. With this event, Rod decided to go on his own as a consulting geophysicist, which he has been for the last thirty years. Almost immediately he became heavily involved in geophysical consulting in the Lake Superior region for many of the world's major mining companies. Some of these include Newmont, INCO, American Copper and Nickel, Cominco American, Noranda, Phelps Dodge, DeBeers, (through their regional affiliate), plus numerous junior companies. Most of this work remains proprietary but one project in particular can be mentioned. He did all the geophysical work for Noranda that led to the discovery of the large Lynne (Cu-Zn) Deposit in northern Wisconsin. Only environmental issues prevented the development of the project into a commercial venture.

He also became extensively involved in Freeport-McMoRan for many years and acted as *de facto* geophysicist on many of their worldwide exploration efforts. He worked extensively in the Iberian Pyrite Belt of Spain and Portugal. One of these efforts led to the discovery of the Agua Blanca nickel deposit, which is Europe's largest nickel producer. He also spent considerable time doing geophysics in the Grasberg area of Indonesia. And he worked on porphyry exploration for Freeport in Baja California.

Consulting work has taken Rod to numerous mining camps around the world. He has spent time at Noril'sk in Russia studying their geophysical exploration techniques. He also did some work for a consortium of companies exploring for gold in the "reefs" south of Lake Victoria in Africa, diamond exploration in Brazil, nickel exploration in Western Australia, uranium exploration in the Athabasca area of Canada, and deeply buried porphyry deposits in the southwest U.S..

In recent years, with the upsurge of mineral exploration in the Lake Superior region, he has spent more time close to home. He has been involved with Polymet Mining and Duluth Metals in the Duluth Complex, and Keweenaw Copper Co. and Bitterroot Exploration in Michigan. However, the results of this work remain proprietary.

In recent years, Rod has been involved in numerous geophysical projects pertaining to environmental and groundwater problems. On a project with Barr Engineering, he helped develop a groundwater resource at the Sherco Power Plant in Becker, MN. For this work the Minnesota Society of Professional Engineers awarded the group a Distinguished Achievement Award. On another project the group used a unique application of the SP geophysical method to delineate karst features in the Keweenawan sandstones near Askov, MN, to help prevent pollution from their sewage treatment plant.

Rod has always been interested in the use of geophysics in archaeological investigations, and he has participated in many studies. He spent two summers in Greece (one on top of Mt. Olympus with the Gods!!) looking at sites from the Homeric Age. On another occasion he used geophysics to look for buried Mayan tombs in Belize.

Rod has been affiliated with many professional organizations during his career. He is an emeritus member of the Society of Exploration Geophysicists, belongs to the Australian Society of Exploration Geophysicists, a member of the American Institute of Professional Geologists and has belonged to the Society of Mining Engineers for many years (and served on seven national committees for them). He is also a founding member, and was on the board of directors of the Minnesota Exploration Association (now Mining Minnesota). He is a Registered Earth Scientist in Minnesota and a Professional Geophysicist in California. He has been involved with the Institute on Lake Superior Geology for over fifty years. The first Institute meeting he attended was the fourth one, in Duluth in 1958, and has subsequently attended approximately 45 meetings.

During his career as a geophysicist, Rod Ikola has made many contributions to our understanding of the geology of the Lake Superior Region, particularly in the areas of government surveys and industry. These accomplishments, as well as his geophysical studies at so many other places around the world, make him highly qualified for the Goldich Medal.

Respectfully submitted,

Gene L. LaBerge
Richard W. Ojakangas

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 2014, the ILSG Board of Governors awarded a \$1000 award from the Student Research Fund to Justin Beermaert.

It should be noted that an especially generous donation was once again provided by Ron Seavoy.

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

Amy Radakovich— Minnesota Geological Survey

Mark Severson — Teck American

Dave Good — Western University

Board of Directors

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

Robert Cundari (2015-2018) – Ontario Geological Survey

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

Allan Blaske (2013-2016) – AECOM

Peter Hinz (2012-2015) – Ontario Geological Survey

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

Mark Jirsa – Treasurer (2014-2017) – Minnesota Geological Survey

Local Committee

Chairs

Peter Hinz – Co-Chair

Ring of Fire Secretariat, Ministry of Northern Development and Mines

Robert Cundari – Co-Chair

Resident Geologist Program, Ontario Geological Survey

Volume Editors

Mark Smyk – Proceedings Volume

Resident Geologist Program, Ontario Geological Survey

Allan MacTavish – Field Trip Guidebook

Panoramic PGMs (Canada) Limited

Banquet Speaker

Steve Beneteau

(Senior Diamond Advisor / Chief Gemmologist for the Province of Ontario and the Manager of the Diamond Sector Unit, Ministry of Northern Development and Mines)

“Ontario’s Diamonds: A Journey from Mine to Market”

Session Chairs

Jim Miller – University of Minnesota Duluth

Anthony Pace - Ontario Geological Survey

Dean Peterson – Peterson Geoscience LLC

Mark Smyk - Ontario Geological Survey

Ann Wilson – Ontario Geological Survey

Laurel Woodruff – United States Geological Survey

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.

Pre-Meeting:

1. Red Lake Geology (2-day) Tuesday May 19th and Wednesday May 20th, 2015

Leaders: **Andreas Lichtblau** (OGS) and **Carmen Storey** (OGS)

2. Western Wabigoon Subprovince Transect (Dryden to Meggisi Lake) Wednesday May 20th, 2015

Leaders: **Mark Puumala** (OGS) and **Dorothy Campbell** (OGS)

3. Mine Reclamation and Legacy Issues at the South Bay Mine Wednesday May 20th, 2015

Leader: **Rob Purdon** (MNDM) [CANCELLED DUE TO UNFORESEEN CIRCUMSTANCES]

4. Geological Setting of the Thunder Lake Gold Deposit

Wednesday May 20th, 2015

Leaders: **Treasury Metals Inc.**

Half-Day:

5. Classic outcrops of the Dryden Area Friday May 22nd, 2015

Leader: **Peter Hinz** (MNDM)

6. Gold Occurrences of Van Horne Township Friday May 22nd, 2015

Leader: **Steve Meade** (OGS)

7. Unique mineralizing event at the Pidgeon Molybdenum Occurrence Friday May 22nd, 2015

Leaders: **Craig Ravnaas** (OGS)

Post-Meeting:

8. Historic Pickle Lake Camp (1.5-day) Friday May 22nd and Saturday May 23rd, 2015

Leaders: **Mark Smyk** (OGS), **Pete Hollings** (Lakehead University) and **Neil Pettigrew** (PC Gold Inc.)

9. Ghost Lake Batholith and Related Pegmatites Saturday May 23rd, 2015

Leader: **Shannon Zurevinski** (Lakehead University)

10. Mattabi/Sturgeon Lake Historic VMS Camp (2-day) Friday May 22nd and Saturday May 23rd, 2015

Leader: **George Hudak** (Natural Resources Research Institute – University of Minnesota Duluth)

Sponsors

The following organizations made generous contributions to the 61st 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. For the past 60 years this organization has thrived as a result of the interest of individuals, corporations, universities and government agencies. The dedication to an exchange of scientific ideas and a passion for field trips has enabled the Institute to provide one of its primary objectives – to promote better understanding of the geology of the Lake Superior Region.

Mary Arthur

Steve Baumann

Leonard Espinosa

Gordon Medaris Jr.

Allan MacTavish

Jim Miller

Paul Weiblen



Canadian Institute of Mining and Metallurgy
Thunder Bay Branch

REPORT OF THE CHAIRS OF THE 60TH ANNUAL MEETING INSTITUTE ON LAKE SUPERIOR GEOLOGY HIBBING, MINNESOTA

The Precambrian Research Center (PRC) of the University of Minnesota Duluth (UMD) and the Minnesota Geological Survey (MGS) of the University of Minnesota – Twin Cities hosted the 60th Annual Institute on Lake Superior Geology on May 14– 17, 2014 at the Hibbing Park Hotel in Hibbing, Minnesota in the heart of the Mesabi Range. This was the first time that the ILSG has been held in Hibbing. We are pleased to report a very vigorous attendance of 225 registrants, including 57 students.

The organizing committee for the meeting was comprised of Jim Miller of UMD-PRC (technical program, meeting and field trip logistics, and registration) and Mark Jirsa of the MGS (field trip coordinator and guidebook editor, student travel awards, and sponsorships). Amy Radakovich of the MGS helped with the procurement and design of T-shirts and beer glasses. Terry Boerboom, also of the MGS, assisted with the organization of the field guidebook. Julie Ann Heinz, an executive office administrator at the UMD Natural Resources Research Institute, provided assistance with meeting registration and creating name tags. During the meeting, a number of UMD students assisted with on-site registration and other institute business.

The two-day technical session held at the Hibbing Park Hotel on Thursday and Friday (5/15 and 5/16) included 30 talks and 35 posters presentations, including 17 oral and 20 poster presentations by students. The number of student presenters and attendees are both ILSG records. The meeting opened with a remembrance of Jack Everett and Ernie Lehmann who passed away in August, 2013 and December, 2013, respectively. Both Jack and Ernie were exceptional exploration geologists who devoted much of their careers to minerals exploration in the Lake Superior region. Both were long-time supporters of the ILSG, with Ernie receiving the Goldich medal in 2002. This year's Goldich medal recipient was Laurel Woodruff of the US Geological Survey. Laurel was recognized for her long and productive 30 year career with the USGS's mineral resources research program, mostly in the Lake Superior region and for her scientific contributions and service to the ILSG, especially her serving as meeting chair in 1996 (Cable, WI), 2003 (Iron Mtn, MI), and 2007 (Lutsen, MN). Laurel was presented the medal at the annual banquet by Bill Cannon, her colleague and mentor at the USGS who received the Goldich medal in 1992. The evening banquet talk was presented by Dr. Francis M. Carroll of the University of Manitoba - Winnipeg and St. Johns University. The title of his talk was: *"A Line in the Trees: History of the US-Canadian Boundary from Lake Superior to Lake of the Woods"*.

The meeting offered six full-day and three Friday afternoon field trips that highlighted various aspects of the geology, ore deposits, and culture of the central Mesabi Range. Most trips were filled to capacity with a cumulative total of 255 field trip attendees. Three pre-meeting field trips run on Wednesday, May 14 included: 1) *Stratigraphy, Sedimentology, Structure, and Mineralization of the Biwabik Iron Formation, Central Mesabi Iron Range* led by Phil Larson (*Duluth Metals*), Marsha Patelke (*UMD-NRRI*), Jakob Wartman (*Cliffs NR*), Michael Totenhagen (*Arcelor*

Mittal), Mark Jirsa (MGS), Steven Losh (Minnesota State University-Mankato), and Peter Jongewaard (Cliffs NR); 2) ***A Walk in the Park – Neoproterozoic Geology of Lake Vermilion State Park*** led by George Hudak (UMD-NRRI), Amy Radakovich (MGS), Geoff Pignotta (UW - Eau Claire), and Kelly Schwierske (UW - Eau Claire); and 3) ***Western Mesabi Range Mining Operations*** led by Doug Halverson (Cliffs NR), Dan Cervin (Cliffs NR), William Everett (Essar Steel), Kevin Kangas (Essar Steel), and Joey Nielsen (Magnetation).

Three Friday afternoon trips included: 1) ***State Drill Core Library – Hibbing, Minnesota*** led by Dave Dahl, Barry Frey, and other MNDNR staff and Dean Rossell (Kennecott Exploration, Rio Tinto); 2) ***Hibbing's Iron Mining and Cultural History*** led by Henry Djerlev, Bob Kearney, Erica Larson and other Hibbing Historical Society staff; and 3) ***Mineview from a Canoe*** led by Mark Jirsa (MGS), Dan Jordan (IRRRB), and Dale Cartwright (MNDNR).

Three post-meeting trips were run on Saturday, May 17 and included: 1) ***Visions of Maturi: The Geology of the South Kawishiwi Intrusion*** led by Dean Peterson (Duluth Metals Ltd.); 2) ***The St. Louis Sublobe and Glacial Lake Upham*** led by Phil Larson (Duluth Metals Ltd.), Alan Knaeble (MGS), Howard Mooers (UMD), and Lisa Marlo (Halcon Resources Corp.); and 3) ***Geology and Gold Mineralization of the Virginia Horn Area*** led by Mark Jirsa (MGS), Bill Rowell (Vermillion Gold), Rick Sandri (Vermillion Gold), and Jason Richter (MN DOT).

The student paper committee comprised of Andrew Ware (PolyMet Mining), Prajukti Bhattacharyya (University of Wisconsin-Whitewater), and Rob Cundari (Ontario Geological Survey) had the onerous task of judging 17 oral and 20 poster presentations by students. The committee awarded 4 Doug Duskin Student Paper Awards with a cash prize of \$500 each to Amanda Van Lankfelt (U Mass.), Adrian Arts (Lakehead), Monica Karman (Lakehead), and Darcy Jacobson (Michigan Tech.).

To defray student's expenses for travel and registration, a total of \$6400 was distributed to 32 students representing 8 different schools. This generous aid was provided by the Eisenbrey Student Travel Awards. Additional student travel support was provided by funds contributed by 11 meeting registrants (Mary Arthur, Jack Berkley, Karl Everett, John Green, George Hudak, Peter Jongewaard, Steven Losh, Al MacTavish, Gordon Medaris, Michael Mudrey, and Jill Peterman), and several corporations and organizations (Eagle Mine, Teck American, Midwest Institute of Geosciences and Engineering, and GEI Consultants). Ron Seavoy provided a particularly generous donation to establish and maintain the Joe Mancuso Student Research Grant program. Three \$500 Mancuso research grants were awarded in 2014 to Michael Doyle (UMD), Michael Fedorchuk (UW-Milwaukee), and Sarah Sauer (UMD).

The Institute's Board of Directors met on May 15, 2014. The meeting was attended by meeting co-chair Jim Miller, Treasurer Mark Jirsa, Secretary Peter Hollings, and board members Allan Blaske (2013 chair) and Al MacTavish (2012 chair). Incoming chair for the 2015 ILSG, Pete Hinz, also attended. Secretary Hollings took the minutes of the Board meeting that are as follows:

1. Accepted report of the Chairs for the 59th ILSG, Houghton, Michigan; as printed in the Proceeding Volume (Blaske), and minutes of last Board meeting, May 9, 2013 (Hollings)

2. Received, discussed, and accepted 2013-2014 ILSG Financial Summary (Jirsa).
3. Received, discussed, and accepted 2013-2014 report of the Secretary (Hollings).
4. Approved Jim Miller as on-going ILSG Board member
5. Approved Dryden as the site for the 61st annual ILSG meeting. The meeting will be hosted by the Ontario Geological Survey with Peter Hinz and Rob Cundari serving as co-chairs.
6. Discussed and approved renewal of Mark Jirsa as Institute Secretary (end of term 2017). This was later approved by a vote of the membership
7. Discussed and approved replacing Graham Wilson as the “member from industry” on Goldich Committee (end of term 2017) with Helene Lukey
8. Discussed student attendance and presentations at future meetings.

We would like to thank the participants, especially the students, for supporting the Institute by their attendance and enthusiasm, the field trip leaders for their hard work, the presenters for their high quality and informative talks and posters, the session chairs and subcommittee members for their important contributions, and the meeting sponsors for their generosity in helping students participate in the Institute.

Respectfully submitted,

Jim Miller and Mark Jirsa
Co-Chairs, 60th Institute on Lake Superior Geology

PROGRAM

SCHEDULED ACTIVITIES AND FIELD TRIPS

Tuesday, May 19th, 2015

8:00 a.m. – 6:00 p.m. Field Trip 1 Red Lake Geology (Day One)

Wednesday, May 20th, 2015

8:00 a.m. – 6:00 p.m. Field Trip 1 Red Lake Geology (Day Two)
 Field Trip 2 Western Wabigoon Subprovince Transect
 Field Trip 3 Mine Reclamation and Legacy Issues at the South Bay Mine [cancelled]
 Field Trip 4 Geological Setting of the Thunder Lake Gold Deposit / Gold occurrences of
 Van Horne Township

7:00 p.m. – 10:00 p.m. Registration at Best Western
 Poster Session (Gemini Room) / Ice Breaker Social (Centennial Room)

Thursday, May 21st, 2015

8:00 a.m. – 12:00 p.m. Registration continues
 9:00 a.m. – 12:00 p.m. Technical Session I
 12:00 p.m. – 1:30 p.m. Lunch (provided)
 1:30 p.m. – 4:00 p.m. Technical Session II
 6:00 p.m. – 7:00 p.m. Mixer / Cash Bar
 7:00 p.m. – 10:00 p.m. Annual Banquet, Keynote Speaker and Awards Presentation (Sunset Ballroom)

Friday, May 22nd, 2015

9:00 a.m. – 11:10 a.m. Technical Session III
 11:10 a.m. – 12:00 p.m. Student Awards presentations
 12:00 p.m. – 1:30 p.m. Lunch (provided)
 1:30 p.m. – 6:00 p.m. Field Trip 5 Classic outcrops of the Dryden Area
 Field Trip 6 Gold Occurrences of Van Horne Township
 Field Trip 7 Unique mineralizing event at the Pidgeon Molybdenum Occurrence
 Field Trip 8 (departs for Pickle Lake)
 6:00 p.m. – 7:00 p.m. Field Trip 10 (departs for Ignace)

Saturday, May 23rd, 2015

8:00 a.m. – 6:00 p.m. Field Trip 8 Historic Pickle Lake Camp (return to Ignace / Dryden)
 Field Trip 9 Ghost Lake Batholith and Related Pegmatites (return to Dryden)
 Field Trip 10 Mattabi / Sturgeon Lake Historic VMS Camp (Day One; return to Ignace)

Sunday, May 24th, 2015

8:00 a.m. – 6:00 p.m. Field Trip 10 Mattabi / Sturgeon Lake Historic VMS Camp (Day Two; return to Dryden)

TUESDAY, MAY 19TH

8:00 am – 6:00 pm Pre-Meeting Field Trip:
 1. Red Lake Geology (Day One; overnight in Red Lake)
 Leaders: Andreas Lichtblau (OGS) and Carmen Storey (OGS)

WEDNESDAY, MAY 20TH

- 8:00 am – 6:00 pm Pre-Meeting Field Trips:
- 1. Red Lake Geology (Day Two; return to Dryden)**
Leaders: Andreas Lichtblau (OGS) and Carmen Storey (OGS)
 - 2. Western Wabigoon Subprovince Transect**
Leaders: Mark Puumala (OGS) and Dorothy Campbell (OGS)
 - 3. Mine Reclamation and Legacy Issues at the South Bay Mine**
Leader: Rob Purdon (MNDM)[cancelled due to unforeseen circumstances]
 - 4. Geological Setting of the Thunder Lake Gold Deposit**
Leaders: Treasury Metals Inc.
- 7:00 p.m. – 11:00 p.m. **Registration at Best Western**
Poster Session (Gemini Room) / **Ice Breaker Social** (Centennial Room)

THURSDAY, MAY 21ST

- 8:00 – 12:00 pm Registration continues
- 8:50 - 9:00 am **OPENING REMARKS, UPDATES**
Peter Hinz and Robert Cundari, Co-Chairs, 2015 ILSG
- 9:00 – 9:10 am Welcoming Remarks

TECHNICAL SESSION I

(*denotes a student eligible for Best Student Paper Award)

Session Chairs: **Laurel Woodruff** – United States Geological Survey
 Anthony Pace - Ontario Geological Survey

- 9:10 – 9:50 am **Bill Cannon, Bill Addison, Greg Brumpton and Mark Jirsa**
The Sudbury Impact Event in the Lake Superior region: Ten years of research on ten minutes of geologic time
- 9:50 – 10:10 am **Daniel Lafontaine* and Mary Louise Hill**
Structural control on the Borden Gold deposit, Chapleau, ON
- 10:10 – 10:40 am COFFEE BREAK AND POSTER VIEWING

10:40 – 11:00 am **Jim Miller**

Role of Felsic and Feldspathic Rocks in Triggering Subvolcanic Emplacement of Mafic Intrusions: Evidence from the Midcontinent Rift in Northeastern Minnesota

11:00 – 11:20 am **David Good, Peter Hollings, Robert Cundari and Doreen Ames**

Significance of LREE-enriched mantle source to genesis of basalt in the Coldwell Alkaline Complex, Midcontinent Rift, Ontario

11:20 – 11:40 am **Michael Doyle* and 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

11:40– 12:00 pm **Sarah Sauer* and Jim Miller**

Petrologic study of the "Chill" zone of the Layered Series at Duluth: Testing a possible plutonic-volcanic correlation within the Midcontinent Rift

12:00 – 1:30 pm **LUNCH (provided) / MEETING OF THE BOARD OF DIRECTORS**

TECHNICAL SESSION II

(*denotes a student eligible for Best Student Paper Award)

Session Chairs: **Dean Peterson** – Peterson Geoscience LLC

Ann Wilson – Ontario Geological Survey

1:30 – 1:50 pm **Robert Mahin**

The Eagle Mine in Production: U.S.A.'s Only Primary Nickel Producer

1:50 – 2:10 pm **Kristofer Asp*, Christian Schardt, and Lev Spivak-Birndorf**

Evidence of high temperature Ni isotopic fractionation during the formation of Cu-Ni-PGE sulfide deposits in the Duluth Complex

- 2:10 – 2:30 pm **David Good, Louis Cabri and Doreen Ames**
Comparison of PGM assemblages for the Marathon, Geordie Lake and Area 41 deposits, Coldwell Alkaline Complex, Ontario
- 2:30 – 2:50 pm **Jeffrey Mauk, Poul Emsbo and Peter Theodorakos**
Evaporated seawater formed sediment-hosted stratiform copper orebodies and second-stage copper mineralization in the Mesoproterozoic Nonesuch Formation of the Midcontinent Rift
- 2:50 – 3:20 pm COFFEE BREAK AND POSTER VIEWING
- 3:20 – 3:40 pm **Amos Albert*, Jessica Eagle-Bluestone* and Bernie Saini-Eidukat**
Chemistry and Mineralogy of Nopeming metasiltstone at the Grandview Site, Duluth, Minnesota
- 3:40 – 4:00 pm **Adrian Arts* and Phil Fralick**
Iron-rich siliceous stromatolites from the upper algal unit of the Gunflint and Biwabik Iron Formations
- 4:00 – 4:20 pm **Christopher Yip* and Phil Fralick**
Exposure Surfaces of the Gunflint Iron Formation, Northwestern Ontario
- 4:20 – 4:40 pm **Riku Metsaranta and Phil Fralick**
Sedimentology and Geochemistry of a 1.4 Ga Continental Playa System, the Lower Sibley Group, Northwestern Ontario: Implications for the Mesoproterozoic Hydrosphere and Atmosphere
- 4:40 – 5:00 pm **Paul Fix* and Tamara Diedrich**
Characterization of secondary minerals formed on weathered Duluth Complex Cu-Ni-PGE deposit rock and implications for controls on metal mobility
- 6:00 pm **RECEPTION – CASH BAR**
- 7:00 pm **ANNUAL BANQUET** (Sunset Ballroom)
– Announcement of 62nd Annual Meeting Location

- 2015 Goldich Award Presentation to **Rodney Ikola**
- Banquet Presentation by Steve Beneteau (MNDM)
“Ontario’s Diamonds: A Journey from Mine to Market”

FRIDAY, MAY 22ND

8:50 – 9:00 am **OPENING REMARKS, UPDATES**
Peter Hinz and Rob Cundari, Co-Chairs, 2015 ILSG

TECHNICAL SESSION III

Session Chairs: **Mark Smyk - Ontario Geological Survey**
 Jim Miller – University of Minnesota Duluth

9:00 – 9:20 am **Brent Trevisan, Pete Hollings, Doreen Ames and Nicole Rayner**
The petrology, mineralization and regional context of the Thunder mafic to ultramafic intrusion, Midcontinent Rift, Thunder Bay, Ontario

9:20 – 9:40 am **Seamus Magnus**
Geology and geochemistry of the Lang Lake greenstone belt, Uchi Domain, Superior Province

9:40 – 10:00 am **Phil Fralick**
Lateral Geochemical Gradients and Physical Processes Associated with the Genesis of Iron Formations: Examples from the Paleoproterozoic to Mesoproterozoic of Superior Province

10:00 – 10:30 am **COFFEE BREAK AND POSTER VIEWING**

10:30 – 10:50 am **Steve Kissin**
Rainy River, northwestern Ontario's first meteorite

10:50 – 11:10 am **Dennis Smyk, William Ross and Mark Smyk**
Images on stone: Pictographs of the Ignace area, northwestern Ontario

11:10 – 11:30 am **Dean Peterson**

So, an Environmental Impact Statement is required: Some Lake Superior area Geologic Parameters for Geologists, Consultants, Companies, and Regulators

11:30 – 12:00 pm **BEST STUDENT PAPER AWARDS AND STUDENT TRAVEL AWARDS**

12:00 – 1:30 pm **LUNCH** (provided)

1:30 – 6:00 pm **FRIDAY AFTERNOON FIELD TRIPS**

5. Classic outcrops of the Dryden Area

Leader: Peter Hinz (MNDM)

6. Gold Occurrences of Van Horne Township

Leader: Steve Meade (OGS)

7. Unique mineralizing event at the Pidgeon Molybdenum Occurrence

Leader: Craig Ravnaas (OGS)

8. Historic Pickle Lake Camp (departs Dryden for Pickle Lake)

Leaders: Mark Smyk (OGS), Peter Hollings (Lakehead University) and Neil Pettigrew (PC Gold Inc.)

6:00 – 7:00 pm **10. Mattabi / Sturgeon Lake Historic VMS Camp** (departs Dryden for Ignace)

Leader: George Hudak (NRRI – University of Minnesota Duluth)

SATURDAY, MAY 23RD

8:00 am – 6:00 pm **POST-MEETING FIELD TRIPS**

8. Historic Pickle Lake Camp (returns to Ignace / Dryden in evening)

9. Ghost Lake Batholith and Related Pegmatites

Leader: Shannon Zurevinski (Lakehead University)

10. Mattabi/Sturgeon Lake Historic VMS Camp (Day One)

SUNDAY, MAY 24TH

8:00 am – 6:00 pm **POST-MEETING FIELD TRIPS**

10. Mattabi/Sturgeon Lake Historic VMS Camp (Day Two; returns to Ignace / Dryden in evening)

POSTER PRESENTATIONS

(*denotes a student eligible for Best Student Paper Award)

Eric Anderson, Ashley Quigley, Patrick Quigley and Thomas Monecke

Geophysical imaging of the bedrock geology of the Pembine-Wausau terrane, Wisconsin: Constraints on the setting of volcanogenic massive sulfide deposits

Eric Anderson, V. Grauch, Michael Powers and Bill Cannon

Seismic, gravimetric, and magnetic modeling over the Bayfield Peninsula, Wisconsin: Testing hypotheses on the source of a gravity low

Jordan Baird* and Mary Louise Hill

Fold analyses in the Gunflint Formation: working towards a characterization of regional deformation in the Animikie Group near Thunder Bay, Ontario

Steven Baumann, Alexandra Cory and Sandra Dylka

Interpretation of the St. Amour Deep Stratigraphic Test Well, Alger County, Michigan

Greg Brumpton and Steve Kissin

Large hypervelocity impacts on Earth: Empirical observations and validation of computational model predictions for Sudbury and Chicxulub

Tom Buchholz, Alexander Falster and W. B. Simmons

Tainiolite from the Stettin Intrusion, Wausau Complex, Marathon County, Wisconsin

Benjamin Drenth, Chad Ailes and Eric Anderson

Re-digitized public aeromagnetic data for the Baraga basin and surrounding region, Upper Peninsula, Michigan

Esprey Essig*, George Hudak, Geoff Pignotta and Robert Lodge

Petrographic Analysis of Felsic Tuffs within the Neoarchean Soudan Member of the Ely Greenstone Formation, Northeastern Minnesota

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

Preliminary 3D model of the Midcontinent Rift System in western Lake Superior region

Steve Hauck, John Heine, Mark Severson, Sara Post, Sarah Chlebecek, Stephen Monson Geerts, Julie Oreskovich, Sarah Gordee and George Hudak

Geological and Geochemical Reconnaissance for Rare Earth Element (REE) Mineralization in Minnesota

Jonathan Haynes*, Joyashish Thakurta and Tom Quigley

Petrological and geochemical evaluation of the Sturgeon Falls Igneous Body and its relationship with the Penokean Orogenic Belt

Benjamin Hinks*, Joyashish Thakurta and Bob Mahin

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

George Hudak, Stephen Monson Geerts, Larry Zanko, Sara Post and Bryan Bandli
The Minnesota Taconite Workers Health Study: Environmental Study of Airborne Particulate Matter - 2015 Update

Mark Jirsa, Terry Boerboom, Val Chandler and Mark Schmitz
Geology and geochronology of Archean rocks in the International Falls and Littlefork 30X60' quadrangles, north-central Minnesota

Steve Kissin and Greg Brumpton
Studies on PDFs in shocked quartz from distal Sudbury ejecta in the Thunder Bay area compared with Chicxulub

Benjamin Krogmeier, Dylan McKeivitt, Elizabeth Roepke, Michael Sara, Paul Szkilnyk and Mark Jirsa
Geologic mapping of Neoarchean and Proterozoic rocks near Knife Lake, Northeastern Minnesota, by students of the Precambrian Research Center's 2014 field camp

Nathan Lentsch* and Jim Miller
Incorporation of Duluth Complex maps into GIS platform

Jim Miller, Christopher Beaver, Timothy Hahn, Nikolas Miller, Joseph Puliese and Erick Wright
Geology of the North and South Temperance Lakes Area of the Boundary Waters Canoe Area, Cook County, Minnesota - 2014 Precambrian Field Camp Capstone Mapping

Doug Nikkila* and Shannon Zurevinski
The mineralogy and petrology of a newly discovered REE occurrence within the Coldwell Complex near Marathon, Ontario

Sean O'Brien*, Pete Hollings and Jim Miller
Petrology, geochemistry and mineral chemistry of the Crystal Lake and Mount Mollie mafic intrusions, Northwestern Ontario

Mark Puumala, Rob Cundari, Dorothy Campbell, Desmond Rainsford and Riku Metsaranta
New airborne geophysical data for the Lake Superior Region of northwestern Ontario: A new tool for the identification of Neoarchean to Mesoproterozoic structures and associated mafic-ultramafic intrusions

Patrick Quigley* and Thomas Monecke
Spectrum of Volcanogenic Massive Sulfide Deposits in the Penokean Volcanic Belt, Great Lakes Region, USA

Andrew Sasso* and Joyashish Thakurta

Geochemical and Petrologic Characterizations of Peridotite, Marquette County, Michigan

Laurel Woodruff and Carrie Jennings

Bedrock and Soil Chemistry in Paired Watersheds in Northeastern Minnesota

Chemistry and Mineralogy of Nopeming metasilstone at the Grandview Site, Duluth, Minnesota

ALBERT, Amos, EAGLE-BLUESTONE, Jessica, and SAINI-EIDUKAT, Bernhardt

Department of Geosciences, North Dakota State University, Fargo, ND 58102 USA

The series of outcrops in the Grandview area of Duluth, Minnesota, is considered a classic geologic exposure (Mattis, 1972; Jirsa and Morey, 1987). Here, we examined the contact between the Middle Proterozoic Nopeming Sandstone and the lower magnetically reversed Ely's Peak Basalts of the North Shore Volcanic Group. We investigated whether prominent light/dark banding in the uppermost siltstone portion of the Nopeming formation resulted from sedimentary deposition or metamorphism, and whether any chemical and mineralogical differences exist.

The sample was taken from the metasilstone layer directly beneath the basalt (Fig. 1). After carrying out petrographic analysis, polished samples were examined by SEM-EDS (NDSU). In preparation for XRD (NDSU) and ICP analysis (Activation Laboratories), we crushed the sample and hand-sorted the light and dark grains.

Grain size varies from fine silt in the light bands to clay size in the dark colored bands. Although there are areas of disrupted banding where light and dark materials are intimately mixed, the bands counted (n= 30 total) have average widths of 2.8 mm and 2.25 mm respectively (Fig. 2). Light bands contain coarser grains compared to dark bands. Fining from light to dark bands represents a graded bedded sequence of sedimentation. A few thin bands, less than ~40 µm in width, of opaque grains with reaction rims surrounding each grain were also observed.

XRD and petrography show the light bands are richer in quartz and albite, plus some augite. Dark bands consist mainly of quartz, albite, hornblende, and actinolite. SEM-EDS indicates a reaction rim assemblage of ~ 25 µm grains consisting of ilmenite cores with titanite rims (Fig. 3), in a matrix of actinolite and albite. Zircon, diopside, potassium feldspar and quartz were also observed.

Whole rock chemistry shows both light and dark bands are silica rich, but the dark bands contain less silica (61.59 wt. %) than the light bands (69.22 wt.%) (Table 1). Higher amounts of Al₂O₃, Fe₂O₃, MnO, MgO, CaO, K₂O and TiO₂ were found in the dark bands. Dark bands also contain more total REE (147 ppm) vs. light (131 ppm), consistent with the concept of higher original clay content in the dark bands. Both light and dark bands show marked CN LREE enrichment with a small negative Eu anomaly and flat HREEs. The overall pattern is similar to average sedimentary and crustal REE patterns (McLennan, 1989) (Fig. 4). On a PAAS normalized diagram, both light and dark bands plot near unity, although the LREES have ratios slightly <1 while the HREE's are slightly >1 (Fig. 4). It is unclear why a disproportional amount of barium (1467 ppm) was found in the dark bands, vs. 273 ppm in the light ones.

Ilmenite-titanite reaction rims appear as sharp boundaries between the two minerals. Ilmenite has high FeTiO₃ content suggesting that it crystallized in conditions of higher T and/or lower fO₂. Titanite often occurs as product of late stage oxidation. Textural evidence suggests that titanite + ferroactinolite assemblage is due to a hydration reaction, following such as below from Harlov et al. (2006) (Fig. 5, Reaction 4).



We conclude the banding resulted from a process producing fining upward graded bedding, perhaps by small turbidities in a shallow aqueous environment. The presence of hornblende and actinolite indicates the emplacement of the Ely's Peak Basalt altered the original mineralogy to a

metamorphic grade between hornblende-hornfels and amphibolite facies. This event also produced the observed ilmenite-titanite assemblage.



Fig. 1. Metasiltstone in outcrop. UTM 15T 555,616E/5,174,699N



Fig. 2. Cut sample showing banding

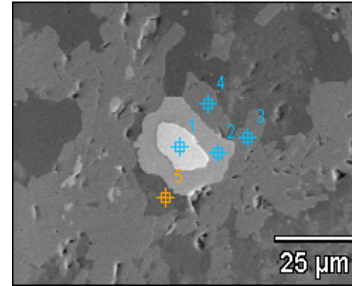


Fig. 3. SEM image of ilmenite w titanite rim. 1: Ilmenite; 2: Titanite; 3,4: Actinolite; 5: Albite

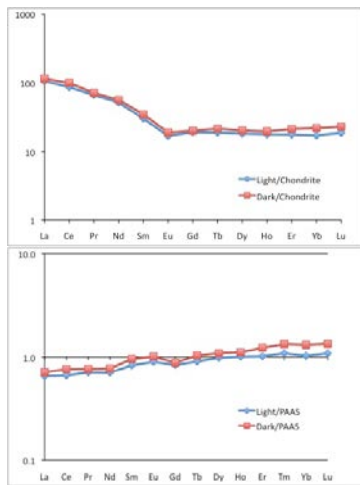


Fig. 4. Chondrite and PAAS normalized REE spiderplots for the light and dark bands.

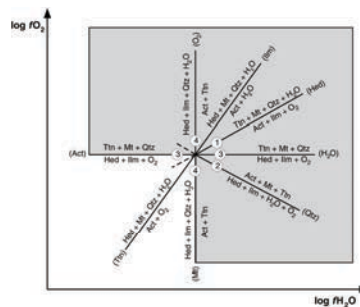


Fig. 5. Schematic phase relationships in the system CaO-Fe₂O₃-TiO₂-SiO₂-H₂O-O₂ involving titanite (Ttn), ilmenite (Ilm), magnetite (Mt), hedenbergite (Hed), Fe-actinolite (Act), and quartz (Qtz) as a function of log f_{O_2} and log f_{H_2O} at constant temperature and pressure (Harlov et al., 2006)

wt. %	Light	Dark
SiO ₂	69.22	61.59
Al ₂ O ₃	7.98	8.94
Fe ₂ O _{3t}	3.34	5.3
MnO	0.179	0.203
MgO	6.02	9.28
CaO	9.37	9.74
Na ₂ O	1.95	2.03
K ₂ O	0.98	1.3
TiO ₂	0.678	0.834
P ₂ O ₅	0.09	0.1
LOI	n.a.	0.89
Total	99.81	100.21

Table 1. Whole rock major element chemistry for the light and dark bands of the metasiltstone. n.a.: not analyzed

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**Seismic, gravimetric, and magnetic modeling over the Bayfield Peninsula, Wisconsin:
Testing hypotheses on the source of a gravity low**

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A prominent gravity low lies over the Bayfield Peninsula in northern Wisconsin (Figure 1). The mapped bedrock geology includes sedimentary rocks of the Oronto and Bayfield Groups that overlie Midcontinent rift-related volcanic and intrusive rocks. The nearly 100 mGal amplitude anomaly has been interpreted to reflect low density Archean granite that is surrounded by higher density basalt (White, 1966; Allen and others, 1997). Two-dimensional (2D) gravity and magnetic models, constrained by limited seismic reflection data, are being developed to test possible sources for the gravity anomaly.

Seismic reflection data acquired in 1984 were licensed from Seismic Exchange International for portions of several lines on the Bayfield Peninsula. Plots of two-way travel times across the western gradient of the gravity low (Figure 1) show relatively flat and continuous reflections within the Bayfield and Oronto Group rocks. Calculated depths from two-way travel times for the base of the sedimentary rocks vary slightly from 2.7 km in the west to 3.6 km in the east, indicating that the rocks have an apparent dip to the east. On the western side of the seismic profile are reflections that dip moderately to the west which can be observed to estimated depths of 7.6 km. These westerly dipping reflections pinch-out at around 3.5 km depth near the east-central part of the profile. The contrasting dip direction indicates that the source rocks are in unconformable contact with the overlying, gently dipping reflections attributed to the sedimentary rocks. This angular unconformity has been interpreted to represent the contact between the Oronto Group and the Midcontinent rift-related volcanic rocks (Allen and others, 1997). Seismic reflections are not apparent beneath the volcanic rocks where the geology is inferred to be Archean granite.

Publically available gravity and magnetic data map contrasting physical properties that are related to changes in subsurface geology. The gravity data with stations spaced approximately 2 km on-shore and 5 km off-shore indicate that low-density crustal material underlies the Bayfield Peninsula. Magnetic anomaly data show that a moderate amplitude, long wavelength anomaly high occurs over much of the gravity low which likely reflects a relatively deep magnetic source. Forward models of gravity and magnetic data along a 160 km east-west profile that spans the Bouguer gravity low (Figure 1; line A-A') were constructed using reported physical property values (Chandler and Lively, 2011). The results confirm that the gravity anomaly can be explained by a ridge of low density material, possibly Archean granite, flanked by west-dipping high density rocks, both of which are overlain by low density sedimentary rocks. Magnetic depth estimates and model sensitivity to changes in source magnetization at depths ranging 3 to 12 km suggest that the west-dipping rocks, constrained by the seismic data, are magnetic. However, reported basalt magnetizations did not produce acceptable model response, indicating that true magnetizations are much lower and possibly indistinguishable from the adjacent Archean rocks. These results suggest basalt is present, but may have reversed-polarity or reduced magnetization compared to elsewhere.

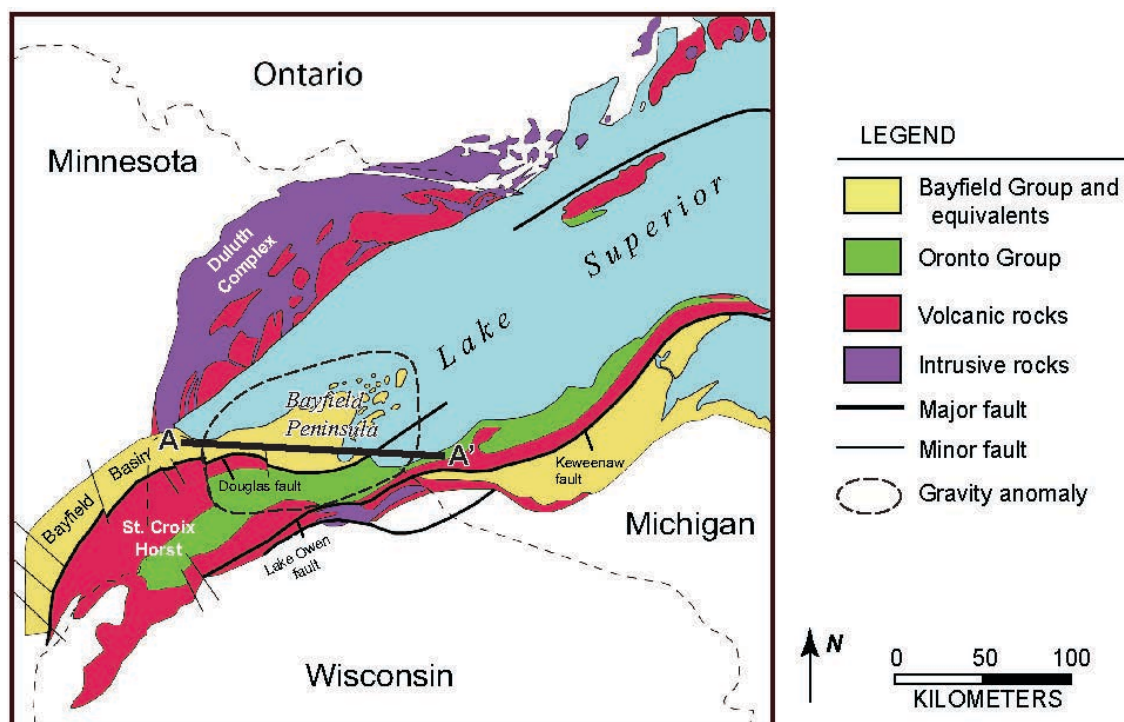


Figure 1: Generalized geology map of western Lake Superior showing location of prominent gravity low over the Bayfield Peninsula. Seismic lines provide detailed subsurface imaging that helps constrain 2D gravity and magnetic models to test possible sources for the gravity low. Forward models of gravity and magnetic data were constructed along line A-A'.

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Geophysical imaging of the bedrock geology of the Pembine-Wausau terrane, Wisconsin: Constraints on the setting of volcanogenic massive sulfide deposits

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The Pembine-Wausau terrane in Wisconsin (Figure 1) represents a major Paleoproterozoic belt of metavolcanic rocks that have formed in an island-arc setting at the southern limit of the Superior Craton (Schulz and Cannon, 2007). The terrane is known to host a number of significant volcanogenic massive sulfide deposits, including the world-class Crandon deposit which comprises a total resource of 65.8 million metric tons of massive sulfides. Despite its potential future economic significance, little is known about the bedrock geology of this terrane. A thick cover of glacial deposits makes field observations difficult. Existing geologic reconnaissance map compilations indicate that many of the known VMS prospects occur within a succession dominated by bimodal metavolcanic rocks (Nicholson and others, 2004). Existing regional-scale potential field data provide a continuous set of observations across the entire terrane. This study reinterprets these data and applies filters to highlight changes in rock properties that may in part reflect magmatic controls on the location of the VMS deposits. The interpretations are being integrated with on-going geochemical and geochronological studies to better understand the observed geophysical anomalies over an accreted island-arc setting.

The gravity compilation contains stations spaced approximately 1.6 km where access was not limited (Snyder and others, 2004). The data were gridded to a 400 m cell size from which filtered data sets were generated. The complete Bouguer anomaly map highlights dense mafic volcano-plutonic rocks that were intruded by less dense, syn- and post-tectonic granite-tonalite rocks. Large northeast-southwest and east-west trending gradients coincide with mapped and inferred buried faults that indicate offset crustal blocks of varying densities within, or beneath, the bimodal metavolcanic rocks. Such structures may reflect bounding faults enclosing grabens within which the VMS deposits may have formed.

Aeromagnetic data were collected along north-south flight lines spaced 800 m at a nominal height of 150 m (Karl, 1986). These data were contoured using a cell size of 250 m from which filtered data sets were generated. The reduced-to-pole (RTP) transformation shows that the mafic volcano-plutonic rocks produce strong magnetic anomaly highs. Moderate amplitude RTP anomaly highs are observed over the younger granite-tonalite plutons. Bimodal volcanic rocks produce magnetic lows; however, within these lows are circular and linear magnetic highs that trend northeast-southwest and east-west, some of which are associated with gabbro rocks. The analytic signal (AS) transformation shows high gradients over the mafic volcano-plutonic rocks. The AS highlights isolated magnetic anomalies within the bimodal volcanic rocks, some of which may be imaging synvolcanic plutons that may have acted as heat sources for VMS hydrothermal systems. Several circular and linear AS anomalies occur along the gravity gradients and mapped faults. The tilt derivative (TDR) transform highlights a northeast-trending magnetic fabric within both the mafic volcano-plutonic rocks and the bimodal volcanic rocks. TDR lineaments occur in higher concentrations proximal to mapped faults. These lineaments are parallel to bedding orientations and major structures and, are therefore, interpreted to reflect the strike of mafic flows within the volcanic rock package.

Together, the gravity and magnetic data are able to identify the structural framework and the buried extents of the bimodal metavolcanic rocks that are the targets for VMS exploration. In addition, these data help map the location of plutons that are critical to understanding the thermal evolution of the region.

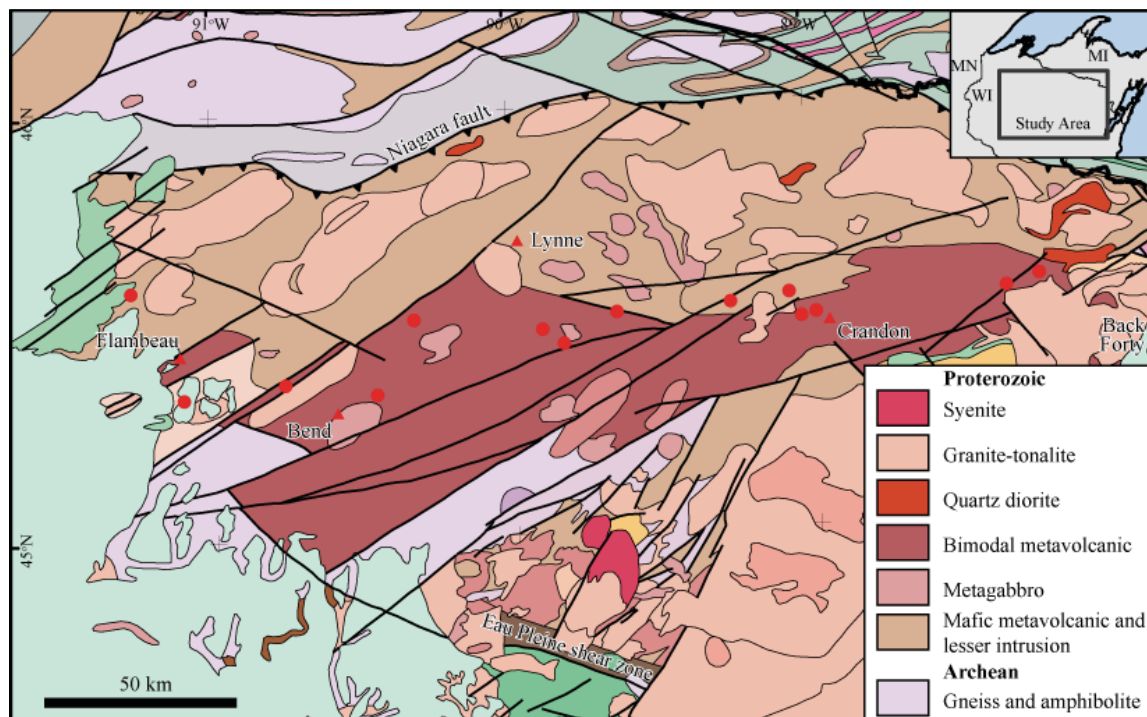


Figure 1: Generalized geology map showing major rock types within the Pembine-Wausau terrane between the Niagara fault and Eau Pleine shear zone (Nicholson and others, 2004). Red triangles and circles depict VMS deposits and prospects, respectively.

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Iron-rich siliceous stromatolites from the upper algal unit of the Gunflint and Biwabik iron formations

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The Gunflint and Biwabik formations comprise the middle units of the Proterozoic Animikie Group that crop out along the north shore of Lake Superior. Two stromatolitic units are present within these formations; a basal unit that the stromatolites grow directly on the peneplained Archean basement or on the conglomerate which forms the base of the Animikie, and a second upper unit roughly 45 meters above the base. The Animikie stromatolites are unique in that they are mainly composed of finely laminated, fine grained, bands of iron-rich silica. This is unusual as most stromatolites, modern and ancient are composed primarily of carbonate. Since their initial discovery, speculation as to their original mineralogy have been raised (Barghoorn & Tyler, 1965; Cloud 1965; Lougheed 1983; Sommers et al, 2000).

This study was conducted on the two stromatolitic horizons to determine whether these iron-silica-rich stromatolites represent a primary mineralogy or if there is evidence for silicification of an earlier carbonate phase. The utilization of high resolution, field emission scanning electron microscopy (SEM), x-ray diffraction (XRD), whole rock geochemistry, and transmitted light microscopy revealed several pieces of compelling evidence within the upper algal unit.

Hand samples cut horizontally, (Fig. 1A) show the fine grained, hematite-rich laminae located within the columns (white arrows). In thin section, erosive scouring of the siliceous stromatolite column tops is common, with new siliceous bacterial mat truncating the old (Fig. 1B). The sharp contact between the scour-truncation suggest lithification prior to the development of the younger laminae. The microquartz which the stromatolitic laminae are composed of, is in sharp contrast to the mega quartz cement found within the interspace between the columns (Fig. 1C). Note the thin ($\leq 10\mu\text{m}$) microquartz wisps overlaying the coated grains bridging the columns, suggesting a fossilized bacterial mat (white arrow). Intraformational clasts containing pieces of lithified stromatolite are common, especially as nucleation sites of ooids (Fig. 1D, 1E). Finally, energy dispersive x-ray (EDX) mapping show distinct alternation of silica-iron-manganese in ooid coatings and stromatolite laminae (Figs. 1F-1I).

The above strongly indicates the Gunflint and Biwabik stromatolites were originally siliceous and formed by a different precipitation mechanism than Proterozoic carbonate stromatolites or modern agglutinated forms did.

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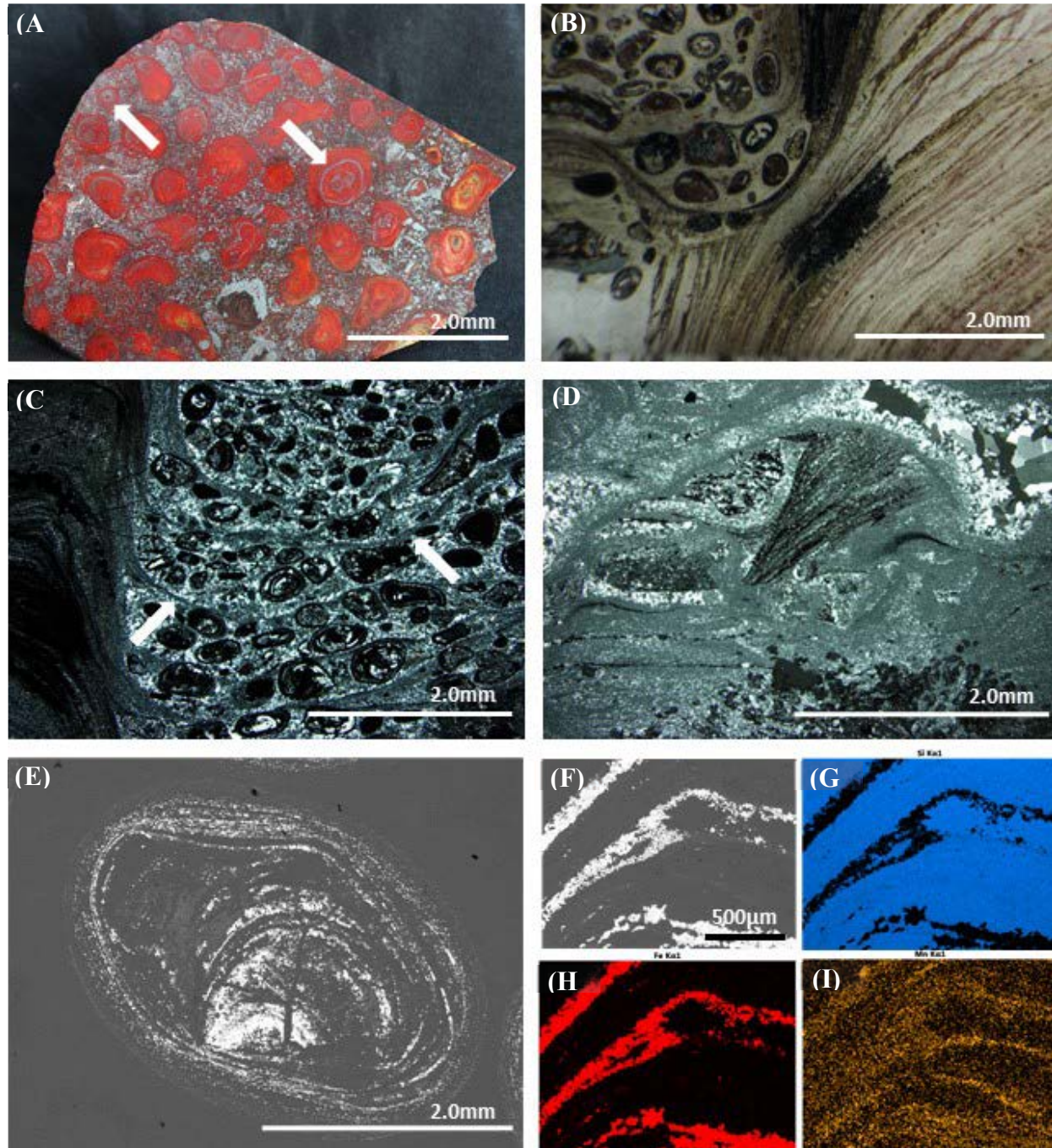


Figure. 1. Features of the silica-iron-rich stromatolites within the Gunflint and Biwabik Formations. (A) Horizontal section through stromatolite columns showing fine grained hematite laminae within the column (white arrows). (B) Photomicrograph illustrating the truncation and subsequent overgrowth of stromatolite columns by fine grained, thin laminae composed of iron-rich jasper (red/brown) and quartz (clear). (C) XPL photomicrograph highlighting difference between microquartz stromatolitic laminae, and blocky quartz cement in interspace. The bridging by a thin siliceous algal mat between two columns (white arrow), suggests a rapid growth of mat over the grainstone. (D) Clast containing coated grains and piece of stromatolite column. (E) SEM-BSE image of an ooid containing a broken piece of stromatolite as its nucleation point. This suggests the stromatolite was lithified prior to the development of the ooid lamination. (F-I) EDX false colour images of alternating silica (G), iron (H), manganese (I) stromatolitic laminae.

Evidence of high-temperature Ni isotopic fractionation during the formation of Cu-Ni-PGE sulfide deposits in the Duluth Complex

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The Duluth Complex in northeastern Minnesota is an extensive, largely gabbroic body that formed during the 1.1 Ga Midcontinent Rift event. The basal zones of the complex, the South Kawishiwi (SKI) and Partridge River intrusions (PRI), host extensive Cu-Ni-PGE mineralization in a number of recognized deposits that are actively being explored. Previous research, using sulfur isotopes, indicates the underlying Virginia formation as a source of sulfur during the formation of these deposits [1]. Recent studies have shown significant Ni isotopic variations of up to 1.1‰ in high-temperature magmatic rocks associated with magmatic sulfide mineralization [2-4]. The heterogeneous mineralogy and mafic lithologies in the basal Duluth Complex indicate a range of different processes active during crystallization.

The primary goal of this study is to examine mineralized and unmineralized Duluth Complex material to assess the potential of Ni isotopic fractionation between early cumulates, subsequent Cu-Ni-PGE mineralization, and weathering products. Of particular interest is the exploration potential of Ni isotopes for magmatic sulfides recorded in weathered products at the surface. Sample material collected includes till, outcrop material, and in-situ mineralization as well as control samples unconnected to the SKI or PRI. Massive sulfides, disseminated sulfides, and non-mineralized gabbro were selected to obtain Ni isotopic signatures from both a sulfide and silicate source. Till and surface samples were collected in the vicinity of known Cu-Ni-PGE deposits, including Spruce Road, Maturi, Mesaba, Serpentine, and NorthMet. In-situ mineralized material from drill core was provided by local mining companies (Duluth Metals/Twin Metals, PolyMet, Teck, Encampment Minerals) that hold mineral rights to individual deposits. Material from other deposits, including Birch Lake, Wetlegs, and Wyman Creek was sampled from drill core available from the Minnesota DNR.

Samples were processed to produce thin sections and polished thick to observe representative textures and mineral compositions for the Cu-Ni-PGE mineralization and host rock gabbro. Material from each deposit was analyzed using XRD, whole rock, and trace element geochemistry. Electric pulse disaggregation (EPD) was used to separate 1 cm³ samples into individual mineral grains and olivine was separated for isotopic analysis. EPD olivine crystals, along with till, massive sulfide material, and weathered surface samples were ground to < 70 µm using a shatterbox and sent for nickel isotope analysis to the University of Indiana using the double-spiking method outlined in [2]. Ni isotope ratios are reported relative to the NIST SRM 968 standard with conventional delta notation and a general 2σ error of 0.06‰.

Isotopic results show a spread of δ^{60/58}Ni values from -0.97‰ to +0.21‰, within the range of Ni isotopic values reported previously [2,3]. The least fractionated values come from unmineralized mafic intrusives (-0.07‰), while Ni isotopic ratios become progressively lighter with increasing sulfide content, ranging from -0.16 ‰ to -0.97‰ (Fig. 1). Till samples record intermediate values (-0.02 ‰ to -0.77‰) and weathered surface samples can span the entire range.

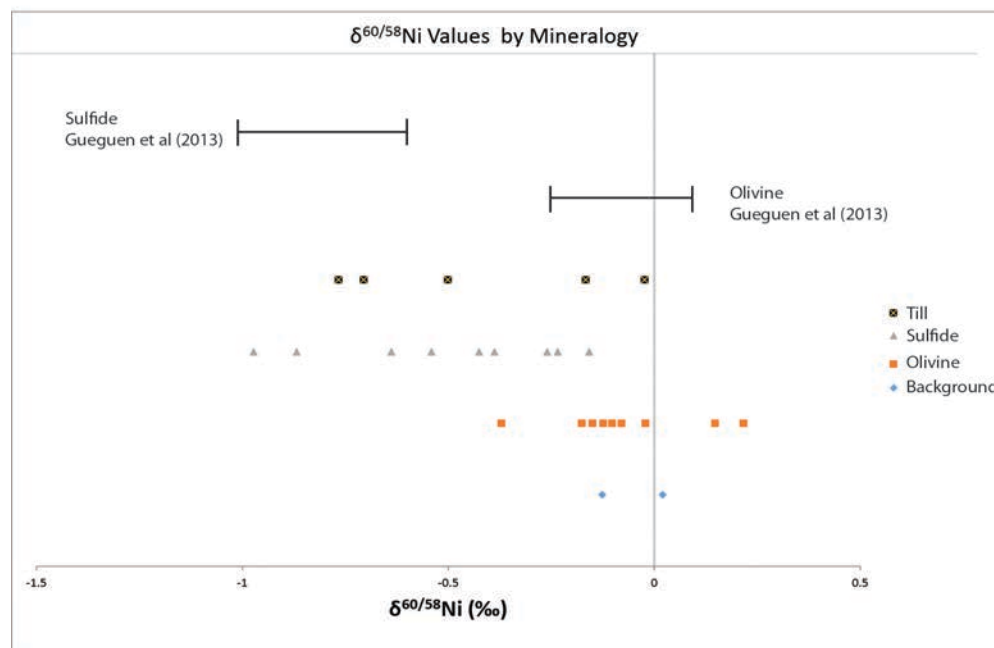


Figure 1: $\delta^{60/58}\text{Ni}$ values for sulfide, olivine, and till compared to background values and data from previous studies.

The isotopic data indicate an isotopic fractionation trend in the Duluth Complex from unfractionated values around zero, assumed to be bulk silicate earth, for early crystallizing phases to notably fractionated sulfide mineralization, accumulated at some later stage. This fractionation of up to 0.81‰ suggests that Ni was fractionated during the Ni sulfide formation by incorporating preferentially lighter Ni into the accumulating sulfide melt and resulting Ni sulfides.

Ni isotopic values for till and mineralized surface samples, and their correlation with known deposits, may be useful in distinguishing regions overlying Cu-Ni-PGE mineralization from barren areas. Data may also help to identify the entry point of the mineralizing magma based on the location and isotopic signature of individual sulfide deposits. This will require a more detailed sampling of selected locations and materials.

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Fold analyses in the Gunflint Formation: working towards a characterization of regional deformation in the Animikie Group near Thunder Bay, Ontario

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Deformation in the Animikie Group near Thunder Bay is characterized by intense, localized fold-and-thrust belt deformation within units that are otherwise relatively undeformed and flat-lying. This deformation is interpreted to be the result regional stress during Proterozoic tectonism. Stereographic analyses of structural measurements and outcrop observations are used to determine beta-axes (mean fold axes) for fold populations observed, as well as to determine structural relationships within the region. Two main fold populations are observable in the data. The primary population exhibits a north-south trending beta-axis, indicating east-west compressive stress. The secondary population exhibits an east-west trending beta-axis, indicating either north-south compressive stress or the presence of lateral ramps. Slickenlines are also observed to trend north-south and east-west, depending on outcrop location. East-west trending slickenlines tend to be in areas of more intense folding, indicating that they may be older than the north-south trending slickenlines. Older slickenlines may have been destroyed when fault surfaces were reactivated in areas of less intense folding, replaced by the slickenlines associated with the most recent deformation. Additional observations include the presence of fold-hinge breccia associated with non-cylindrical folding, which may indicate lateral ramp formation, as well as the presence of a possible cleavage duplex structure, which may indicate repetitive east-verging thrusting.

A specific tectonic history for the Animikie Group has been suggested based on these observations. It has been proposed here that primary east-verging thrusting was associated with the Trans-Hudson orogeny in the Paleoproterozoic. Following this, there may or may not have been a secondary compressional phase due to the Yavapai-Mazatzal orogenies during the early to middle Proterozoic; the effects of these orogenies remain unclear. Deformation likely culminated in the late Proterozoic with north-south extension related to the Midcontinent Rift.

Interpretation of the St. Amour Deep Stratigraphic Test Well, Alger County, Michigan
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The Amoco Production St. Amour (1-29R) was a petroleum deep test well, drilled in 1988 to a depth of 7238 feet below ground surface (bgs). Surface elevation of the well was approximately 910 feet above mean sea level. The GPS coordinates for the well are 46.354591° - 86.584370°.

The well passed through 110 feet of glacial material at the surface. Below the glacial material is 411 feet of Paleozoic sediments. Under the Paleozoic is 2132 feet of the Precambrian Jacobsville Formation (this differs from Ojakangas' 2002 interpretation). The Jacobsville can be subdivided into three distinct units that are very similar to the formations of the Bayfield Group in Wisconsin. Chequamegon type lithology is encountered at 521-1470 feet bgs, Devils Island type lithology is encountered at 1470-1939 feet bgs, and Orienta type lithology is encountered at 1939-2653 feet bgs. Beneath the Jacobsville lies 3197 feet of the Freda Formation, which can also be divided into three units. There is an upper red to gray and light brown, fine to medium grained arkose (2653-2830 feet bgs). The middle unit is composed of mostly red, silty, very fine to medium grained arkose, with beds of red siltstone and shale (2830-3260 feet below the surface). The basal Freda is a fining upwards sequence of red to gray mottled pale brown (occasionally green), fine to coarse grained arkose with beds of deep red shale, and pebbles are common. Below the Freda is a unit not seen elsewhere in the Oronto Group. There is 675 feet of a red, hematitic quartz arenite with thick beds of quartz conglomerate (unit Y(x), Figure 1). This unit is very mature for its stratigraphic position and appears unique from above and below units.

From a depth of 625-6933 was described as a "heterogeneous unit" (Ojakangas 2002). It consists of 203 feet of faulted basalt interbedded with sandstone, siltstone, and conglomerate (unit Y(xx), Figure 1). This unit appears to be unconformable at its base, although this is difficult to determine for sure in the core. Below this unit (6728-6783 feet bgs) is what has been interpreted as 145 feet of the Nonesuch Formation. We agree with this interpretation since the stratigraphy matches up well with the lower three units in the Big Iron River at Bonanza Falls (Susek 1997). Below the Nonesuch lies 50 feet of a basalt flow (unit B₁, Figure 1) over a gabbro diabase (unit B₂, Figure 1). The gabbro diabase appears to be a later intrusion into units Y(bb) and Y(xxx) and may have been emplaced during the Grenville Orogeny. Under the gabbro is 10 feet of red and gray siltstone and shale underlain by conglomerate, unit Y(xxx). The deepest unit penetrated is 350 feet of rhyolite and ignimbrite, which has been dated at 1.083 ± 0.003 Gya old. The only known igneous rocks younger than this within the Mid-continental Rift belong to the Bear Lake Rhyolite Stock in the Freda Formation (1.054 ± 0.034 Gya).

There are two faults present within the St. Amour core. There is a 32 foot long stretch highly sheered red and green sandstone from 6573-6605 feet bgs. A smaller second fault, which contains 12 feet of gray and red sandstone and shale is present at 6691-6703 feet bgs. Figure 1 shows the interpretive relationship between the geologic units from 6400-7000 feet bgs. In our interpretation both faults are high angle reverse faults that dip about 73° from the horizontal (the strike of the core is not known so the dip direction could not be obtained). The smaller of the two faults has been modeled parallel to the larger fault. However, in reality, it likely branches off from it and represents a faulted shatter zone. Total fault displacement is about 121 feet. There are two basalt units above the Nonesuch within the core. The upper one is 48 feet thick and lies

above the faults. The second is about 43 feet thick and lies between the two faults. Both basalts have mostly sandstone and siltstone with some conglomerate below them. Due to their similar thickness and lithology, we interpret them to be the same unit offset by the faults (units Y(ba), Figure 1). The basalt has not been dated but since it overlies the rhyolite, it has to be younger. If it were to be dated we could be able to bracket the time of deposition for the Nonesuch Formation.

Based on our analysis of the core we partially agree with Ojakangas and Dickas' 2002 interpretation that late Mid-continent Rift volcanism occurred later than in other areas because of the core's proximity to the mantle plume. We also postulate that the area around the core may represent a buried stratovolcano similar to the one at Porcupine Mountains (located about 150 miles west-northwest of the St. Amour core location). We propose that a high altitude composite volcano existed in the area until about 1.080 Gya, until the complete deposition of the Nonesuch Formation. At that time main volcanism ceased and the area began to rapidly subside allowing for the deposition of thick quartz sandstone (unit Y(x), Figure 1) over the youngest basalt (unit Y(ba), Figure 1), thus burying the volcano. The main fault in the core may have originated as a normal growth fault that was later reactivated as a reverse fault during the Grenville Orogeny, creating smaller offshoot faults. Until more deep cores are obtained from the area of the St. Amour test well, the presence of a subsurface volcano cannot be verified.

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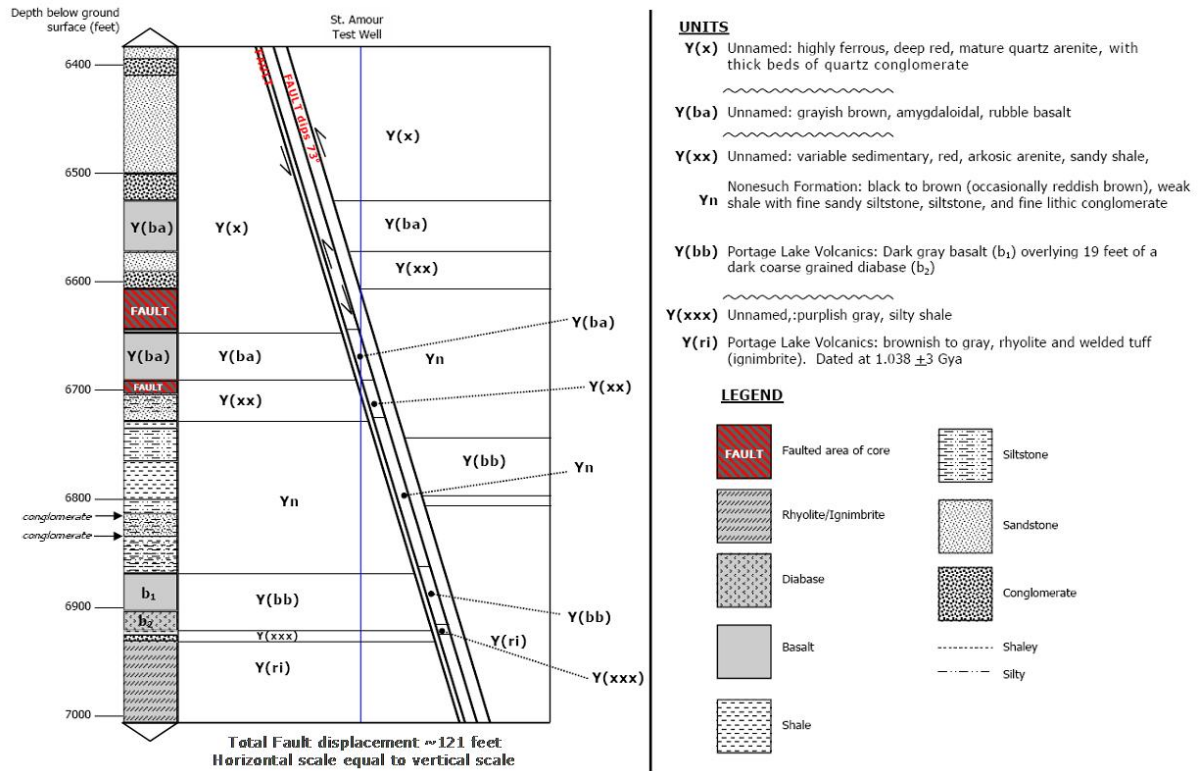


Figure 1: Structural Interpretation of the St. Amour Core from 6400-7000 feet Below the Surface

Linking the Ordovician L-Chondrite Event to the Terrestrial Cratering Record: a North-American Perspective

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Based on abundant evidence of shock metamorphism and partially or wholly reset Ar ages of a class of meteorites (low metal or “L-chondrites”), meteorite researchers have hypothesized that a catastrophic impact and breakup event took place in the asteroid belt about 500 million years ago (Keil et al., 1994), spawning a large population of meteoritic fragments some of which were perturbed into Earth crossing orbits.

This hypothesis received a major boost with the discovery of numerous L-chondrite meteorite fragments in limestone quarries in southern Sweden (Thorslund et al., 1984; Nyström et al., 1988; Schmitz et al., 1996), preserved *in-situ* across a section of Middle Ordovician stratigraphy (ca. 470 Ma). The L-chondrite-bearing, condensed, shallow marine limestones are also characterized by a sharply increased heavy mineral count of extraterrestrial Ni spinels, also of L-chondrite affinity (Schmitz et al., 2003). This Ni spinel “rain out” has now been documented not only in Sweden but also in China (Heck, et al., 2010), and by all expectations should constitute a global signal. Since then, more detailed Ar-Ar dating of the partially degassed meteorites has refined the likely age of the breakup event to 470±6 Ma (Korochantseva et al., 2007). A number of small meteorite impact craters in Scandinavia has been linked to this event, e.g. the 458 Ma Lockne crater in central Sweden (Grahn et al., 1996; Alwmark and Schmitz, 2007).

With Earth moving through a dynamically evolving swarm of asteroid debris (e.g., Nesvorný et al., 2009), the effects of this event should have been global. Numerous, possibly large, impact craters should be linked to this event, particularly in North America with its large cratonic target area and a robust population of ~60 confirmed impact structures.

We have previously linked the well-known Brent impact crater to this event (Bleeker, 2011), with a stratigraphically constrained age of ca. 460-450 Ma (Lozej and Beales, 1975) and with a melt/breccia sheet that is known to contain geochemical traces of an L-chondrite bolide (Palme et al., 1981). Among the ~32 confirmed and possible impact craters in Canada alone (e.g., see Grieve, 2006), there could be as many as 5-10 structures that are linked to the same broad event: Brent, Holleford, Skeleton Lake, Nicholson, Pilot Lake, Presqu’île, Couture, La Moinerie, and the large Slate Island structure in Lake Superior. Scattered and non-definitive K-Ar and Ar-Ar ages could extend this list to the large (~50-55 km-diameter) Carswell structure, and perhaps the buried but unconfirmed Can-Am crater. We have recently redated this structure, using Ar-Ar stepwise heating on pristine adularia crystals, to 481±1 Ma (Bleeker et al., 2015), confirming it as part of the Ordovician impact spike.

Even if only the most likely subgroup of this list is indeed related to a ca. 470-440 Ma impact spike of L-chondrites, the proportion of impact craters linked to this event is very large (1 in 5?), as similarly suggested by the more limited sample of just the Swedish crater record alone.

The same conclusion is also reached for craters in the remainder of North America (mainly the USA), where among ~30 confirmed craters the following could be linked to the same event: Ames, Calvin, Glasford, Glover Bluff, Newporte, Rock Elm and Versailles (again, a proportionally similar and very large subpopulation, as in Canada). Several of these structures have stratigraphically constrained ages in the 470-440 Ma interval (e.g., see Koeberl et al., 2001, for Ames; Millstein, 1994, for Calvin; McHone et al., 1986 for Glasford).

It is concluded that the Ordovician L-chondrite event left a major imprint in the North American and by inference global cratering record and, as recognized by Birger Schmitz and coworkers (Schmitz et al., 2008), must have jarred the Earth system throughout much of the Middle and Late Ordovician. During the 470-440 Ma interval, the flux of large impactors appears to have been an order of magnitude higher than during the remainder of the Phanerozoic. To gauge the full scope of this event, an integrated effort to produce better and more precise ages for all major impact structures is needed, with equal emphasis on stratigraphic and isotopic constraints. Important rewards could be an improved understanding of the

dynamical evolution of an asteroidal breakup swarm, a quantification of the overall impact flux during this interval, and a better appreciation of how the Earth system and biota responded to this major event.

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Large hypervelocity impacts on Earth: Empirical observations and validation of computational model predictions for Sudbury and Chicxulub

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Johnson and Melosh (2014) reported on a high-resolution, two-dimensional computational model of effects during a hypervelocity 10km impactor collision with Earth at 20km/s. This early version of the model focused on three impact products, melt droplets, melt fragments and accretionary impact lapilli. They estimated the size of the ejecta products using simple analytical expressions and information determined from their hydrocode models.

Prediction of the size of the ejecta products depends on the impactor size, impact velocity and ejection velocity from the forming crater. Johnson and Melosh sought to find a consensus between model predictions describing the formation of the ejecta products and actual geological observations. Modeled estimates of the sizes of melt droplets and accretionary impact lapilli are generally within one order of magnitude of limited empirical measurements at Chicxulub and Sudbury. This agreement acts as a validation of their model and illustrates a process whereby geologic observations can be applied so as to improve the model.

Our studies on Sudbury ejecta from the Thunder Bay area (Addison et al. 2005; 2010) have considered the predictions of the Johnson and Melosh model with the results indicated below:

Prediction: The model predicts order of magnitude estimates of the size [mm-scale] of melt droplets and melt fragments.

- Our studies of Sudbury ejecta and comparison with literature information on Chicxulub (Yancey and Guillemette 2008; Yancey and Liu 2013) verify the predictions of the model.

Prediction: Millimeter-sized melt droplets should be found together with accretionary impact lapilli and rarer melt fragments (tektites).

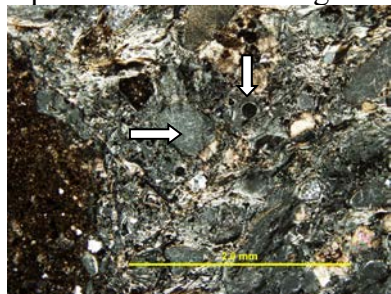


Figure 1. Accretionary lapillus (left), tektite (horizontal arrow) and melt droplet (vertical arrow). MC18A SEM, XPL.

Prediction: A wide range of sizes of melt droplets should be found at any given site.

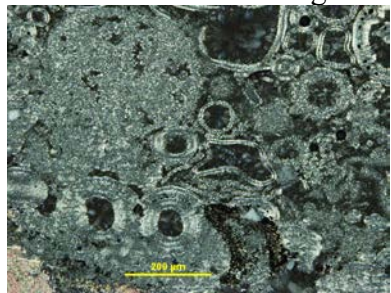


Figure 2. Melt droplets illustrating a range of sizes. JN23, XPL.

Prediction Accretionary impact lapilli form during the ejection process in the turbulent ejecta curtain from fine-grained, solid fragments and molten silicate acts as a binding agent. Lapilli range from larger than 1cm to less than 1mm diameter.

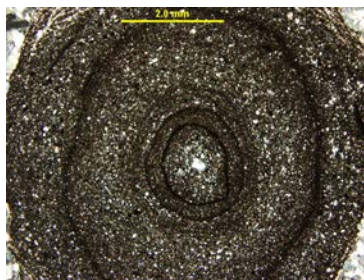


Figure 3. Accretionary lapillus with multiple rings of opaque silicate, cored with crystal fragment. JN29A-2 SEM, XPL

Prediction: There is a tendency for the small solid fragments to follow vapor streamlines so that the small fragments may be swept around the growing lapilli and as a result accrete in rows.



Figure 4. Detail of an accretionary lapillus showing streamlined, rows of fragments apparently deposited by turbulent vapors during growth of the lapillus. JN29A-2 SEM, XPL.

Prediction: The largest melt fragments (tektites) will come from more lightly shocked, near surface, target material. The composition of melt fragments in Sudbury ejecta is consistent with that of surficial sedimentary rocks and granitic gneiss of the target area. They show little if any isotropic silicate melt on the exterior.

Prediction: "A more detailed comparison of our models to known ejecta layers will allow us to test the predicted dependence of ejecta product size on impactor size and may even allow us to empirically constrain some additional products ..." (Johnson and Melosh 2014).

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**Tainiolite from the Stettin intrusion, Wausau Complex, Marathon County, WI.
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The Wausau Syenite Complex (WSC) is composed of four plutons, of which the Stettin Pluton (1565 Ma +3-5) (Van Wyck, 1994) is the oldest and most alkalic.

Tainiolite is a relatively uncommon Li-Mg mica; $\text{KLiMg}_2(\text{Si}_4\text{O}_{10})\text{F}_2$ and occurs in alkalic igneous rocks such as syenites and associated pegmatites. Recently tainiolite has been identified from two sites located in the Stettin Pluton, and probable tainiolite has been found at one other site within the pluton.

The first occurrence is in the Ravine Pegmatite, a small irregular evolved pegmatite located on the west side of the long-dormant Dehnel quarry, near the western edge of the Stettin Pluton. Here, tainiolite occurs as colorless crystals of composition

$(\text{K}_{0.921}\text{Na}_{0.080})\Sigma_{1.001}\text{Li}_{1.000}(\text{Mg}_{1.201}\text{Fe}_{0.705}\text{Mn}_{0.049}\text{Al}_{0.033}\text{Ti}_{0.012}\text{Ca}_{0.009})\Sigma_{2.009}(\text{Si}_{3.910}\text{Al}_{0.090})\Sigma_{4.000}\text{O}_{22}[(\text{F}_{1.811}\text{OH}_{0.189})]\Sigma_{2.000}$ in the miarolitic core zone of the pegmatite and in adjacent intermediate zones, associated with abundant zircon, pyrochlore, bastnaesite-(Ce), bastnaesite-(La), bastnaesite-(Nd), columbite-(Fe), fersmite, aegerine, riebeckite, microcline, albite, and rare baddeleyite. The given analytical results, determined using EMP, XRD and DCPS, are in good agreement with recent published data for tainiolite (e.g. Armbruster et al, 2007).

An additional occurrence was noted in summer 2014 in a cobble of syenite pegmatite recovered from a rock pile located in the western portion of the Stettin intrusion on the north side of Evergreen Drive (southern portion of S. 10, T 29N, R 6 E), near the contact between amphibole syenite and the discontinuous nepheline syenite outer rim of the pluton. Here the tainiolite, of composition $(\text{K}_{0.969}\text{Na}_{0.032})\Sigma_{1.001}\text{Li}_{1.000}(\text{Mg}_{1.109}\text{Fe}_{0.762}\text{Al}_{0.041}\text{Mn}_{0.030}\text{Ti}_{0.010}\text{Ca}_{0.011})\Sigma_{1.936}(\text{Si}_{3.910}\text{Al}_{0.090})\Sigma_{4.000}\text{O}_{22}[(\text{F}_{1.851}\text{OH}_{0.149})]\Sigma_{2.000}$, determined using EMP and DCPS, is found as colorless crystals associated with riebeckite, aegerine and K-spar. Interestingly, despite the likely simultaneous crystallization of riebeckite and probable tainiolite, the riebeckite is virtually Mg-free, suggesting that, given a limited supply of Mg vs Na, Mg may be preferentially taken up by tainiolite as opposed to riebeckite.

The final (probable) occurrence was identified in material from the old Summit prospect (a failed attempt to mine U from a Th-rich pegmatite) obtained from a mineral collection assembled in the early 1960's. The prospect worked a pegmatite located in the south-central portion of the Stettin Intrusion. Here the probable tainiolite occurs as sparse light yellow-brown to colorless flakes in intergrown aegerine, fluorite, zircon, bastnaesite-(Ce) and minor quartz.

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The Sudbury impact event in the Lake Superior region: Ten years of research on ten minutes of geologic time

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The ancient meteor impact near Sudbury, Ontario is the second largest impact event preserved in the geologic record. The impactor was most likely an ordinary or enstatite chondrite based on siderophile element concentrations in melt rocks (Huber et al., 2014; Petrus et al., 2015). It struck Earth at 1850 Ma, the age of the Sudbury Igneous Complex (SIC) (Davis, 2008), a remnant of the melt sheet generated by the impact. The impact formed a crater, now deeply eroded, with a diameter variously estimated from 130 to 250 km. The impactor, if chondritic, must have been 10 to 15 km in diameter to provide adequate energy to account for the crater size and melt volume. An impact of that magnitude undoubtedly spread a layer of debris hundreds of kilometers beyond the crater. Sudbury impact debris (ejecta) was first reported in the Lake Superior region in 2005 (Addison et al., 2005). Many other sites have been identified since in the western Lake Superior region (Pufahl et al., 2007; Cannon et al., 2010; Jirsa et al., 2011). The impact produced a variety of sedimentary and seismic features; the rocks in which these have been found are known collectively as the Sudbury Impact Layer (SIL). Compelling evidence of meteor impact is relict planar deformation features in quartz grains (Fig. 1A), because they are uniquely produced by impact-generated shock. Other common features are millimeter-scale spherules of devitrified impact glass (Fig. 1B), angular glass particles (Fig. 1C), and accretionary lapilli (Fig. 1D). During deposition and reworking, ejecta became mixed with local material to form a hybrid rock. Seismic effects include fracturing and dislocation of pre-impact rocks and seismically triggered submarine debris flows.

The effects of the impact across the Lake Superior region can be simulated using a computational model (Collins et al., 2005). Although there is no unique solution, input parameters of: 1) a chondritic impactor with a density of 3.4 g/cm³, 2) an impact velocity of 25 km/sec, 3) an impactor diameter of 15 km, 4) an impact angle of 45°, and 5) crystalline target rocks, predict: 1) a crater diameter of 193 km, well within the range of estimates, 2) a melt volume of about 12,000 km³, similar to previous estimates (Deutsch et al., 1995), and 3) a melt sheet thickness of about 1.2 km, less than the observed thickness of the preserved SIC. Using those same parameters, the model predicts effects of the impact at various distances from Sudbury, which provides a framework in which to judge observed features (Figure 2).

The currently known extent of the SIL stretches from the Dead River Basin in Michigan, 500 km west of the impact site, to Coleraine in the western Mesabi Iron Range in Minnesota, about 1000 km west of the impact site. It spans the transition from proximal to distal deposits and its character changes markedly over that distance. The SIL also spans a north-south distance of about 150 kilometers, across which it was deposited in conditions ranging from dry land in the Thunder Bay area, across a continental shelf to the south, to deep water in the Iron River and Crystal Falls area. This combination of factors makes the Lake Superior region a unique natural laboratory in which to study the range of effects of the Sudbury impact beyond the crater margin.

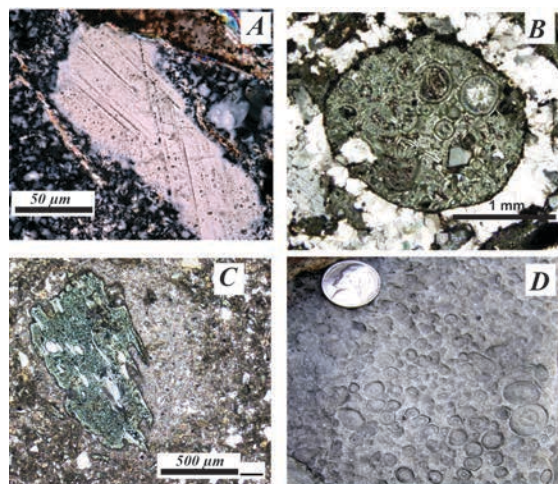


Figure 1. A-quartz grain with relict planar deformation features, Baraga Basin, B- spherule of devitrified vesicular(?) glass, Thunder Bay, C- fragment of glass, Gogebic Range, D- accretionary lapilli, Gunflint Lake.

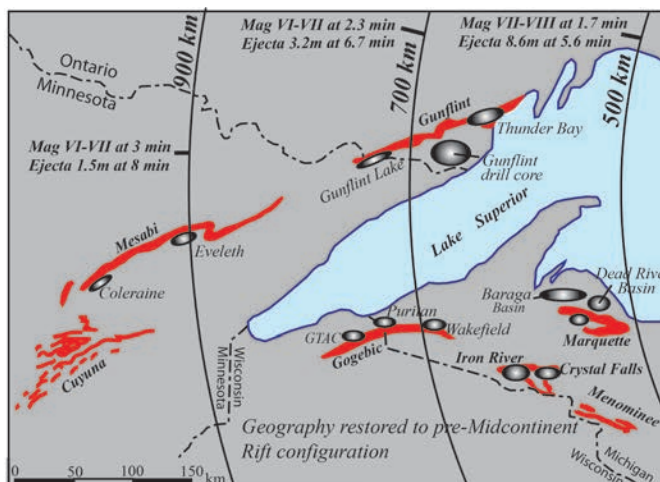


Figure 2. Locations where the Sudbury impact layer has been identified in the Lake Superior iron ranges. Predicted thickness of ejecta, its arrival time after the impact, and the predicted Mercalli intensity and arrival time of the impact-generated earthquake are shown for distances of 500, 700, and 900 km from the impact point.

Seismicity: The Sudbury impact generated an earthquake of Richter magnitude 10 or greater, larger than any possible tectonic-related earthquake. The severity of shaking was as great as Mercalli intensity VIII at the more proximal sites and gradually waned to the west. Because the velocity of seismic waves is greater than the velocity of ejecta, severe shaking began minutes before the arrival of ejecta. This shaking caused liquefaction of pre-impact sediments and brecciation of basement rocks, probably aiding in their incorporation into ground surges of ejecta that followed within minutes. At Gunflint Lake the upper 5-7 m of the Gunflint Iron Formation were liquefied to form coarse breccias of chert in an iron silicate matrix. This is the most distal locality at which strong seismicity has been documented. In the eastern Gogebic Range, upper parts of the Ironwood Iron Formation were mobilized into submarine slump deposits. In the Iron River-Crystal Falls area, in deep-water, massive debris flows were triggered from both the shelf edge to the north and an island arc to the south, resulting in slump deposits as much as 150 m thick. They remained active long enough for ejecta to reach the deep seabed and be incorporated into the slump deposits. In the Dead River Basin, the most proximal SIL localities, Archean basement rocks were intensely fractured and overlying sediments were injected downward into these fractures, probably a few tens of meters below the sea floor.

Ejecta: The Sudbury impact blasted material (ejecta) away from the crater as an “ejecta curtain”, which swept across the entire western Lake Superior region over a span of about 3 minutes with likely velocities of 1.5-2 km/sec. The ejecta included fragments of the pre-impact target rocks of varying sizes, with a predicted average fragment size of 2 cm at the more proximal sites, masses of melted rock, which eventually solidified into spherules and glass fragments (Figure 1B, C), and part of the impacting body itself, largely as high temperature vapor. On landing, the huge mass of material was propelled across the landscape by its forward momentum as a turbulent ground-hugging density current (base surge) for hundreds of kilometers. The energy within the base surge allowed entrainment of underlying rock and unconsolidated sediments resulting in hybrid deposits of true ejecta (material from the crater itself) mixed with more local rock ranging from fine particles to meter-scale boulders. As the energy and velocity of the base surges waned, a discontinuous layer of debris was deposited as a variable thickness of bedded material whose internal structure records the chaotic nature of the transport and deposition of the impact debris.

(Fralick et al., 2012). The most distal base surge deposits are at Gunflint Lake, about 700 km from the impact site, where a layer of breccia and lapillistone about a meter thick overlies the seismically disturbed upper beds of the Gunflint Iron Formation (Jirsa et al., 2011). At more proximal sites near Thunder Bay, base surge deposits are as thick as 4+ m and contain meter-scale and finer clasts of the underlying Gunflint Formation, ejecta rock fragments, devitrified glass, and accretionary lapilli (Addison et al., 2010). In Michigan, deposits are discontinuous. The SIL is absent in many exposures and drill core, but is as thick as 26 m in the Baraga Basin and 40 m in the Dead River Basin (Cannon et al., 2010). All of these deposits contain variable amounts of relatively local material, so the thickness of ejecta is significantly less than the total thickness of the surge deposits.

At sites along the Mesabi Iron Range in Minnesota, beyond the outer fringes of ground surges, the SIL is a discontinuous layer, only tens of centimeters thick, composed mostly of glass spherules and minor clasts of quartz and feldspar, all of which are probably ejecta. These were deposited from a cloud of suspended ejecta material that spread over the region in the minutes to hours after the impact and settled onto the sea floor. The most distal known occurrence of the SIL, near Coleraine, Minnesota, is nearly 1000 km from the impact site, the greatest distance at which rocks of suitable age to record the Sudbury event are exposed in the Lake Superior region.

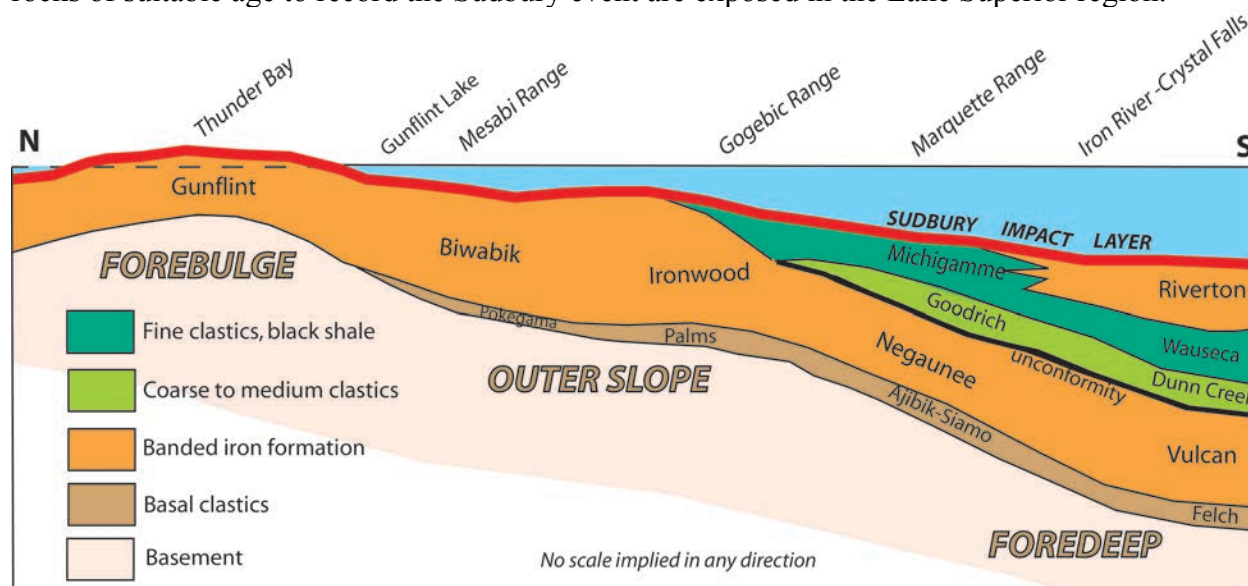


Figure 3. Schematic cross section showing the stratigraphic position and depositional setting of the Sudbury Impact Layer across the Penokean foreland.

The SIL was deposited within an active tectonic belt of the Penokean orogeny that varied from a low lying land area on the north, across a marine continental shelf southward, into a foredeep at the southernmost localities in the Iron River-Crystal Falls area (Fig. 3). The nature of its deposition varied accordingly. Ground surge deposition on the northern land area is the most straight-forward to comprehend, lacking the complexities of interaction of ejecta with seawater. To the south, in the Gunflint Lake, Mesabi, Gogebic, Baraga Basin, and Dead River Basin areas, ejecta appears to have been deposited in a relatively shallow sea in which iron-formations and ferruginous cherts were being deposited. The manner in which the extremely energetic ejecta and ground surges interacted with the ambient shallow ocean remains largely speculative.

Tsunamis: The last impact-generated event that is recorded in the SIL is the inferred reworking of ejecta and underlying breccia by tsunami waves that were generated by the impact. Because these

waves move slowly relative to seismic waves and ejecta, they swept the area some hours after the ejecta was deposited. The magnitude of the tsunamis is poorly understood in theory and depends in part on whether or not the crater was developed in an eastward extension of the ocean that existed at that time in the Lake Superior region. In any case, tsunami waves must have been substantial and possibly enormous. Features formed by those waves have not been reliably differentiated from waning phases of ground surges in many deposits. Perhaps the best indication of wave reworking of ejecta is at Gunflint Lake, where upper beds of the SIL consist of ejecta intermixed with large clasts that are more rounded than typical of lower parts of the layer, indicating energetic reworking.

The day after: An impact of the magnitude of Sudbury surely had global consequences, just as the Chicxulub impact did at the end of the Cretaceous period. A global layer of fine impact material was probably deposited, but has not yet been identified outside of the Lake Superior region. More locally, within the Lake Superior region, land areas were mantled with ejecta that probably dominated both the chemistry of water and physical nature of sediment being carried to the adjacent shallow ocean for a considerable time after the impact. Model studies suggest that the impact also resulted in a global-scale “nuclear winter”, a period of cold and dark conditions, as fine particles in the upper atmosphere blocked sunlight for months or years. This may have severely affected photosynthesizing microorganisms, whose short life cycles coupled with the prolonged lack of sunlight may have led to major population declines if not extinctions. Further study of the immediate post-SIL strata may yield critical information on such effects.

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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

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Over the last century, numerous geological studies have fairly well constrained the overall tectonomagmatic evolution of the Midcontinent Rift (MCR). However, until now, the correlation of the numerous flood basalts with their intrusive feeder systems has not been attempted. This study proposes one such correlation between two of the largest igneous bodies in the MCR: the Beaver River Diabase (BRD) intrusive complex in northeastern Minnesota and the Greenstone Flow (GSF) lava sheet in northern Michigan. The objective of this research is to test the validity of this link through a detailed analysis of the field relationships, petrographic characteristics, and geochemical attributes of these two units.

The GSF is an enormous (at least 1,650 km³) lava sheet exposed over a ~5,000 km² area on Isle Royale and the Keweenaw Peninsula in northern Michigan (White, 1960; Longo, 1984). The GSF forms the prominent ridge that runs the length of the Keweenaw Peninsula (~90 km) where it reaches a maximum thickness of 460 m (Cornwall, 1951). The GSF has been correlated across Isle Royale (Lane, 1893; Longo, 1984) where it reaches a maximum thickness of 260 m (Huber, 1973).

The BRD is an extensive, composite dike and sill complex exposed over a ~600 km² area in northeastern Minnesota. Perhaps the most intriguing feature of the BRD is the occurrence of numerous large (≤ 500 m in diameter), lower crustal anorthosite xenoliths in the BRD (Miller and Green, 2002). That these diabase feeder dikes were at one time wide enough to accommodate such large blocks within several kilometers of the Earth's surface implies that such conduits would most certainly have reached the surface and resulted in enormous outpourings of lava such as those that would have created the GSF.

Field mapping and previous studies have shown that both the BRD and GSF are composite systems formed by multiple pulses of successively fractionated magma. BRD dikes and sills occur as ophitic olivine diabase, with 0.5 – 10 cm augite oikocrysts, which grades into coarser and more subophitic to intergranular olivine oxide gabbro in the medial portions of larger dikes and sills. A distinctive textural attribute of the ophitic diabase is the occurrence of clustered, often radiating, plagioclase laths. Within these dikes and sills are numerous, smaller composite intrusions of more highly fractionated lithologies (ferrodiorite to quartz ferromonzonite) that locally display modal layering and strong foliation. Contacts between dioritic rocks and the enclosing gabbros are sharp, but unchilled. In addition, ophitic olivine diabase locally occurs as altered xenoliths in the intermediate composite intrusions. These composite bodies are especially prevalent in the southern extent of the BRD where they are termed the Silver Bay Intrusions (SBI) (Miller and Green, 2002). Paces and Miller (1993) reported a U-Pb age of 1095.8 ± 1.2 Ma which is within analytical error of the date reported by Davis and Paces (1990) for the GSF (1094.0 ± 1.5 Ma).

Similarly, the GSF can be divided into distinct lithological zones (from bottom to top): the *lower ophite*, *heterolithic*, *upper ophite*, and *entablature*. The *upper* and *lower ophite* zones are composed of ophitic olivine basalt with 0.1-4 cm augite oikocrysts and displaying clustered, often radiating, plagioclase laths. Occupying the central $\frac{1}{4}$ to $\frac{1}{2}$ of the lava sheet is the *heterolithic zone*, which is composed of coarser, subophitic to intergranular olivine oxide gabbro to subprismatic, locally foliated, ferrodiorite. Within the gabbroic/dioritic rocks of the *heterolithic*

zone occur numerous *en echelon* bodies of granophyre-rich lithologies (ferromonzodiorite to quartz ferromonzonite). As in the BRD-SBI intrusions, contacts between these rocks and the host gabbros/diorites are sharp and display no discernable chilled margins. And, as in the BRD intrusions, ophitic olivine basalt commonly occurs as inclusions in the *heterolithic zone* gabbros and diorites.

Whole-rock geochemical analysis shows significant similarities in major and trace element compositions between BRD and GSF lithologies. REE patterns on primitive mantle-normalized diagrams are nearly identical for comparable rocks types of each unit. Gabbroic rocks are characterized by moderate LREE enrichment ($\text{La/Sm}_n = 1.54\text{--}2.49$) and weak HREE fractionation ($\text{Gd/Yb}_n = 1.45\text{--}1.79$). The more highly fractionated rocks of the SBI and GSF *heterolithic zone* show higher LREE enrichment ($\text{La/Sm}_n = 1.86\text{--}2.54$) and HREE fractionation ($\text{Gd/Yb}_n = 1.55\text{--}2.74$), as well as strongly negative Sr anomalies, moderate Zr-Hf anomalies, and weak negative Eu anomalies.

SEM-EDS analysis showed a similar range in pyroxene compositions between comparable rocks of the BRD and GSF. Pyroxenes within the gabbroic rocks of each unit were predominantly augite with lesser pigeonite and minor enstatite while the more highly differentiated lithologies of the SBI intrusions and GSF *heterolithic zone* were generally more Fe-rich (ferroaugite to ferrosilite). Olivine compositions tended to be more Fe-rich in BRD samples than those in the GSF ophites Fo_{28-69} and Fo_{50-66} , respectively. Within the GSF, fresh olivine was only found in the *upper* and *lower ophites* so rocks of the *heterolithic zone* could not be compared with comparable rocks in the BRD-SBI. SEM-EDS analysis was also used to measure the An content in plagioclase phenocrysts in GSF samples. Three phenocrysts from GSF ophites of Isle Royale were found to have anomalously high anorthite contents (An_{71-81}) with respect to the groundmass plagioclase (An_{30-60}). The An content of these calcic phenocrysts (xenocrysts?) is consistent with those reported by Morrison (1983) for the anorthosites xenoliths in the BRD (An_{54-78}) and could be indicative of a similar source.

Based on the evidence obtained during this research, we propose the first ever intrusive-volcanic link between an MCR flood basalt and its intrusive feeder system. Based on the 1) overlap in U-Pb ages; 2) similar composite lithologies and contact relationships; 3) similar mineralogical and textural attributes, especially the occurrence of clustered plagioclase laths; 4) similar major and trace element compositions; 5) similar primary mineral chemistries; 6) similar An contents between anorthosite xenoliths in the BRD and plagioclase megacrysts in the GSF; and, 7) enormous volumes represented by each unit. Collectively, this data points to the conclusion that the BRD acted as the feeder conduit for the GSF. If this is the case, it more than doubles the total volume of the GSF making it perhaps the largest single lava flow on Earth.

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Re-digitized public aeromagnetic data for the Baraga basin and surrounding region, Upper Peninsula, Michigan

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The public aeromagnetic database (Daniels et al., 2009) for Michigan's western Upper Peninsula (UP) is widely regarded as unsuitable for intermediate- and detailed-scale geologic mapping and mineral exploration applications. There are several limitations of the data, including being available only in a native analog format, being acquired with too wide of a line spacing and too high of a terrain clearance, and being digitized at a lower level of detail than shown on original contour maps. This abstract describes a recent experimental effort to re-digitize sample aeromagnetic data from original contour maps in the greatest detail possible. The area chosen is the Proterozoic Baraga basin, containing the Eagle Ni-Cu deposit, and surrounding Archean rocks (Sheet 2 of Case and Gair, 1965).

A fixed-wing total-field aeromagnetic survey was flown in the region in 1950, along north-south lines spaced 400 metres at a nominal terrain clearance of 150 metres (Case and Gair, 1965). After removal of an unspecified base level, the acquired data were interpolated onto contour maps with a minimum contour interval of 50 nT (see Case and Gair, 1965). A subsequent digitization effort from the contour maps followed at an unknown time, and the resulting digitized data are those publically available today from the USGS (e.g., Daniels et al., 2009). However, that digitization effort sampled the contour maps along only every other flightline, effectively simulating a survey with 800 metre line spacing. This resulted in very poor geologic resolution. The same problem plagues several other vintage aeromagnetic datasets acquired in the western UP.

As an experiment we re-digitized a portion of this aeromagnetic dataset, sampling each contour from the original contour map and effectively capturing all of the available detail. The experiment is considered a success, as the resulting map is a far more effective representation of the region's geology. As originally interpreted by Case and Gair (1965), many Keweenaw diabase dikes are imaged against a background of generally weakly magnetized Archean rocks and older Proterozoic metasedimentary rocks. The magnetic anomaly over the Eagle-hosting intrusion is difficult to pick out in the published data due to the wide data spacing, yet is readily apparent in the re-digitized data.

In spite of this successful experiment, the recovered data still have several major and minor limitations that must be considered by interpreters. First, the survey was flown at too wide a line spacing (400 meters) and too far above the ground (~150 meters) for detailed geologic mapping and mineral exploration. Second, the minimum contour interval of 50 nT shown on the original contour maps means that more subtle anomalies and geologic details undoubtedly present in the flightline data will never be recoverable. Third, the exact terrain clearance of the magnetometer was not recorded, and in several localities may have varied significantly from the nominal 150 meter clearance. Finally, the base level removed from the magnetic data wasn't recorded, meaning that the total field intensity and formal total field anomalies cannot be calculated.

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Petrographic Analysis of Felsic Tuffs within the Neoproterozoic Soudan Member of the Ely Greenstone Formation, NE Minnesota

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The Vermilion District of northeastern Minnesota contains one of the classic greenstone belts in the United States, and is composed of a wide variety of greenschist facies metamorphosed Neoproterozoic volcanic, sedimentary, and intrusive rocks that comprise the southwestern part of the Wawa Abitibi Terrane (Stott et al., 2007). The Ely Greenstone Formation occurs within the Western Vermilion District and is composed of calc-alkaline to tholeiitic massive to pillowed basalt, andesite, dacite, and rhyolite lava flows and volcanoclastic rocks (Lower Member); Algoma-type banded iron formations with interbedded tholeiitic massive to pillowed basalt lava flows, rhyodacitic to dacitic tuffs, and polymict volcanoclastic rocks (Soudan Member); and pillowed to massive tholeiitic basalt lava flows and interbedded Algoma-type banded formation horizons (Upper Member; Peterson and Jirsa, 1999).

The purpose of this study is to identify and characterize potential felsic tuff horizons that are interbedded with Algoma-type banded iron formations within the Soudan Member of the Ely Greenstone Formation. This has been accomplished by detailed field mapping, petrographic studies, scanning electron microscopy (SEM) studies, and lithogeochemical studies. In addition to texturally, mineralogically, and chemically characterizing potential felsic tuff units, our research seeks to determine if the felsic tuff units could potentially yield age dates by means of future U/Pb geochronological studies in a manner similar to that which has been done in the Abitibi Belt in northeastern Ontario (Thurston et al., 2008). Despite the long history of geological studies in the Western Vermilion District, relatively few absolute age dates are present (Fig. 1A; Peterson et al., 2001; Lodge et al., 2013), and no absolute age dates exist for the Soudan Member of the Ely Greenstone Formation.

Detailed mapping has identified a light gray, 30-50cm thick, laminated to thinly-bedded, possibly resedimented felsic tuff horizon that is interlayered with laminated to very thinly-bedded magnetite-chert Algoma-type banded iron formation within the uppermost 25 meters of the Soudan Member in the central part of Lake Vermilion State Park. In thin section, the tuff is sparsely quartz-phyric, and comprises a matrix of fine-grained, recrystallized polygonal quartz with up to 1%, up to 1mm in diameter subhedral, recrystallized quartz phenocrysts. Hydrothermal alteration of the tuffs varies from moderate to intense (up to 75% alteration minerals), with the greenschist-facies metamorphosed synvolcanic hydrothermal alteration assemblage now composed of variable amounts of iron carbonate (siderite, ankerite), actinolite, chlorite, and various epidote-group minerals (pistacite, clinozoisite/zoisite). Due to the extremely fine-grained texture of the tuff, and the locally pervasive hydrothermal alteration within the tuff, searching for zircons using standard petrographic analysis has proven to be difficult.

On-going SEM analysis will be used to constrain the mineralogy of the existing alteration and to seek out zircons in a more systematic manner. Lithogeochemical analysis and lithogeochemical classification by means of immobile trace elements (e.g., Pearce, 1996) is ongoing.

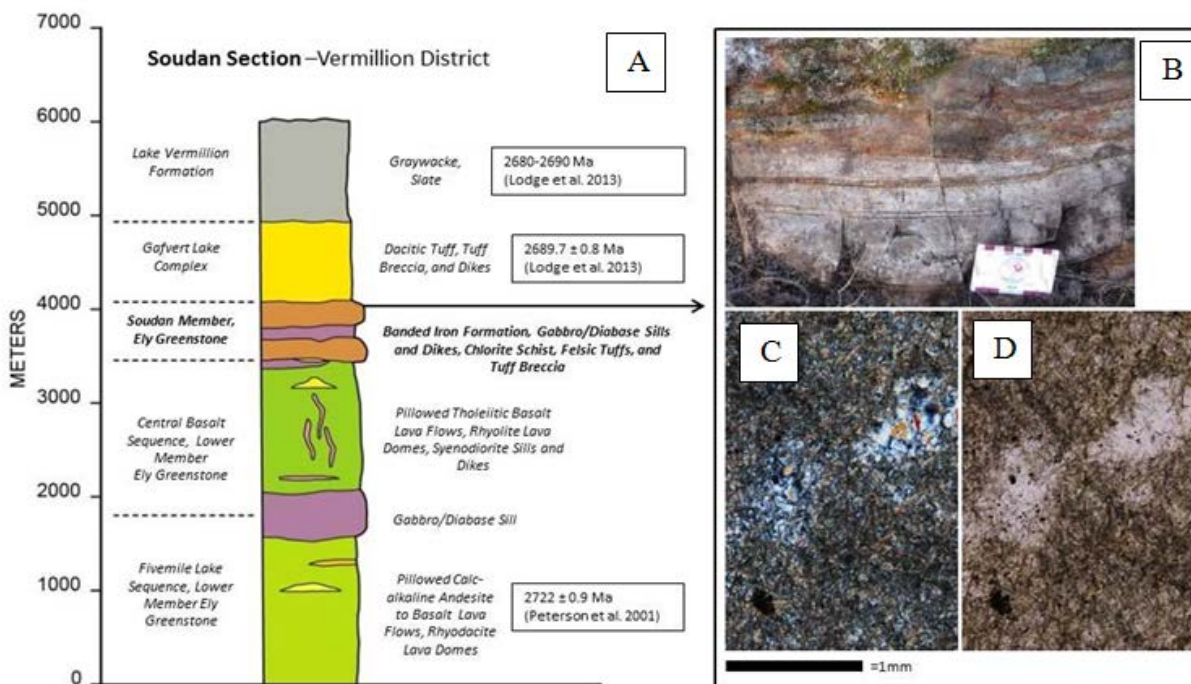


Figure 1: A: Generalized section of the Ely Greenstone Formation in Lake Vermilion State Park (modified from Hudak and Peterson, 2014); B: Field appearance of felsic tuff unit within the uppermost 25 meters of the Soudan Member; C and D: Cross-polarized and plane polarized appearance of hydrothermally altered felsic tuff.

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Characterization of secondary minerals formed on weathered Duluth Complex Cu-Ni-PGE deposit rock and implications for controls on metal mobility

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Secondary minerals and other weathering products can serve as an important control on the concentration of trace metals in mine-impacted waters (for example, Jambor, 2003). Ultimately, aqueous metal concentrations will reflect combined effect of constituent release from primary minerals (e.g. sulfides), as well as, attenuation during weathering from mechanisms such as precipitation of secondary phases, sorption onto solid phase surfaces, and co-precipitation. We characterized weathering products formed on weathered exposures of mineralized Duluth Complex to specifically investigate possible solubility controls for Cu and Ni. Combining these solid phase characterization results with both standard-method mine waste studies (see Lapakko, 2012) and numerical modeling should yield an improved understanding of the mobility of trace metals that would be released during weathering of potential future waste rock.

Opportunistic sampling was conducted at five Duluth Complex exposures at the Mesaba deposit (currently held by Teck American and formerly known as the Babbitt deposit). Exposures included both natural outcrops and a railroad cut. Six samples were collected with the intent of capturing the variety of visual alteration.

Powder X-ray diffraction (XRD) was conducted on weathering products isolated by scraping the outer surfaces of hand sample specimens. XRD of iron-rich material (rusty coatings) generally did not produce diffraction patterns that allowed phase identification, suggesting the material structure is very poorly crystalline to amorphous. However, in one case, poorly crystalline goethite (FeOOH) was identified and appeared to be a product of sulfide mineral replacement. In addition, the secondary minerals malachite ($\text{Cu}_2(\text{CO}_3)(\text{OH})_2$), rozenite ($\text{FeSO}_4 \cdot 4\text{H}_2\text{O}$), alunogen ($\text{Al}_2(\text{SO}_4)_3 \cdot 17\text{H}_2\text{O}$), and epsomite ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$) were identified.

The morphology and semi-quantitative chemistry of weathering products was characterized using a JEOL JSM-6590LV scanning electron microscope, combined with an INCA X-ACT energy dispersive spectroscopy system at University of Minnesota- Duluth. SEM observations of rusty coatings reveal micro-scale banded (alternating Fe and Si rich) features (Figure 1). The coatings commonly contain Fe and Si as major components and variable amounts of Al, S, and Cu as minor elements. It should be noted that Ni was not found to be commonly associated with these features. This could be due to sub-detection limit (< 0.1 wt. %) quantities or absence of Ni. Sorption of trace metals by hydrous ferric oxides in mine-water systems is common.

SEM-EDS analyses indicate Ni and Cu can be associated with sheet silicate minerals, in concentrations that can exceed several percent by weight. Research on similar materials found Ni-rich metallic particles along laths of serpentine and chlorite (Suárez, 2011) and sorption of $\text{Ni}(\text{OH})_2$ onto primary mineral grains (Plante, 2010). It may be possible that Cu and Ni were incorporated during late stage deuteric alteration and not surface weathering. Planned analyses include SEM-EDS of non-weathered rock from the same lithology to determine if trace metal enrichment of sheet silicates is unique to weathered samples as well as TEM analyses to determine nano-scale mineral properties.

Collectively, the mineral characterization techniques employed provide evidence for attenuation of constituents released during weathering of Duluth Complex rock by means of: (1)

secondary mineral precipitation (malachite and sulfate salts); (2) incorporation of Cu and Ni by sheet silicates (likely, but not necessarily occurring during sub-aerial weathering); and (3) formation of iron-oxide rich coatings which may retain trace metals (especially Cu) though adsorption. The degree to which trace metals are attenuated will be function of drainage pH, total iron content, trace metal content, and reactive surface area among other variables.

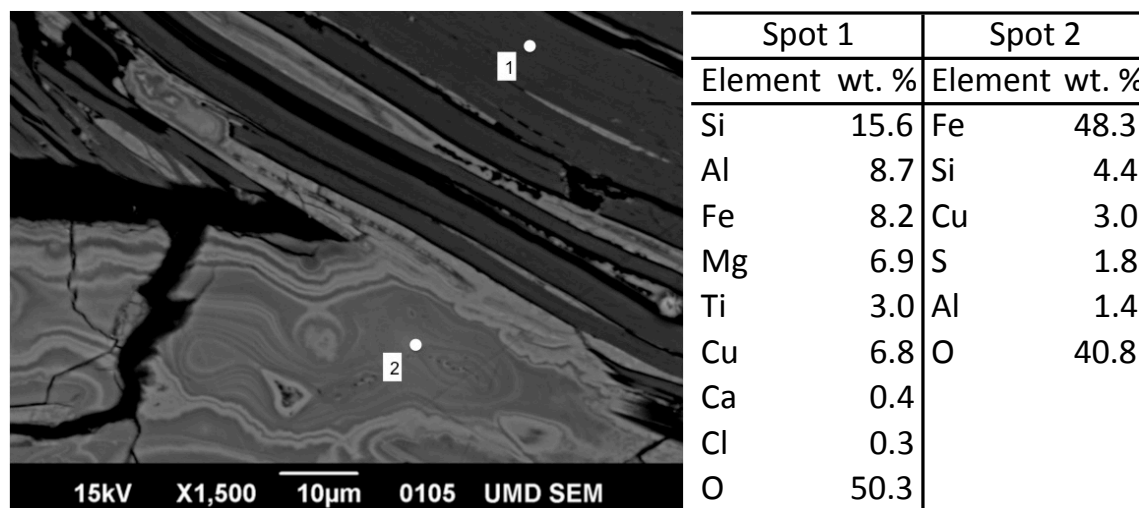


Figure 1: SEM-Backscatter electron image of a weathered Duluth Complex sample. Lower left region shows banding typical of iron rich surface rinds. Upper right phase appears to be a weathered sheet silicate with significant Cu enrichment. Similar phases in our samples have been observed to contain up to 4 wt. % Ni. Iron rich phases (light strips) can also be seen where sheets have parted. Spots indicate locations of semi-quantitative SEM-EDS compositional data (right) and are sized to the approximate analytical volume at these working conditions (15 kV).

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Lateral geochemical gradients and physical processes associated with the genesis of iron formations: Examples from the Paleoproterozoic to Mesoarchean of Superior Province
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The presence of Fe, Si, Mn and P in mineral phases with precursors that were quasi-stable precipitates from the overlying water column necessitates that disequilibrium conditions existed during their formation. Commonly a two box model is used to explain iron precipitation in the Precambrian with an oxic to sub-oxic phytoplankton-rich or CO₂-rich surface layer driving iron precipitation in the underlying anoxic, Fe⁺²-rich ocean. But what is the evidence for this model?

1) On the wide, Paleoproterozoic Gunflint-Mesabi shelf carbonate iron formation (IF) dominated the shallow areas, whereas oxide IF accumulated in more offshore locations. Storm induced geostrophic flows delivered oxygenated inner shelf waters to the offshore instigating formation of the discrete iron to iron+manganese+silica+mud laminae that compose the fine-grained IF. Here frequent storm mixing would have destroyed vertical stratification and Fe⁺² transport across the 150km wide shallow shelf indicates anoxic conditions across the shelf during fair-weather times. 2) The Neoarchean delta-top IFs in the Lake St Joseph area record extremely rapid accumulation of iron hydroxides during limited sediment flux to portions of distributary mouth bar complexes. IF accumulated on short-lived reactivation surfaces of gravel bars to ripples in water depths of a few meters. No IF accumulated further offshore. Its chemistry is virtually identical to deep-water IF deposits. The IF was probably formed by high nutrient flux to the shallows promoting cyanobacteria. 3) Carbonate was deposited on the Mesoarchean, stromatolitic, oxygenated Steep Rock platform, while the generation of free oxygen caused Fe and Mn precipitation offshore. Onshore water movement, probably driven by storm events, deposited iron-rich layers in the limestone and shifted the offshore from Fe to chert or mud accumulation. In these examples IF deposition was dependent on lateral, not vertical, geochemical differences augmented by storm induced mixing.

Comparison of PGM assemblages for the Marathon, Georgie Lake and Area 41 deposits, Coldwell Alkaline Complex, Ontario

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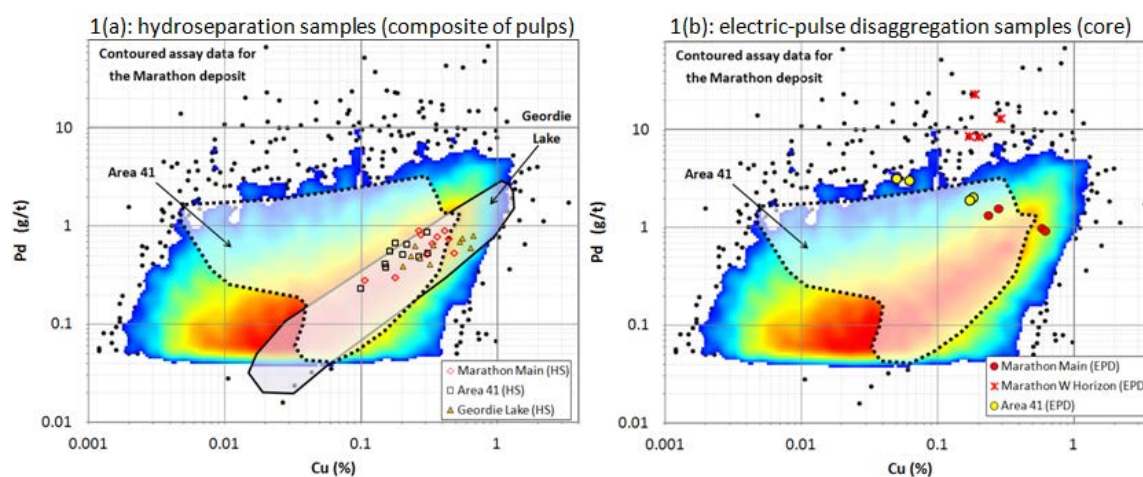
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Numerous Cu-PGE deposits in the Coldwell Alkaline Complex exhibit widely varying mineralization styles and Cu/Pd and Pd/Pt ratios (Ruthart, 2012; Meghji et al., 2013; Good et al., 2015). However, the host gabbro and ultramafic bodies are believed to be co-genetic and differences between the deposits may be explained by variations in mineralizing processes and the respective magma conduit setting.

This study presents results for heavy mineral separates from 5 mineralized zones within three deposits: W horizon and Main zone in the Marathon deposit, Main zone at the Georgie Lake deposit, and the Main and PGE-enriched zones at the Area 41 occurrence. A total of over 9000 PGM comprising 46 PGM species, numerous unknown PGM, and 7 Au/Ag minerals were identified.

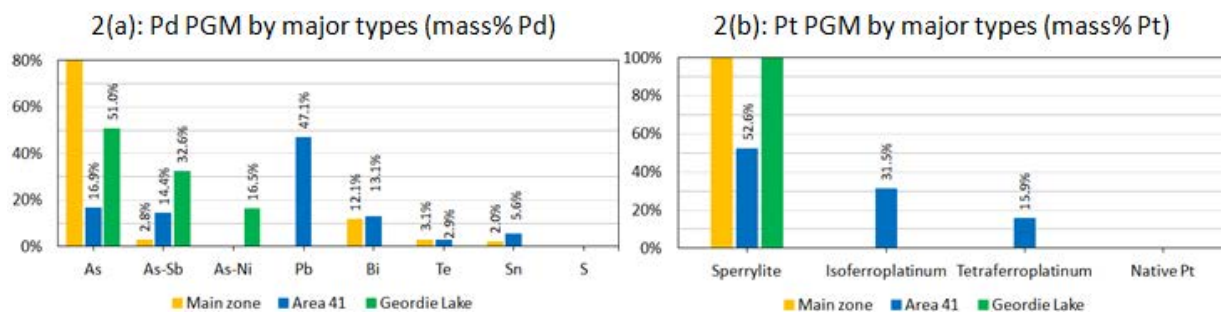
The mineral separates were prepared by two different methods on two different groups of samples. The first group was prepared by hydroseparation (HS) of screened size-by-size composites and the second group by electric-pulse disaggregation (EPD) of drill core (e.g., Cabri et al. 2008). All mineral separates were mounted on polished sections and analysed by SEM-EDS techniques to characterize the platinum group minerals (PGM). The sum of measured surface areas for each mineral are collated to provide estimates of mineral abundances.

Large representative sample sets were prepared from each location. In group one, mineral separates for three composite samples with similar Cu and Pd abundances (Fig. 1a), one from each intrusion, a total of 513 precious metal grains were found and characterized in 15 sized monolayer polished sections. In group two, mineral separates for samples with relatively high PGE abundances were prepared from 12 pieces of drill core, 4 from each of the Main zone, W Horizon, and Area 41 intrusion (Fig. 1b).



The results from group 1 show that three mineralized zones (Main zone, W horizon and Georgie Lake) have distinct precious mineral signatures (Fig. 2), as expected based on the variation of Cu/Pd and Pd/Pt values, and differences between local intrusive settings and

mineralization styles. The Pd PGM in the Main zone sample are dominated (mass%) by arsenian PGM (80%) with less bismuthides (12%); in the Georgie Lake sample, arsenides dominate (51%), followed by arsenian-antimonian (33%), and arsenian-nickeloan PGM (16%); and in the Area 41 sample, plumbian PGM dominate (47%), followed by arsenian PGM (17%), arsenian-antimonian PGM (14%), bismuthides (13%), stannides (6%), and tellurides (3%). The Pt PGM for the Main zone and Georgie Lake are the same, where sperrylite predominates, but are very different for the Area 41 sample where Pt alloys are abundant: sperrylite (~53%), isoferroplatinum (~31%), and tetraferroplatinum (~15%). Results are summarized in Figure 2.



The PGM assemblage at Area 41 resembles that for the W Horizon and is consistent with the very wide range and notably low Cu/Pd values present at both locations. Further, the host gabbros exhibit similar petrographic features and trace element abundances that suggest they formed by similar processes.

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Significance of LREE-enriched mantle source to genesis of basalt in the Coldwell Alkaline Complex, Midcontinent Rift, Ontario

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At least three distinct basaltic packages occur within the Coldwell Alkaline Complex: Lower and Upper basalt units located within the Eastern Gabbro Suite, and the Coubran basalt. Geochemical evidence suggests the Coubran basalt is co-genetic with the Two Duck Lake gabbro, a late phase of the Eastern Gabbro with an age of 1108 ± 1 Ma (Heaman et al., 2007) and thus formed as part of the Early Magmatic stage of the rifting event. The Upper and Lower basalt were re-crystallized during pyroxene hornfels grade metamorphism during intrusion of the Eastern Gabbro suite, and are older than 1108 Ma and possibly represent magma formed during the Initiation stage of the rifting event.

Major element abundances for the Coldwell basalt units are comparable to other Early Stage basaltic units of the Midcontinent rift. Based on Mg number and Ni abundance, the three groups, listed in order from most primitive to most evolved, are Lower basalt, Upper basalt and Coubran basalt.

Spider diagrams were prepared following the method of Pearce (2008) whereby data are normalized in two steps: first by N-MORB and then by Tb (Fig. 1). Note that we normalize to Tb and not Ti. All Coldwell units show depleted HFSE relative to LREE, similar to that demonstrated by Groups 1 and 2 at Mamainse Point. The units listed, from most to least depleted, are Coubran basalt, Upper basalt and Lower basalt.

Although LREE abundances in the Coldwell basalts are consistent with OIB source, the regular pattern of LREE enrichment relative to HFSE indicates a more complicated origin and cannot be explained by crustal contamination. Crustal contamination, if present, would have resulted in elevated SiO₂ and Zr abundances as well as higher Th/La, but these affects were not observed. Further, La enrichment relative to Zr in the Coubran basalt (Fig. 2) cannot easily be explained by crustal contamination. Therefore, it seems more likely that the mantle source was LREE enriched and HFSE abundances are a better indicator of either MORB or OIB source.

The HFSE suggest the Coubran basalt magma was intermediate between E-MORB and OIB. Similarly, the Lower and Upper basalt groups show HFSE signatures that are intermediate between E-MORB and N-MORB.

Coldwell units exhibit Gd/Yb that are intermediate between E-MORB and OIB. These units, in order of decreasing Gd/Yb, are Lower basalt, Coubran basalt and Upper basalt, whereby Lower basalt resembles that of OIB and Upper basalt resembles MORB.

These results suggest a progressive change in the mantle source for the Coldwell basaltic magmas. The mantle source areas have varying degrees of LREE enrichment, possibly introduced by an earlier subduction event as discussed by Shirey et al. (1994) for the MPVG. Our observations for the Coldwell basalts may be explained by partial melting of sources that, from oldest to youngest show, deep depleted mantle having moderate enriched LREE signature (Lower basalt); shallow depleted mantle with significant LREE enrichment (Upper basalt); and finally,

enriched mantle from intermediate depth with significant but heterogeneous LREE enrichment (Coubran basalt).

A model to test origin of Eastern gabbros from heterogeneous LREE enriched mantle source similar to that which produced Coubran basalt is proposed in Figure 2.

Figure 1: Average data for Coubran basalt and Lower and Upper basalts compared to averages for MPVG 1, 2 and 3a (after Shirey et al. 1994). MORB, OIB and E-MORB after Sun and McDonough (1989).

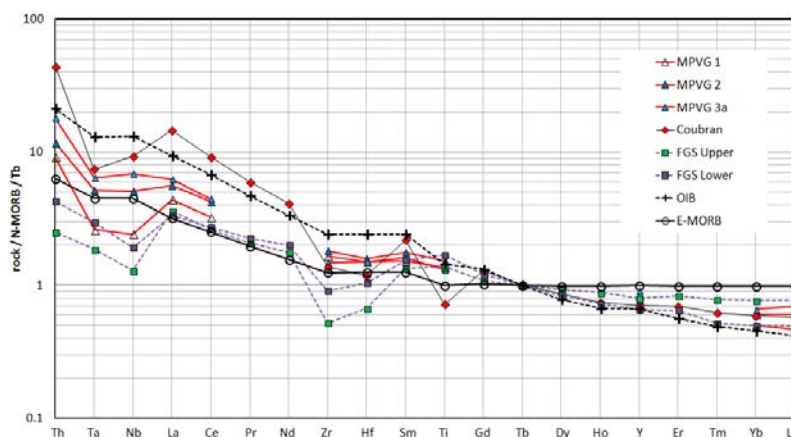
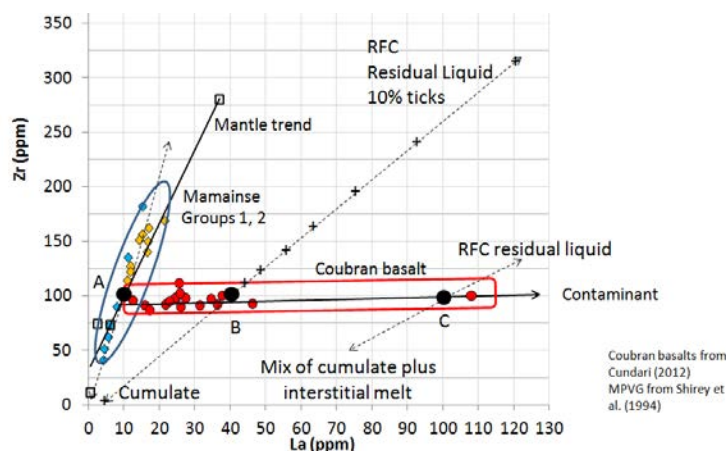


Figure 2: Model for derivation of Eastern gabbros based on contamination trend of Coubran basalt



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Preliminary 3D model of the Midcontinent Rift System in western Lake Superior region
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Over the past several decades, geophysical models have played a large part in developing our understanding of the Midcontinent Rift System (MRS). Technical advances in modeling capabilities, expanded and improved data coverage, and renewed interest in the mineral resources of the MRS provide the motivation for new attempts at 3D digital modeling of the MRS. Efforts are focused on modeling the structure and configuration of sedimentary and volcanic basins in the western Lake Superior region (Fig. 1). Previous workers used geophysical data to identify extremely thick volcanic and sedimentary sections that commonly have unconformable contacts against intervening structural highs. An improved 3D model of the area helps visualize the relations, provides mechanisms to test hypotheses about tectonic history and the spatial distribution of mineralization, and helps identify areas where more detailed analysis is required.

The 3D model is regional and intended to show broad variations in geology. Only three generalized, MRS-related geologic packages are represented, following previous 3D models of Allen (1994; Allen et al., 1997). The packages, from oldest to youngest, are 1) undivided Keweenaw plutonic and volcanic rocks, 2) Oronto Group sedimentary rocks, and 3) Bayfield Group and equivalent sedimentary rocks. A fourth package represents undivided pre-rift rocks (basement). In addition, three major fault systems are modeled: the Douglas, Lake Owen, and Keweenaw fault systems (Fig. 1). The modeling strategy involves digitizing the bottoms of the rift-related geologic packages, fault locations, and general orientation data along 2D sections and from a geologic map. The 3D modeling software then connects the digitized points into surfaces and volumes in 3D space, using simple geologic rules for stratigraphic and onlap relations and for the lateral extents of the influences of faults.

Steps that have been accomplished for the new 3D model are the following.

1. Images were captured from published 2D geophysical models, interpreted seismic-reflection sections, and geologic cross-sections. They were geo-registered and hung in 3D model space by projecting them onto 20 different sections crossing the model area. Digital and analog geologic maps from several sources provided information in plan view.
2. Contacts between geologic packages were determined for available, industry seismic-reflection time sections using surfaces derived from previous 3D models (Allen and others, 1997) as guides. In addition, selected, proprietary industry seismic-reflection data from the Bayfield Peninsula, which only a few workers have previously seen, were licensed to the U.S. Geological Survey. Time was converted to depth for the sections using root-mean-square velocities derived from industry data processing.
3. Selected points representing fault surfaces and the bases of the geologic packages were digitized, then rendered into 3D volumes and surfaces by the modeling software.

A 3D perspective view of the modeled volume of the Oronto Group is shown in Figure 2. Although this and the previous model (Allen and others, 1997) are intentionally very similar, there are significant differences. First, the newly acquired seismic data provided corrections for several significant errors in the current digital rendition of the previous 3D model that would not have been known other-wise. Second, due to advances in software capabilities, faults are now properly represented rather than handled by gridded surfaces. Finally, even though all apparent constraints from 2D sections were met, the Oronto Group in the Bayfield Basin does not extend as far south underneath the Bayfield Group in the new model as it does in the old one. This discrepancy

brings up the difficult problem of determining the contact between the Bayfield and Oronto Groups from geophysical data, and is yet to be resolved.

Future work involves more extensive analysis of existing seismic data in conjunction with gravity and magnetic modeling; division of intrusive from extrusive Keweenaw igneous rocks; and addition of layers to the volumes of the generalized geologic packages to better represent dips, stratigraphic variations, and unconformities.

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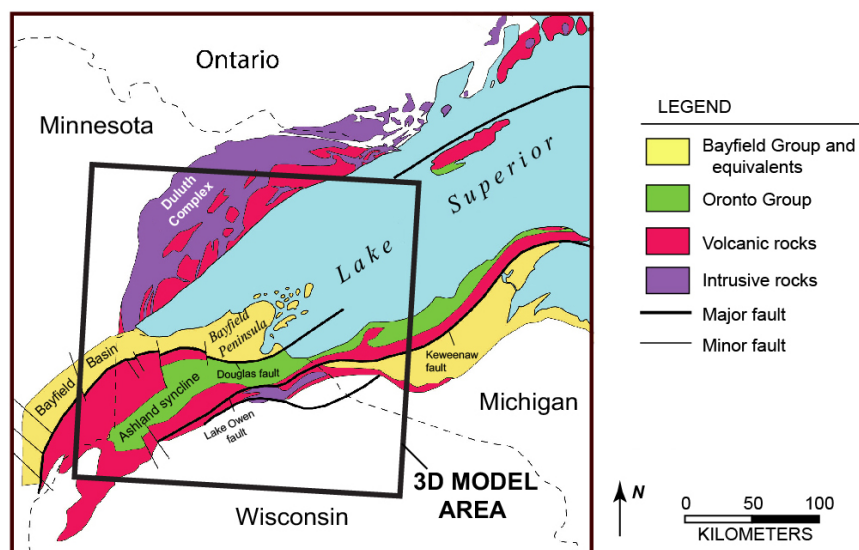


Figure 1: Generalized rock units of the Midcontinent rift system in the western Lake Superior region and area covered by the 3D model. Geographic boundaries are shown by dashed lines.

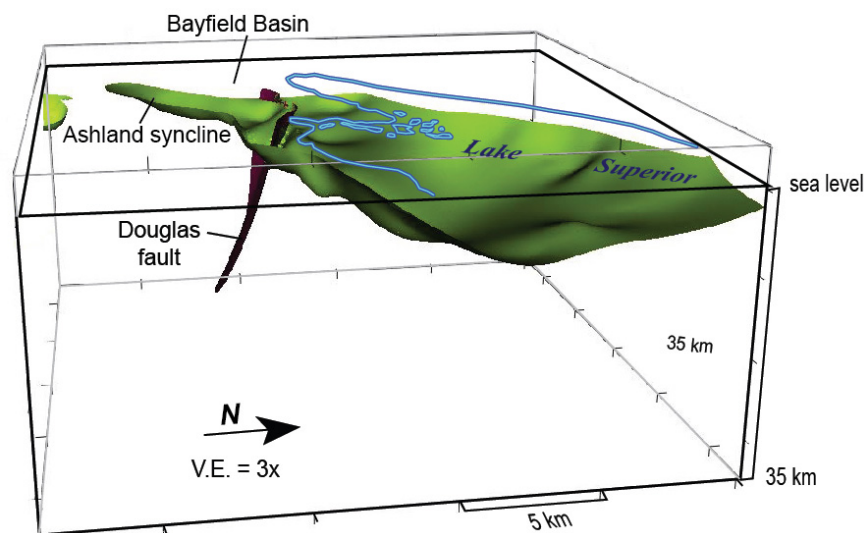


Figure 2: 3D perspective view of the modeled base of the Oronto Group (green) and surface representing the Douglas fault (dark purple) for the model area located on Fig. 1. View is to the west-northwest.

Geological and geochemical reconnaissance for rare earth element (REE) mineralization in Minnesota

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The purpose of this study was to: 1) collect rock samples from across Minnesota and assay them for Rare Earth Elements (REEs); 2) evaluate the assay results; and 3) via a combination of acquisition and evaluation of both new data and historical geochemical data, identify locations or regions within Minnesota that possess anomalous REE concentrations that may warrant further characterization for potentially economic REE mineral deposits (Hauck et al., 2014).

Currently, approximately 90-95% of the world's REE processing and sales are controlled by China. REEs are vital to the U.S. economy, particularly in components used by the U.S. military, in windmills and other equipment that use REE-containing magnets, and in green economy products such as hybrid vehicles.

This study is multi-dimensional, and includes: 1) collection of new REE geochemical data through detailed geological mapping, sampling, and analysis; 2) compilation of previously published REE data from a variety of scientific publications; and 3) re-analysis of one historical sample containing anomalous REE contents to confirm the validity of the historic analysis. Resulting from this study are: 1) a new, detailed 1:5,000 scale geologic map in NE Minnesota showing anomalous REE contents; 2) a new lithogeochemical dataset containing 287 samples compiling both new and historic REE data to provide the exploration industry up-to-date lithogeochemical resource data for designing future REE exploration programs in the State; 3) new maps illustrating both historic and new geochemical sampling location and 4), a new interpretation of areas that may host anomalous REE mineralization.

Based upon currently mined REE ore deposits, igneous rocks or ionic clays are most likely to contain anomalous REE contents, and, therefore, sample collection concentrated primarily on silica-rich igneous rocks (rocks containing >67% SiO₂). Two hundred twenty-two rock samples were collected. Of these, 147 rock samples were analyzed. Based upon the availability of outcrops and diamond drill core samples, the majority of the samples were from St. Louis, Lake of the Woods, Koochiching, and Lake Counties. The rock samples were analyzed at Acme Labs, Vancouver, B.C., for multi-element chemical analyses, including a complete suite of REEs+Y+Sc.

The geochemical data received was combined with lithogeochemistry from a previous study (Klenner et al., 2012) to provide as complete a dataset of REE values of Minnesota rocks for interpretation as possible. This combined data set contains over 280 REE analyses, with sample analyses from diamond drill holes comprising ~33% of the combined geochemical assays and ~67% of the data were from outcrop samples from all regions of the state. This compiled data set indicated that 25 samples from around the State had TREEs > 425 ppm. The highest seven REE analyses occurred in samples from NE MN in Koochiching and St. Louis Counties. Lac Qui Parle County, in SW MN, contained the only anomalous sample outside of the NE section of the State, and this sample contained 760.36 ppm TREE.

The most promising sample in this study was identified from a review of publications on Minnesota geology. Morey and McDonald (1989) reported a highly anomalous sample, GSP-47,

from near Ray, MN that had a TREE analysis of 11,313.50 ppm and 1,100 ppm Thorium (a common component of REE mineralization). Although this original TREE analysis was incomplete (some heavy rare earth elements (HREEs) were missing), the location of the sample, as well as a powdered sample split from the original analysis were both available, and afforded the NRRI the opportunity to re-evaluate the original sample, which provided an almost duplicate REE and Th analysis, and added the missing HREEs. The sample location is west of Ray, MN.

The Minnesota Geological Survey provided a split of the original sample. Reanalysis confirmed its anomalous nature, i.e., 11,139.46 ppm TREE and 1,162.3 ppm Th. Upon confirmation of the original anomalous REE contents of GSP-47, detailed geological mapping (1:5000 scale) and additional geochemical sampling was done west of Ray, MN. The sample site was mapped and sampled (8 samples), and two samples assayed had > 4,000 ppm TREE and > 425 ppm Th, confirming the anomalous nature of this geologic area.

Further work is recommended to more fully characterize the nature of the geological areas associated with anomalous TREE and Th contents identified in this study. Such work recommended for future exploration and characterization includes detailed airborne and ground radiometric surveys of exposed rock outcroppings of favorable REE host rocks, follow-up/confirmation assaying, detailed geologic mapping, and, if warranted, diamond drilling. As well, future geologic and geophysical studies should be conducted to further characterize, and if possible, confirm the existence of carbonatites in the southwest part of the state as suggested by Southwick (2014). Such carbonatites are currently the major source of REEs in China and the U.S. (Molycorp) and may afford Minnesota an excellent target for future REE exploration and characterization.

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Petrological and geochemical evaluation of the Sturgeon Falls Igneous Body and its relationship with the Penokean Orogenic Belt

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The Sturgeon Falls Igneous Body (SFIB) is a mafic to ultramafic intrusion located along the Michigan-Wisconsin border just south of the town of Norway, MI. The SFIB is bounded to the north by the Niagara Shear Zone and the Michigamme Formation (Schulz and Cannon, 2006) and to the south by an unnamed thrust fault zone and the Quinnesec Formation (Sims and Schulz, 1993). Field mapping has shown that the SFIB is composed almost entirely of metagabbro, with isolated outcrops peridotite and serpentinite. The metagabbro reached greenschist facies (Prinz, 1959), and is mostly composed of plagioclase, clinopyroxene, and hornblende. Hornblende is present as both a primary and secondary alteration mineral. The level of alteration within this rock is spatially varied within the SFIB. The portions of the SFIB near the fault zones have been metamorphosed to the point where their original fabric and mineral composition has been lost. This area has been named the Heterogeneous Altered zone. It is rich with secondary amphibole, with weak foliation often present. Prinz (1959) observed that the metagabbro cut the ultramafic rocks indicating that they were formed as part of an earlier magmatic event.

Schulz and LeBerge (2003) proposed that the SFIB is part of a larger suprasubduction ophiolite sequence that formed along with the Pembine-Wausau Terrane. Major and trace element geochemistry of approximately 35 samples was compared to other known suprasubduction zone ophiolites, as well as island arcs suites. The results show that the major element geochemistry of the SFIB matches well with both suprasubduction zone ophiolites and island arc terranes. Trace element geochemical signatures such as enrichment in light REE and LILE elements are often used to distinguish suprasubduction zone ophiolites (Shervais, 2001), however in this case, these methods prove problematic for several reasons. First, light REE are highly mobile during metamorphism (Yumal, 1996). Secondly, these characteristics are also common to Island Arcs, so they are not in themselves sufficient to distinguish an ophiolite sequence. In order to identify an ophiolite sequence, a comprehensive study of the lithology, structure, and geochemistry must be used, one method by itself is insufficient. While the geochemistry of the SFIB is roughly in agreement with the ophiolite theory, the evidence available for consideration is not sufficient to distinguish the SFIB as an ophiolite sequence as opposed to an arc related intrusion.

Representative geochemistry from each rock unit within the SFIB

Sample	SF-149	SF-097	CY-05
Lithology	MG	HET	UM
SiO ₂	46.75	52.49	39.03
Al ₂ O ₃	17.83	14.61	0.49
Fe ₂ O ₃	11	10.42	11.29
MnO	0.166	0.18	0.17
MgO	8.14	8.94	36.2
CaO	10.802	3.956	0.1
Na ₂ O	2.41	4.39	0.05
K ₂ O	0.27	1.25	<0.01
P ₂ O ₅	0.028	0.066	<0.01
Cr ₂ O ₃	0.08	0.02	0.75
TiO ₂	0.49	0.67	0.01
BaO	<0.004	0.03	<0.01
LOI	2.82	3.63	11.85
Total	100.8	100.66	99.94

Table 1 is a representative geochemistry from each rock unit within the SFIB shown as oxides. MG= metagabbro, HET= Heterogenous Altered Zone, UM= Ultramafic. Concentrations expressed in weight %.

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

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The ~1.1 Ga Eagle deposit is a small mafic to ultramafic sulfide-bearing intrusion located in the north central portion of Michigan's Upper Peninsula within Michigamme Township, Marquette County (Figure 1). The Eagle and East Eagle intrusions penetrate Paleoproterozoic rocks of the Marquette Supergroup that were deposited in the 400 km² Baraga Basin during the ~1.85 Ga Penocean orogeny (Ding et al. 2010). The Eagle and East Eagle intrusions are a part of the east-west trending Marquette-Baraga dike swarm that is associated with ~1.1 Ga Midcontinent Rift System (MRS) magmatism (Ding et al. 2010). The age of the Eagle intrusions were determined using uranium-lead dating to be 1107.3 ± 3.7 Ma, which constrains their formation to the early stages of Midcontinent Rift System formation (Ding et al. 2010). The current proven and probable reserves for Eagle are 5.2 million tonnes with an average grade of 3.11% Ni, 2.55% Cu, 0.08% Co, 0.69 gpt Pt, 0.47 gpt Pd, and 0.28 gpt Au (R. Mahin, pers. comm.).

This study will attempt to constrain the mechanisms responsible for the formation of sulfide minerals at the Eagle deposit and the source(s) of external sulfur required to produce the sulfide ores. Principle objectives include identifying the source(s) of external sulfur required to form sulfide minerals and the geochemical/ petrological relationships between the intrusions, country rocks and sulfide deposits. It is well known that the Eagle intrusion hosts high-grade Ni-Cu sulfide ores, while the East Eagle intrusion is weakly mineralized (Ding et al. 2010). As of now a relationship between the two intrusions has not been well established. Further analysis will attempt to constrain the connection between the Eagle and East Eagle intrusions. Geochemical studies done through previous research have suggested multiple sources of external sulfur from Archean and Paleoproterozoic country rocks, even though sulfur isotope signatures are indicative of mantle values (Ding et al. 2012). Further analysis of sulfur isotope data from the Eagle and East Eagle deposits will help to address the question of external sulfur in the magmatic system. Petrographic analysis of rocks from the intrusions and the country rocks will be used to study textural characteristics. From the results generated in this study we hope to identify a set of characteristics that can be used for the identification of other sulfide deposits in the Upper Peninsula of Michigan.

Preliminary hand sample analyses of previously collected core samples have yielded three main rock types in decreasing olivine contents: feldspathic peridotite, melatroctolite and olivine melagabbro (Ding et al. 2010). Primary sulfur textures are disseminated, semi-massive and massive sulfide mineralization with major sulfide minerals of pyrrhotite, chalcopyrite, pentlandite and traces of bornite. Disseminated sulfide mineralization tends to occur as scattered blebs with 3-15% sulfide minerals. Semi-massive sulfide mineralization occurs as a net-textured matrix containing 30-50% sulfide minerals. Massive sulfide mineralization is characterized by a leopard-textured matrix with stringers of sulfide minerals. Massive sulfides contain >50% sulfide minerals.

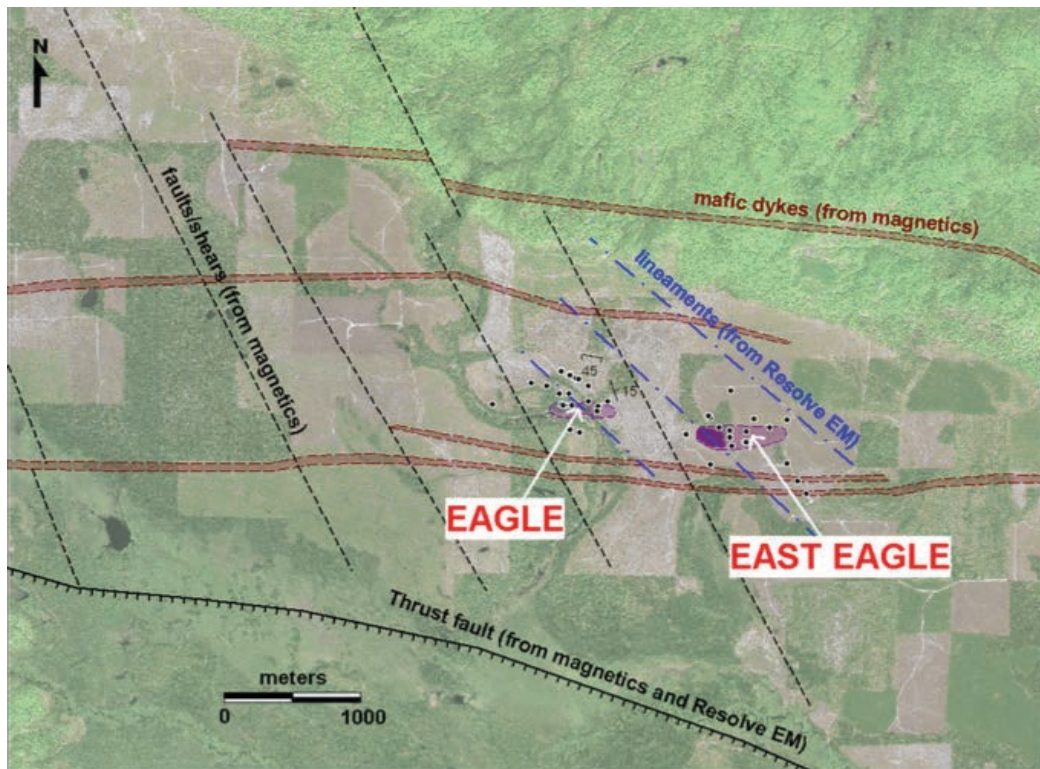


Figure 1: Eagle area geology. Mafic dykes determined from magnetics are shown in red. Purple zones are the locations of the Eagle and East Eagle intrusions. Fault zones determined from magnetics are shown as black lines. Blue lines represent gravity lineaments from Resolve electromagnetics. Black dots are representative of borehole locations.

From: Rossell et al. 2005

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

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The Natural Resources Research Institute (NRRI) 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 (PM) within currently operating taconite processing plants, in MIR communities surrounding taconite mining/processing operations, and in population centers in Minnesota not associated with taconite mining. Characterization studies of age-dated lake sediments are also being conducted to determine the composition of past PM deposition. NRRI's sampling and characterization work represents the community/environmental component of the Minnesota Taconite Workers Health Study, a broad University of Minnesota (UM) research effort involving both the NRRI and the School of Public Health.

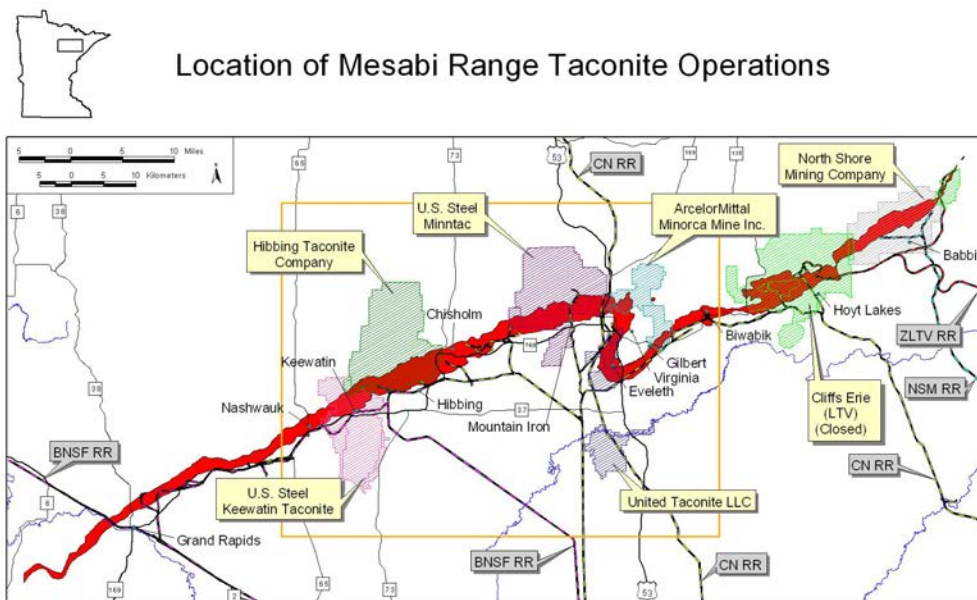


Figure 1. Locations of taconite processing plants on the Mesabi Iron Range being sampled during this study (after Oreskovich and Patelke, 2006)

Air sampling was performed within taconite operations, MIR communities, and non-MIR communities by NRRI scientists during both winter and summer seasons from 2009-2012. Sampling was conducted at four process locations within taconite operations, including: 1) secondary crushers; 2) magnetic separators/concentrators; 3) agglomerators/ball drums; and 4) kiln/pellet discharge areas. Community sampling took place on centrally-located rooftops of public buildings, or in the case of the northern most background site, in a remote sampling location to evaluate the air quality away from the MIR. Airborne particles were collected using: 1) a micro orifice uniform deposit impactor (MOUDI) (Marple et al., 1991, 2014), which enables size-

fractionated PM collection; and 2) a Total Filter Sampler (TFS). Particulate matter was evaluated via gravimetric analysis and was subsequently subjected to comprehensive 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 PM obtained from sampling at the taconite operations and MIR/non-MIR communities. This includes analysis of 55 taconite plants; 73 northeastern Minnesota community and 6 Minneapolis samples. Lake sediment analysis has been completed, 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).

Taconite plant results to date are as follows:

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

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Geology and geochronology of Archean rocks in the International Falls and Littlefork 30X60' quadrangles, north-central Minnesota

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The International Falls and Littlefork quadrangles provide a transect across parts of 3 subprovinces of the Archean Superior Province—Wabigoon, Quetico, and Wawa (Fig. 1). The interpretation of bedrock geology described here was recently published as MGS *Miscellaneous Map M-197*. The map incorporates field work and geophysical modeling by the authors, augmented by lidar, air photography, reprocessed aeromagnetic data, and unpublished field notes of former MGS geologists. In addition, 4 samples were submitted for high-precision U-Pb geochronologic analysis of zircons (Fig. 2) to quantify ages for some units and temporally constrain some events. The map depicts a complex history of volcanism, sedimentation, intrusion, multiple episodes of migmatization involving partial melting and melt dispersion, and several periods of deformation and metamorphism.

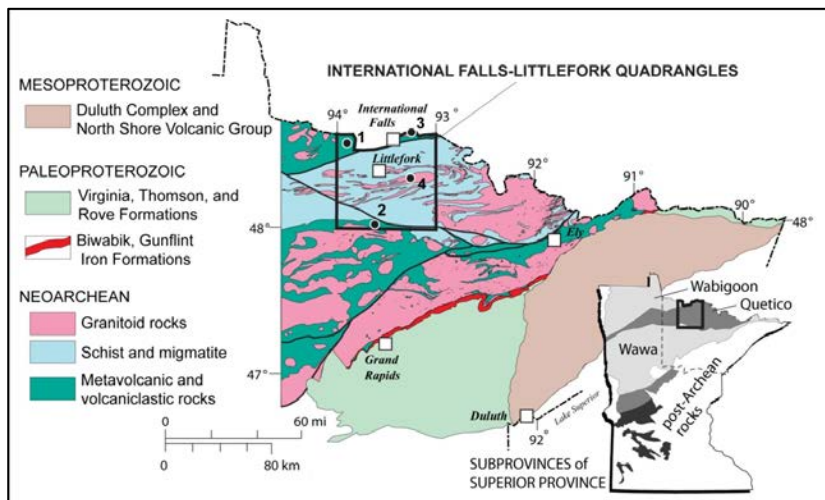


Figure 1. Generalized geologic setting of subject map area showing the approximate locations from which samples were taken for geochronologic analysis (solid circles #1-4). See Fig. 2 for sample details.

The structural grain of the subprovinces is largely a product of three major orogenic events—each involving a component of NW-SE-directed compressional and transpressional deformation—referred to here as D₁, D₂, D₃. The Wabigoon and Wawa subprovinces are greenstone-granite terranes inferred to represent oceanic and island arc settings. The intervening Quetico subprovince consists of sedimentary rocks deposited in continental margin and oceanic environs that were subsequently deformed, metamorphosed, partially melted, and multiply intruded. Various estimates bracket volcanism in the Wabigoon subprovince in Ontario between ~2728-2725 Ma. Geochronologic analyses conducted for this mapping project indicate that a younger sequence of felsic volcanic strata (2702.9 ± 0.6 Ma) marks the southernmost part of the subprovince (Figs. 1 and 2, sample 1.). Similar rock types occur in the northern Wawa subprovince, but ages there are less well constrained, as only a single age of ~2722 Ma exists from a sample acquired 85 miles east of the map area. A new age of 2715.8 ± 0.5 Ma (Figs. 1 and 2, sample 2) acquired from felsic volcanic rocks in this map area establishes broad equivalence across the northern part of the Wawa subprovince. Rocks of the Quetico subprovince consist of biotite-plagioclase schist, granitoid and minor mafic intrusions, and complex migmatite containing multiple paleosomatic and neosomatic components. Based on detrital zircons in Canadian analogs, the schist was derived from graywacke and pelitic sediments deposited ~2698-2692 Ma in an accretionary prism during early

stages of collision between the Wawa subprovince island arc to the south, and the Superior craton (superterrane) to the north. Later stages of this D₁ collisional event produced tilting, folding that included broad nappe structures locally, and thrust imbrication of volcanoplutonic rocks in subprovinces north and south of the Quetico, and recumbent folding within the Quetico. This D₁ deformation was followed by what may have been a regional extensional event that produced localized calc-alkalic volcanism, and sediments containing clasts derived from all precursor rock types deposited in isolated, unconformity- and fault-bounded basins. The remnants of one such basin in the International Falls area is known as the Seine Group. A new age of 2693.9 ± 0.6 Ma was acquired from a clast of trachyandesite in Seine conglomerate (Figs. 1 and 2, sample 3). A second deformation event (D₂) occurred at about 2680 Ma during the Minnesotan orogeny. It produced regional penetrative fabrics, folds, and prograde metamorphism in all 3 subprovinces, and partial melting of Quetico schist to form an early suite of leucogranite, granodiorite, trondhjemitic, and tonalite that is interlayered on all scales with biotite schist, forming complex migmatites. A third deformation event (D₃) is manifest in shear and fault zones in the volcanoplutonic subprovinces; and broad, east- and west-plunging folds (synforms, antiforms) of D₂ fabrics in the Quetico subprovince. At least part of this deformation was synchronous with or just preceded migmatization and emplacement of 2-mica leucogranite and slightly younger, typically red, variably magnetic biotite granite known as the Lac La Croix. An age of 2661.3 ± 0.3 Ma was acquired in this map area from a late granitic intrusion lithologically similar to the Lac La Croix (Figs. 1 and 2, sample 4). The grade of metamorphism is more or less symmetrical along the northeast-trending axis of the Quetico subprovince, having greenschist facies at the margins, and middle to upper amphibolite facies near the axis. Metamorphism was generally syntectonic with D₂ and D₃ deformations; and a contact metamorphic overprint occurs locally in rocks adjacent to the Lac La Croix Granite and similar late intrusions. The axis of the Quetico is coincident with a large post-metamorphic anticlinorium, increased neosome abundance, and moderately high magnetic and gravity expression, despite the presence of less dense rocks at surface. Collectively, these attributes indicate exposure of more deeply buried crust. The presence of dense, magnetic rocks at depth that may represent the uplifted floor on which sedimentary strata were deposited.

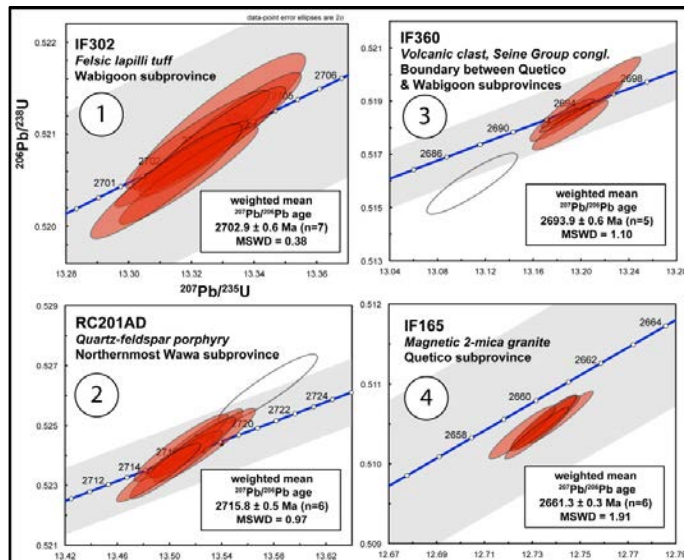


Figure 2. Concordia plots showing results of LA-ICPMS geochronologic analysis of zircons. Ages reported here are taken from calculations of $^{207}\text{Pb}/^{206}\text{Pb}$. Details of this work are available from published MGS digital files associated with *Miscellaneous Map M-197*. Sample locations in UTM NAD83 coordinates:

1. 436644E/5382588N
2. 454692E/5316937N
3. 485860E/5383472N
4. 476489E/5354520N

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Rainy River, northwestern Ontario's first meteorite

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The only meteorite previously known from northern Ontario is the Osseo iron meteorite, found in 1931 in the easternmost part of Ontario in the vicinity of the Cobalt silver camp (Buchwald, 1975). In 2000, Robert Weaver found a 3.26 kg iron object in a field on his farm, near Rainy River, Ontario. It is now in the possession of Howard Williams of Winnipeg, who presented the specimen for identification in 2013. A polished slab of 47.26 g has been deposited as the type specimen in the Royal Ontario Museum.

The meteorite is oxidized on its exterior and is of a roughly ellipsoidal shape with dimensions of 17.4 cm x 13.2 cm x 9.5 cm (Figure 1). The interior is unoxidized except minor patches near the thin exterior iron oxide crust and along kamacite grain boundaries. The meteorite is an octahedrite, with coarse kamacite lamellae of irregular width and a stubby aspect of L: W= 3:1 to 4:1. The residual taenite lamellae are very narrow where preserved and only one area of net plessite was observed (Figure 2).

The other minerals present are troilite, in the form of small, intergranular veinlets, and schreibersite, as small, globular forms and as small, euhedral, crystals known as rhabdites. The rhabdites are very abundant and display strong preferred orientation within kamacite lamellae.

The meteorite has experienced moderate cosmic shock as seen in the abundant Neumann lines, some of which have been bent in places. The kamacite lamellae have been polygonalized due to brittle fracture. Hardness of kamacite (VHN=254±13) and taenite (VHN= 492±28) is also evidence of work hardening due to shock.

Analysis by neutron activation yielded the following minor and trace element composition: Ni= 7.23 wt%, Co=0.463 wt%, Sb= 410 ppb, all in ppm Cr=19, Cu=114, Ga=91, Ge=170, As 13.9, W=<10, Re=0.64, Ir=3.87, Pt=7.8, Au=1.47. Together with the details of the structure, the meteorite is a member of the group IAB complex, as defined by Wasson and Kallemeyn (2003). However, the Au-content is at low extreme of the group, thus suggesting that the meteorite may belong to the Algarrabo duo of Wasson and Kallemeyn. Moreover, other trace element contents, especially Ge and Ga, are similar to those of one of the duo, Livingston (Tennessee). As well, the structure of Livingston (Tennessee) is similar to that of Rainy River in that Ni-content does not agree with the normally expected kamacite bandwidth, which should be in the range of 2.5-3 mm in well-defined Widmanstaetten structure (Buchwald, 1975). Buchwald further proposed an usual thermal history for Livingston (Tennessee), which may also have applied to Rainy River.

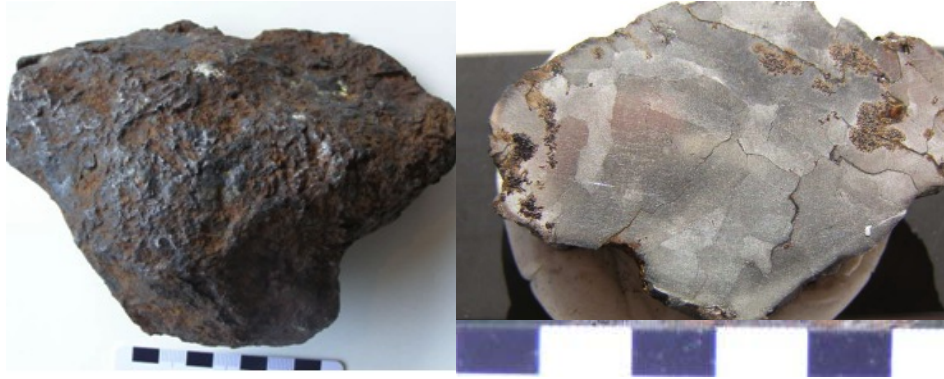


Figure 1: Main mass of the Rainy River meteorite, less off-cut for type specimen. Scale in cm.

Figure 2: Polished surface of the type specimen. Some kamacite lamellae outlined by weathering. Scale in cm.

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Studies on PDFs in shocked quartz from distal Sudbury ejecta in the Thunder Bay area compared with Chicxulub

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Planar deformation features (PDFs) in Sudbury ejecta in the Marquette, Michigan area have been studied briefly by Cannon et al. (2010) and more extensively by Pufahl et al. (2007) and briefly in the Thunder Bay area by Kissin & Brumpton (2014). We have made an extensive study of PDFs in quartz from ejecta from various localities in the Thunder Bay area. A total of 153 PDFs from 104 quartz grains were measured on the universal stage (Table 1). Of these, 77 PDFs were measured in 55 grains within accretionary lapilli, and 76 PDFs were measured in 49 grains in the matrix of the ejecta. Indexing was carried out by both the use of stereographic projection and use of the ANIE program of Huber et al. (2011). Agreement between the two methods was generally good, although the ANIE program eliminated drawing errors that may be introduced in the stereographic projection method.

Comparison of the distribution of indexed PDFs in grains in lapilli vs. those of grains in the matrix revealed no significant difference at 95% confidence using the Wilcoxon matched-pairs signed-ranks test, although the source of the grains may have differed. Differences were noted in that grains within lapilli are smaller (50-100 μm) as opposed to those in the matrix (100-500 μm). As well, grains in the matrix were frequently rounded, whereas those in the lapilli were almost always angular. These observations suggest that the grains in lapilli were predominantly from crystalline basement rocks of the target area, whereas those in the matrix had a considerable contribution from sedimentary surficial rocks.

The distribution of the PDFs in this study was compared with the results of Nakano et al. (2008) who studied PDFs in distal ejecta at various distances from the Chicxulub impact crater (Table 2). The PDF sets are grouped in five-degree bins containing most of the major PDFs. Note that Nakano et al. did not include the $\{10\bar{1}4\}$ set, which is abundant in both their and our data sets. Analysis of all the data sets in Table 2 using the Friedman test yields a Friedman Statistic of 0.9592. Thus, the probability is $> 95\%$ that the sum of the ranks (rows) is the same in each column. As well, the PDF sets from each of the Chicxulub sites was compared with the Sudbury ejecta set using the Wilcoxon matched-pairs signed ranks test. In all cases except for the DSDP 536 set, the nonparametric Spearman correlation coefficient and the one-tailed P value indicated pairing of the ranks. The DSDP 536 data were slightly less than statistically significantly paired. These tests indicate the similarity of distribution of PDF sets in Sudbury and Chicxulub distal ejecta.

The formation of PDFs in quartz has been experimentally calibrated in response to shock pressure, as reviewed by Stöffler and Langenhorst (1994). The PDFs in Sudbury and Chicxulub ejecta correspond to a wide range of shock pressures extending as high as 35 GPa. Even higher shock pressures are indicated by the occurrence of diaplectic quartz glass and incipient melting of quartz grains. This range of shock pressures is indicative of the impact process and the location of the quartz grains to it, as has been modeled by Nakano et al. (2008).

{0001}	3.9
{1014}	30.1
{1013}	13.7
{1012}	7.8
{1122}	1.3
{1011}	2.6
{2132}	5.9
{1121}	5.2
{2131}	5.9
{2241}	2.0
{3141}	1.3
{4041}	0
{5161}	7.8
{1010}	1.3
{1120}	0.7
{5160}	2.6
unindexed	7.8

Table 1. Absolute frequency of PDF sets (153 sets)

Table 2. PDF sets in Sudbury ejecta compared with distal Chicxulub ejecta sets						
	Thunder Bay area 650km	YAX-1 60km	DSDP 536 500km	Cacarajicara Fm 500km	Peñalver Fm (mean) 500km	Moncada Fm (mean) 500-800km
{0001}	5.1	0	3.33	1.78	4.84	4.1
{1013}	30.7	32.3	49.48	47.27	42.71	40.5
{1012}	15.4	24.6	7.92	18.22	16.74	12.9
{1122}+{1011}	7.7	1.6	15.73	12.74	19.85	22.0
{1121}	14.1	24.6	6.77	7.26	5.75	9.8
{2241}+{5161}	11.5	13.9	13.43	7.26	6.57	6.0
{1010}+{1120}	6.4	3.1	3.33	5.48	3.51	4.6
no. of sets						
absolute	78	80	102	68	79	335
frequency (%)						

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Geologic mapping of Neoarchean and Proterozoic rocks near Knife Lake, northeastern Minnesota, by students of the Precambrian Research Center's 2014 field camp
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The University of Minnesota-Duluth's Precambrian Research Center conducted its eighth annual field camp in 2014, and this presentation is one of a series that show results of "capstone" mapping projects. The projects test student skills by creating new geologic maps in areas of poorly known geology, which benefits both students and mentor organizations. This capstone project involved mapping an area of ~12 mi² in the Boundary Waters Canoe Area Wilderness (BWCAW), centered on the south arm of Knife Lake (Fig. 1). The resulting map provides details about the complex depositional and tectonic history of a Neoarchean metavolcanic and metasedimentary terrane that is part of the Wawa subprovince of Superior Province, and rare diabasic dikes that intruded it.

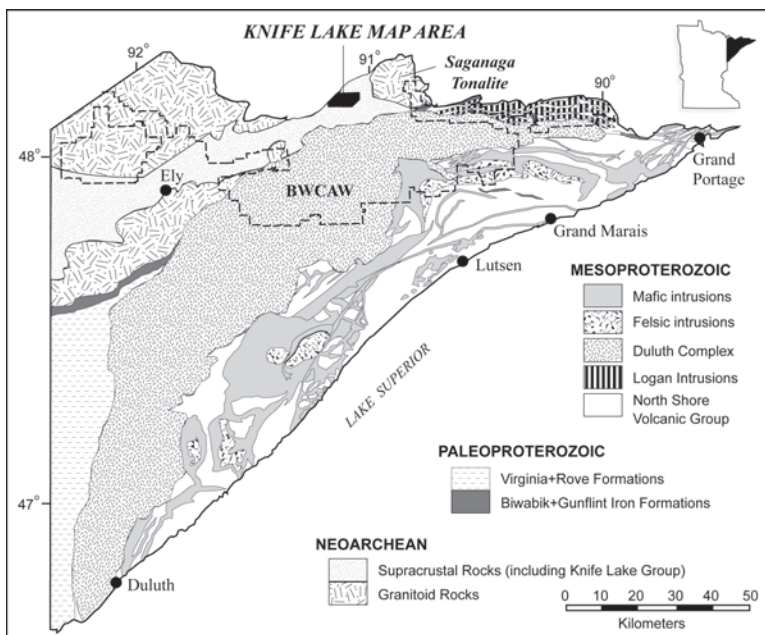


Figure 1. Generalized bedrock geologic map of NE Minnesota showing the Knife Lake capstone area (solid black polygon). The Neoarchean unit labeled "Supracrustal Rocks" encloses both older volcanic sequences and younger, largely sedimentary ones. Outline of Boundary Waters Canoe Area Wilderness is dashed.

The Neoarchean rocks in the central BWCAW comprise a Timiskaming-type extensional basin and its apparent wall- and floor-rocks. The geologic units are parceled into structural lozenges separated by anastomosing shear and fault zones. Although rock types are comparatively pristine within each lozenge, correlation of units from one fault-bounded block to another is challenging. Nevertheless, this project and the several that

preceded it in prior years of mapping attempt to "unstrain" the rocks within each parcel to reveal stratigraphic variations that may reflect fluctuations in basin geometry and progressive erosional dissection of basin wall rocks. Understanding the lithologic details and the apparent post-depositional tilt of individual lozenges of rock are essential to this objective. The Knife Lake map area provides a window into this complex terrane. It consists of 2 sequences of broadly folded metasedimentary rocks that are part of the Knife Lake Group, separated by an east-trending block of vertically dipping, southward-facing, variolitic metabasalt as thick as 0.5 km. The sedimentary strata include tuffaceous graywacke and mudstone, locally containing conglomeratic and gritstone layers having clasts of the metabasalt, Saganaga Tonalite (~2.69 Ga), and other calc-alkalic igneous rocks. All these rocks were deformed and metamorphosed to very low greenschist facies during the Minnesotan Orogeny (~2.68 Ga)—thus constraining deposition of the sediments to the approximate interval 2.69-2.68 Ga. The primary objective of this mapping was to delineate and interpret the nature of contacts between the

apparently older metabasalt and superjacent sedimentary strata derived in part from it. Highlights of our mapping include the following:

- 1) The abundance of graded sequences of sand- to mud-sized detritus implies deposition of much of the strata was submarine (or lacustrine).
- 2) Local sequences of polymictic and oligomictic conglomerate, and arkose containing matrix-supported, subrounded metabasalt fragments as large as 20 cm implies occasional subaerial deposition of more chaotic debris flow, alluvial fan, and fluvial sediments. This is consistent with episodic uplift of wall rocks adjacent to the developing fault- and unconformity-bounded basin.
- 3) The abundance of white-weathered tuff and tuffaceous siltstone and mudstone implies calc-alkalic volcanism may have been contemporaneous with deposition, or volcanic strata were not fully lithified at the time of deposition.
- 4) Although both northern and southern sedimentary sequences are broadly folded; stratigraphic facing near contacts with the medial basalt block is consistently away from the basalt.
- 5) The northern contact of basalt with sedimentary strata is poorly exposed, but appears to be a fault. It lies along the down-section part of the basalt, and thus is stratigraphically discordant.
- 6) The southern contact of basalt with sedimentary strata is visible in several areas where it varies from an angular unconformity developed on relatively fresh basalt, to one developed on paleosaprolitic basalt. A spectacular paleosaprolite of basaltic protolith is exposed at one locality.
- 7) Major fold axes in the northern sedimentary sequence plunge shallowly to the northeast; those in the southern sequence plunge to the southwest.
- 8) From these observations it appears that the block containing basalt unconformably overlain by the southern sedimentary sequence was uplifted on its north side (Fig. 2). In addition, the divergence of major fold plunges in sedimentary sequences north and south of the fault implies a scissor motion that tilted the southern block down on the west. Judging from inferred structural position and lithologic

similarities, it is also likely that some portions of the two sedimentary sequences may have been fault-duplicated. Although the precise age of rare diabase dikes is unknown, most trend northwest and dip nearly vertically, similar to the Paleoproterozoic Kenora-Kabetogama dike swarm. However, a Mesoproterozoic age may be indicated by the trend of one dike that is nearly horizontal, which is quite anomalous for Paleoproterozoic dikes in the Superior Province. We speculate that it may represent emplacement at very high levels in the crust, where comparatively less lithostatic load permitted delamination along horizontal exfoliation structures in host rocks. *This and other capstone mapping projects can be viewed at www.d.umn.edu/prc.*

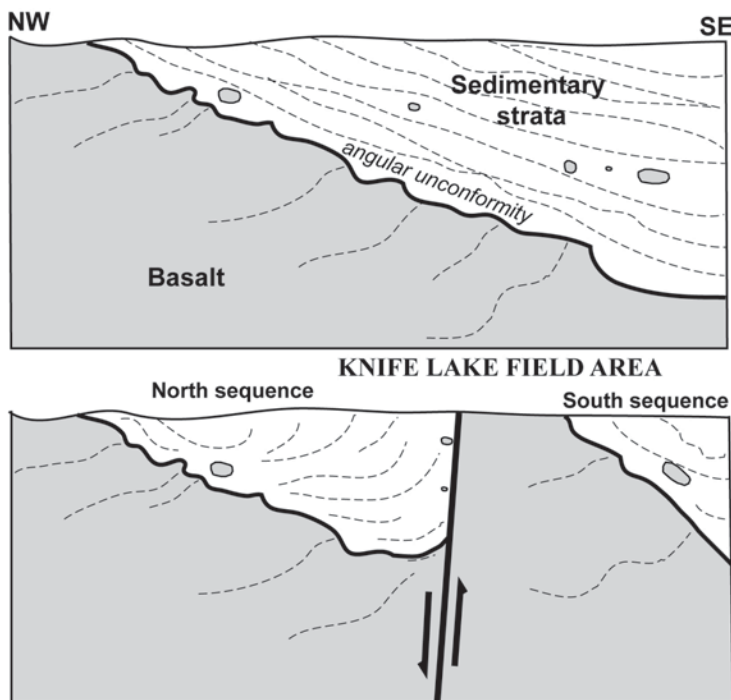


Figure 2. Schematic cross-sectional model to explain the distribution of map units and partial repetition of stratigraphic sequences by faulting.

Structural control on the Borden Gold deposit, Chapleau, Ontario

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The multi-million-ounce Borden Gold deposit is located 20 km east of Chapleau, within the Wawa Subprovince of the Superior Province. Interestingly, it is hosted in upper amphibolite to granulite facies metamorphic rocks at the southern margin of the Kapuskasing Structural Zone. Competent lithons 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. Competency contrasts between the granulite and retrograde amphibolite facies lithologies created heterogeneous strain, ideal for gold mineralization, during ductile deformation at amphibolite facies metamorphic temperatures. Gold is typically observed in competent rocks with weakly developed foliation and also in competent rocks that are bordered by strongly foliated units. Garnet-biotite geothermometry on unzoned almandine garnets yields temperatures ranging from 579°C to 690°C $\pm$ 50°C for metamorphism of the garnet-biotite schist. Temperatures increase from the garnet core towards the rim, indicating that garnets equilibrated rapidly during prograde metamorphism from the upper amphibolite to granulite facies. Fieldwork and microstructural analysis have identified a variety of competent lithologies and minerals, which provide low-strain environments for gold mineralization. On the macroscopic scale, the relict granulite facies rock behaves more competently than the retrograde amphibolite facies rock. Competent minerals that provide a low-strain site for fluid transport and gold mineralization include relict orthopyroxene, garnet, pyrite and coarse sillimanite. Preliminary results indicate an important relationship between gold mineralization, metamorphism and deformation, and understanding this relationship will benefit exploration and development of the Borden Gold deposit.

Incorporation of Duluth Complex maps into GIS platform **LENTSCH, Nathan¹ and MILLER, Jim¹**

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In 2001, Jim Miller and colleagues compiled much of the mapping existing at the time into a digital geologic map and database for the Duluth Complex that was published by the Minnesota Geological Survey (MGS) as Miscellaneous Map M-119 (Miller et al., 2001). Because this compilation was focused on areas of the complex that were open to minerals exploration, a substantial amount of historical field data collected within the Boundary Water Canoe Area Wilderness (BWCAW) was largely excluded from this digital compilation, this includes data collected by Phinney (1972) and Miller (1986).

In the 1960's, William Phinney, an igneous petrology professor at the University of Minnesota-Twin Cities, conducted bedrock mapping for the MGS in the northwestern part of the Duluth Complex. In the summers of 1966 to 1969 Phinney conducted extensive reconnaissance mapping of lakeshore exposures by canoe and floatplane support in areas of the Duluth Complex now contained entirely within the BWCAW (established in 1976) and only accessible by canoe or by foot. Although he did not publish any maps from this field work, Phinney summarized his studies in the MGS's Centennial Volume on the Geology of Minnesota publication (Phinney, 1972). In 1970, he left the University to take a job with NASA. In 1979, Dr. Phinney passed along all field journals, maps, and thin sections of his Duluth Complex mapping to Dr. Miller, who at the time was a PhD candidate planning his own detailed mapping study in part of an area of the complex that Phinney had previous reconnaissance mapped. In 1981, Dr. Miller conducted four months of detailed mapping in an area focused on the Lake One - Lake Four chain in the Snowbank 7.5' quadrangle. Miller's outcrop mapping is preserved only as a blueprint map in his PhD thesis (Miller, 1986), field maps on airphoto bases, and field notebooks. Only his geological linework and structural measurements were digitized for the M-119 map. None of Phinney's original outcrop data has been digitized.

The goal of my research project, which was funded by the University of Minnesota Duluth's UROP program (Undergraduate Research Opportunity Program), was to compile outcrop-based field data into a digital database using ArcMAP 10 for the area of the Duluth Complex mapped by Phinney (unpublished data) and Miller (1986) in the Snowbank Lake 7.5' quadrangle. Digitally compiling these field observations, measurements, and sample locations is important for several reasons: 1) it will preserve an important database of geologic information, some of which previously only existed as fragile paper copies; 2) whereas only one copy of Phinney's and Miller's field data had existed, digitally archiving their field maps and observations will allow open access to future geologists and researchers; 3) with most of their mapping covering areas deep into the BWCAW, it is likely that in many areas, their mapping will be all that exists for the foreseeable future; and 4) this project gave me the opportunity to learn the powerful geospatial tool that is ArcMap.

To efficiently and accurately trace the locations and shapes of the numerous outcrops mapped by Dr. Miller, scans of field maps on aerial photo bases were inserted as a layer under a partially transparent topographic map layer in ArcMAP. Figure 1 shows an example of what this process looked like. As of this writing, over 1,000 outcrops have been digitized, each linked to a table of attributes. Recorded attributes include the outcrop station, the date visited, the major and minor lithologies observed, and a short description for each. An example of this table is shown in Figure 2.

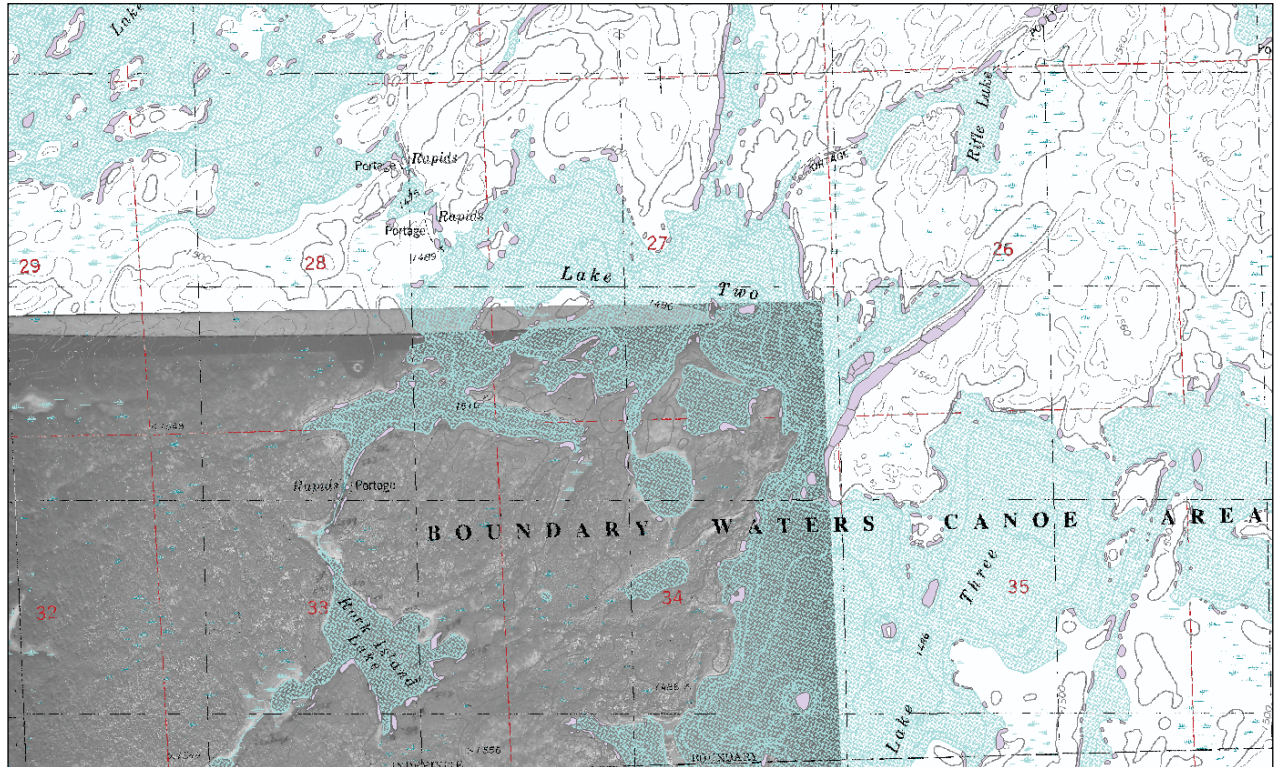


Figure 1: GIS map showing areas of the BWCAW. Aerial photo as a base layer in bottom left. Light gray outcrops around Lake Two were digitized from Dr. Miller's 1981 mapping data (Miller, 1986).

FID	Shape *	ID	STATION	DATE	GEO	MAJOR LITH	MINOR LITH	DESCRIPTION
46	Polygon	0	298	71681	JDM	Troctolitic Anorthosite	Olivine	Foliated, layered olivine
45	Polygon	0	299	71681	JDM	Troctolitic Anorthosite	Olivine	Fine grained, poor exposure
44	Polygon	0	300	71681	JDM	Anorthosite	Olivine	Good foliation, olivine oikocrysts up to 7cm, oikocrysts show layering
38	Polygon	0	301	71681	JDM	Troctolite	Augite, FeO	Med-grained, poor foliation
53	Polygon	0	302	71681	JDM	Troctolite	Olivine	Med- to fine-grained, good foliation, olivine <45%
54	Polygon	0	304	71681	JDM	Troctolite/Anorthosite	Olivine, Augite, FeO	Gabbroic anorthosite, foliated, troctolite finer grained
57	Polygon	0	305	71681	JDM	Troctolite	Augite, FeO	Moderate foliation, megacrysts of plagioclase, oikocrysts of augite
42	Polygon	0	306	71781	JDM	Troctolitic Anorthosite	Olivine	Foliated
197	Polygon	0	307	71781	JDM	Anorthosite	Olivine, Augite, FeO	Olivine oikocrysts elongate in foliation, average 6cm X 3cm
43	Polygon	0	308	71881	JDM	Troctolitic Anorthosite	Olivine, Augite, FeO	Med- to coarse-grained, good foliation, oikocrysts, troctolitic dike
61	Polygon	0	309	71881	JDM	Troctolitic Anorthosite		Well foliated, poor exposure
62	Polygon	0	310	71881	JDM	Troctolitic Anorthosite	Augite, FeO	Med- to coarse-grained, strong foliation
63	Polygon	0	311	71881	JDM	Troctolitic Anorthosite	Augite, FeO	Augite oikocrysts, poor foliation
65	Polygon	0	312	71881	JDM	Troctolitic Anorthosite		Good foliation, weathered
66	Polygon	0	313	71881	JDM	Troctolitic Anorthosite	Olivine	Med- to coarse-grained, ranges from troctolitic anorthosite to anorthosite, olivine oikocrysts, foliated

Figure 2: Table of attributes associated with outcrops in GIS. Each outcrop can be referenced by major/minor lithology and physical description.

Given the time constraints of this project, only Dr. Miller's field data was able to be digitized thus far. This leaves the door open for future work done by another eager undergraduate who would like to become familiar with GIS and the Duluth Complex mapped by Phinney.

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Geology and geochemistry of the Lang Lake greenstone belt, Uchi Domain, Superior Province

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The Lang Lake greenstone belt, located 70 km WNW of Pickle Lake, Ontario, lies within the central Uchi domain of the greater North Caribou terrane. The belt is composed of ca. 2750 Ma dominantly greenschist facies volcanic, volcanoclastic and sedimentary rocks, and is intruded by various syn-volcanic and syn-to-post-tectonic plutonic rocks.

Following the initial discovery of gold in the Shonia Lake area in 1928 and subsequent mapping of the surrounding greenstone by Laird (1930), the Lang Lake greenstone belt received little attention until mapping by the Ontario Geological Survey in the 1970s (Fenwick 1970, 1971; Fenwick & Srivastava 1972). These 3 maps were compiled and ground-checked as part of “Operation Pickle Lake” by Sage and Breaks (1973), who later released an Ontario Geological Survey Open File Report (Sage and Breaks 1982) which included a brief lithologic description of the greenstone belt.

Unlike the neighbouring greenstone belts of the central Uchi domain, which have been subject of modern geological studies (government and academic) throughout the 1990s and 2000s, the Lang Lake greenstone belt represented a significant gap in our regional geoscience knowledge. To fill this gap and to supplement the Cat Lake First Nations land use plan, the Lang Lake greenstone belt was mapped during the 2014 field season at a scale of 1:20,000. 278 hand samples were collected for whole rock major and trace element geochemical analysis, 6 samples were submitted for U-Pb zircon geochronological analysis, and 16 samples were submitted for whole rock Sm-Nd isotopic analysis as part of an HBS thesis conducted by Matthew Hanewich at Carleton University.

Preliminary geochemical analysis of the coherent facies metavolcanic rocks and syn-volcanic dikes indicates the presence of primitive (i.e. derived from “Primitive Mantle”) Fe-tholeiitic basalt, calc-alkaline basaltic andesite and calc-alkaline FII rhyolite. Volcanoclastic rocks contain whole rock major and trace element compositions equivalent to calc-alkalic basalt, andesite, dacite and rhyolite, suggesting that they were proximally sourced, and may represent a mixture of material from the aforementioned tholeiitic and calc-alkalic flows.

Interflow volcanoclastic mudstones and wackes are intercalated with bands of magnetite-chert iron formation which extend across the entire strike-length of the greenstone belt. Similar bands of iron formation are interbedded with clastic metasedimentary rocks which dominate the eastern half of the greenstone belt. Facies include mudstone, wacke, arenite and several lenses of granitoid-clast-bearing conglomeratic rocks similar to those found in the Billet Assemblage of the nearby Meen-Dempster greenstone belt (Stott and Corfu 1993). Whole rock geochemical trends and concentrations overlap those of the metavolcanic and metavolcanoclastic rocks, thus making them difficult to distinguish geochemically.

Whole rock geochemical analysis of the mafic intrusive rocks at McVicar Lake and the tonalitic stock which cuts them suggests that these intrusive rocks represent a high level magma chamber which acted as a feeder conduit for the overlying metavolcanic rocks. Magma mingling, assimilation, hybridization and fractional crystallization textures are visible at an outcrop scale throughout the mineralogically and geochemically diverse pluton, supporting the proposed genetic relationship between the local intrusive and extrusive igneous rocks.

The supracrustal rocks are surrounded and intruded by calc-alkalic, magnesian, peraluminous to metaluminous biotite tonalite to granodiorite. A pluton of alkali-calcic syenodiorite to quartz syenite of unknown age is hosted by volcanoclastic rocks between Lang Lake and McVicar Lake, and contains trace element concentrations indicative of a metasomatised mantle source. In contrast the late alkalic Otokwin pluton (granodiorite to gabbro), just northeast of the greenstone belt, and several intermediate alkalic dikes, appear to have been derived from an unaltered mantle source.

Four phases of deformation have been identified within the greenstone belt, including i) one purely compressional event that occurred during emplacement of the surrounding granodioritic intrusions, ii) a sinistral transpressional event which produces the S-asymmetry observed throughout the belt and within the surrounding intrusive rocks, iii) a dextral transpressional event associated with movement along the northwest trending Bear Head Shear Zone at the west end of the belt, and finally another iv) compressional event which formed a series of discrete NNE-trending shear zones that offset all of the previous structural features.

This mapping project has provided some broad insights into the petrogenesis and structural history of the Lang Lake greenstone belt. The belt contains abundant prospects for further academic study which would help relate this belt to others within the Uchi province, provide new insights into Archean igneous processes, and aid in the pursuit of economic gold mineralization.

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The Eagle Mine in Production: U.S.A.'s Only Primary Nickel Producer
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Lundin Mining Corporation's Eagle Mine is located in Marquette County in the Upper Peninsula of Michigan. The Eagle deposit is an ultramafic-intrusive-hosted high grade Ni-Cu deposit, with associated cobalt, platinum, palladium, silver and gold. Published (2014) P&P reserves for Eagle are 5.2MT @ 3.11% NI and 2.55% Cu. Lundin acquired the partially developed project from Rio Tinto in July, 2013. Capital expenditure, including purchase and construction completion are \$770M.

As of Q1 2015, full commercial production was achieved significantly ahead of schedule. Annual production over the first three full years (2015 - 2017) is expected to average approximately 23,000 tonnes of nickel and 20,000 tonnes of copper per annum, with additional by-product credits of precious metals and cobalt.

The orebody is accessed from surface by a 1 mile long, 13% grade decline. The mine employs longhole open stoping. The majority of the stopes will be mined as transverse bench and fill stopes, with some thinner zones mined as longitudinal retreat stopes. Stope drilling is accomplished by top hammer vertical drilling from the top sill cut with a breakthrough to the bottom sill cut. Stope dimensions are 10 meters wide by 18 to 29 meters high sill to sill. The stope lengths vary with the thickness of the orebody (15 to 85 meters). The sill will be cut the full width of the stopes at 10 meters wide and 5 meters high. Level spacing varies between 18-29 meters and there are nine mining horizons. Stopes will be mined from the bottom up in an alternating sequence of primary and secondary stopes with cemented rock fill in the primaries and rock fill in the secondary stopes. After mining the uppermost stopes, backfill will be placed tight to the stope backs with a jammer to prevent subsidence.

Approximately forty-five truckloads per day deliver ore 65 miles to the Humboldt Mill. The mill is a renovated pellet processing plant with a capacity of 2000 tonne per day. Conventional flotation produces separate nickel and copper concentrates with approximate recoveries of 82% Ni and 93% Cu. Flotation tailings are thickened and deposited subaqueously into the flooded Humboldt open pit. Concentrates are railed directly to either Canadian smelters or to port for overseas shipping. The average life of mine (8 years) production of 17 ktpa Ni and 17ktpa Cu is expected at cash costs (excl. royalties) of approximately \$2.50/lb Ni.

Since inception the company has striven for open and transparent communication with the community. Eagle has committed to a 75% local hire goal, created programs to support small business development, and hosts semiannual town hall meetings. In addition, the company helped develop a precedent-setting third party community environmental monitoring program (CEMP). The CEMP provides independent verification monitoring for the Eagle Mine, Humboldt Mill, and transportation route. Full-time employment, including long-term primary contractors will be approximately 330. Over the 13 year life of the mine, including construction and closure, the economic impact for Marquette County is predicted to be on the order of \$4 billion.

Eagle is actively exploring for additional mineralization. Exploration is largely geology driven and based on an open-system magma conduit (chonolith) model. Efforts have focused on identifying and tracing the feeder dikes to Eagle and a sister intrusion, Eagle East (a.k.a. the Yellowdog Peridotite). In 2014, exploration successfully intersected significant mineralization in what is interpreted as the feeder dike to Eagle East.

Evaporated seawater formed sediment-hosted stratiform copper orebodies and second-stage copper mineralization in the Mesoproterozoic Nonesuch Formation of the Midcontinent Rift
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The Mesoproterozoic North American Midcontinent Rift System contains sediment hosted stratiform Cu deposits at White Pine and Copperwood, which combined host at least 4 Mt Cu and 75 Moz Ag (Nicholson et al., 1992; Bornhorst and Williams, 2013). Main stage sediment-hosted Cu mineralization formed at both deposits during diagenesis at temperatures near or cooler than 100°C. White Pine also contains structurally controlled second-stage mineralization that was likely synchronous with Keweenaw Peninsula native Cu mineralization (Mauk et al., 1992). Here, we report chemical data from fluid inclusions from main- and second-stage mineralization at White Pine to constrain the origin of these mineralizing fluids.

We measured the solute compositions of ore-forming brines from fluid inclusions in main-stage chalcocite, and second-stage calcite and chalcocite from the White Pine deposit. Fluid inclusions were extracted from 100-600 mg of calcite and chalcocite, and analyzed for Na^{+1} , NH_4^{+1} , Ca^{+2} , Mg^{+2} , K^{+1} , Rb^{+1} , Sr^{+2} , Ba^{+2} , Cl^{-1} , Br^{-1} , F^{-1} , $\text{S}_2\text{O}_3^{-2}$, SO_4^{-2} , and acetate using the ion chromatography methods described by Viets et al. (1996).

The Cl-Br-Na data from main- and second-stage minerals from White Pine plot in a relatively small compositional field, with Cl/Br molar ratios that are less than 300, and Na/Cl molar ratios that are less than 0.3. Main- and second-stage fluids may occupy slightly different fields, but this minor difference may only be apparent due to the relatively few analyses of main-stage chalcocite. The Cl-Br-Na data plot close to or along the seawater evaporation curve with no evidence for the dissolution of salt or input from non-marine brines, which would have much greater Cl/Br ratios (Fig. 1). The Na/Cl molar ratios are distinctly depleted compared to those of most basinal fluids worldwide, suggesting that the brines evolved significantly beyond halite precipitation, and approached Mg- and K-salt saturation.

Terrestrial fluvial environments played a key role in the sediment deposition that followed the volcanic phase of the Midcontinent Rift, but debate continues on whether the fine-grained clastic sedimentary rocks of the Nonesuch Formation, which host the White Pine and Copperwood deposits, formed in a marine or lacustrine environment (e.g., Cumming et al., 2013, and references therein). Our data require seawater that evaporated to the point of salt deposition, which supports a marine depositional environment for the Nonesuch Formation. Furthermore, the evaporation of seawater beyond halite saturation required by our data, plus the enormous volume of brine required to form the Cu deposits, would require a significant evaporite basin filled with gypsum, halite, and potentially even bittern salts occurred somewhere in the rift basin. If preserved, the most likely location of this thick evaporite sequence was in the thickest and deepest axial portion of the rift, which lies under present-day Lake Superior.

The similar composition of main- and second-stage brines raises the intriguing possibility that these two stages of mineralization, despite apparently being separated by nearly 60 m.y. (Ohr, 1993), formed from the same brine. If so, a large basin was required to store the large volume of brine necessary to form second-stage Cu at White Pine.

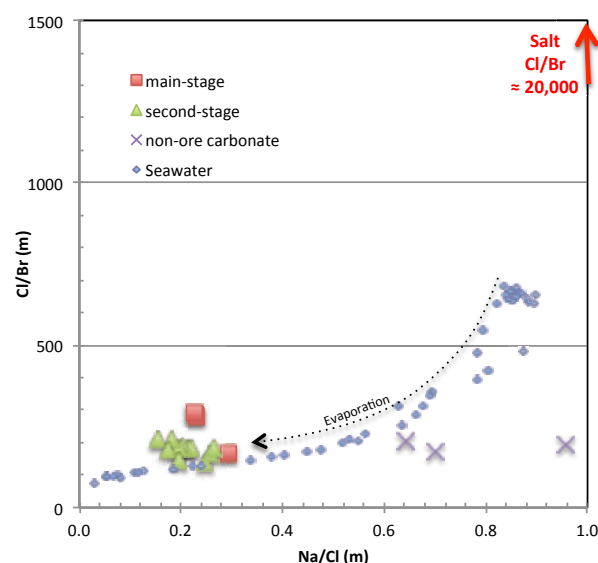


Figure 1: Cl/Br versus Na/Cl molar ratios for main-stage chalcocite and second-stage calcite and chalcocite from the White Pine deposit.

Integrating these results with current understanding of basin architecture and location of deposits may provide new insights into why some areas of the rift produced world-class deposits and other segments are barren. Furthermore, analyses of minerals from the Keweenaw native Cu deposits, which presumably formed synchronously with White Pine second-stage mineralization (Mauk et al., 1992; Bornhorst, 1997), could test whether these large Cu endowments formed from the same fluid, or whether different brines produced mineralization in different portions of the rift.

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Sedimentology and Geochemistry of a 1.4 Ga Continental Playa System, the Lower Sibley Group, Northwestern Ontario: Implications for the Mesoproterozoic Hydrosphere and Atmosphere

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The 900 m thick Sibley Group consists of playa to deltaic to aeolian deposits outcropping north of Lake Superior and east of Thunder Bay. The lowermost 100 m thick succession of highly oxidized siliciclastic rocks and dolostone was deposited in a north-south trending half graben. The sediments can be divided into 15 lithofacies associations representing distinct depositional environments. The lower siliciclastic unit contains: boulder conglomerate-sandstone-dolomite (proximal ephemeral braided stream), pebble to cobble conglomerate (ephemeral braided stream), trough cross-stratified sandstone (braided stream), green sandstone-siltstone (delta), massive cobble conglomerate (transgressive shoreline lag), planar cross-stratified sandstones (nearshore lacustrine sandwaves), and thinning-upward sandstones (lacustrine storm sand sheets). The overlying mixed siliciclastic-carbonate unit contains: red siltstone (non-saline lake), red siltstone-dolomite or dolomitic sandstone (saline lake), and halite-mudstone (ephemeral salt pans). Next is the upper siliciclastic unit with: sheet sandstones (lake infilling) and stromatolitic dolomite-chert (shoreline). After final desiccation of the lake terra rosa soils, collapse breccias and intraformational conglomerates developed. Paleocurrents, detrital zircon geochronology and sulfur isotopes indicate a change in drainage directions resulting in sand sheets infilling the saline lake. Sr isotopes reflect shallow groundwater circulation and lacustrine dolomite containing significant radiogenic Sr. Carbon and O isotopes are heavier upward in the saline lake deposits, probably due to evaporation and residence time effects. Most interestingly, REE patterns for dolomite in the dolomite, stromatolitic shoreline deposits and overlying intraformational conglomerates have patterns similar to modern oxygenated groundwater, whereas the saline lake dolomites have hat-shaped patterns resembling modern groundwater draining waterlogged, organic-rich areas.

Role of felsic and feldspathic rocks in triggering subvolcanic emplacement of mafic intrusions: evidence from the Midcontinent Rift in northeastern Minnesota

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Subvolcanic mafic intrusions make up over 40% of the igneous rocks of NE Minnesota associated with the 1.1Ga Midcontinent Rift. The greatest concentration of mafic intrusions comprise the enormous (~20,000 km³) Duluth Complex, which was emplaced into the basal section of a 5-10 km thick edifice of comagmatic volcanics. Most Duluth Complex intrusions, and mafic intrusions emplaced higher in the volcanic pile, occur as sheet-like bodies that commonly underlie either felsic rocks (rhyolite flows or granophyre intrusions) or feldspathic rocks (gabbroic to troctolitic anorthosite). In all cases, field relationships indicate that the felsic/feldspathic rocks are consistently older than the mafic rocks that underlie them.

Three styles of mafic underplating are recognized in the Midcontinent Rift of northeastern Minnesota (Fig. 1):

- 1) Mafic layered intrusions beneath large granophyre bodies. Examples of this style of underplating are the Poplar Lake Intrusion beneath the Misquah Hill Granophyre in the Gunflint Trail area; the Sawbill Lake intrusion beneath the Eagle Mountain Granophyre, and the Sonju Lake Intusion beneath the Finland Granite. In all three cases, the mafic intrusion is well differentiated and in gradational contact with the overlying granophyre. The gradational contact is best explained by partial melting of the base of the granophyre and subsequent assimilation.
- 2) Mafic layered intrusions beneath anorthositic rocks. This style of mafic underplating is evident in almost all Layered Series intrusions of the Duluth Complex which are intruded beneath Anorthositic Series rocks (Fig. 1). The Layered Series intrusions that will be highlighted in this talk include the Layered Series at Duluth, the Partridge River Intrusion, and the Tuscarora Intrusion.
- 3) Diabase sheets beneath thick rhyolite flows. Examples of this style of mafic underplating include the Endion Sill beneath the Tischer Creek Rhyolite and the Lester River Sill beneath the Lakewood Rhyolite, both in the Duluth area, the Beaver River Diabase beneath the Palisade Head Rhyolite in the Beaver Bay Complex, and the Mink Mountain diabase emplaced beneath and into the Grand Marais Felsites.

Empirical evidence and density/viscosity/thermal considerations suggest that the felsic/feldspathic rocks served as density barriers to mafic magmas, which had risen into the upper crust to the point of neutral bouyancy. The felsic/feldspathic rocks not only triggered underplating of the mafic magmas, but also commonly served as thermal insulators to the underplated mafic bodies, thus resulting in their slow cooling and crystallization differentiation.

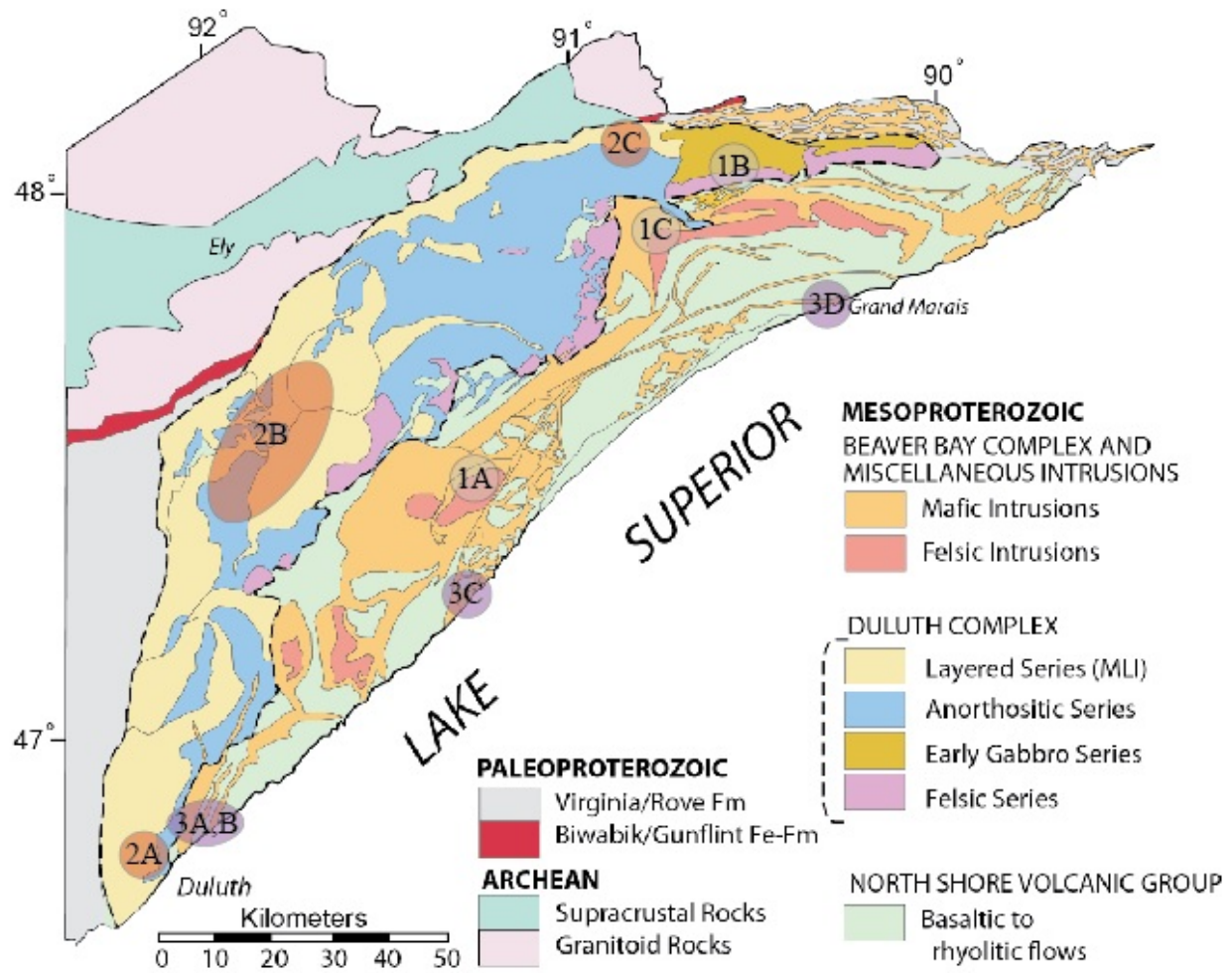


Figure 1. Generalized geology of northeastern Minnesota showing locations of examples of the three styles of mafic underplating in Midcontinent Rift-related rocks that are illustrated in this presentation - (1A-C) mafic layered intrusions beneath large granophyre bodies; (2A-C) mafic layered intrusions beneath anorthositic bodies; and (3A-D) diabase sheets beneath thick rhyolite flows.

Geology of the North and South Temperance Lakes area of the Boundary Waters Canoe Area, Cook County, Minnesota - 2014 Precambrian field camp capstone mapping

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As a capstone mapping project for the 2014 Precambrian field camp, a crew of five students under the supervision of Jim Miller conducted five days of field mapping bedrock geology in the South and North Temperance Lakes area. This area is located in the Boundary Waters Canoe Area west of Brule Lake in Cook County, Minnesota. The area is accessible from the Caribou Trail, which heads north from Tofte to a canoe landing on Brule Lake, and then via a 5-mile paddle to the west end of Brule Lake and a portage into South Temperance Lake. The main objective of this project was to conduct bedrock geologic mapping of rocks that previous capstone mapping has shown to comprise part of the footwall to the Sawbill Lake intrusion (Brooker and Miller, 2013).

Previous studies of the Temperance Lakes area include reconnaissance mapping by Grout et al. (1959) and Davidson (1977). Grout's (~1:100,000-scale) township maps of the area (Figures XXIII and XXIV, Grout et al., 1959) show it to contain granophyric granite and mafic volcanic rocks intruded by gabbro. Davidson's (1:24,000-scale) reconnaissance map of the Cherokee Lake 7.5' quadrangle show a similar mix of rock types in the Temperance Lakes area, but he subdivides the gabbroic rocks into an olivine gabbro unit and an anorthositic gabbro unit. The latter unit, Davidson correlates to the anorthositic series of the Duluth Complex.

Capstone mapping conducted for UMD's Precambrian field camp in the summers of 2007 (Frost et al., 2007), 2009 (Blakely et al., 2009), 2010 (Brooker et al., 2010), and 2011 (Asp et al., 2011) and field mapping conducted by Ben Brooker as part of his MS thesis at UMD in 2011 (MS, in preparation) revealed the existence of well differentiated, mafic layered intrusion which has been named the Sawbill Lake intrusion (SbLI; Brooker and Miller, 2012, 2013). Mapping of the lower contact of the SbLI showed lower troctolitic cumulates were in contact with a footwall of evolved ferrodioritic cumulates that locally contain hornfels basalt inclusions. This observation and aeromagnetic data (Chandler, 1983) showing curvilinear anomalies in the footwall rocks that are conformable to similar anomalies internal to the SbLI suggest that another well differentiated mafic layered intrusion might exist beneath the SbLI.

The 2014 capstone mapping project focused mapping shoreline exposures in the South and North Temperance Lakes which covers a 3 km wide by 4 km tall area extending north from the basal contact of the SbLI. The result of this mapping clearly shows that a well differentiated tholeiitic mafic layered intrusion indeed is situated conformably beneath the SbLI. This as yet unnamed intrusion can be subdivided into seven distinct units based on dominant lithology, internal structure and position within the intrusion. Internal structure within the intrusion (layering and igneous foliation dips 20-40°) to the south.

The base of the intrusion is exposed in the northern part of North Temperance Lake where a fine- to medium-grained, locally plagioclase-phyric, subophitic to ophitic olivine diabase is found in intrusive contact with granophyric leucogranite of the Misquah Hills granophyre – part of Duluth Complex Felsic Series. The diabase cuts the granophyre in an orthogonal pattern of N-S/E-W dikes and shows chilled contacts. In the southern part of North Temperance Lake, the olivine diabase grades into an ophitic augite troctolite that locally displays moderate foliation and layering defined by augite oikocryst concentrations. This Pl+Ol cumulate persists upsection into the northern part of South Temperance Lake. In the mid-section of South Temperance Lake, a

troctolite-olivine gabbro transitional unit is defined by the intermittent (cyclical?) occurrence of cumulus augite and Fe-Ti oxide. The southern part of South Temperance Lake is dominated by a medium-grained, locally layered, moderately to well foliated, intergranular olivine oxide gabbro – a Pl+Cpx+Ox+Ol cumulate. Along the portage trail following the Temperance River south of South Temperance Lake, the olivine oxide gabbro transitions into an apatite ferrodiorite (Pl+Cpx+Ox+Ol+Ap cumulate), which in turn grades into a ferromonzodiorite with abundant basaltic hornfels inclusions. At the south end of the portage trail, the ferromonzodiorite abruptly transitions into a fine-grained, subophitic olivine diabase, which is the base of the overlying Sawbill Lake Intrusion. This olivine diabase is also observed to cross cut the upper three units of the Temperance Lakes sequence, clearly indicating that the Sawbill Lake was emplaced later by overplating the Temperance Lake sequence.

Plans for the 2015 capstone mapping project are to follow the igneous stratigraphy defined in the Temperance Lakes area to the west and north into the Cherokee Lake area.

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The mineralogy and petrology of a newly-discovered REE occurrence within the Coldwell Complex near Marathon, Ontario

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The Coldwell Complex is situated within the Archean Schreiber-White River metavolcanic-metasediment of the Superior Province. Spanning over 25 km in diameter, it is the largest alkaline intrusion in North America (Figure 1). The 1108 +/- 1 Ma age of the Coldwell complex and close spatial proximity supports a strong relationship to the magmatism of the Keweenawan Midcontinent Rift (Heaman and Machado 1992). Early studies define three magmatic centers of the Coldwell Complex, which in order of intrusion are Center I, Center II and Center III (Mitchell and Platt 1982). Center I consists of an oldest phase gabbro, which borders a ferroaugite syenite to the east and north. Center II includes a nepheline-bearing biotite-gabbro and several intrusions of nepheline syenites, and Center III is composed of four syenites which in order of intrusion are: magnesiohornblende syenite, contaminated ferroedenite syenite, ferroedenite syenite, and quartz syenite.

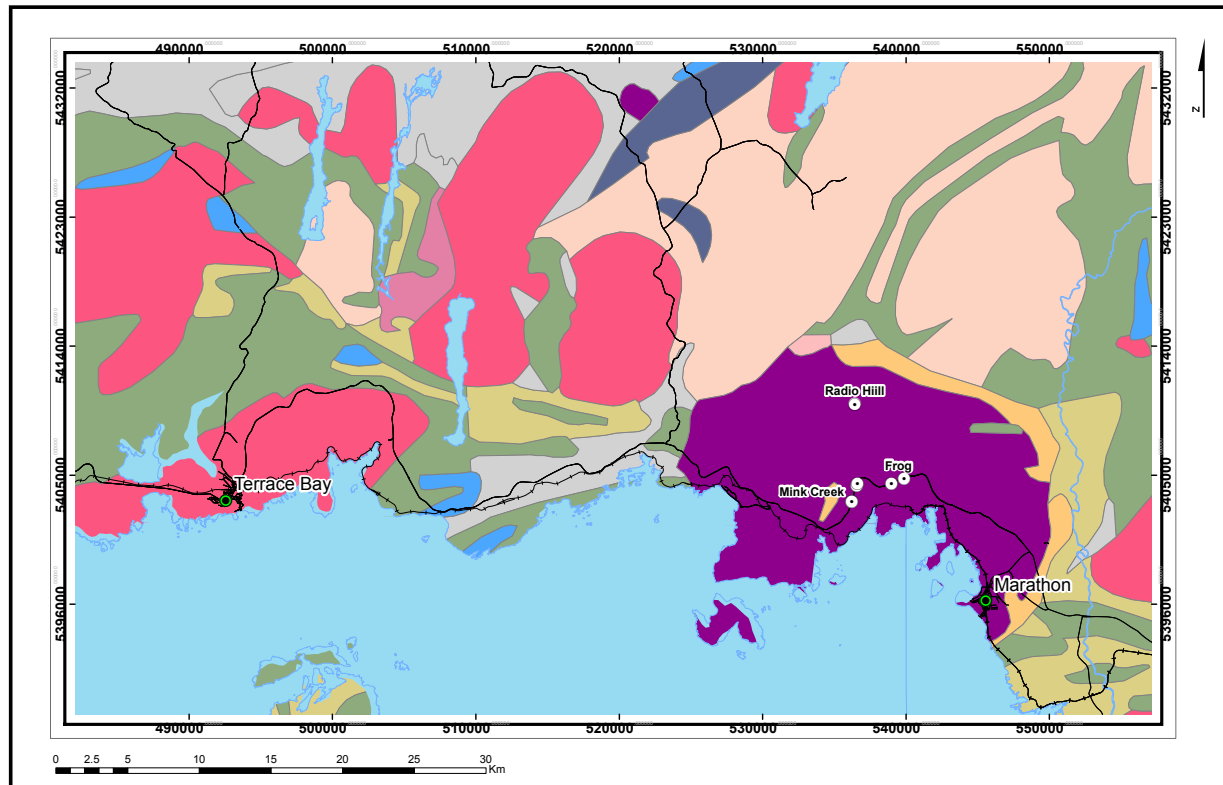


Figure 1: Regional geology of the Coldwell Complex (purple).

As part of an undergraduate thesis project, the focus of this study was to classify syenite rocks related to the three intrusive centers, and identify any REE-bearing minerals present. Fieldwork was completed along HW-17 roadcuts, and North of the highway on Canada Rare Earth claim blocks, termed the 'Radio Hill' occurrence (Figure 1). The syenites of the Radio Hill occurrence had not previously been identified due to limited access to the area. Through petrography, Highway-17 samples were classified as Center II Nepheline syenites, where the

textures of amphibole, biotite, pyroxene and natrolite compared well to the nepheline syenites previously described by Mitchell and Platt (1982). Syenites of the Radio Hill occurrence were classified as Center III, specifically, ferroedenite syenites. The Radio Hill syenites show an increase in the modal abundance of quartz, and a decrease in natrolite. Compositions of the amphiboles from the Radio Hill syenites compare well with the silicic ferroedenite and hastingsitic hornblende compositions, with a trend to Na, Si, and Fe enrichment with Ca and Al depletion. Radio Hill mica has been identified as annite end-member compositions, with Mg # ranging from 0.082 to 0.294. Radio Hill plagioclase feldspar compositions show An % from 0 to 12.04 %, representing albite to oligoclase end-members.

Rare earth element minerals were described and identified from the Radio Hill occurrence using qualitative identification methods with the scanning electron microscope (SEM-EDX) at Lakehead University. Minerals found occurring in the Radio Hill syenites, in order of abundance, include apatite (elevated La, Ce, Nd, and Th), plumbopyrochlore ((Pb, Y, U, Ca)_{2-x}Nb₂O₆(OH)), ceriopyrochlore ((Ce, Ca, Y)₂(Nb, Ta)₂O₆(OH, F)), monazite ((La, Ce, Nd)PO₄), and fluorite.

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Petrology, geochemistry and mineral chemistry of the Crystal Lake and Mount Mollie mafic intrusions, northwestern Ontario

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The Midcontinent Rift (MCR) extends ~2500 km through Canada and the United States, and comprises ~1,500,000 km³ of volcanic and intrusive rocks spanning four distinct stages of activity ranging from 1150-1087 Ma (Heaman et al., 2007). The 1108-1105 and 1100-1094 Ma periods has been interpreted by Heaman et al. (2007), to represent the main formation and maturation of the rift system and is associated with the majority of the igneous activity, producing mafic to ultramafic intrusions, basaltic sills, dikes and flows as well as alkaline rocks. The extent and volume of magmatic activity has led previous researchers to conclude that a plume was most likely the cause of the MCR (Miller and Nicholson, 2013).

In this study, two mafic intrusions related to the MCR will be investigated using detailed petrography, geochemistry and mineral chemistry. The two intrusions, Crystal Lake and Mount Mollie, are located ~40 km south of Thunder Bay, Ontario and are located within a few km of each other. Crystal Lake is a Y-shaped layered intrusion with a north limb striking W-NW for 5 km and a south limb striking E-NE for 2.75 km. Mount Mollie varies from 60 to 350 m wide and extends for ~35 km, and is located just east of the Crystal Lake intrusion (Fig. 1). The intrusions have been targets for exploration for the past few decades as they both contain disseminated sulphides and are host to Ni-Cu-PGE mineralization (Smith and Sutcliffe, 1987; Lightfoot and Lavigne, 1995). The two units are very similar, consisting mainly of gabbro, troctolite and olivine gabbro with some disseminated sulphides, chromite and other spinels. The close spatial relationship led to the belief that the intrusions were related and contemporaneous (Lightfoot and Lavigne 1995), however, recent geochronology has shown that the Mount Mollie intrusion has an age of 1109.3 ± 6.3 Ma whereas Crystal Lake has been dated at 1099.6 ± 1.2 Ma (Hollings et al., 2010).

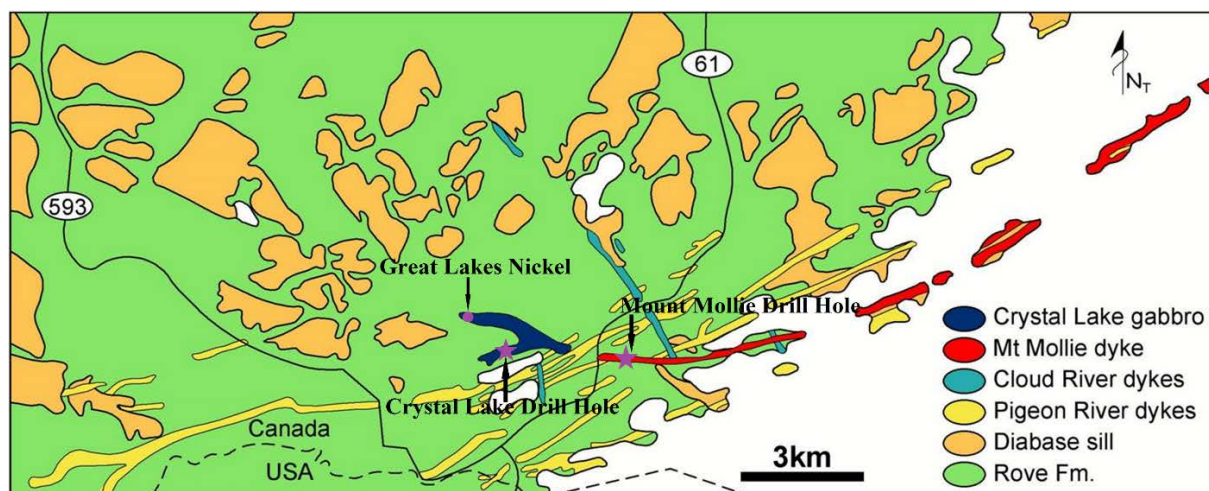


Figure 1. Generalized map of Crystal Lake gabbro, Mount Mollie dike and surrounding rocks, adapted from Cundari (2013).

Preliminary results suggest the Mount Mollie dike may in fact be contemporaneous with Crystal Lake. Core logging revealed that ~10 m of intrusive mafic rocks occur at the top of the drill core, overlaying ~20 m of sandstone, followed by gabbroic rocks. It is unclear whether the gabbros above and below the sandstone layer are directly related. With two generations of igneous activity a possibility, the temporal relationship between the two intrusions needs to be investigated further.

Full descriptions of the mineralogy and textures of both intrusions, particularly the layering styles (i.e., modal, graded, and phase layering), will be completed through core logging and detailed petrography of thin sections. These results will be combined with whole-rock geochemical data to investigate fractionation trends, mixing and crustal contamination signatures to understand the evolution of the intrusions and the genesis of the mineralized horizons. Mineral chemistry of olivine and spinels will be used to determine cryptic layering. Olivine mineral chemistry is especially important as it can further constrain the evolution of the magmas, with an emphasis on the forsterite-fayalite and nickel contents, and to give insight into parental melt compositions. Spinel mineral chemistry will be used to help understand parental melt compositions as chromite is one of the first minerals to crystallize from the melt and is refractory. SEM analysis of the platinum group minerals (PGMs) will be conducted to determine textural and mineralogical associations as well as what compositional varieties are present, (i.e. alloys, sulphides, arsenides, etc.). This detailed study will allow us to build a model for how these two intrusions formed, how they fit into the Midcontinent Rift, and what the style of mineralization is.

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So, an Environmental Impact Statement is required: Some Lake Superior area Geologic Parameters for Geologists, Consultants, Companies, and Regulators

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Since the birth of the environmental movement in the early 1970s, modern society has evolved into an “environmentally concerned world”, where the public demands that industry (herein the mining industry) reduce its physical, social and environmental footprint have translated into specific national legislation. Under United States environmental law, an environmental impact statement (EIS) is a document required by the National Environmental Policy Act (NEPA) for certain actions “significantly affecting the quality of the human environment”. Similar Canadian environmental law documents are required by the Canadian Environmental Assessment Act. An EIS type document is a project specific tool for decision making, and typically includes four sections: (1) an introductory statement of the **Purpose and Need** of the **Proposed Action**, (2) a description of the **Affected Environment**, (3) a **Range of Alternatives** to the proposed action, and (4) an **Analysis** of the environmental of each of the possible alternatives.

In the Lake Superior area, certain environmental groups vehemently oppose all activities related to the mining industry and actively coordinate their opposition to the general public through meetings, web sites, social media, and the press. Most coordinated opposition ties directly into published EIS documents in general, and specifically on the Analysis of water quality for the proposed actions. To the author, environmental misinformation, half-truths, and outright lies constitute much of the anti-mining opposition. Have you read about “Sulfide Mining”, acid mine drainage, degraded water quality, highly fractured bedrock, canoeing to the white house, the 500 years, etc.....?

So, what are field geologists to do?

Geologists must first recognize and defend the fact that the basis for every type of geologic study related to an EIS is fundamentally rooted in observations made of rocks in their natural habitat, “in the field”. An intimate understanding of the projects geology gives company geologists an appreciation of the coherent and compelling field-based scientific arguments from which all other geology-based EIS interpretations grow. Company geologists working on mining related projects have to interact with a diverse group of people during the EIS process, and must vigorously defend the fundamental observations of the projects “in the field” geology. Geologists have to ask themselves this question: Do the lawyers, PR folks, environmental consulting firms, regulators, NGO’s, and the general public know the details of the projects geology as much as I do? As geologists, we must always remember Francis Pettijohn’s famous quote, “The rocks are the final court of appeal”.

This talk will highlight some fundamental geologic parameters of the Lake Superior area that geologists, consultants, companies, and regulators need to understand to better design and complete mining related EIS documents.

New airborne geophysical data for the Lake Superior Region of northwestern Ontario: A new tool for the identification of Neoarchean to Mesoproterozoic structures and associated mafic-ultramafic intrusions

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Recent discoveries of mafic-ultramafic intrusion hosted Ni-Cu-PGE mineralization throughout the Midcontinent Rift (MCR) region (e.g. in Canada: Current Lake, Sunday Lake, Thunder, Steepleadge, Marathon; in the U.S.A. Tamarack, Eagle) have revitalized exploration interest in the area surrounding Lake Superior. Airborne magnetic and radiometric surveys that were flown during 2014 (Figure 1; Ontario Geological Survey, 2015a, b) have provided new high-resolution public domain airborne geophysical coverage that will assist in these exploration efforts. The new surveys cover a large portion of the northwest Lake Superior region in Ontario including areas underlain by MCR-related rocks, Paleoproterozoic and Mesoproterozoic sedimentary rocks of the Animikie and Sibley Groups, as well as parts of the Archean Quetico, Wawa and Wabigoon subprovinces.

In the Lake Superior region, Ni-Cu-PGE mineralized mafic-to-ultramafic rocks were emplaced in a variety of settings during several tectonic events that occurred over a time period extending from the Mesoarchean to the Mesoproterozoic (Smyk et al. 2002, Smyk and Franklin 2007). As a result, these intrusions display a wide range of geochemical affinities and morphologies. In spite of these geochemical and physical differences, most of these mafic-to-ultramafic intrusions have a close spatial association with major crustal-scale structures (Rogers et al. 1995, Hart and MacDonald 2007), and many can be recognized by their distinctive magnetic signatures (i.e., positive or negative anomalies).

When the new airborne survey magnetic data are combined with data from previous magnetic surveys (Ontario Geological Survey 2003, 2004), they highlight numerous structures that could have controlled the emplacement of mineralized MCR-related intrusions into Archean country rocks along the northwest margins of the rift north of Thunder Bay. One such structure is marked by several magnetic discontinuities and anomalies that can be traced for at least 145 km along an east-northeast (063°) trending line from the southeast end of Northern Light Lake (near the Ontario-Minnesota border), through to Greenwich Lake (50 km northeast of Thunder Bay). This structure is approximately parallel to Midcontinent Rift-related faults and dikes that are located farther to the southeast (Sutcliffe 1991) and Neoarchean faults that have been mapped to the northwest (Hart and MacDonald 2007). A second parallel structure is also evident in the magnetic data approximately 10 km further to the south-southeast.

Ni-Cu-PGE mineralized mafic-ultramafic rocks of the Sunday Lake, Steepleadge Lake and Current Lake intrusive complexes occur in a linear array that closely follows the Northern Light-Greenwich Lakes structure (NLGLS), suggesting that it may have played a role in their emplacement. The NLGLS, which has been mapped as a fault over a portion of its length (Lodge et al. 2014), is also located in close proximity to Neoarchean gold (Tower Mountain) and komatiite-hosted Ni-Cu-PGE (Bateman Lake) mineralization in Conmee Township. This observation, together with its proximity to Mesoproterozoic and Neoarchean faults of similar orientations, suggests that the NLGLS may have been tectonically active both during the accretion

of the Superior Craton, and during the Midcontinent Rift event. As a result, it presents an attractive target for both Ni-Cu-PGE and gold exploration.

Preliminary observations indicate that the NLGLS may continue further to the northeast, where it eventually merges with the Gravel River fault (GRF) approximately 60 km north of Terrace Bay). The GRF extends northeast along approximately the same trend to the James Bay Basin (Williams 1991), and it is also interesting to note its close spatial association with the Albany Graphite deposit.

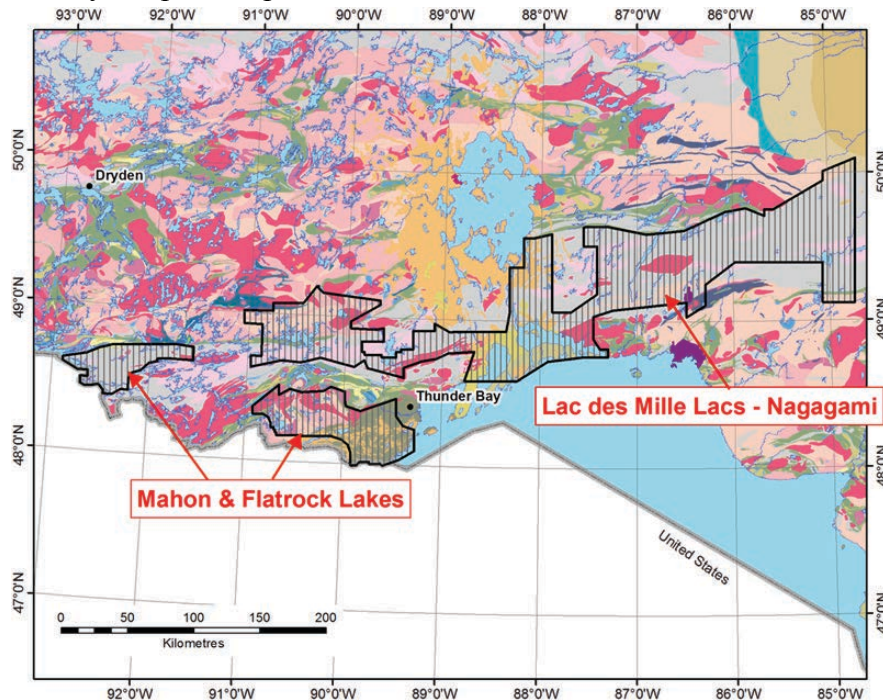


Figure 1. Location of new airborne geophysical surveys carried out over the Thunder Bay region during 2014 (geology from Ontario Geological Survey 2011). The data were released during the winter and spring of 2015 as Geophysical Data Sets 1077 (Mahon & Flatrock Lakes) and 1078 (Lac des Mille Lacs – Nagagami).

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Spectrum of volcanogenic massive sulfide deposits in the Penokean Volcanic Belt, Great Lakes Region, USA

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The Paleoproterozoic (ca. 1880Ma) Penokean volcanic belt extends for over 250 kilometers across northern Wisconsin and western Michigan. The dominantly submarine volcanic rocks comprising the belt were formed in an island arc-related setting at the southern edge of the Superior craton. Despite relatively minor exploration, the majority of which occurred intermittently from 1960 to 1990, approximately 100 million metric tons of polymetallic massive sulfide ores have been delineated. Only the supergene enrichment zone of the Flambeau deposit has reached commercial production. The mined resource accounts for less than 2% of known mineral reserves, which makes the Penokean volcanic belt one of the most accessible, undeveloped, and underexplored volcanic terranes worldwide.

The present study aims to characterize the volcanic setting, deposit characteristics, and alteration signature of significant deposits within the Penokean volcanic belt to provide a comprehensive metallogenetic model. To accomplish this goal, detailed core logging has been conducted at seven deposits across the belt, namely Back Forty, Bend, Flambeau, Horseshoe, Lynne, Reef, and Ritchie Creek. Representative sampling has been conducted at all deposits for detailed petrographic and geochemical investigation.

Ongoing research has revealed a wide spectrum of volcanic environments and alteration styles across the Penokean volcanic belt. All major deposits occur within felsic-dominated volcanic successions and are hosted by vent-proximal volcanic facies associations. For example, the Back Forty deposit is hosted within a felsic succession (apparent stratigraphic thickness of 1,200 m) comprising coherent rhyolite units and associated volcanic breccias. Felsic volcanism was broadly contemporaneous with the deposition of mass-flow-derived volcanoclastic debris presumably generated by an explosive eruption of a rhyolite source. Mafic-dominated host rock successions are less common in the Penokean volcanic belt and appear to host some of the smaller tonnage deposits, including Horseshoe and Ritchie Creek.

The styles of hydrothermal alteration vary between deposits, with sericite-chlorite-quartz alteration occurring at Back Forty, Bend, and Horseshoe. Acid-style alteration represented by andalusite-biotite-sericite schists has been noted at Flambeau and calc-silicate mineral assemblages are present at Lynne, Ritchie Creek, and Reef. Calc-silicate mineral associations have also been observed at the Pelican River and Spirit deposits, possibly suggesting that the volcanic host rocks were originally interbedded with limestone. Regional metamorphism varies from lower greenschist to amphibolite grade and has obscured relationships in some deposits. Most notable, primary volcanic textures are difficult to recognize at the Reef deposit, which is an unusual disseminated to quartz-sulfide vein confined Au-Cu deposit hosted by strongly deformed and recrystallized rocks. Recognition of significant variations in setting and deposit characteristics across the Penokean volcanic belt likely reflects first-order tectonostratigraphic controls during the development of the Penokean orogeny.

Geochemical and petrologic characterizations of peridotite, Marquette County, Michigan
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The discovery of the Eagle magmatic sulfide deposit, in 2002, sparked a renewed interest in exploration for magmatic sulfide mineral deposits associated with peridotite in Michigan's Upper Peninsula. This study is a preliminary attempt to determine if other sulfide mineral deposits could potentially exist in association with the peridotites of Marquette County, Michigan.

In order to achieve its goal, this study is attempting to determine if any petrologic or geochemical relationship exists between the peridotites of Marquette County, Michigan. As shown by Figure 1, peridotite has been mapped at four locations across the county: the Yellowdog Peridotite, located at the site of the Eagle Mine (Rossell and Coombes, 2005), the Presque Isle Peridotite, located in Marquette (Gair and Thaden, 1968), the Deer Lake Peridotite, located just north of Ishpeming (Clark, Cannon, and Klassner, 1975), and Black Rock Point, located north of Big Bay (Case and Gair, 1965). Field work was conducted in May, 2014 and was followed by petrographic analyses of collected samples.

A peridotite rock unit could not be located at Black Rock Point by initial field work and petrographic studies. The area is composed of three major rock units. The southernmost unit is gabbro, the largest of the three units present. To the north there is an abrupt change to a heavily veined granite which is cut by at least two mafic dikes. The northern most unit of the area is a gneissic rock which has a much smaller outcrop than the other units.

Thin section analysis of samples collected from Presque Isle revealed that the rock is a serpentized lherzolite. Primary minerals include olivine, clinopyroxene, and orthopyroxene. A large portion of the rock has been altered to serpentine. Other secondary minerals such as chlorite and calcite are also present.

Thin sections from samples of the Deer Lake peridotite show a fine-grained rock with a texture suggestive of hypabyssal origin, which has been heavily serpentized. Serpentine is by far the most abundant mineral in all samples analyzed thus far. Primary minerals including olivine, clinopyroxene and orthopyroxene are present in small quantities. Other secondary minerals include chlorite, and calcite.

New geochemical, petrologic, and structural data collected by this study will be included in detailed geologic maps of each site. The investigation will address the relationships of the peridotite units with respect to one another as well as their relationships with the surrounding rocks. The final results generated from this study will be useful in the creation of a new set of criteria to assess the mineralization potentials of peridotite units in Marquette County.

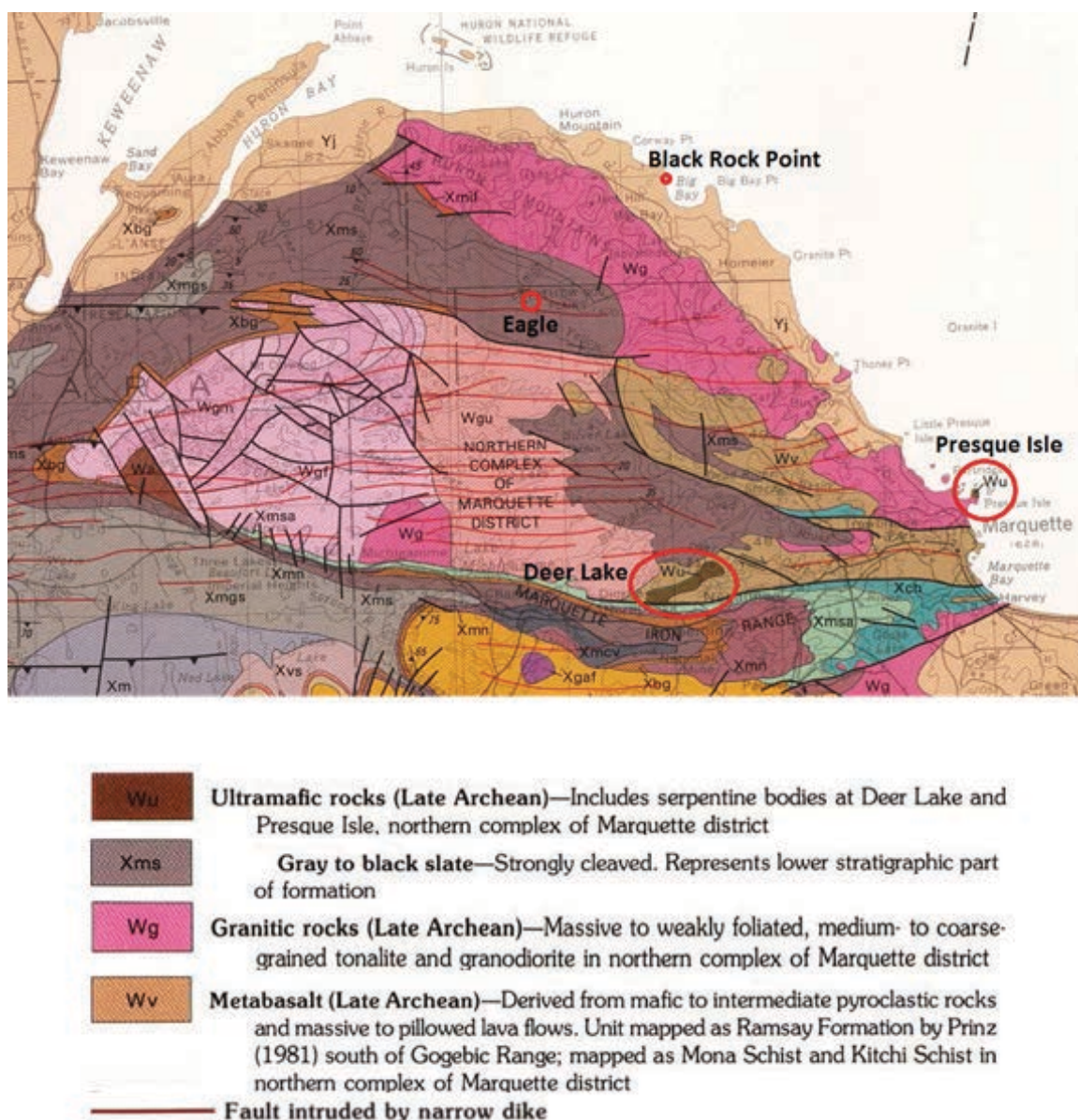


Figure 1. Modified map of locations of the four research areas and their surrounding geology. Compiled by Simms, 1992.

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Petrologic study of the “Chill” zone of the Layered Series at Duluth: Testing a possible plutonic-volcanic correlation within the Midcontinent Rift

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The Duluth Complex is a multiple intrusive mafic complex that represents the largest exposed plutonic component of the 1.1 Ga Midcontinent rift. Results from extensive field mapping and petrologic studies (Miller and Green, 2008a, 2008b; Green and Miller, 2008) of the mafic cumulates comprising the type locality of the Duluth Complex at Duluth have confirmed that it is composed of two fundamentally distinct rock series, and provided further detail regarding the igneous stratigraphy, internal structure of each series and thus the petrogenetic relationship between them. The Anorthositic Series (DAS), which forms a ~ 1-km thick cap to the Duluth Complex at Duluth, is a suite of structurally complex plagioclase-rich gabbroic rocks which are interpreted to have formed by multiple intrusions of a plagioclase crystal mush from a lower crustal magma chamber (Miller and Weiblen, 1990). Underlying the DAS cap is a 3-4.5 km thick, well differentiated, stratiform sequence of troctolitic to gabbroic cumulates forming the layered series at Duluth (DLS). The DLS is thought to have formed by open system crystallization differentiation (Miller and Ripley, 1997). Based on lithology and stratigraphic position, the DLS can be subdivided into five major zones: basal contact zone, troctolite zone, cyclic zone, gabbro zone and upper contact zone. The DAS had long been interpreted to be significantly older than the DLS based on the abundance of DAS inclusions in the DLS and, especially, on the occurrence of a fine-grained mafic rock that occurs at the sharp upper contact of the DLS with the overlying DAS, referred to as the DLS “chill”. However, high precision U-Pb ages from DAS and DLS samples (Paces and Miller, 1993) has shown that these two rock series are essentially identical in age at 1099 ± 0.5 Ma relative to the 30m.y. window of MCR magmatism. This revelation warrants a reinterpretation of the relationship between the two series, along with reevaluating the origin of the DLS “chill.”

Since the similar ages of the DLS and DAS preclude the DLS “chill” being a thermal quench of DLS parental magma against the DAS, Miller (Miller and Ripley, 1997; Miller, 2011) has suggested that quenching of DLS magma was caused by the decompression of a volatile-saturated magma accompanying volcanic venting from the subvolcanic DLS chamber. Several features lend evidence in support of a decompression quenching of hydrous magma interpretation including: 1) the evolved composition of the DLS “chill”, 2) the presence of biotite phenocrysts in the “chill”, and 3) the extensive hydrothermal alteration of overlying DAS rocks. Miller has further suggested that periodic venting of hydrous magma may have played an important role in the formation of the cyclic zone in the medial part of the DLS, particularly the occurrence of microgabbro cumulates in the upper parts of phase-layered macrocycles.

This study seeks to test whether the DLS “chill” composition could be formed by decompression quenching of a volatile saturated magma and whether that magma is in equilibrium with the microgabbros of the Cyclic Zone and possible volcanic products represented in the NSVG overlying the Duluth Complex. To accomplish this, the lithological, petrographic and geochemical attributes of the DLS “chill”, microgabbros and flows from the NSVG were evaluated. Taking advantage of the fact that Brannon (1984) analyzed the chemistry of all mafic lavas occurring between 3-5 kilometers above the top of the Duluth Complex, the chemostratigraphy of the overlying NSVG were searched for compositions matching the DLS “chill”. If a correlative lava can be found, it would provide valuable constraints on the depth and pressure of the DLS magma

chamber. Once a pressure of crystallization is established, the DLS “chill” composition can be applied to PELE, a MELTS-based phase equilibrium modeling program developed by Boudreau (2006), to simulate whether pressure fluctuations caused by devolatilization and venting could effectively quench a volatile-saturated magma during decompression. PELE can also be used to evaluate the comagmatic relationship between the DLS “chill” and Cyclic Zone microgabbros by determining the mineral phases in equilibrium with the “chill” composition and comparing them to the phase compositions observed in the microgabbros.

Preliminary results indicate two sequences of flows (Brannon’s (1984) flows 28-38 and 65) have the best match to the “chill” composition. Both series had the best fit for most major and trace elements, but most notable, however, was flow 65 which corresponds to the upper-most flow of an eight-flow sequence that defines an obvious differentiation trend. Flow 65 shows a good fit to the “chill” composition and parallel patterns of depletion of incompatible trace elements evident in the successively lower flows of the differentiation sequence. Treating these two sequences of flows as the potential volcanic products would indicate that the top of the DLS was emplaced within the volcanic edifice at a depth of ~4-5km. This depth is consistent with estimates for the formation of shallow reservoirs of magma (2-4km) beneath mafic volcanic centers like Kilauea in Hawaii (Ryan, 1987).

Modeling with the PELE program is just underway. We hope to have results to present at the time of the meeting.

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Images on stone: Pictographs of the Ignace area, northwestern Ontario
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More than 400 rock paintings (pictographs) had been documented on outcrops of the Canadian Shield from Quebec, across Ontario and as far west as Saskatchewan (Rajnovich 1994). The senior author, an avocational archaeologist, has found and documented an additional 150 pictograph sites over the past 50 years. Most of them are situated within 160 km of Ignace, midway between Thunder Bay and Kenora in northwestern Ontario. Pictographs are the legacy of the Algonquian-speaking, early Cree and Ojibway peoples, whose roots may extend to the beginnings of post-glacial human occupancy in the area almost 10,000 years ago.

This region of northwestern Ontario is underlain by Archean rocks of the Superior Province that are overlain by thin, discontinuous, unconsolidated glacial, lacustrine and organic deposits. The vast majority of pictograph sites are located on shoreline bedrock exposures of lakes and interconnecting rivers. Sites with relatively homogeneous and leucocratic bedrock faces (e.g., granitoids) are preferred, although more mafic rocks also host pictographs.

Many sites consist of single elements (e.g., a canoe), while others are more complex with many figures and motifs. In many cases, there may only be one site on a lake, whereas in other examples, several sites may be scattered along a lakeshore. The largest concentration of pictographs found to date has 28 sites on cliffs on both sides of a 8 km-long, narrow stretch of lake.

In almost all cases, the paintings are red, but one site with a gold handprint was found and documented by the senior author on Eagle Lake, southwest of Dryden. Discovered in the mid-1960s, the unique Smyk Site (Figure 1), northeast of Ignace, is the only known local site with the three distinct colours of red, gold and dark purple. Although there is some scattered and anecdotal evidence of ochre quarrying, there has been only limited research into possible sources of natural pigmenting agents and the ochres themselves.

Unlike sites in the Thunder Bay area, the geoarchaeology of the area west of the Lake Superior basin remains largely cursory. Much work remains in identifying and documenting pictograph sites and relating them in the larger context of spiritual places, habitation sites, transport and trading routes, local geologic materials and deglaciation history.

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Figure 1: Pictographs of three distinct colours (red, gold and dark purple) on Archean granitoid rocks at the Smyk Site, northeast of Ignace. Exposed panel is approximately 1 m across.

The petrology, mineralization and regional context of the Thunder mafic to ultramafic intrusion, Midcontinent Rift, Thunder Bay, Ontario

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The 1108 Ma Thunder mafic to ultramafic intrusion is a small, 800 x 100 x 500 m, Cu-PGE (platinum group element) mineralized body, located on the outskirts of Thunder Bay, Ontario. The intrusion was explored by Rio Tinto (formerly Kennecott Canada Exploration Inc.) in 2005 and 2007 (Fig. 1; Bidwell and Marino, 2007). It is associated with the early magmatic stages of the Midcontinent Rift (MCR) based on geochemical similarities to mafic and ultramafic rocks of the Nipigon Embayment and a ²⁰⁷Pb/²⁰⁶Pb zircon age of 1108.0 ± 1.0 Ma (Trevisan, 2014; Trevisan et al., 2015).

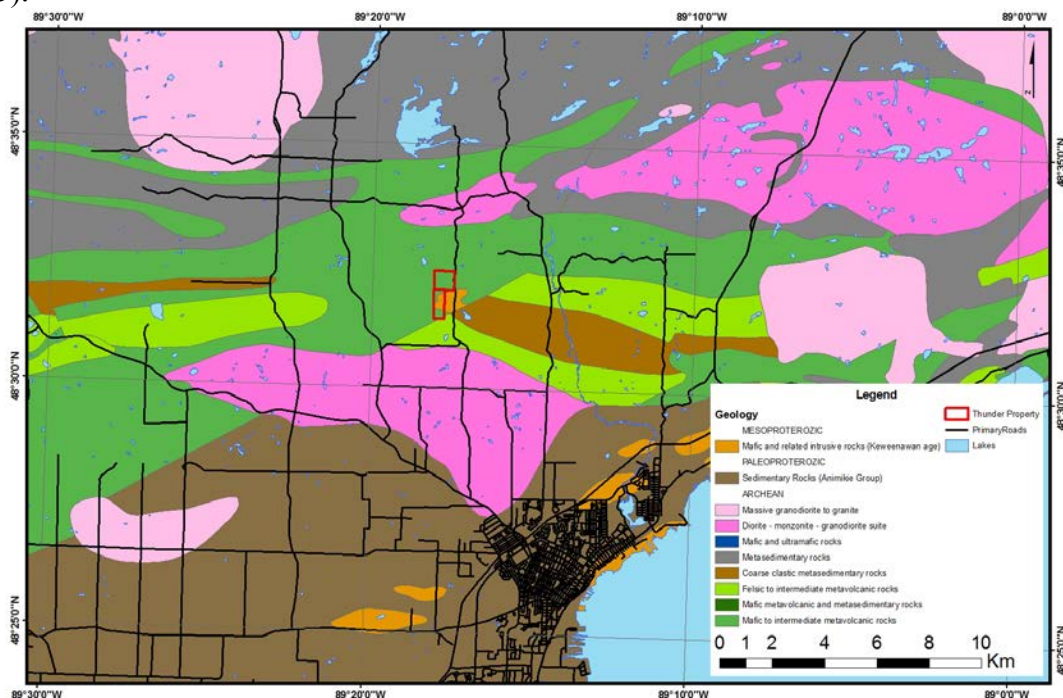


Figure 1: Geological map of the greater Thunder Bay area including major road networks and outline of the current mineral claims that enclose the Thunder intrusion. The Thunder intrusion is located on the outskirts of the City of Thunder Bay, within Gorham Township and situated within the eastern limb of the Archean Shebandowan greenstone belt. Geospatial data from OGS (2011).

The Thunder intrusion is similar to the other known mineralized early-rift MCR intrusions; however, it is the only known mafic/ultramafic intrusion of the MCR hosted in an Archean greenstone belt (Shebandowan). Major textural and geochemical differences can be used to subdivide the intrusion into a lower mafic to ultramafic unit and an upper gabbroic unit; the similar trace and rare earth element ratios of the two units suggest a single magmatic pulse that has undergone subsequent fractional crystallization and related cumulate phase layering. The estimated parental composition of the Thunder intrusion has a mg# ($\text{MgO}/(\text{MgO}+\text{FeO}^{\text{Tot}})$, mole %) of 57 which represents a more evolved magma than other early-rift mafic to ultramafic intrusions. This may indicate the involvement of multiple staging chambers during the ascent of the parent magma.

Trace and rare earth element geochemical patterns are consistent with a mantle plume ocean island basalt-like source but, with high Th concentrations and the presence of a negative Nb anomaly, indicative of contamination. ϵNd_t values from the intrusion range between -0.7 and +1.0, but lack trends indicative of progressive wall rock contamination, whereas the $^{87}\text{Sr}/^{86}\text{Sr}_i$ ratios range from 0.70288 to 0.70611 and trend towards wall rock values of 0.70712 and 0.70873. The weak correlation at Thunder between ϵNd_t and $^{87}\text{Sr}/^{86}\text{Sr}_i$ is also a feature of the Nipigon Sills where it has been interpreted to be due to shallow-level crustal contamination whereas plots of MgO and SiO₂ versus ϵNd_t indicate contamination at depth by an older crustal source.

Ni-Cu-PGE sulphide mineralization (20 m of 0.22 wt. % Cu, 0.06 wt. % Ni, 0.25 ppm Pt and 0.29 ppm Pd) is hosted by feldspathic peridotite in the lower mafic to ultramafic unit adjacent to the footwall of the Thunder intrusion. Sulphides typically occur from 1 - 5 modal %, rarely up to 30 modal %, 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 occur along with the trace Pd, Ag, Au and rare Pt minerals, michenerite, kotulskite, merenskyite, sperrylite, hessite, electrum and argentian pentlandite. Whole-rock geochemical data display fractionated Ni-Cu-PGE patterns with depletion of iridium subgroup relative to the platinum subgroup of the platinum group elements.

Sulphide $\delta^{34}\text{S}$ values from the Thunder intrusion range from -2.0 to +3.8 ‰ and are similar to values for the metavolcanic host rock that range from -3.1 to +2.3 ‰. Two samples from the basal mineralization zone sulphides yield $\Delta^{33}\text{S}$ values of 0.066 and 0.122 ‰ and one sample from the metavolcanic wall rock yields 0.149 ‰. The $\delta^{34}\text{S}$ and $\Delta^{33}\text{S}$ values for the Thunder intrusion fall within range of typical upper mantle compositions. The sulphur source appears to be of mantle origin; however, assimilation of crustal sulphur is a possibility but hard to resolve as the wall rock S isotope and S/Se_{Tot} signature is similar to that of upper mantle.

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Bedrock and soil chemistry in paired watersheds in northeastern Minnesota
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Bedrock and soil have been collected and analyzed in two adjacent watersheds (Filson and Keeley) in northeastern Minnesota (Fig. 1). This sample collection effort is part of a three-year study to determine baseline geochemistry of solid media and water quality in this part of Minnesota.

The Filson watershed, which includes Filson and South Filson Creeks, drains an area of about 26.3 km² (~10.2 mi²) and discharges into the South Fork of the Kawishiwi River. The geology of the Filson watershed is complex. Bedrock includes the Archean Giants Range Batholith and the Duluth Complex. The Duluth Complex in the Filson watershed is mainly represented by the South Kawishiwi Intrusion, a thick sequence of troctolite and augite troctolite (with a heterogeneous sulfide-bearing, basal zone in contact with Archean quartz monzonite), the Anorthosite Series, and the Nickel Lake Macrodiike, composed of oxide-rich gabbro and foliated troctolite (Fig.1). Two major mineral deposits in the Filson watershed are the Spruce Road deposit and the South Filson deposit (Fig.1). At the Spruce Road deposit, discontinuous sulfide-bearing heterogeneous troctolite is exposed at the surface across the northern part of the watershed. The South Filson deposit is a combination of primary disseminated Cu-Ni sulfide mineralization and secondary hydrothermal mineralization along fracture zones. Primary mineralization at South Filson occurs both at depth and sporadically in troctolite outcrop within a limited area; secondary mineralization occurs in fine-grained veinlets proximal to a northeast-southwest trending, highly altered fault zone.

The adjacent Keeley Creek watershed, south and west of the Filson watershed, drains an area of about 28 km² (~10.9 mi²) and discharges into Birch Lake. The geology of the Keeley watershed is fairly simple, with bedrock dominated by relatively homogeneous, typically unmineralized anorthositic troctolite to troctolite of the South Kawishiwi Intrusion (Fig.1). A thin zone of sulfide-bearing melatroctolite has recently been mapped within the trace of the creek (D. Peterson, personal communication, 2014).

In both the Filson and Keeley watersheds topography is largely controlled by the resistance to chemical weathering of underlying bedrock and subsequent removal of the saprolith by glacial erosion. Glacial cover is very thin. The landscape within the watersheds mainly consists of bedrock highlands surrounded by wetlands. In the Filson watershed soil was collected from 16 upland sites along two broad transects that cut across the general trend of the major bedrock types. In the Keeley watershed, the monotonous sea of anorthosite troctolite resulted in selection of 14 upland soil sites based on the rather problematic road access. At all soil sites, up to 3 samples were collected using hand tools, including the soil O horizon (where present – this area has abundant invasive earthworms that typically convert organic soil to mineral soil), the soil A horizon, and a deeper soil. Final sample depths were typically constrained by the stony substrate. Bedrock samples were collected from the abundant outcrop within each watershed. Bedrock sample sites were selected to be proximal to soil sample sites, if possible, or to capture the diversity of rock types. Bedrock was collected at 14 sites in the Filson watershed and 9 sites in the Keeley watershed. Soil and bedrock were analyzed for 44 major and trace elements following a near-total 4-acid digestion.

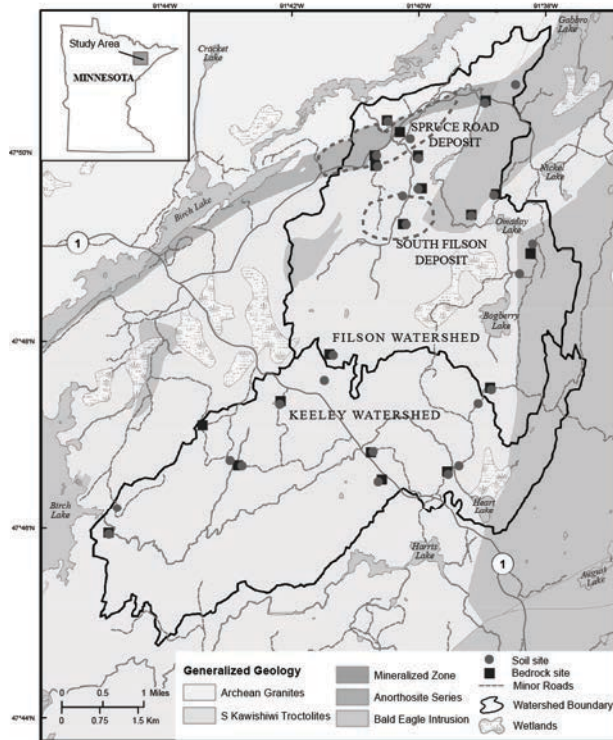


Figure 1. Location map showing the distribution of soil and bedrock sample sites in the Keeley and Filson watersheds.

Copper and Ni concentrations in mineralized bedrock in the vicinity of the exposed Spruce Road deposit are 4,600 ppm Cu and 1,130 ppm Ni. Non-mineralized South Kawishiwi Intrusion anorthosite contained Cu concentrations that range from 50 to 203 ppm and Ni concentrations that range from 119 ppm to 296 ppm; rocks of the Anorthosite Series in the Filson watershed have Cu concentrations from 67 to 235 ppm and Ni concentrations from 56 to 70 ppm.

Soils collected over the exposed footprint of the Spruce Road deposit and in the down-ice direction from the Spruce Road have high Cu and Ni concentrations; a single soil sample collected in the vicinity of the South Filson deposit has relatively high Cu and Ni (Fig. 2A). The distribution of Ni and Cu in Fig. 2A is consistent with variable contributions to soil parent materials from sulfide (for example, high Cu and Ni) versus ferromagnesian silicate minerals (for example, high Ni but low Cu); plots of other elements, such as Co, Cr, Fe, Mg, and Mn provide similar evidence. Surface soils

typically have metal values consistent with deeper soils. Because glacial transport distances are short and glacial cover thin, soil chemistry, for the most part, can be related back to bedrock contributions to soil parent material (Fig. 2B).

Although these data are rather sparse, they describe the natural distribution of many elements within these two watersheds that can be attributed to geologic processes. The combination of these data with the on-going collection of water quality data in this three-year study will provide valuable information on the geochemical landscape in this region of potential mineral resource development.

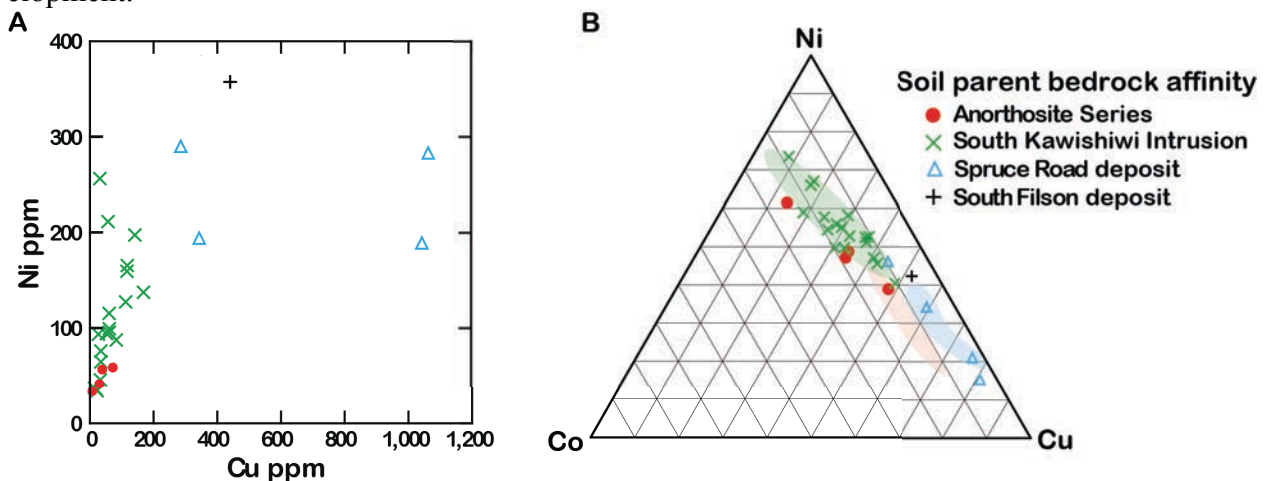


Figure 2. A) Box plot of Ni vs. Cu (in ppm) in soil; B) Ternary plot of Cu-Ni-Co in soil; bedrock data within solid similarly colored fields.

Exposure Surfaces of the Gunflint iron formation, northwestern Ontario YIP, Christopher, and FRALICK, Philip

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Exposure surfaces present in Precambrian rocks can be used as an environmental record of the conditions prior to their being covered by depositing sediments. The surfaces can show alteration of the preexisting rocks, which were exposed to the Precambrian atmosphere. The 1.88Ga Gunflint Formation in northern Ontario has two identifiable exposure surfaces found within its stratigraphy. The first one makes up the basal contact of the iron formation and is comprised of the basement rocks in places overlain by the thin Kakabeka Conglomerate all capped off by microbialite and/or grainstone of the Gunflint Formation marking the initial transgression of the sea. The second exposure surface is found approximately 45m above the basal contact. It records the regression of the ancient sea and is underlain by Gunflint grainstone and overlain by stromatolitic growth marking the shallowing of the sea. In the basal contact, the Archean rocks forming the exposed surface can show high levels of alteration. There are three outcrops present near Thunder Bay, Ontario, which contain complete sections of the basal exposure surface. The sample sites selected are two outcrops on the shoulder of Highway 11/17 and one on the shoulder of Highway 590. These three outcrops exhibit various alteration patterns within rocks near the paleosurface (Figure 1).



Figure 1: Three examples of the Gunflint Iron Formation's basal contact exposure surface showing the complete section through the exposure surface. The alteration horizons (1) are demarked. A) The formation of large core stones during alteration of the outcrop on the shoulder of Highway 11/17. B) The alteration of the KOA Hill outcrop showing the change in foliation from the vertical schistosity to the flaky altered horizon. C) The outcrop on Kakabeka Falls showing an indistinct difference between the unaltered and darker altered portion of the granodiorite unit.

The first outcrop on Highway 11/17 shows high levels of alteration through the formation of the large core stones as well as replacement of the original mineralogy of the granodiorite by mostly iron-rich chlorite. The outcrop at KOA hill on the shoulder of Highway 11/17 exhibits a change in the foliation in the Archean metasedimentary basement from a vertical schistosity to a flaky layer with no discernable pattern. The appearance of the Kakabeka Falls outcrop exhibits minor amounts of dark discolouration, but extensive replacement of the original mineralogy. The alteration history of these three outcrops and in particular the former, can be related to an earlier phase of surface weathering overprinted by massive diagenetic addition of Fe and Mn and extensive leaching of the initial constituents of the rocks. The exposure surface that is approximately 45m above the base of the Gunflint Formation consist of lithified grainstone blocks, some up to boulder size, that were in places rotated by current activity (Figure 2). This rubble zone and fractured basement below it contains small, wispy hematite dykes. Stromatolites developed on this lithified brecciated surface.

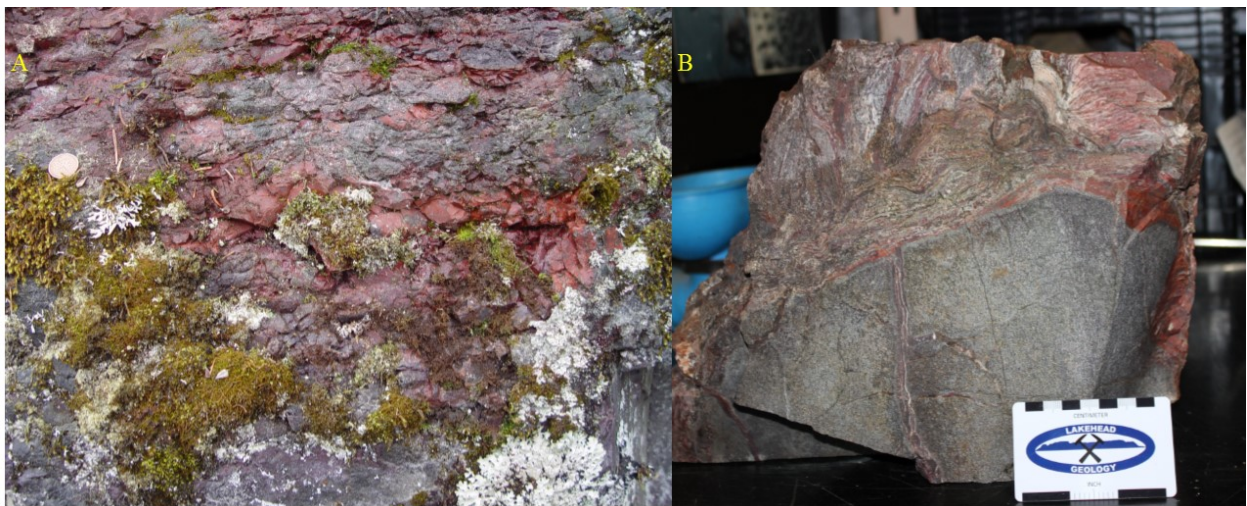


Figure 2: Two representations of the exposure surface present approximately 45m above the base of the outcrop. A) The outcrop to the immediate north of Mink Mountain exhibits brecciation of the lithified grainstones with hematite dykes filling the fractures. B) A boulder removed from an outcrop present on Old School Road showing stromatolites forming above a brecciated grainstone boulder as well as hematite dykes filling the fractured boulder.