

56TH ANNUAL MEETING



**INSTITUTE ON LAKE SUPERIOR GEOLOGY
INTERNATIONAL FALLS, MINNESOTA
MAY 19-22, 2010**



**PROCEEDINGS VOLUME 56
PART 1 – PROGRAMS AND ABSTRACTS**



INSTITUTE ON LAKE SUPERIOR GEOLOGY

**56TH ANNUAL MEETING
MAY 19-22, 2010
INTERNATIONAL FALLS, MINNESOTA**

**PETER HOLLINGS, PETER HINZ, MARK SMYK,
MARK JIRSA, AND TERRY BOERBOOM
Co-Chairs**

Proceedings Volume 56

Part 1 – Program and Abstracts

Edited by Terrence J. Boerboom, Minnesota Geological Survey

Cover Photos: Conglomerate in Seine Group (Field Trip 6)

56TH INSTITUTE ON LAKE SUPERIOR GEOLOGY

CONTENTS OF PROCEEDINGS VOLUME 56:

PART 1: PROGRAM AND ABSTRACTS

PART 2: FIELD TRIP GUIDEBOOK

TRIP 1: MINERAL DEPOSITS OF THE RAINY RIVER AREA (CAN)

TRIP 2: GEOLOGY OF AN ARCHEAN SUCCESSION AT ATIKOKAN (CAN)

TRIP 3: STRUCTURAL GEOLOGY ALONG THE QUETICO FAULT (CAN)

TRIP 4: ARCHEAN GEOLOGY OF VOYAGEURS NATIONAL PARK AND
LITTLE AMERICA GOLD MINE (US)

TRIP 5: ASH RIVER NEUTRINO DETECTOR LABORATORY AND THE ARCHEAN
VERMILION GRANITIC COMPLEX (US)

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

Boerboom, T. J., 2010, Latest bedrock geologic map of Carlton County, east-central Minnesota and revisions to the southern edge of the Animikie basin [abstract]: Institute on Lake Superior Geology Proceedings, 56th Annual Meeting, International Falls, MN, v. 56, part 1, p. 1-2.

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PREVIOUS INSTITUTES ON LAKE SUPERIOR GEOLOGY, 1955-2009

ILSG	YEAR	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 and 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 and 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 and 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. La Berge
31	1985	Kenora, Ontario	C.E. Blackburn
32	1986	Wisconsin Rapids, Wisconsin	J.K. Greenberg
33	1987	Wawa, Ontario	E.D. Frey and 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 and W. Meyer
44	1998	Minneapolis, Minnesota	J.D. Miller, Jr. and M.A. Jirsa
45	1999	Marquette, Michigan	T.J. Bornhorst and R.S. Regis
46	2000	Thunder Bay, Ontario	S.A. Kissin and P. Fralick
47	2001	Madison, Wisconsin	M.G. Mudrey, Jr. and B.A. Brown
48	2002	Kenora, Ontario	P. Hinz and R.C. Beard
49	2003	Iron Mountain, Michigan	L.G. Woodruff and W.F. Cannon
50	2004	Duluth, Minnesota	S.A. Hauck and M. Severson
51	2005	Nipigon, Ontario	P. Hollings and M.C. Smyk
52	2006	Sault Ste. Marie, Ontario	R.P. Sage and A.C. Wilson
53	2007	Lutsen, Minnesota	L.G. Woodruff and J.D. Miller, Jr.
54	2008	Marquette, Michigan	T.J. Bornhorst and J.S. Klasner
55	2009	Ely, Minnesota	J.D. Miller, Jr., G.J. Hudak, D.M. Peterson
56	2010	International Falls, Minnesota	P. Hollings, P. Hinz, M. Smyk, M. Jirsa, and T. Boerboom

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

PAST GOLDICH MEDALISTS

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

2010 JOINT GOLDICH MEDAL RECIPIENTS

**William D. Addison
and
Gregory R. Brumpton**

Thunder Bay, Ontario

GOLDICH MEDAL COMMITTEE

Serving for the meeting years shown in parentheses

Terry Boerboom (2007-2010)

Allan MacTavish (2008-2011)

Mary Louise-Hill (2009-2012)

Government representative

Industry representative

Academic representative

CITATION FOR GOLDICH MEDAL RECIPIENTS

William D. Addison and Gregory R. Brumpton 2010 Goldich Medal Recipients

Bill Addison and Greg Brumpton are the first joint recipients of the Goldich Medal of the Institute on Lake Superior Geology. It is my privilege and pleasure to make this presentation in recognition of their remarkable contributions to the geology of the Lake Superior region. Bill and Greg worked as an inseparable team for more than a decade in the search for, and eventual discovery of the Sudbury impact layer, a bed containing material ejected from the crater near Sudbury, Ontario by the giant impact event at 1850 Ma. Their discovery and resulting publications constitute a fundamental contribution to the geology of the region and have ignited a renewed interest by many colleagues in studies of the classic geology of the iron ranges of the region where extensions of their original discoveries have since been documented.



Greg Brumpton (left) and Bill Addison in their natural habitat near Thunder Bay.

Before further discussing their scientific contributions I would like to present some biographical information on each of our medalists. Unlike so many of our career-long members, Bill and Greg appeared on our scene with a bang within the past decade, as mature, fully-formed researchers with something truly important to tell us. In assembling this biographical sketch it became apparent that virtually no one in the geologic community knew much of their pre-impact existence and they were truly international men of mystery to all of us. Even Google failed to provide enlightenment. “William D. Addison”, for instance, yields 18,800 hits suggesting that Bill clearly has multiple personae. So I was forced to go directly to the source and ask Bill and Greg themselves to give some pertinent information. Here are their abridged autobiographies.

Bill Addison was born at an undisclosed location on April 27, 1939. His lifelong fascination and love of nature was instilled at an early age by his parents through many outdoor activities and their encouragement to not only enjoy nature but understand what he was experiencing in the outdoors. Bill’s formal education was at the University of Toronto where he received a B.Sc. in forestry in 1963 and M.Sc. in fish physiology in 1966. Bill married his wife, Wendy, in 1966 and promptly treated her to a long honeymoon wilderness adventure in a remote corner of the Northwest Territories. Bill’s early career was with the Ontario Department of Lands and Forests as a walleye research biologist. In 1970 he began his 28 year career as a science teacher as Westgate High School in Thunder Bay.

Greg Brumpton was born in Windsor, Ontario on July 16, 1941. His family's business in horticulture lead to an interest in agriculture and biology and Greg received his undergraduate degree in agriculture from the Ontario Agricultural College in Guelph, Ontario. He then studied at the University of Wisconsin-Madison, where he received his M.S. degree in entomology in 1966. Greg became a high school teacher in Windsor, Ontario in 1966 and married his wife, Carol Ann, in 1968. In 1970 Greg and Carol Ann moved to Thunder Bay and Greg continued his science teaching career at Westgate High School, arriving coincident with Bill Addison, thus beginning their lifelong collegial partnership. Greg, like Bill, retired in 1998 and the two soon took up their hobby of revolutionizing our understanding of the Paleoproterozoic history of the Lake Superior region.

The discovery by Bill and Greg of the ejecta-bearing bed produced by the Sudbury impact, documented in their Geology paper in 2005, was a revelation to many of us with long experience in the geology of the Lake Superior region, as well as to the broader community of impact geologists. But it was a quiet labor of dedication and perseverance by our two medalists that spanned more than a decade of frustrations and false leads before their ultimate success and their sudden appearance in our midst with their remarkable discovery. Greg became interested in the topic of impact-induced mass extinctions in the 1980's and by 1991 had recognized that, in the Thunder Bay area, the highly fossiliferous Gunflint Formation was overlain by the nonfossiliferous Rove Formation and that the Gunflint/Rove boundary might be the same age as the Sudbury impact. He proposed therefore to examine that boundary for signs of ejecta and a possible mass extinction event. The hunt proved more difficult than it might have seemed because of sparse exposures and few drill holes to provide samples from the critical horizon. But perseverance ultimately paid off with discoveries of ejecta both in outcrop and drill cores.

For many of us in the ILSG community who have followed Bill and Greg's discovery and subsequent investigations for the past five years, its importance to the geology of our favorite region is clear. To a great extent "You heard it here first" because they have honored the Institute by presenting their findings through a series of papers at ILSG meetings. But, we also need to appreciate how their work has been received by the broader community of impact researchers. Bevan French, one of the most eminent researchers in the field of impact geology for many decades, and a pioneer in documenting the Sudbury impact itself, wrote the following in support of Bill and Greg's nomination. *"I consider Addison and Brumpton's study to be one of the most exciting discoveries in geology in recent years. It has provided one of those rare and unexpected major insights which permanently change our existing picture of geology, and, at the same time, indicate new and unexpected directions of research."*

You may have noticed that I have not mentioned the word "geology" anywhere in Bill's and Greg's professional training or experience. This is not an oversight. These two remarkable gentlemen are entirely self taught in our field of research. Their curiosity and intellectual enthusiasm have brought them to a level of geologic knowledge such that even close colleagues might not realize this lack of formal training were it not for their modesty in frequently pointing out this "flaw" in their backgrounds. I believe that never in the history of ILSG have two self-taught individuals had such a profound impact on understanding the geologic history of the Lake Superior region or stimulated as much new research as our two medalists have done.

It was my honor to have nominated Bill Addison and Greg Brumpton for the 2010 Goldich Medal. But I also would like to acknowledge the strong support of that nomination provided by Klaus Schulz and Laurel Woodruff of the USGS, Phil Fralick of Lakehead University, John Klasner of Marquette, Michigan, Jorma Kalliokoski of Houghton, Michigan, David Kring of the Lunar and Planetary Institute in Houston, Texas, and Bevan French, of NASA (retired) and scientist emeritus at the Smithsonian Institution Museum of Natural History in Washington, DC. On behalf of these supporters, and with great personal pleasure, I congratulate William D. Addison and Gregory R. Brumpton as recipients of the Goldich Medal of the Institute on Lake Superior Geology.

William F. Cannon
May, 2010

ILSG STUDENT RESEARCH FUND

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 researcher's supervisor.

In 2009 the ILSG Board of Governors awarded two \$500 awards from the Student Research Fund. The winners are listed below, along with the title of the presentation they will be giving this year.

Amanda van Lankvelt (Lawrence University) – *Baraboo-interval quartzite breccias.*

Shelby Frost (University of Minnesota – Duluth) – *Effects of contact metamorphism by the Duluth Complex on Proterozoic footwall rocks in northeastern Minnesota*

STUDENT PAPER AWARDS

Each year, the Institute selects the best of the student presentations and honors presenters with a monetary award. Funding for the award is generated from registrations of the annual meeting. The Student Paper Committee is appointed by the annual meeting Chair in such a manner as to represent a broad range of professional and geologic expertise. Criteria for best student paper—last modified by the Board in 2001—follow:

- The contribution must be demonstrably the work of the student.
- The student must present the contribution in-person.
- The Student Paper and Poster Committee shall decide how many awards to grant, and whether or not to give separate awards for poster vs. oral presentations.
- 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.
- 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).
- 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 and Poster 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.
- 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 are noted on the Program.

(continued next page)

STUDENT PAPER AWARDS (CONTINUED)

In 2009 the ILSG Student Paper Committee presented several awards from the ILSG Student Paper Fund. Each of the following recipients received awards ranging from 80 to 100 dollars:

Best oral presentations:

Benedek Gal (Eötvös Loránd University, Budapest)) – *Magmatic vs. hydrothermal processes in the South Filson Creek mineralization, South Kawishiwi Intrusion, Duluth Complex.*

Natalie Pietrzak (University of Western Ontario) – *Ore textures and Mineral Chemistry within the oxide-carbonate-silicate flotation ores at the Cliffs Natural Resources' Tilden Mine, Michigan*

Best poster presentations:

Ryan Dayton (University of Minnesota-Duluth) – *Quantifying assimilation vs. fractional crystallization using Sm-Nd, Lu-Hf and Pb isotope systems: The geochemical evolution of the Sonju Lake Intrusion, Finland, MN*

James Hiller (California State University) – *Detailed petrographic analysis of anthraxolite morphology in the Biwabik Iron-Formation, northern Minnesota*

Andrew Jansen (University of Wisconsin-Oshkosh) – *Lithogeochemical evaluation of Neoproterozoic mafic volcanic rocks comprising the footwall of the Soudan Member of the Ely Greenstone Formation, northeastern Minnesota*

Kyle Makovsky (Minnesota State University-Mankato) – *Fluid movement through the Mesabi Iron Range, Minnesota*

Dan Costello (University of Minnesota-Duluth) – *Geology of the Tuscarora Intrusion, northeastern Minnesota and its relationship to the anorthositic series of the Duluth Complex*

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 annual Chair in consultation with the Secretary-Treasurer determines the number of awards and value. Recipients will be announced at the annual banquet. The student travel award application is available on the ILSG website.

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

- 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.
- Students who are the senior author on either an oral or poster paper will be given favored consideration.
- It is desirable for two or more students to jointly request travel assistance.
- In general, priority will be given to those in the Institute region who are farthest away from the meeting location.
- 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.

In 2009 the ILSG awarded 12 travel awards from the ILSG Eisenbrey Student Travel Fund, to students:

Dan Costello	University of Minnesota – Duluth
Michael DeAngelis	University of Tennessee – Knoxville
Adam Fage	Lakehead University
Nathan Forslund	Lakehead University
Benedek Gal	Eötvös Loránd University
James Hiller	California State University Chico
Angela Hull	Kent State University
Andrew Jansen	University of Wisconsin – Oshkosh
Maura Kolb	Lakehead University
Cara Leitheiser	University of Minnesota – Duluth
Natalie Pietrzak	University of Western Ontario
Victoria Stinson	Lakehead University

**REPORT OF THE CHAIRS OF THE 55TH ANNUAL MEETING
INSTITUTE ON LAKE SUPERIOR GEOLOGY
ELY, MINNESOTA**

The Precambrian Research Center (PRC) of the University of Minnesota Duluth hosted the 55th Annual Institute on Lake Superior Geology on May 5 – 10, 2009 at the Grand Ely Lodge in Ely, Minnesota – Gateway to the Boundary Waters Canoe Area Wilderness. Despite this area being well known for its classic Precambrian geology, this was the first time that the ILSG has been held in Ely. We are pleased to report that this was one of the best attended meetings in the 55 year history of ILSG with a total of 234 registrants, including 45 students.

The organizing committee for the meeting was comprised of the three PRC directors: Jim Miller (meeting and field trip logistics, promotion, fundraising, and registration), George Hudak (technical program, student travel, and best paper awards), and Dean Peterson (field trip guidebook). Julie Ann Heinz, an executive office administrator at the UMD Natural Resources Research Institute, provided valuable assistance with meeting registration and planning. During the meeting, Julie Ann and Ginny Aldag handled on-site registration and other institute business.

The two-day technical session held at the Grand Ely Lodge on Thursday and Friday (5/7 and 5/8) included 21 talks and 24 posters presentations, including 4 oral and 14 poster presentations by students. The meeting opened with a remembrance of Joe Mancuso who passed away in April of 2009. Joe was a professor of economic geology at Bowling Green State University (OH) and a long-time ILSG member (attended the 1st meeting in 1955). He received the Goldich medal in 2007. This year's Goldich medal recipient was L. Gordon Medaris of the University of Wisconsin-Madison. Gordon was recognized for his long and productive career studying the Paleoproterozoic of Wisconsin, in particular the Baraboo interval, and for his many contributions to the Institute. Gordon was presented the medal at the annual banquet by Bob Dott, his renowned colleague at UW Madison. The evening banquet talk was presented by Marvin Marshak, a physics professor at the University of Minnesota – Twin Cities and founder of the Soudan Underground Physics Laboratory. Dr. Marshak gave a very humorous and informative talk on the search for subatomic particles entitled "*The Deep Underground Sky*".

The meeting offered seven field trips that highlighted various aspects of the geology and ore deposits in the Ely area. Most trips were filled to capacity with a cumulative total of 325 field trip attendees. Pre-meeting field trips included a very popular two-day trip on the **CU-NI DEPOSITS OF THE DULUTH COMPLEX** led by Rich Patelke (*Polymet Mining*), Mark Severson (*Natural Resources Research Institute, UMD*), Dean Peterson (*Duluth Metals Ltd.*), Tim Jefferson (*Teck American*), and Ernie Lehmann (*Franconia Minerals*) and a one-day trip on **GLACIAL GEOLOGY OF THE VERMILION MORaine** led by Phil Larson (*Cliffs Natural Resources*) and Howard Mooers (*Department of Geological Sciences, UMD*). On Friday afternoon following the completion of the technical session, two field trips were offered. One gave participants an underground tour of **THE SOUDAN IRON MINE AND PHYSICS LAB** led by Dean Peterson (*Duluth Metals Ltd.*), James Pointer – (*Minnesota Department of Natural Resources, Parks and Recreation*) and Marvin Marshak (*Department of Physics, University of Minnesota*). The other had Mark Jirsa (*Minnesota Geological Survey*) lead a **PIONEER MINE CANOE EXCURSION** around the perimeter of Miners Lake, just across the road from the meeting site in Ely.

Several post meeting trips completed the meeting. A one-day trip on the **GEOLOGY AND METAMORPHISM OF THE EASTERN MESABI RANGE** led by Dick Ojakangas (*Department of Geological Sciences, UMD*), Mark Severson (*Natural Resources Research Institute, UMD*), Doug Halverson, Jeff Bird, Tom Campbell, Jarred Lubben, and Peter Jongewaard (*Cliffs Natural Resources*), and William Everett (*Mesabi Nugget*). A two-day trip on the **ARCHITECTURE OF AN ARCHEAN GREENSTONE BELT** was led by Dean Peterson (*Duluth Metals Ltd.*), Mark Jirsa (*Minnesota Geological Survey*), and George Hudak (*Department of Geology, University of Wisconsin Oshkosh*). Jim Miller (*Dept. of Geological Sciences, UMD*) led a two-day canoe excursion into the BWCA on the **GEOLOGY OF THE LAKE ONE TROCTOLITE**.

The student paper committee comprised of Tom Fitz (Northland College), John Gartner (Prime Meridian Resources), and Dorothy Campbell (Ontario Geological Survey) once again had a difficult job of selecting among the 18 student oral and poster presentations.

More than half of the students received financial aid to defray travel and registration expenses. A total of \$5400 was distributed to 23 students from 13 different schools. This generous aid was provided by funds contributed by meeting registrants and several corporations and organizations. Specifically, meeting registrations surcharges generated \$2000 and the ILSG Eisenbrey Fund contributed \$1000. The American Institute of Professional Geologists (AIPG-Minnesota Chapter) contributed \$1000, the Minnesota Mineral Resource Education Foundation (affiliated with Mining Minnesota) contributed \$500, Northland Securities gave \$500, and the Mesabi Range Geological Society contributed \$500 (to UMD students). In addition to these contributions for student support, the meeting benefitted greatly by a \$2000 contribution from Duluth Metals Ltd., which allowed the guidebook to be printed in color. Also, Barr Engineering contributed \$1000 that went to sponsor the welcoming reception on Wednesday evening. See the 55th Program and Abstract volume for more details on student funding. .

The Institute's Board of Directors met on May 7, 2009. The meeting was called to order by Chair George Hudak. The meeting was attended by the three co-chairs of the Ely meeting (Miller, Hudak, and Peterson), Treasurer Mark Jirsa, Secretary Peter Hollings, and Board Members Ted Bornhorst (2008 chair) and Ann Wilson (2006 chair). Secretary Hollings took the minutes of the Board meeting that are as follows:

1. Report of the Chairs (Bornhorst and Klasner) for the 54th ILSG, Marquette, Michigan was received and accepted.
2. Received, discussed, and accepted 2008-2009 ILSG Financial Summary (Jirsa).
3. Received, discussed, and accepted 2008-2009 ILSG Secretary's report (Hollings)
4. Appointed meeting chair (George Hudak) as on-going ILSG Board Member.
5. Discussed application process for ILSG Student Research Awards. Hollings to prepare a two-page form and circulate to the board
6. International Fall, MN was approved as the site for the 2010 (56th Annual) meeting location with Mark Jirsa (MGS) and Pete Hollings (Lakehead) serving as co-chairs, and Terry Boerboom (MGS) and Mark Smyk (OGS) serving on the organizing committee..

7. Approved replacement of Richard Ojakangas as “academic member” on Goldich Committee (end of term 2009) with Mary Louise Hill (Lakehead U).
8. Discussed moving toward advertising of the annual meetings exclusively by email and website. Miller gave a positive report on how this approach worked for the Ely meeting. Miller reported compiling an email list of over 750 contacts.
9. It was agreed that Jirsa would order 10 new Goldich medals. It was also agreed that Hollings would prepare a letter that could be sent to new Goldich committee members explaining the process. This letter will be distributed to the Board prior to being sent out
10. Hudak suggested that a notice page be added to the web site to be used to post job and graduate opportunities. It was agreed that the proceedings of the institute would now be posted immediately after each meeting. The hosting of the ILSG web site was discussed, Miller to investigate the possibility of hosting the site through the Precambrian Research Center.
11. The board thanked Mudrey and Hollings for their work on digitizing the volumes. These have proved a useful resource for researchers

The co-chairs would like to thank the participants, especially the students, for their enthusiasm, the field trip leaders for their hard work, the presenters for their informative talks and posters, Marvin Marshak for his classic banquet talk, the session chairs and subcommittee members for their important contributions, and the meeting sponsors for their generosity. A big thank you to Julie Ann Heinz for her cheerfulness and organization in handling the registrations. Thanks also to Sue Marturano, Sue Salveson, and Denise Endicott for handling the budgeting. Thanks to our wives, Ginny Aldag, Rachel Pastoor and Deb Rausch, for their support and understanding. Thanks to Barb Lyke, Tara Akeman, and the entire staff of the Grand Ely Lodge for being accommodating, flexible and very professional.

Although there were some things that we could have improved upon (e.g. a projector that showed true colors), we are pleased with how the meeting went. We are particularly gratified by the near record attendance, the popularity of the field trips, and the generally favorable comments we receive about the technical meeting. It made the planning, organizing, and oversight of the meeting worth the effort. You all should try it sometime...really. See you all in International Falls.

Respectfully submitted,

Jim Miller, George Hudak, and Dean Peterson
Co-Chairs, 55th Institute on Lake Superior Geology

2010 BOARD OF DIRECTORS

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

Peter Hinz, Co-Chair, 56th Meeting

Ontario Geological Survey

Peter Hollings, Co-Chair, 56th Meeting

Lakehead University, Thunder Bay, ON

Mark Smyk, Co-Chair 56th Meeting

Ontario Geological Survey

Mark Jirsa, Co-Chair, 56th Meeting

Minnesota Geological Survey, St. Paul, MN

Terry Boerboom, Co-Chair, 56th Meeting

Minnesota Geological Survey, St. Paul, MN

Jim Miller (2010)

University of Minnesota – Duluth, MN

Peter Hollings – Secretary (2010)

Lakehead University, Thunder Bay, ON

Theodore J. Bornhorst (2011)

Michigan Technological University, MI

Mark A. Jirsa – Treasurer (2011)

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Precambrian Research Center and Natural Resources Research Institute

2010 SESSION CHAIRS

Peter Hinz Ontario Geological Survey

Mark Smyk, Ontario Geological Survey

Peter McSwiggen, McSwiggen and Associates

Charlie Blackburn, Blackburn Geological

Leonard Espinosa, Retired, Michigan Department of Natural Resources

2010 STUDENT PAPER AWARDS COMMITTEE

Graham Wilson (Chair), Turnstone Geological Services Ltd.

Jim Miller, University of Minnesota – Duluth

Anthony Pace, Ontario Geological Survey

2010 MEETING SPONSORS

The organizers wish to sincerely thank the several companies and organizations who have contributed financial support and support in kind to various components the meeting.



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Prime Meridian Resources
Q-Gold
Rainy River Resources
Society for Mining, Metallurgy, and Exploration (SME) – Minnesota
Voyageurs National Park
William Miller – University of Minnesota School of Physics and Astronomy NOVA project

2010 BANQUET SPEAKER

The Importance of Being Cratered:

The New Role of Meteorite Impact as a 'Normal' Geological Process

Dr Bevan M. French

Adjunct Professor

Smithsonian Institution

National Museum of Natural History

Planetary geologist, petrologist and author



PROGRAM

WEDNESDAY MAY 19, 2010

8:30 a.m. **FIELD TRIP 1: MINERAL DEPOSITS OF THE RAINY RIVER AREA (CAN)**

Wally Rayner – *Rainy River Resources*

CJ Baker – *Rainy River Resources*

Craig Ravnaas – *Ontario Geological Survey*

77 passenger tour bus

Return to rec centre approximately 6:00 p.m.

TRIP LEAVES FROM AND RETURNS TO THE FORT FRANCES MEMORIAL SPORTS CENTER*, FORT FRANCES, ONTARIO

***SEE MAP ON PAGE 75 IN BACK OF THIS VOLUME FOR LOCATION**

8:30 a.m. **FIELD TRIP 2: GEOLOGY OF ARCHEAN SUCCESSION AT ATIKOKAN**

Phil Fralick – *Lakehead University*

77 passenger tour bus

Return to White Otter Inn approximately 5:00 p.m.

TRIP LEAVES FROM AND RETURNS TO THE WHITE OTTER INN, ATIKOKAN, ONTARIO

8:30 a.m. **FIELD TRIP 3: STRUCTURAL GEOLOGY ALONG THE QUETICO FAULT**

Dyanna Czeck – *University of Wisconsin - Milwaukee*

Howard Poulsen – *Consultant*

9 – passenger vans

Return to rec centre approximately 6:00 p.m.

TRIP LEAVES FROM AND RETURNS TO THE FORT FRANCES MEMORIAL SPORTS CENTER*, FORT FRANCES, ONTARIO

***SEE MAP ON PAGE 75 IN BACK OF THIS VOLUME FOR LOCATION**

4:00 p.m. - 10:00 p.m. **REGISTRATION AT RAINY RIVER INN**, INTERNATIONAL FALLS, MN**

7:00 p.m. - 10:00 p.m. **ICE BREAKER AND POSTER SESSION**

****THE RAINY RIVER INN IS THE FORMER HOLIDAY INN**

THURSDAY MAY 20, 2010 A.M.

8:00 a.m. - 12:00 noon **REGISTRATION**

8:30 a.m. **INTRODUCTORY REMARKS**

Mark Smyk and Peter Hinz, Ontario Geological Survey

TECHNICAL SESSION I

Session Chairs:

Mark Smyk and Peter Hinz, Ontario Geological Survey

8:40 a.m. **Miller**, James D., and Stifter, Eric

Cyclical Phase Layering in the Duluth Complex at Duluth – Evidence for Periodic Magma Venting from a Shallow Staging Chamber?

9:00 a.m. **Hoaglund, S.A.***, Miller, J.D., Crowley, J.L., Schmitz, M.D.

U-Pb zircon geochronology of the Duluth Complex and related hypabyssal intrusions: investigating the emplacement history of a large multiphase intrusive complex related to the 1.1 Ga Midcontinent Rift

9:20 a.m. **Cundari, Robert***, Hollings, Peter, and Smyk, Mark

Geology and geochemistry of the Rove basalts, a possible Midcontinent-Rift related extrusive unit south of Thunder Bay, Ontario

9:40 a.m. **COFFEE BREAK AND POSTER SESSION**

10:20 a.m. **Magnus, Seamus***, Kissin, Stephen

Assimilation and petrogenesis in the Navilus and Terry Fox sills, Thunder Bay, Ontario

10:40 a.m. **Puchalski, Raya***, Hollings, Peter, and Smyk, Mark

The petrology and geochemistry of the Riverdale Sill

11:00 a.m. **Hollings, Peter**, and Smyk, Mark

Radiogenic isotope characteristics of Midcontinent Rift-related intrusions south of Thunder Bay

11:20 a.m. **Lunch Break (2010 ILSG Board Meeting - by invitation)**

THURSDAY MAY 20, 2010 P.M.

TECHNICAL SESSION II

Session Chair:

Peter McSwiggen, *McSwiggen and Associates*

- 1:00 p.m. **van Lankvelt, Amanda***, and Bjornerud, Marcia
Revisiting the Baraboo breccias
- 1:20 p.m. **Pietrzak, Natalie***, Duke, Norm, Scott, Glenn, and Lukey, Helene,
Hydrothermal Overprint by Greenstone Sills within the Tilden Pit, Michigan
- 1:40 p.m. **Noah Planavsky***, Andrey Bekker, Olivier J. Rouxel, Balz Kamber, Axel Hofmann,
Andrew Knudsen, Timothy W. Lyons
*The rare earth element and yttrium composition of Archean and Paleoproterozoic iron
formations revisited: A new perspective on significance and mechanisms of iron
formation deposition*
- 2:00 p.m. **O'Hare, Sean*** and Fralick, Philip
*Sedimentological study of the glaciogenic Bruce Formation, Huronian Supergroup, in
the North Shore area, Ontario*
- 2:20 p.m. **COFFEE BREAK AND POSTER SESSION**
- 3:00 p.m. **Jirsa, Mark A.**
Stratigraphy of Sudbury "impactite" near Gunflint Lake, NE Minnesota
- 3:20 p.m. **Weiblen, Paul, W.**, Jirsa, Mark A., and McSwiggen, Peter
*Sudbury impact ejecta – amphiboles in samples from the vicinity of the Gunflint Trail,
Minnesota*
- 3:20 p.m. **Cannon, William F.**, and Slack, John F.
*Global effects of the Sudbury bolide impact at 1850 Ma: Potential link to the evolution
of marine mineral deposits*

6:00 p.m. **ICE BREAKER – MIXER – CASH BAR**

7:00 p.m. **ANNUAL BANQUET AND AWARD PRESENTATION AT BACKUS COMMUNITY CENTER**
(SEE MAP ON PAGE 76 IN BACK OF THIS VOLUME FOR LOCATION)

- **Announcement of 57th Annual Meeting Location**
- **2010 Goldich Award Presentation to:**
 - **William D. Addison and Gregory R. Brumpton**
- **2010 Banquet Address by Dr. Bevan M. French, Smithsonian Institution**

All registered participants are welcome to the banquet address

FRIDAY MAY 21, 2010 A.M.

8:30 a.m. **INTRODUCTORY REMARKS**

Mark Jirsa, 2010 ILSG Co-Chair

TECHNICAL SESSION III

Session Chair:

Charlie Blackburn, *Blackburn Geological*

8:40 a.m. **Kolb, Maura J.*** and Hill, Mary Louise

A microstructural study of gold mineralization at Musselwhite Mine and Hammond Reef shear-zone-hosted gold deposits

9:00 a.m. **Stinson, Victoria R.***, and Hill, Mary Louise

Structural control at Hammond Reef gold deposit north of Atikokan, Ontario

9:20 a.m. **Siemieniuk, Steven***, Hollings, Pete, McCuaig, Cam, and Porwal, Alok

Gold in the Wabigoon Subprovince – GIS-based Mineral Potential Mapping

9:40 a.m. **Scott, Robert J.*** and Hill, Mary Louise

Quartz eyes of the Moose Lake Porphyry Complex, Hemlo, Ontario

10:00 a.m. **COFFEE BREAK AND LAST POSTER SESSION**

10:40 a.m. **Gilbert, Paul**

Geology and geochemistry of arc and ocean-floor volcanic rocks in the Northern Flin Flon Belt, Manitoba

11:00 a.m. **Fralick, Philip**

Anatomy of an Archean carbonate platform: Geology of the Steep Rock Group, Canada

11:20 a.m. **Smyk, Mark**, Stott, Greg, and Atkinson, Brian

The Ring of Fire: An Overview of the Geology, Mineral Deposits and Exploration History of the McFaulds Lake Area

11:40 p.m. **LUNCH BREAK AND MEETING OF THE STUDENT PAPER COMMITTEE**

FRIDAY MAY 21, 2010 P.M.

TECHNICAL SESSION IV

Session Chair:

Leonard Espinosa

Retired - Michigan Department of Natural Resources

1:00 p.m. **Boerboom, Terrence J.**

Latest bedrock geologic map of Carlton County, east-central Minnesota and revisions to the southern Animikie Basin edge

1:20 p.m. **Chandler, Val W..**

The Search for Magnetic Basement in Minnesota: Sliding Along with the Euler Equation

1:40 p.m. **Waggoner, T.D.**

Post Penokean Age of Mineralization on the Marquette Range, Michigan

2:00 p.m. **PRESENTATION OF THE STUDENT TRAVEL AND BEST PAPER AWARDS**

2:20 p.m. **COMPLETION OF 2010 ILSG TECHNICAL SESSIONS AND FINAL STATEMENTS BY THE 2009 ILSG CO-CHAIRS**

3:00 p.m. **FIELD TRIP 4: ARCHEAN GEOLOGY OF VOYAGEURS NATIONAL PARK AND LITTLE AMERICA GOLD MINE (US)**

Chris Hemstad – Boreal Explorations

Return to Rainy River Inn approximately 6:00 p.m.

TRIP LEAVES FROM AND RETURNS TO THE RAINY RIVER INN, INTERNATIONAL FALLS, MN**

3:00 p.m. **FIELD TRIP 5: ASH RIVER NEUTRINO DETECTOR LABORATORY AND THE ARCHEAN VERMILION GRANITIC COMPLEX**

*Mark Jirsa – Minnesota Geological Survey
Ash River laboratory staff*

Return to Rainy River Inn approximately 6:00 p.m.

TRIP LEAVES FROM AND RETURNS TO THE RAINY RIVER INN, INTERNATIONAL FALLS, MN**

****THE RAINY RIVER INN IS THE FORMER HOLIDAY INN**

SATURDAY MAY 22, 2010

8:30 a.m. **FIELD TRIP 6: TRANSECT THROUGH THE QUETICO-WABIGOON SUBPROVINCE BOUNDARY (US)**

Mark Jirsa – *Minnesota Geological Survey*
Chris Hemstad – *Boreal Explorations*

47 passenger tour bus

Return to Rainy River Inn approximately 5:30 p.m.

TRIP LEAVES FROM AND RETURNS TO THE RAINY RIVER INN, INTERNATIONAL FALLS, MN**

****THE RAINY RIVER INN IS THE FORMER HOLIDAY INN**

8:30 a.m. **FIELD TRIP 7: MINERAL DEPOSITS OF THE MINE CENTRE – RAINY LAKE AREA (CAN)**

Peter Hinz – *Ontario Geological Survey*
Other industry geologists

9 – passenger vans

Return to rec centre approximately 6:00 p.m.

**TRIP LEAVES FROM AND RETURNS TO THE FORT FRANCES MEMORIAL SPORTS CENTER*, FORT
FRANCES, ONTARIO**

***SEE MAP ON PAGE 75 IN BACK OF THIS VOLUME FOR LOCATION**

8:30 a.m. **FIELD TRIP 8: GEOLOGY AND ENVIRONMENTAL ISSUES OF THE STEEP ROCK MINE (CAN)**

Andrew Conly – *Lakehead University*
Rob Purdon – *Ontario Ministry of Natural Resources*

Mini-vans

Return to White Otter Inn, Atikokan, approximately 6:00 p.m.

TRIP LEAVES FROM AND RETURNS THE WHITE OTTER INN, ATIKOKAN, ONTARIO

56TH ANNUAL INSTITUTE ON LAKE SUPERIOR GEOLOGY ENDS

POSTER PRESENTATIONS

- Blakely, S., Brown, A., Foley, D., Rowland, A., Stifter, E., and Miller J.D., Jr.,**
Mesoproterozoic Bedrock Geology of the Homer Lake – Vern Lake Area, Cook County, Northeastern Minnesota
- Boerboom, T. J., Magnuson, A., Creighton, Dalyce, McGinn**
Mapping of Mesoproterozoic bedrock in the Tait Lake quadrangle, Northeastern Minnesota
- Buchholz, T. W., Falster, A. U. and Simmons, W. B.**
Additions and New Data on the Mineralogy of the Keweenaw Copper District, MI.
- Bultman, M. W.**
Preliminary analysis of ground-based magnetic profile data aimed at understanding the concealed mineral resource potential of the Wisconsin magmatic terranes
- Fage*, A. and Hollings, P.**
Geology and Geochemistry of the Hemlo East Property, Schreiber-Hemlo Greenstone Belt, Ontario
- Fahrenkrog, Brooke, Totenhagen, Mike, Jaret, Steven, Watson, Tabitha, and Jirsa, Mark A.**
Geologic mapping of Archean and Proterozoic rocks near Bingshick Lake, Boundary Waters Canoe Area Wilderness, by students of the Precambrian Research Center's 2009 field camp
- Fralick, P., Brumpton, G.R., Jirsa, M.A., Kissin, S.A., Severson, M.J.**
Sedimentology of the Paleoproterozoic ejecta layer from the Sudbury impact event
- Frost*, S. J**
Effects of contact metamorphism by the Duluth Complex on Proterozoic footwall rocks in northeastern Minnesota
- Hudak, G., Diedrich, T., Monson-Geerts, S., Schreiber, M., Zanko, L., and Schwanke, A.**
Taconite-derived mineral dust in population centers on Mesabi Iron Range: an update
- Markwood*, Levi W. and Zieg, Michael J.,**
Textural analysis of a simple igneous intrusion, Nipigon, Ontario
- Medaris, L. G. Jr. and Koellner, S. E.**
Ferromagnesian Minerals in the Stettin Syenite Complex, Marathon County, Wisconsin: Compositions and Contrasts with the Wolf River Batholith
- Mulvey, Lucy, Ross, Cabin, Zeitler, Joseph, Pendleton, Matthew, McCarthy, Andrew, Copp, Lee, Nowak, Robert, Hudak, George, and Peterson, Dean,**
Bedrock geologic map of the Disappointment Lake area, Lake County, Northeastern Minnesota
- Patelke, R.L., and Severson, M.J.**
Virginia Formation outcrop (New outcrops versus old concepts)
- Ryan*, A. J. and Zieg, M. J.**
Petrographic and geochemical analysis of a Nipigon diabase sill

Triplett*, J., Saini-Eidukat, B., Feit, S., and Dolezal, D.

Identification and Characterization of Fibrous Zeolites in Western North Dakota

Weiblen, Paul W.

New ways to study old problems.

White, Chris R., and Albers, Paul B.

Geologic map of the central Seine Bay/ Bad Vermilion Lake Intrusion with accompanying airborne Geophysics, relating to Numax Resources, Inc., Mine Centre Property, Mine Centre, Ontario

Thursday a.m.**Technical Session I**

Session chair:

Mark Smyk and Peter Hinz

Session 1a. Midcontinent Rift8:30 AM *introductory remarks*8:40 AM **Miller**9:00 AM **Hoaglund***9:20 AM **Cundari***9:40 AM *Coffee break
and poster session***Session 1b. MCR Mafic Sills**10:20 AM **Magnus***10:40 AM **Puchalski***11:00 AM **Hollings**11:20 AM *Lunch break*
2010 ILSG Board Meeting**Thursday p.m.****Technical Session II**

Session chairs:

Peter McSwiggen

Session 2a. Misc. Paleoprot.1:00 PM **VanLankveldt***1:20 PM **Pietrzak***1:40 PM **Planavsky***2:00 PM **Ohare***2:20 PM *Coffee break
and poster session***Session 2b. Sudbury Impact**3:00 PM **Jirsa**3:20 PM **Weiblen**3:40 PM **Cannon****Friday a.m.****Technical Session III**

Session chairs:

Charlie Blackburn

Session 3a. Archean Econ. Geol.8:40 AM **Kolb***9:00 AM **Stinson***9:20 AM **Siemieniuk***9:40 AM **Scott***10:00 AM *Coffee break
and poster session***Session 3b. Proterozoic**10:40 AM **Gilbert**11:00 AM **Fralick**11:20 AM **Smyk**11:40 PM *Lunch break***Friday p.m.****Technical Session III**

Session chairs:

Leonard Espinosa

Session 4a. Archean Geology1:00pm **Boerboom**1:20 PM **Chandler**1:40 PM **Waggoner**2:00 PM *Student paper, poster,***Session 4b. Afternoon Field Trips**

3:00 PM depart for field trips



ABSTRACTS

MAPPING OF MESOPROTEROZOIC BEDROCK IN THE TAIT LAKE QUADRANGLE, NORTHEASTERN MINNESOTA

Boerboom, T.J., Magnuson, A., Creighton, D., and McGinn, K.

Precambrian Research Center, University of Minnesota Duluth, Duluth, MN 55812

The Precambrian Research Center (PRC) field camp culminates in several ‘capstone’ mapping projects located in different geographical areas/geological terranes in northeastern Minnesota. One of the 2009 PRC capstone projects was focused on mapping an area within the North Shore Volcanic Group that is intruded by components of the Beaver Bay Complex.

Compared to the other capstone projects, which were largely canoe-based and in areas of plentiful and clean bedrock exposures, this map area was just the opposite – no lakeshore outcrops, overgrown clearcuts, and relatively small and scattered outcrops located mostly near the apex of topographic knobs. As such, the participants in this camp gained a different perspective of ‘real-life’ field geology: the reality of field work in most northern forested areas – thick brush, insects, heat, and lack of water. Nevertheless, the mappers persevered and were able to provide significant refinements to our understanding of the bedrock geology of the southwestern Tait Lake quadrangle.

Prior to the PRC effort, the only mapping in the area was reconnaissance outcrop studies by John Green from the University of Minnesota-Duluth. This information was used in the construction of a regional, 1:200,000-scale geologic map, which portrayed the bedrock units as largely undifferentiated volcanic rocks (Miller et al., 2001). Based on the results of the PRC capstone project, within the chosen map area we have defined a southeast-dipping series of volcanic rocks that includes quartz- and feldspar-phyric rhyolite, sparsely plagioclase-porphyritic andesite, and porphyritic basalt. These volcanic rocks are intruded by the Lake Clara diabase, a southeast-dipping semi-conformable sill which was known only in a general fashion from prior work. Our new mapping has identified a thin ferrodiorite layer that is apparently semi-conformable to the base of the diabase sill, which may be the product of partial melting of the rhyolite below the sill and contamination of the adjacent diabase.

Tentative plans for the 2010 capstone project are to continue mapping in the northwest corner of the Tait Lake 7.5’ quadrangle, in a zone that transitions from the Eagle Mountain granophyre (1098.6±3.6 Ma; Vervoort and others, 2007) into volcanic rocks of the North Shore Volcanic Group. This mapping would be continuous with prior detailed mapping to the north in the Brule Lake quadrangle (Davidson and Burnell, 1977). However, difficult access may present a serious impediment to this plan in which case work may proceed elsewhere.

References:

- Davidson, D.M., Jr., and Burnell, J.R., 1977, Reconnaissance geologic map of the Brule Lake quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-29, scale 1:24,000.
- Miller, J.D., Jr., Green, J.C., Severson, M.J., Chandler, V.W., and Peterson, D.E., 2001, Geologic map of the Duluth Complex and related rocks, northeastern Minnesota. Miscellaneous Map Series, M-119, scale 1:200,000, 2 sheets.
- Vervoort, J.D., Wirth, K., Kennedy, B., Sandland, T., and Harpp, K.S., 2007, The magmatic evolution of the Midcontinent rift: New geochronologic and geochemical evidence from felsic magmatism, *Precambrian Research* 157 (2007) 235–268.

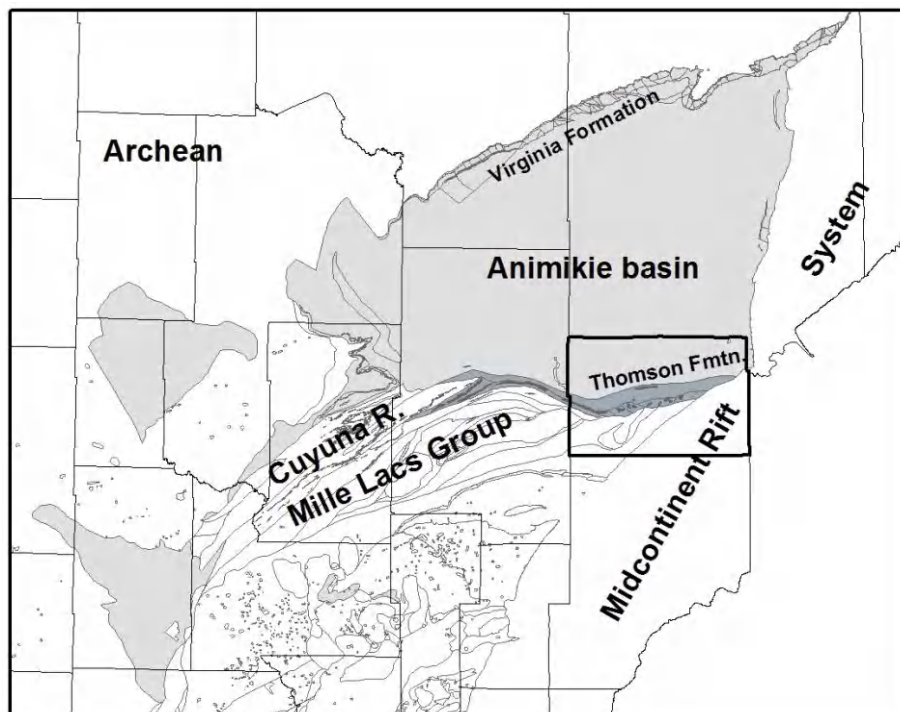
LATEST BEDROCK GEOLOGIC MAP OF CARLTON COUNTY, EAST-CENTRAL MINNESOTA AND REVISIONS TO THE SOUTHERN ANIMIKIE BASIN EDGE

Boerboom, Terrence J., Minnesota Geological Survey (boerb001@umn.edu)

As part of the Minnesota Geological Survey's ongoing County Geologic Atlas Program, a revised bedrock geologic map has recently been released for Carlton County, in east-central Minnesota. As with other county atlases produced by the Minnesota Geological Survey, this atlas was funded by a combination of state and county funds.

Carlton County straddles the southern edge of the Animikie basin (Figure), which contains strata dominated by graywacke-slate, and includes the Virginia Formation to the north and the Thomson Formation to the south. To the north the Virginia Formation overlies the Biwabik Iron Formation and the Pokegama Quartzite, the latter of which was deposited directly on Archean basement as well as eroded ca. 2.1 Ga Kenora-Kabetogama dikes. In contrast, the Thomson Formation at the southern margin unconformably overlies metamorphosed sedimentary and igneous rocks of the Paleoproterozoic Mille Lacs Group. This paper focuses on the Thomson Formation at the southern margin of the Animikie basin.

The bedrock geology of east-central Minnesota has been mapped numerous times, each version taking into account the latest geologic concepts and newly-acquired geophysical and drill-hole data. In early regional compilations the Thomson Formation included some rocks now assigned to the Mille Lacs Group, and the Cuyuna North and South Range strata were correlated to those in the lower part of the Animikie basin. However, more recent geologic interpretations associate



the Cuyuna ranges with the older Mille Lacs Group, as part of a belt that was deformed and uplifted during the Penokean Orogeny, and upon which the Animikie strata were deposited in a foreland basin setting. This scenario is supported by the ca. 1,850 Ma metamorphic ages obtained in both the Mille Lacs Group and the Cuyuna North Range, and ca. 1,800 Ma detrital zircons in the Thomson Formation.

Figure showing extent of Animikie basin (gray) in Minnesota.
Twice-deformed Thomson in dark gray. Carlton County outlined

Holst (1982) documented two structural domains in the Thomson Formation, separated by what is colloquially known as ‘Holst’s line’. Slate and graywacke south of this line (southern domain) contain a subhorizontal S_1 foliation overprinted by regional F_2 folds and accompanying S_2 crenulation cleavage, whereas rocks north of this line (northern domain) were deformed and folded only once by the regional D_2 deformation. Winchell (1899) described an outcrop of conglomerate with clasts of metagraywacke, slate, and black chert, in the vicinity of what is now ‘Holst’s line’. Although this outcrop has apparently been buried by road construction, its reported location and lithology imply a possible unconformity at the base of the northern domain. A second conglomerate, intersected by a deep drill hole near the base of the southern domain, contains clasts of granitoid rocks, metagraywacke, chert, and marble; this may represent a second, lower unconformity between the base of the southern Thomson domain and the older Mille Lacs Group. A possible scenario is that the southern domain may represent an early proto-Animikie depositional basin marked by a basal conglomerate, which was deformed and uplifted to provide sediment to the main, northern domain of the Animikie basin, the base of which is marked by a second conglomerate.

Based on examination of drill cores and outcrops, multiple east-west trending, low-amplitude aeromagnetic anomalies over the southern domain of the Thomson Formation are considered to be caused by sulfidic intervals spatially associated with thin to thick beds of chert as well as local metagabbro sills. The aeromagnetic anomalies, which coincide with electromagnetic and gravity anomalies, continue west into areas formerly designated as Cuyuna South Range. It is proposed that much of what has mapped as Cuyuna South Range is actually infolded remnants of the lowermost Animikie basin strata. In this case the lower Animikie basin would include a substantial proportion of mafic volcanic rocks and hypabyssal intrusions. Geophysical modeling implies that the magnetic source to these anomalies is a north-dipping sheet, consistent with the inferred geometry of the Animikie basin. These sulfidic horizons may be analogous to thin oxide- and sulfide-facies iron-formations in the lower part of the Michigamme Formation in Michigan, which is correlative with this part of the Animikie basin (Rossell, 2008; Ware and others, 2008).

Metamorphic ages in the Mille Lacs Group and the Cuyuna North Range show a Penokean metamorphic event (ca. 1,850 Ma), and a later Yavapai metamorphic overprint (ca. 1,760 Ma). However no metamorphic ages have been obtained from the Cuyuna South Range or from the Thomson Formation; an older ca. 1850 Ma age in the Cuyuna South Range would disprove the proposed correlation of the south range with the Animikie basin. The once-deformed Thomson Formation at its type locality contains detrital zircons as young as 1,800 Ma, the same age as the Hillman tonalite to the south. If that were the source for the zircons, deep erosion may have accompanied Yavapai uplift and deformation.

References:

- Holst, T.B., 1982, Evidence for multiple deformations during the Penokean Orogeny in the Middle Precambrian Thomson Formation, Minnesota: *Canadian Journal of Earth Sciences* v. 19, p. 2043-2047.
- Rossell, D., 2008, Trip 7: Geology of the Keweenaw BIC intrusion, *in* 54th Annual Institute on Lake Superior Geology Proceedings Vol. 54, part 2 – Field Trip Guidebook; Bornhorst, T.J., and Klasner, J.S., eds., p. 181-199.
- Ware, A., Cherry, J., and Ding, X., 2008, Trips 4 and 8: Geology of the Eagle Project: *in* 54th Annual Institute on Lake Superior Geology Proceedings Volume 54, part 2 – Field Trip Guidebook; Bornhorst, T.J., and Klasner, J.S., eds., p. 87-115.
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ADDITIONS AND NEW DATA ON THE MINERALOGY OF THE KEWEENAW COPPER DISTRICT, MI.

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Recent work on material from several former mines on the Keweenaw Peninsula, MI has revealed the presence of several minerals not previously reported from the district. Heinrich & Robinson (2004) mentioned the possible occurrence of anilite (Cu_7S_4) near Painesdale, MI. In an attempt to search for possible anilite and associated minerals, carbonate matrix was partially removed from samples of chalcocite-bearing vein material from the nearby Baltic Mine in order to better expose the sulfides. Small grains of a soft, deep blue sulfide showing excellent cleavage and evidence of multiple twinning were noted on a few samples. XRD analysis (Gandolfi camera) of a small crystal fragment yielded a pattern showing good agreement with anilite. The anilite seems restricted to quartz-rich portions of thin carbonate-quartz-sulfide veinlets, is intimately associated with chalcocite, and is usually spatially associated with late cross-cutting fractures. Associated minerals in the veinlets include native copper, metallic grains of Cu-As alloys showing highly variable Cu-As ratios and spongy appearing masses of Cu-arsenide phases that seem to be composed of fine-grained domains with widely variable compositions. Work continues to attempt to characterize these phases.

Several of the samples from the Baltic Mine dump revealed crude wires of native silver associated with chalcocite, quartz and minor barite. Small patches of a Cu-Ag sulfide were noted closely associated with the native silver during examination of this material using SEM/EDS. The Cu-Ag sulfide is identical in overall appearance to chalcocite and was analyzed via electron microprobe. The result, $[(\text{Cu}_{1.024} \text{Fe}_{0.012} \text{Mn}_{0.001})_{\Sigma 1.037} (\text{Ag}_{0.955}) (\text{S}_{0.998} \text{As}_{0.009})_{\Sigma 1.007}]$, is in good agreement with stromeyerite, CuAgS , and is the first report of this mineral for Michigan. It has been suggested that alteration of silver-bearing sulfides and sulfosalts may promote the growth of wire silver; if correct, it seems possible that Ag released by stromeyerite alteration supported the growth of these wire silvers.

A small sample from the Wolverine #2 mine contained silvery inclusions in calcite that were confirmed as arsenopyrite by EMP: $(\text{Fe}_{0.990} \text{Cu}_{0.003} \text{Co}_{0.001})_{\Sigma 0.994} \text{As}_{0.997} \text{S}_{1.009}$, in good agreement with the accepted formula FeAsS . The arsenopyrite crystals were perched on a silvery to dark gray colored matrix. Portions of the matrix were analyzed by EMP and are an intergrowth of cobaltite, $[(\text{Co}_{0.771} \text{Fe}_{0.158} \text{Ni}_{0.047} \text{Cu}_{0.023})_{\Sigma 0.999} \text{As}_{0.994} \text{S}_{1.007}]$ (analyzed) vs CoAsS , skutterudite, $[(\text{Co}_{0.825} \text{Fe}_{0.189} \text{Cu}_{0.006} \text{Ni}_{0.003})_{\Sigma 1.023} (\text{As}_{2.800} \text{S}_{0.177})_{\Sigma 2.977}]$ (analyzed) vs CoAs_3 , and other As-S bearing phases. Minute well-formed crystals of probable safflorite, $[(\text{Co}_{0.587} \text{Fe}_{0.378} \text{Cu}_{0.059} \text{Ni}_{0.002})_{\Sigma 1.026} (\text{As}_{1.850} \text{S}_{0.119} \text{Se}_{0.004})_{\Sigma 1.973}]$ (analyzed) vs CoAs_2 , are exposed on surfaces of the matrix and exhibit good orthorhombic morphology. Work continues to characterize additional phases in the matrix. Small grains and crystals of silver (0.12 wt% Hg, 0.21 wt% Se) are present throughout and upon the matrix. Neither arsenopyrite, cobaltite nor safflorite have been previously reported from the Keweenaw Peninsula, though undefined Co-arsenides have been reported from the Mohawk #2 mine, part of the same mineralized trend as the Wolverine mines (Moore, 1962; Heinrich & Robinson, 2004; Butler & Burbank, 1929).

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PRELIMINARY ANALYSIS OF GROUND-BASED MAGNETIC PROFILE DATA AIMED AT UNDERSTANDING THE CONCEALED MINERAL RESOURCE POTENTIAL OF THE WISCONSIN MAGMATIC TERRANES

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The Wisconsin magmatic terranes host numerous volcanogenic massive sulfide (VMS) mineral deposits ranging in size from uneconomic to the world class Crandon deposit with 72.5 million tons resource (DeMatties, 1994). While there has been extensive exploration in the terranes, an understanding of the total VMS resource is hindered by thick glacial deposits and/or relatively thin Cambrian sandstones that cover most of the area where permissive host rocks might occur. No medium size VMS deposits (10 to 60 million tons resource) are known in the area, and it is likely that some undiscovered deposits in this size range occur here (DeMatties, 1994). All known economic VMS deposits are associated with syngenetic and epigenetic strata-bound to stratiform mineralization within, along the flanks of, or near the top of felsic volcanic centers (DeMatties, 1994). Felsic centers are found within more mafic metavolcanic rocks creating a bimodal assemblage of volcanic rocks. The ability to distinguish concealed felsic centers from more mafic metavolcanic rocks would contribute to knowledge of the potential distribution and extent of these deposits and serve as an exploration tool.

In order to discriminate concealed felsic centers from more mafic concealed metavolcanic lithologies, Earth's total intensity magnetic field profile data were acquired by a truck-mounted cesium vapor magnetometer. The magnetometer is mounted at 3.5 meters height and acquires data at measurement intervals of 1.5 to 2.0 meters. These data include information on the spatial distribution of near surface magnetic dipoles that in many cases are unique to a specific lithology. These magnetic signatures have distinct textures (the physical appearance of the data, especially groups of anomalies) that can be compared visually and characterized by several descriptive statistics. Ground-based magnetic profile data have been used successfully in the Basin and Range Province of North America for the identification of bedrock lithology concealed by 100 meters or more of Cenozoic basin fill (Bultman, 2009).

In the Basin and Range Province, candidate lithologies (lithologies that may be found concealed by basin fill sediments) often outcrop in the mountain ranges directly adjacent to the basin. This allows the magnetic signature of a candidate lithology to be field calibrated and precisely defined. In areas with thick (10's of meters) continuous cover of glacial sediments, it is impossible to acquire the magnetic signature of a candidate lithology. As felsic rocks are generally less magnetic, they display a low amplitude signal in the ground-based magnetic profile data. The mafic metavolcanic rocks displays a much higher amplitude signal that is easily visible in profile data and is easily discriminated from felsic center profile data. Figure 1 displays approximately 6 km of ground-based magnetic profile data plotted along the road over which it was acquired. Numerous cultural features are identified within the profile, which is also plotted on a background image of the aeromagnetic data (Daniels and Snyder, 2002). A significant change in texture is indicated on the profile data and defines the location of a concealed

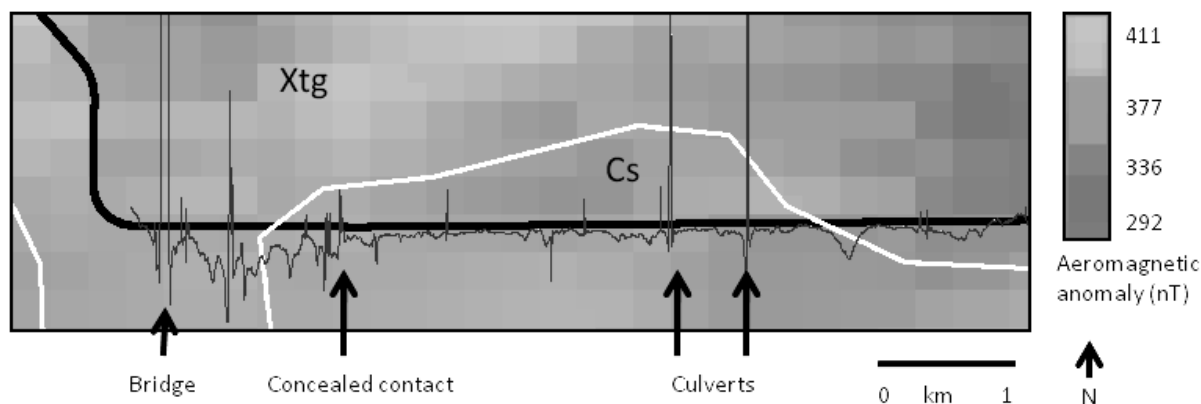


Figure 1: Ground-based magnetic profile data (thin black line) acquired from west to east along County Roads I and V (black line), Rusk County, Wisconsin plotted on top of the Wisconsin aeromagnetic map (Daniels and Snyder, 2002). Location of a concealed contact between more mafic concealed lithology to the west and a more felsic concealed lithology to the east is indicated along with anomalies due to cultural features. Mapped contacts (Sims, 1989) are shown by white lines. Mapped units are: Cs= Upper Cambrian Mount Simon Sandstone and Xtg=Early Proterozoic felsic volcanic and volcanogenic rocks (after Sims, 1989).

contact between more mafic rock to the west and felsic rock to the east. There is no indication of this change in concealed lithology on the aeromagnetic image, displayed in the background of Figure 1. This change in lithology can also be identified using statistical analysis of the ground-based magnetic profile data. Using this technique, known felsic centers have been identified and partially mapped at the Flambeau, Bend, Schoolhouse, Lynne, and Crandon deposits. In addition, several areas with very low amplitude magnetic signals in the over 1000 km of ground-based magnetic profile data acquired to date may represent additional concealed felsic centers. Presently, it is impossible to differentiate felsic metasediments from felsic centers, and it may be difficult to reconcile this issue.

Future work includes the addition of more ground-based magnetic profile data in the Wisconsin magmatic terranes, acquisition of data on thin Cambrian sandstones that overlie the western end of the terrane, and acquisition and analysis of data over other terranes concealed by glacial drift in the upper Midwest.

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GLOBAL EFFECTS OF THE SUDBURY BOLIDE IMPACT AT 1850 MA: POTENTIAL LINK TO THE EVOLUTION OF MARINE MINERAL DEPOSITS

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The bolide impact at Sudbury, Ontario at 1850 Ma is of comparable magnitude to the Chicxulub impact that produced profound and well-documented global biological and environmental changes at the K-P boundary. Like Chicxulub, Sudbury probably produced global effects and we have speculated that it caused changes in ocean chemistry and structure which, in turn, influenced the nature of marine mineral deposits (Slack and Cannon, 2009). Several studies (Figure 1) show that circa 1850 Ma was a time of substantial changes in the occurrence and global abundance of sedimentary manganese deposits, volcanogenic massive sulfide (VMS) deposits, sedimentary-exhalative (SEDEX) sulfides, and deep-water (Cu-rich) VMS-related exhalites, in addition to Superior-type banded iron-formations (BIF), which is our focus here. From these changes it appears that 1850 Ma was a pivotal moment in marine metallogeny.

The deposition of BIF required a stratified water body in which deep anoxic waters allowed high concentrations of dissolved ferrous iron, which was then deposited by oxidation to insoluble ferric iron where the chemocline intersected the shallow seafloor. Deposition of BIFs on continental shelves and in foreland basins implies that the entire ocean was stratified for the long periods of Earth history during which BIFs were deposited (Fig. 1). We suggest that the disappearance at 1850 Ma of BIFs (and granular iron formations) from open-marine settings marks the end of anoxic deep water conditions. The change from mainly reduced (sulfide) facies to oxidized (hematite, magnetite) facies in deep-water exhalites at approximately this time is consistent with loss of the deep mass of anoxic seawater. Secular correspondence of several fundamental changes in marine metallogeny shown in Figure 1 and the Sudbury impact is striking, a timing that we suggest is not coincidental. We propose that the Sudbury impact disrupted the previously stratified ocean and mixed deep anoxic water with shallow oxygenated water thus ending the requisite conditions for BIF mineralization. At 1850 Ma the Earth's surface (Fig. 2) contained a single supercontinent, Columbia, surrounded by a single ocean (Zhao, et al., 2004), a situation that is critical for evaluating global effects of the Sudbury impact into an epicontinental sea near the margin of Columbia. We propose three mechanisms that might have broken down the preexisting ocean stratification:

1-Giant tsunami: Impacts of large bolides into oceans produce giant tsunamis. Impacts may excavate a crater in the ocean water with a diameter 1.5 times that produced in the underlying crust; the crater is caused by both vaporization of water and physically impelling the water laterally. Tsunami waves result both from lateral expulsion of water and return flow into the crater. Models indicate that in open oceans with depths typically greater than 4 km, these waves can be hundreds of meters high, capable of disturbing the entire water column, and scouring the sea floor over large regions. The Sudbury impact into continental crust, although probably covered by an epicontinental sea, may have produced tsunami waves of lower amplitude. Data to estimate maximum wave heights from the Sudbury impact are lacking. Thus, the capability of Sudbury-related waves to mix the global ocean cannot be predicted accurately by models.

2-Shelf collapse and debris flows: Earthquakes generated by the Chicxulub impact caused massive failure of much of the outer continental shelf of eastern North American, and spread a layer of debris as much as several meters thick across the western North Atlantic seabed (Norris and Firth,

2002). Shelf failure was common for at least 4,000 km from the impact site; lesser failure is known at distances up to 7,000 km. A 4,000 km circle centered on Sudbury (Fig. 2) indicates that virtually the entire continental margin of Columbia was likely susceptible to shelf failure from the Sudbury impact. Debris flows radiating out from Columbia may have stirred and mixed ocean waters, creating a new suboxic state for deep seawater by mixing with oxygenated surface water.

Antipodal effects: The massive earthquake caused by the Sudbury impact may have had global consequences, but the phenomenon of antipodal focusing of seismic energy should be considered in addition to simple hemispheric transmission and attenuation of seismic energy. Axial focusing of seismic energy and the delivery of a strong seismic signal at the antipode of an earthquake's origin is widely observed and well understood in theory. Large-scale deformed terranes are known on both Mercury and the Moon that are antipodal to major impact sites. We suggest that the intuitive notion of decreased seismicity away from Sudbury needs to be modified and the possibility of significant antipodal effects thoroughly evaluated. For instance, if the Sudbury impact produced major surface deformation at its antipode, probably on the deep seabed, significant tsunamis could have been generated there that were transmitted back toward the Columbia landmass, with physical mixing of ocean waters occurring at the antipode as well as closer to Sudbury.

We propose that these three phenomena, all likely consequences of the Sudbury bolide impact, possibly acting in unison, resulted in profound changes in the nature of the 1850 Ma global ocean and in the numerous observed changes in the character of marine mineral deposits at that time.

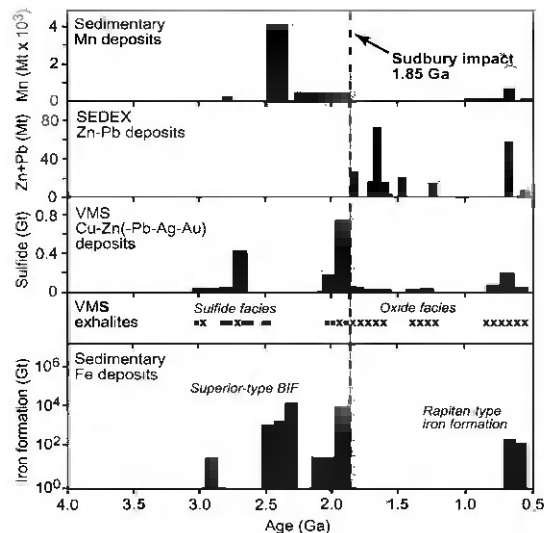


Figure 1. Distribution of marine mineral deposits through time showing the changes that coincide closely with the Sudbury impact.

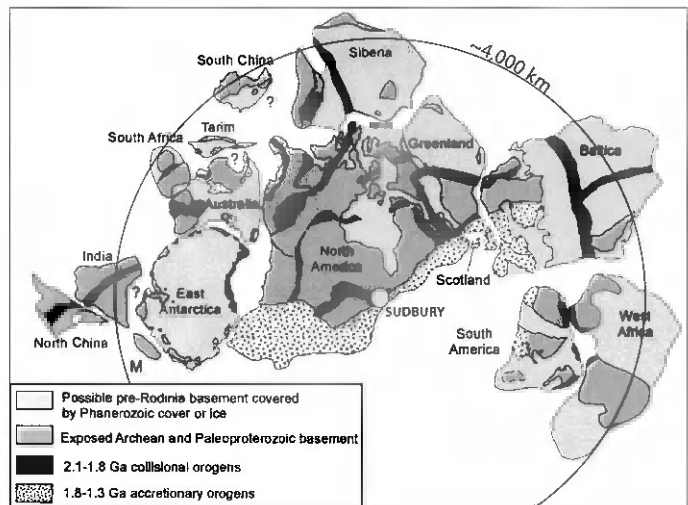


Figure 2. Reconstruction of the Supercontinent Columbia (Zhao et al., 2004) showing the location of the Sudbury impact and a 4,000 km radius circle around the impact site.

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THE SEARCH FOR MAGNETIC BASEMENT IN MINNESOTA: SLIDING ALONG WITH THE EULER EQUATION

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Among the most commonly derived estimates from aeromagnetic data are depths to the top of magnetic sources, or “magnetic basement”. Originally these estimates were done graphically using profile records or contour maps, but in recent decades a variety of computer-based techniques have been developed. One particularly robust approach is based on Euler’s homogeneity equation; which is iteratively solved within windowed subsets of gridded aeromagnetic data, thereby providing estimates of source locations in three-dimensional space (Reid and others, 1990). The Euler method requires no *a priori* information regarding source magnetization, and only requires selecting a structural index (SI), which is the power of the rate of field change that is sensitive to source-type. For example a SI=1 is consistent with a thin sheet (dike or sill) whereas a SI of 0.5 is commonly used to approximate contact solutions. The Euler Method is used here to investigate the Precambrian geology and upper crustal structure of Minnesota and adjacent areas. This study employs the “located” Euler approach (Geosoft Inc.), in which the analytical signal is used to focus the Euler analysis to areas maximum anomaly gradients, where solutions are most likely to be accurate.

Euler analysis of an aeromagnetic grid that has been continued to a relatively low level of 300 meters yields abundant information about sources at or near the Precambrian bedrock surface. In addition to providing thousands of estimates of depth, the Euler solutions form numerous chains of solutions that can facilitate geologic mapping. Not surprisingly, areas of near-surface Precambrian rocks are usually associated with noticeable concentrations of shallow depth estimates, but other solutions in these and in deeper bedrock areas indicate that some anomaly sources may actually lie 100’s of meters below the Precambrian surface.

Euler analysis of aeromagnetic data that were smoothed by upward continuing to a level of 1000 meters was useful for investigating deeper (1000-5000 meters) features, such as the Paleoproterozoic Animikie basin and the upper Keweenawan basins of the Mesoproterozoic Midcontinent Rift. Euler analysis of the Animikie basin using a structural index of 1 yields results that are comparable to earlier magnetic-based estimates, and indicates that the deeper parts of the Animikie basin contain 2500 to 4500 meters of non-magnetic strata. The deepest part of the Animikie basin lies to the east, along the basal contact of the Duluth Complex, perhaps reflecting a regional tilting related to Keweenawan rifting. Estimate of dip along this apparent slope averages around 5 degrees. A shelf along the northwestern margin of the Animikie basin corresponds to the west-southwestward extension of the Virginia Horn. Along the Midcontinent Rift, Euler analysis with a structural index of 0.5 indicates that sedimentary basins east and west of the St. Croix Horst typically contain 3-5 km and 2-3 km thick packages of strata, respectively (Figure 1), whereas the basins atop the horst typically have 1-2 km (Ashland Syncline) and 3-5 km (ancestral Twin Cities basin) of strata. These estimates are generally consistent with those using seismic data (Chandler, 1989; Allen, 1994), and they provide some new insights on those parts of the rift that lack seismic data. For example, the Euler results imply an unusually deep (>5000 meters) basin in south-central Minnesota along the Belle Plaine Fault (Figure 1), and further investigation is warranted.

The results of this study indicate that the Euler method is a viable geophysical tool that will help in understanding Minnesota's geology in all three dimensions.

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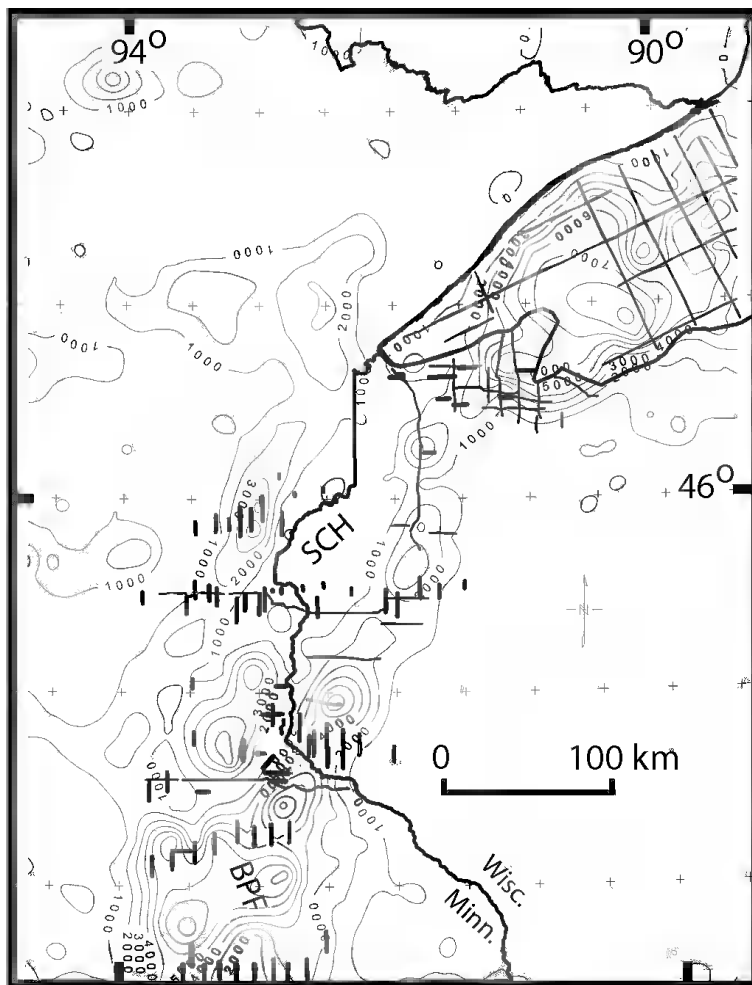


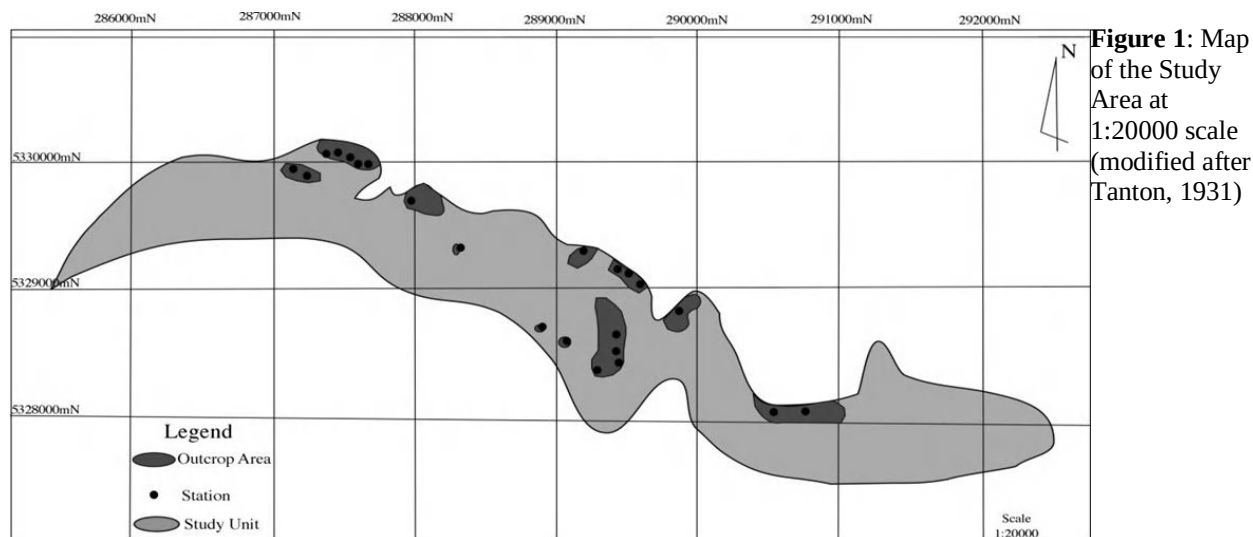
Figure 1. Depth to magnetic basement of the Midcontinent Rift in Minnesota and Wisconsin, based on Euler analysis of 1000 meter level aeromagnetic data with a structural index of 0.5. Contour interval is 1000 meters, heavy lines represent seismic refraction profiles by Mooney and others (1970), and lighter lines represent seismic reflection lines used by Allen (1994). SCH, and BPF designate the approximate location of the St. Croix Horst, and the Belle Plaine Fault, respectively.

GEOLOGY AND GEOCHEMISTRY OF THE ROVE BASALTS, A POSSIBLE MID-CONTINENT RIFT-RELATED EXTRUSIVE UNIT SOUTH OF THUNDER BAY, ONTARIO

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A unit of mafic rock in Devon Township, south of Thunder Bay, was mapped by Tanton (1931) and was termed Rove Formation Basalt. Geul (1970) mapped this unit as a Logan diabase sill. The primary objective of this study was to characterize the unit and test whether it is of intrusive or volcanic origin. This was achieved by mapping the unit at a scale of 1:20 000 (Fig. 1), and through petrographic and geochemical analysis.

The unit is exposed on a plateau 7 km long and 0.8 to 1.0 km wide. The unit is 4 to 6 m thick and is in apparent conformable contact with the underlying shales of the Paleoproterozoic Rove Formation, where a pronounced chilled margin consists of variolitic material up to 20 cm thick. The flow-top also exhibits a variolitic texture up to 15 cm thick. The presence of ropy flow top and amygdules, as well as quench textures, support a volcanic origin.



Major element chemistry reveals a tholeiitic, intermediate composition with samples plotting in the basaltic andesite to andesite fields as well as in the basaltic trachy-andesite to trachy-andesite fields on a TAS diagram. The unit typically has an intergranular texture consisting of randomly oriented plagioclase laths with interstitial chlorite, an alteration product of primary augite. Most samples contain minor serpentine (after olivine), opaque minerals, secondary quartz, oxides, pyrite and calcite. Amygdules are present in most samples and are infilled with some combination of calcite, quartz, chlorite and pyrite. Lower flow contacts and flow-tops are typically glassy with abundant spherulites that sometimes coalesce into bands.

Rare-earth element geochemistry shows the unit to be relatively enriched in both HREEs and LREEs, similar to the ultramafic sills of the Nipigon Embayment as well as the Riverdale Sill

(Hollings et al., 2007, 2009) (Fig. 2). A primitive mantle-normalized REE plot shows that the volcanic unit is characteristic of an Ocean-Island Basalt (Fig. 3), but with a negative Nb anomaly, most likely the result of lower crustal contamination. This evidence is further supported by an epsilon $\text{Nd}_{(T=1100\text{Ma})}$ of -3.48, which also suggests contamination of the unit by a lower crustal source. The trace element characteristics of the volcanic unit suggest an origin in Keweenawan time as they are geochemically similar to volcanic units of the Midcontinent Rift (Hollings et al., 2007) rather than Paleoproterozoic volcanic units of the Gunflint Formation.

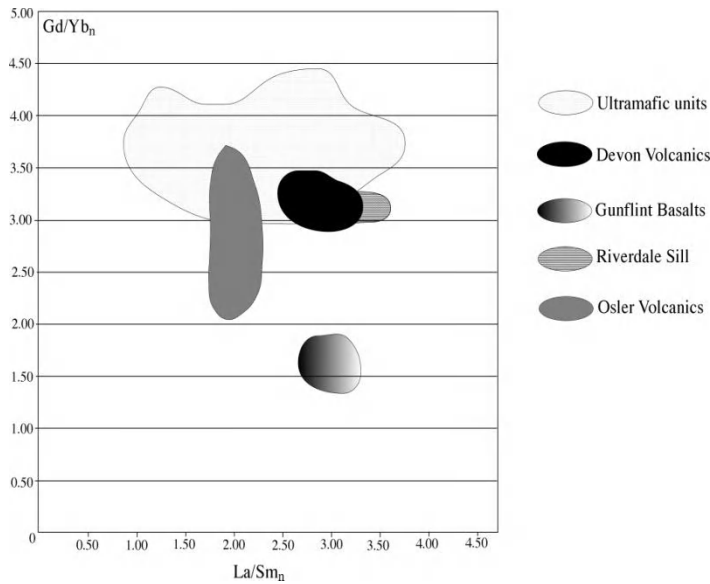


Figure 2: Gd/Yb_n versus La/Sm_n showing comparison between the study unit and other Keweenawan Midcontinent rift-related units. Fields from Hollings et al., (2007, 2009).

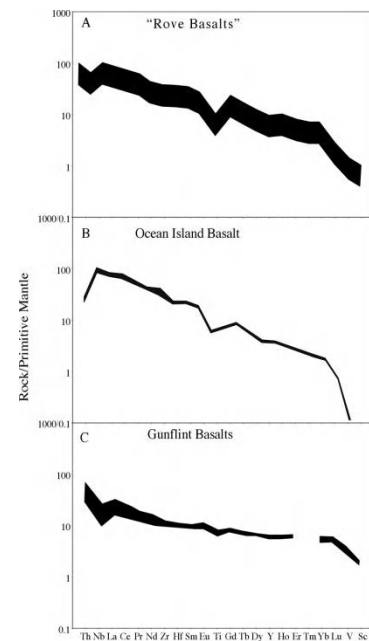


Figure 3: Comparison of primitive mantle-normalized plots from the study unit (A) with Ocean Island Basalt (OIB) (B) and Gunflint volcanic rocks (C). OIB data from Hollings et al. (2007), and Gunflint data from Fralick (unpublished).

Field, petrographical and geochemical analysis suggests that the unit is of volcanic origin with emplacement likely during Keweenawan Midcontinent rifting. Thus, we are proposing that the unit be renamed the Devon Volcanics.

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GEOLOGY AND GEOCHEMISTRY OF THE HEMLO EAST PROPERTY, SCHREIBER-HEMLO GREENSTONE BELT, ONTARIO

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The Hemlo East property, owned by Metalcorp Limited, is located approximately 50 kilometres east of the town of Marathon, Ontario and is situated within the Schreiber-Hemlo greenstone belt of the Wawa subprovince of the Archean Superior Province. Hemlo East has been extensively explored over the past 40 years, mainly being examined for Hemlo-type gold deposits. The property is sandwiched between the Cedar Lake Pluton (2688 – 2687 Ma, Corfu and Muir, 1989) to the north and the Pukaskwa Batholith (2719 and 2688 Ma, Corfu and Muir, 1989) to the south. The geology is dominated by generally east trending and north dipping metasedimentary rocks with mafic to intermediate metavolcanic rocks and minor felsic metavolcanic rocks. High level intrusive dykes and Proterozoic diabase dykes crosscut all lithologies. The entire Schreiber-Hemlo Greenstone belt has been affected by lower to mid amphibolite facies metamorphism (Pan and Fleet, 1993).

Tholeiitic basalts are the prevalent volcanic rock type. Mg# varies from 64 to 36 over a SiO₂ range of 45-54 wt%. Cr and Ni correlate with Mg# while Fe, Ti, Zr and all REE have a negative correlation (Fig. 1). These rocks are characterized by a near-flat pattern on a primitive mantle normalized plot and have been described as having a plume-derived oceanic plateau association by Polat (2008).

Tholeiitic to calc-alkaline basalts, andesites, rhyodacites, and rhyolites make up a minor portion of the volcanic rocks and are characterized by LREE enrichment as well as Nb depletion; relative to Th and La (Fig. 1). Rhyolites also exhibit HREE depletion. These rocks possess a subduction-derived oceanic island arc association (Polat, 2008). Preliminary zircon ²⁰⁶Pb/²³⁸U age dating on a rhyolite yielded an age of 2694.5±1 Ma.

Depleted initial Nd isotopic compositions (ϵ_{Nd} = +1.76 to +2.11) are consistent with long-term depleted heterogeneous mantle sources (Polat, 2008). The presence of both oceanic plateau and island arc associations of the volcanic rocks can be explained with a subduction zone at the edge of an oceanic plateau which led to rifting and the formation of a backarc basin; this is consistent with the findings of Polat (2008).

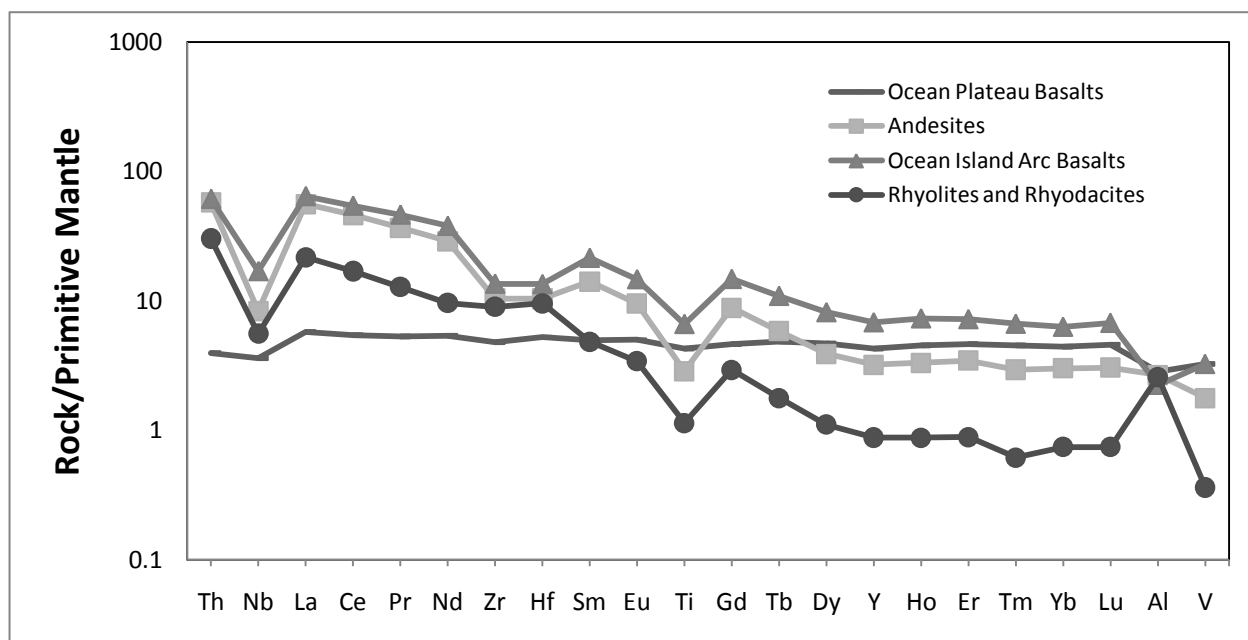


Figure 1. Primitive mantle normalised diagram for average compositions of volcanic rocks of the Hemlo East property (normalising values from Sun and McDonough, 1989).

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GEOLOGIC MAPPING OF ARCHEAN AND PROTEROZOIC ROCKS NEAR BINGSHICK LAKE, BOUNDARY WATERS CANOE AREA WILDERNESS, BY STUDENTS OF THE PRECAMBRIAN RESEARCH CENTER'S 2009 FIELD CAMP

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The Precambrian Research Center—a branch of the University of Minnesota, Duluth—conducted its third season of field camp in 2009. After 5 weeks of field training, students were assigned “Capstone Projects” that provide an opportunity to create new geologic maps in areas of poorly understood geology. The students mapped Archean and Proterozoic bedrock in the Bingshick Lake area (Figure 1) that was impacted by forest fires in 2006 and 2007. The fires greatly improved access to and visibility of geologic features, allowing detailed mapping of rock units and illuminating complex contact relationships.

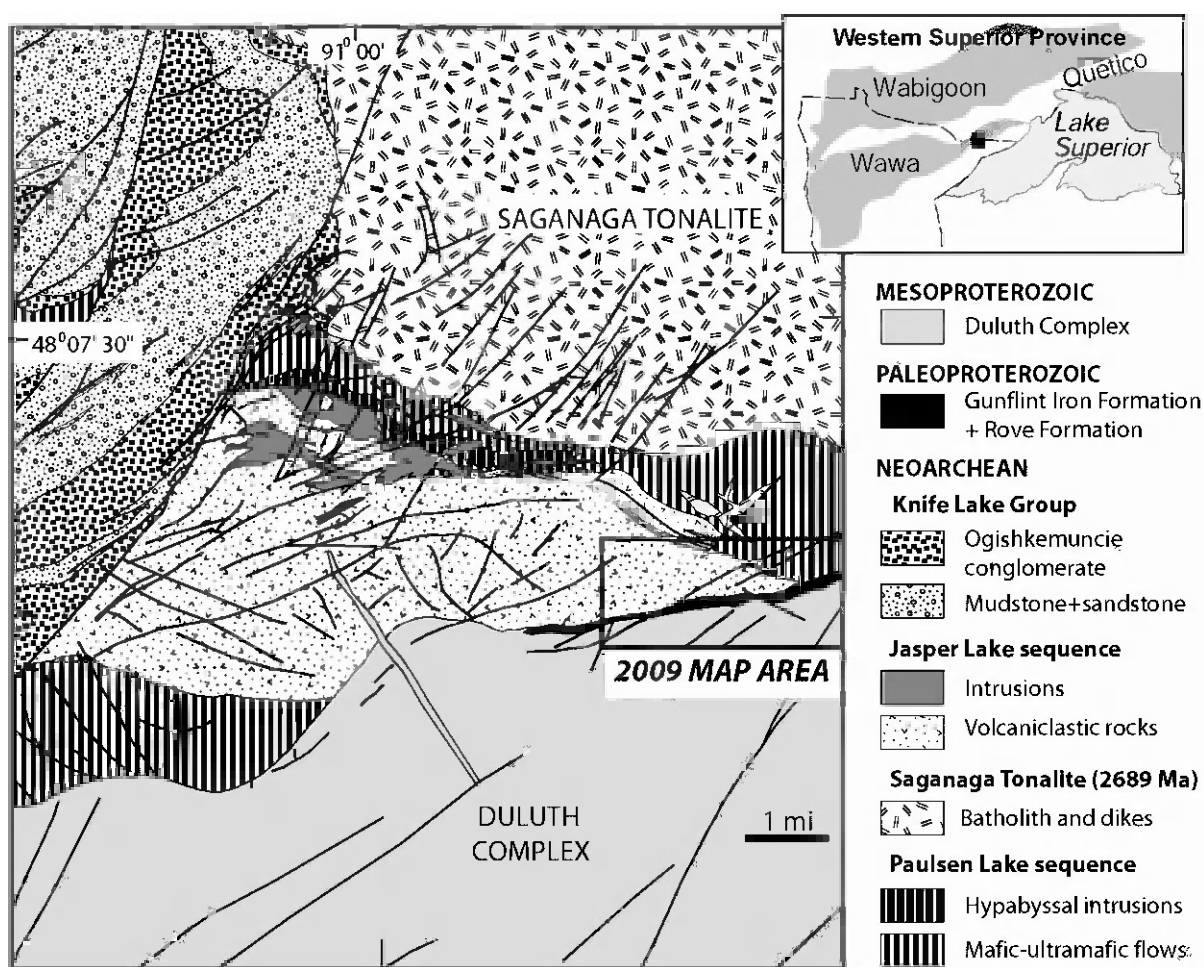


Figure 1. Regional geology (simplified from Jirsa and Starns, 2008) showing map area of 2009 PRC students.

Listed below, from youngest to oldest, are the principle map units:

Mesoproterozoic

Heterogeneous troctolite of the Tuscarora Intrusion of Duluth Complex: Light grey to grey, medium to coarse grained, heterogeneous troctolite with localized pegmatitic patches and ophitic clinopyroxene. The

highly variable unit contains localized zones of augite-troctolite, mela-troctolite, and troctolite, with sulfide-rich patches occurring locally. Light orange oxidation staining occurs on weathered surfaces. Diabase dike (age uncertain): Consists of fine- to medium-grained, dark-colored mafic rock, with aphanitic chilled contacts against country rocks.

Paleoproterozoic

Gunflint Iron Formation: Grey to white, fine to coarse grained, Superior-type banded iron-formation. The unit is weakly to strongly magnetic. It consists of alternating medium regular-bedded slaty magnetite rich beds and massive cherty beds locally containing magnetite halos, diffuse structures and intraclasts of slate. Coarse magnetite and quartzite grains were observed near baked zones along the contact with younger troctolite. Red oxidation surfaces occur along the baked zone and on weathered surfaces.

Rove Formation: Light to medium gray, brecciated or conglomeratic, biotite-rich schist.

Neoarchean

Trachyandesite of the Jasper Lake sequence (of Jirsa and Starns, 2008): Tan, fine to medium grained, heterogeneous trachyandesitic volcanic conglomerate and breccia. Angular to subangular fragments (up to 1 foot in diameter) ranging widely in composition from felsic to intermediate to mafic. Interbedded layers (as much as to 1 foot in thickness) of siltstone occur locally. Light chlorite and actinolite alteration occur throughout unit.

Metagabbro of the Paulsen Lake sequence (of Jirsa and Starns, 2008): Grey, medium-grained, subophitic metagabbro. The unit displays what appears to be chlorite-actinolite alteration that locally replaced as much as 40% of precursor pyroxene.

Metabasalt of the Paulsen Lake sequence: Light green to grey, aphanitic to fine-medium grained, metabasalt, with heavy chlorite and quartz-epidote alteration present throughout. The unit is weakly foliated and alternates between pillowed, massive, and pillow breccia flows.

The most significant findings of our field research involved more accurate positioning of previously defined contacts, and investigating those contacts to shed light on the apparent age relationships between units. The main findings are as follows:

1) Discovery of an angular unconformity between pillowed and autobrecciated mafic-ultramafic flows of the Archean Paulsen Lake sequence and younger, but also Archean volcanic conglomerate of the Jasper Lake sequence. Some of the alteration in the older volcanic strata beneath the unconformity may be the result of paleoweathering during the hiatus. These attributes are similar to those described by Jirsa and Driese, 2009 (ILSG) for the post-2689 Ma erosional unconformity between the Ogishkemuncie conglomerate and Saganaga Tonalite.

2) Discovery of breccia at the stratigraphic top of Gunflint Iron Formation that may be related to 1850 Ma Sudbury meteorite impact event. The breccia occurs within a few hundred feet of the basal Duluth Complex, and therefore is highly metamorphosed.

3) The observation at the western edge of the map area that cherty units of the Gunflint Iron Formation lie directly on eroded Archean bedrock, with no intervening clastic horizon. This contrasts with areas to the east near the Gunflint trail and west on the Mesabi Iron Range where clastic units (Kakabeka Conglomerate and Pokegama Quartzite) occur at the unconformity.

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SEDIMENTOLOGY OF THE PALEOPROTEROZOIC EJECTA LAYER FROM THE SUDBURY IMPACT EVENT

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At 1850 Ma an object, probably in excess of ten kilometers in diameter, struck the edge of Superior Craton in the area that is now Sudbury, Ontario. The impact produced the second largest known crater on the surface of the Earth, propelling an immense amount of material into the atmosphere. The area four to seven hundred kilometers west of the impact site consisted of a peneplained terrain that was sub-aerial in its northern extremity, with lithified Gunflint Formation bedrock, and possibly flooded with very shallow marine conditions in its central and southern portions. The ejecta cloud swept across this setting, entraining locally derived material. In places the impact layer deposited by this surge was altered by possible tsunami activity, sub-aerial reworking and diagenesis, and fifteen million years later was buried by sediment of the transgressing ocean.

Addison et al. (2005) first discovered this layer, which has since been described at other locations by Pufahl et al. (2007), Cannon et al. (2010) and Addison et al. (in press). To date over twenty outcrop and core sections through the layer have been found. It is extremely laterally variable, ranging from totally absent in some sections to tens of meters in thickness in others. Sections within a few hundred meters of one another can be composed of different material with contrasting textures and sedimentary structures. Common components of the deposits are: 1) pebbles to boulders of predominantly locally derived chert and carbonate, 2) pebble to sand-sized devitrified glass, 3) 3 to 20mm accretionary lapilli, 4) unshocked quartz and feldspar grains, and 5) quartz with planar deformation features (PDFs). Where pebble-sized devitrified glass is common accretionary lapilli are usually absent. Conversely, sections with lapilli in grain-support commonly do not contain devitrified glass. Massive carbonate and silica replacement has occurred. In sub-aerially exposed sections blocky calcite cements developed first, then this was overprinted (including lapilli) by quartz and iron carbonate. This lithified material occasionally locally collapsed forming boulder piles along what were probably fault scarps.

The two most typical types of successions are: 1) up to 7 meter thick boulder conglomerates with devitrified glass +/- lapilli, and 2) thin (averaging approximately 50 cm) graded sand- to granule-sized material with lapilli. The thick successions commonly overlie fractured to shattered bedrock with large rotated blocks. In other areas the boulder conglomerates overlie what had been water-saturated sediment that liquefied allowing sinking of interstratified, brecciated, chert layers. Models suggest this area would have experienced an earthquake of approximately magnitude 10, quite capable of producing these effects. The overlying disorganized pebble to boulder conglomerate contains clasts up to 3.5 meters in length that are commonly in matrix support, but in some portions of the sections are in clast support. Pebbles of devitrified glass can be mixed throughout the matrix or may appear only in the upper half of the conglomerate where they are commonly small pebble- to granule-sized. In some sections the conglomerates are organized as a series of stacked lenses that decrease in size upwards with some small lenses near the top filled with the first appearance of accretionary lapilli. In other sections lapilli are scattered between the disorganized boulders of the massive conglomeratic deposit. At some locations, approximately one meter of clast-supported, parallel laminated to trough cross-stratified lapilli, with possible chute and pool structures, interlayered with sand- to granule-sized material, overlies the conglomerate. Alternatively, at some locations it is overlain by a massive layer of devitrified glass

pebbles or a thick assemblage of massive or large-scale cross-stratified, sand-sized material. These thicker successions appear to fill depressions. The thinner sections of impact related debris mostly overlie intact bedrock, which apparently was swept clean of the earthquake rubble. They commonly show grading, consisting of either: 1) one or more successions that are normally graded from sand and granules, with lapilli, to silt, or 2) are reverse then normally graded with the granules and lapilli concentrated in the middle of the tens of centimeters thick unit.

Without modern analogues interpretation of these successions is difficult. The presence of areas with slickensides and chute and pool structures in some of the outcrops denotes deposition by a high velocity base surge, whereas multiple graded units in some drill-holes are possibly the product of tsunami activity. It is unlikely some other sections represent tsunami deposits as the accretionary lapilli and glass fragments would have arrived in the area via ballistic trajectories and the surge cloud prior to arrival of the tsunami. Thus, any tsunami deposit should have some of this material incorporated throughout it. However, in many sequences the glass and lapilli are not present near the base, making tsunami deposition of sediment in these sections unlikely. Alternatively, in base surges, steam with few solid particles forms the leading front of the cloud followed by the ejecta-rich portion. It is reasonable to visualize the earthquake-generated loose debris being initially redeposited in hollows by the steam-surge, with glass and lapilli deposited from the main surge cloud mixed with the local sediment capping this. As the velocity of the debris cloud decreased and the terrain developed at least a partial covering of impact-related sediment the abundance of locally derived chert and carbonate grainstone clasts diminished and better sorted layers rich in either glass or accretionary lapilli developed. A further decrease in the velocity of the blast cloud resulted in a transition from pebble- and granule-sized material to sand-sized glass fragments and other debris. Tsunami reworking of these successions into more chaotic masses in some areas is possible. Deposition on a locally fault brecciated erosional surface with topographic relief led to rapid lateral changes in lithofacies and thickness. It is likely that the thicker, coarser basal units are confined to topographic lows, as, in places, they can be seen to pile-up against bedrock cliffs facing the impact site. The thin, reverse-graded ejecta layers are typical of small volume base surges. These probably formed from the lower density tail of the flow on topographically higher areas that were erosively swept clean by the main flow. Reworking of some of the deposits in whole or in part by gravity sliding or possibly fluvial activity is also indicated.

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ANATOMY OF AN ARCHEAN CARBONATE PLATFORM: GEOLOGY OF THE STEEP ROCK GROUP, CANADA

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Carbonate platforms capping oceanic islands and plateaus are not uncommon in the modern ocean. However, they are rare in the rock record of the Archean. The 200 to possibly 500 meter thick succession of calcium carbonate rocks present at the long abandoned Steep Rock iron mine, Ontario, Canada, is one of the few such examples of an extensive Mesoarchean-Neoproterozoic limestone platform. The approximately 2.8 Ga sedimentary assemblage is dominated by limestones that unconformably overlie 3.0 Ga tonalitic gneiss incised by a paleochannel network backfilled with fluvial sandstones and conglomerates. The lower meters of the limestone contains scattered tonalitic sand and gravel, but the remainder has very low amounts of siliciclastic material.

Wilks and Nisbet (1985, 1988) have provided excellent descriptions of the Steep Rock platform succession; from *Stratifera*-like and *Irregularia*-like structures that pass upward to laterally linked hemispherical stromatolites, branching walled and unwalled columnar forms and giant domes. They also noted the presence of crystal fans, which are probably the deposits originally described as the supposed fossil *Atikokania* by Walcott (1912). The present study adds details of lithotypes, and suggests the presence of grainstones in the interval underlying the giant domes and possibly interlayered with some domes. Mudcrack-like structures were observed on the upper surface of one dome. Giant domes dominate the upper 70 m of the succession. They are persistently elongated, suggesting current-influence, and range up to 5 m in length, 2 m in width and 1.4 m in height. Inter-dome sediment is usually lacking. The giant domes are distinctly banded and composed of centimeter-decimeter layers of crystal fans alternating with cusped fenestral fabric (fenestrate microbialite, Sumner, 2000; Sumner and Grotzinger, 2000). Large domes are not developed in lithologies that lack cusped fenestral fabric, and these show a variety of centimetric interlayers that include wavy, irregularly fenestral, and possibly granular fabrics, together with thin sheet cracks.

Twenty-seven samples from various lithofacies were analyzed for major and trace elements and carbon isotope ratios. Carbon varies from $\delta 0$ to 2.7, with the lightest values consistently present in the columnar stromatolites and the heaviest in the crystal fans. There is a progression from lighter carbon isotope values at the base of the section upward to heavier values at the lowest zone of crystal fans. Above this the values rapidly decline to near 0 where the columnar stromatolites are located, and then gradually rise again to the heavy carbon enriched upper third of the section dominated by the crystal fans. Strontium and barium concentrations have similar trends, whereas the concentrations of iron, and to a lesser extent manganese, behave in an inverse manner. Iron carbonate present in iron formation overlying the limestone has low levels of Sr and Ba, and contains significant amounts of Fe and to a lesser degree Mn. Its carbon isotopic ratio is -5.6, which is similar to values derived from other iron formations of similar age.

Fralick et al. (2008) suggested that the oceanic plateau was drowned during isostatically driven subsidence. It is clear that carbonate deposition was able to keep pace with sea-level during most of the subsequent load-driven subsidence of the carbonate platform. The dominance of calcite rather than an iron carbonate in the sequence indicates lower levels of Fe^{+2} dissolved in the water over the shallow plateau than deeper portions of the plateau where siderite was accumulating. This possibly reflects a sub-oxic, shallow water zone created by photosynthetically released oxygen together with restricted circulation above a chemocline. Heavier carbon isotopic ratios could reflect evaporitic loss of C^{12} leading to aragonite crystal fan precipitation. Low Sr contents indicate that the non-crystal fan carbonates were deposited as calcite, except for the columnar stromatolites that are dolomite and may have been deposited as dolomite in the low sulfur Archean ocean. These stromatolites also have the lowest C isotopic ratio and high concentrations of iron and manganese. This suggests less saline conditions and better connection with the open ocean during deposition of the columnar stromatolites. A possible relationship between stromatolite morphology and salinity further indicates the organisms that constructed these features may not have been very salt tolerant. Conversely, they may have been iron or manganese oxidizers that could not survive when water on the shallow portions of the plateau became more stagnant and concentrations of Fe and Mn in solution dropped.

The emerging picture is of an oceanic platform where carbonate deposition outpaced subsidence, sustaining very shallow water conditions that limited incursion of Fe- and Mn-rich open ocean water, increased salinity, and promoted precipitation of aragonitic fans. Carbonate deposition ended when the balance controlling water level switched in favor of relative sea-level rise. Deeper water conditions allowed the chemocline to advance over the area and iron formation deposition ensued

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EFFECTS OF CONTACT METAMORPHISM BY THE DULUTH COMPLEX ON PROTEROZOIC FOOTWALL ROCKS IN NORTHEASTERN MINNESOTA

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The Duluth Complex is composed of numerous mafic intrusions that were emplaced in northeastern Minnesota during formation of the Midcontinent Rift approximately 1.1 Ga (Miller et. al., 2002). When it intruded, the heat of this igneous body significantly affected the wall rocks around it, including those in the Animikie Group, and created a contact metamorphic aureole.

The purpose of this research is to understand crustal conditions associated with emplacement of a large igneous complex, and develop a better idea of the thermal state of the crust during the time of rifting. To understand crustal conditions we must determine the effects that intrusion of the Duluth Complex had on adjacent wall rocks, in particular the Thomson and Virginia formations of the Animike Group. These effects include the extent and grade of metamorphism.

Optical petrography was used to determine mineralogical and textural relationships between minerals. The Animikie Group was subjected to two metamorphic events based on sedimentary features such as relict sedimentary bedding, regional metamorphic features such as disrupted bedding, and contact metamorphic features such as porphyroblasts and mortar texture. Scanning electron microscopy and EDS analysis helped identify major metamorphic minerals including rare high-K cordierite.

A thermal model was constructed to model heat flow from the Duluth Complex into the wall rocks, and mimic a thermal gradient similar to the one observed in nature. The two-dimensional model was a very simplified version of the parameters of the intrusion observed in nature, and ultimately we obtained discordant results that we can't explain.

Based on this petrographic study, the contact metamorphic aureole extends from the Duluth Complex into the Animikie Group for approximately 30 m. This coincides with estimates made by Severson (1995) and Duchesne (2004). The aureole is so thin because the wall rocks were fairly cool when the Duluth Complex intruded, and probably had a temperature around 75°C. The peak metamorphic mineral assemblage includes minerals such as ferrosilite, gedrite, and cordierite, which occur at temperatures around 600-700°C and a pressures around 2.5 Kbar (Duchense, 2004).

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GEOLOGY AND GEOCHEMISTRY OF ARC AND OCEAN-FLOOR VOLCANIC ROCKS IN THE NORTHERN FLIN FLON BELT, MANITOBA.

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The Flin Flon Belt is one of the most prolific mining districts in Canada, with combined reserves and production to 2007 of 183 million tonnes of Cu-Zn-Au-Ag ore from 26 different deposits. The Flin Flon Belt has a protracted magmatic history spanning approximately 60 million years (Stern et al., 1999). Juvenile arc magmatism (1.90–1.88 Ga) in an intra-oceanic setting was characterized by tholeiitic to calcalkaline and late alkaline (shoshonitic) volcanism, accompanied by rifting and subsequent back-arc basin development. Collisional tectonism, development of a 1.87–1.84 Ma ‘successor arc’, and late brittle deformation resulted in the present complex structural geometry of the belt.

Detailed geological mapping and numerous research projects have focused largely on the central part of the belt where almost all of the ore deposits are located. This paper is based on mapping of the northern Flin Flon Belt (NFFB), in which an approximately 15 km by 35 km area contains more than 20 tectonically distinct blocks or fault slices of diverse volcanic, related intrusive and subordinate sedimentary rocks. Most of these components are akin to modern analogues of arc and MORB volcanic rock types (Figure 1) and are part of the Flin Flon arc assemblage (Stern et al., 1995a). Mid-ocean ridge (MORB)–like volcanic rocks are structurally intercalated with juvenile arc rocks, and an extensive area of depleted-MORB-type rocks (Dismal Lake Terrane) extends along and across the northern boundary of the Flin Flon Belt, where it is locally in fault contact with paragneiss and orthogneiss of the Kisseynew Domain to the north (Gilbert, 2004). Arc-type rocks in the NFFB are assumed to be associated with subduction at a former oceanic arc, whereas MORB and depleted-MORB types are interpreted to have been associated with rifting and emplacement in a back-arc basin environment. Volcanic rocks of the Flin Flon arc assemblage are 1890 to 1878 Ma in age (Lucas et al., 1994; Stern et al., 1999; N. Rayner, pers. comm., 2009). MORB-type rocks in the NFFB may be roughly coeval with the arc assemblage, based on the 1.90 Ga age of synvolcanic intrusions in MORB-type volcanic rocks elsewhere in the Flin Flon Belt (Elbow-Athapapuskow ocean-floor assemblage; Stern et al., 1995b).

Six lenseoid enclaves of turbiditic sedimentary rocks are structurally intercalated with the volcanic fault blocks in the NFFB. These turbidite deposits, apparently devoid of volcanic interlayers, are distinguished from lithologically similar but older, fine-grained sedimentary rocks that occur within 1890–1878 Ma, juvenile arc volcanic sequences. Detrital zircon data from greywacke within the westernmost turbidite enclave suggest the depositional age likely does not exceed 1860 Ma (N. Rayner, pers. comm., 2009) and that the turbidites are thus of successor-arc age. Turbidite fault slices elsewhere in the NFFB may also be of successor-arc age or relatively older, penecontemporaneous with juvenile arc volcanism (e.g., the 1885 Ma Vick Lake tuff; Stern et al., 1993).

Fluvial-alluvial conglomerate and cross-bedded sandstone (Missi Group) at the west margin of the Flin Flon Belt are the youngest known supracrustal rocks in the NFFB. These sedimentary deposits and associated volcanic rocks are unconformable or in fault contact with volcanic rocks of the Flin Flon arc assemblage and were deposited between 1845 and 1835 Ma (Ansdell et al., 1999).

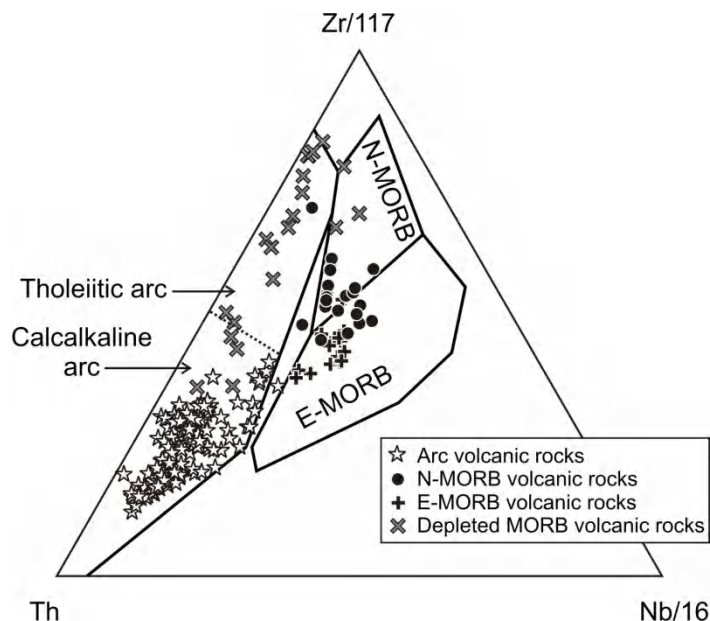


Figure 1: Th-Hf-Nb diagram showing the distinctive fields of arc and MORB-type volcanic rock suites in the northern Flin Flon Belt. Compositional fields of modern volcanic rocks after Wood (1980). Abbreviations: E-MORB, enriched mid-ocean ridge basalt; N-MORB, normal mid-ocean ridge basalt.

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U-PB ZIRCON GEOCHRONOLOGY OF THE DULUTH COMPLEX AND RELATED HYPABYSSAL INTRUSIONS: INVESTIGATING THE EMPLACEMENT HISTORY OF A LARGE MULTIPHASE INTRUSIVE COMPLEX RELATED TO THE 1.1 GA MIDCONTINENT RIFT

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Previous geochronology of mafic intrusive magmatism associated with the 1.1 Ga Midcontinent Rift in NE Minnesota by Paces and Miller (1993) established, with high precision, the main intrusive periods that created the Duluth Complex and related intrusions. This study did not, however, resolve differences in emplacement ages within and between major intrusive units due to a small number of dated samples. We present new high-precision isotope dilution U-Pb baddeleyite and CA-TIMS zircon ages from four mafic intrusions that build on the work of Paces and Miller (1993). Three of these are from troctolitic intrusions (Partridge River, Bald Eagle, Tuscarora) belonging to the layered series of the Duluth Complex (DC) that, based on field relationships, appear to represent the entire range of layered series intrusive activity. They yielded irresolvable weighted mean $\text{Pb}^{207}/\text{Pb}^{206}$ ages between 1098.8 ± 0.3 and 1098.0 ± 0.7 Ma (Table 1). These ages fall in line with the 1098.6 ± 0.5 Ma and 1099.3 ± 0.3 Ma ages reported by Paces and Miller for two layered series intrusions (Figure 1). Moreover, these ages are irresolvable from the ages of two DC anorthositic series samples analyzed by Paces and Miller (1099.0 ± 0.6 Ma and 1099.1 ± 0.5 Ma) and recently confirmed by unpublished data from the Boise State University isotope laboratory.

An early intrusion from the Beaver Bay Complex (BBC), the Houghtaling Creek troctolite, was also dated in this study to test the implication from Paces and Miller's study that a 3 Ma magmatic hiatus exists between emplacement of the deeper seated DC and the more hypabyssal BBC. The Houghtaling Creek sample yielded an age, which is irresolvable from the Duluth Complex ages and thus implies that BBC and DC magmatism likely overlaps.

The evidently synchronous emplacement of layered series and anorthositic series intrusions indicate that voluminous main stage magmatism occurred during an extremely short interval of within 1 Ma. Reasonable estimates of the geometry of the dozen or so layered series intrusions that comprise the DC indicate that over $15,000 \text{ km}^3$ of mafic magma intruded during emplacement of the layered series alone. The total volume of intruded magma is likely much higher when erosion is factored in and rocks of the anorthositic series and early BBC are included.

Table 1. Summary of high-precision U-Pb zircon/baddeleyite data for the Duluth Complex and Beaver Bay Complex intrusions. All errors are reported at the 95% confidence interval.

Sample Name ^a	Stratigraphic Unit	Rock Type	Grain Type	Pb ²⁰⁷ /Pb ²⁰⁶ age (Ma)	Pb ²⁰⁶ /U ²³⁸ age (Ma)
WLFG	Early Phase (BBC)	ferrogabbro	zrc./bad.	1095.75 ± 0.92	1091.88 ± 0.35
HCT	Early Phase (BBC)	augite troctolite	zrc.	1098.62 ± 0.50	1095.31 ± 0.25
BEI	Late Phase (DC)	olivine gabbro	zrc.	1097.97 ± 0.72	1095.64 ± 0.19
PRI	Early Phase (DC)	augite troctolite	zrc.	1097.98 ± 0.37	1095.94 ± 0.18
TI	Early Phase (DC)	troctolite	bad.	1098.81 ± 0.32	not defined
ES	Misc. intrusion	augite troctolite	zrc.	not defined	not defined

^aWLFG = Wilson Lake ferrogabbro; HCT = Houghtaling Creek troctolite; BEI = Bald Eagle intrusion; PRI = Partridge River intrusion; TI = Tuscarora intrusion; ES = Endion sill

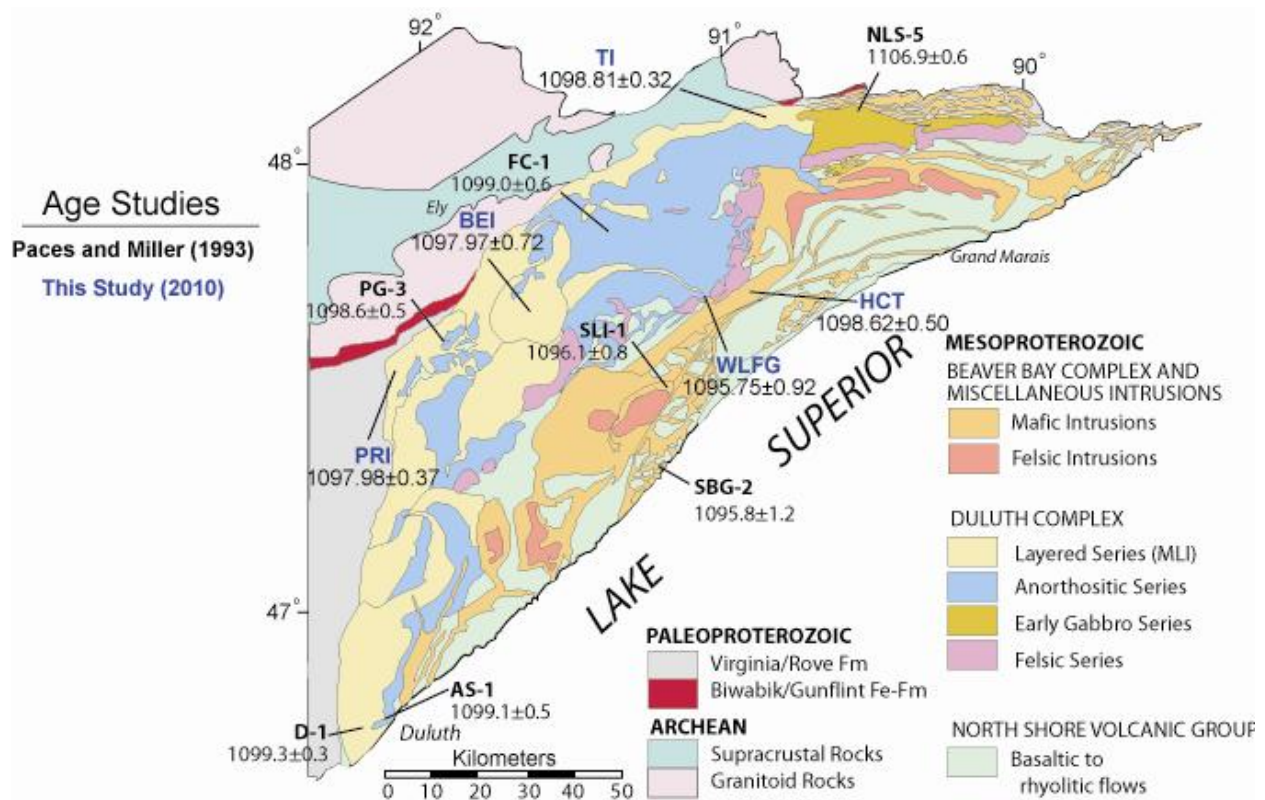


Figure 1. Summary of weighted mean Pb²⁰⁷/Pb²⁰⁶ ages for Duluth Complex and Beaver Bay Complex magmatism from Paces and Miller (1993) and this study (modified from Miller, 2008, unpublished figure).

RADIOGENIC ISOTOPE CHARACTERISTICS OF MIDCONTINENT RIFT-RELATED INTRUSIONS SOUTH OF THUNDER BAY

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New geochronological, geochemical and paleomagnetic data for Mesoproterozoic Midcontinent Rift-related dikes and sills located in and south of Thunder Bay, Ontario demonstrate the presence of three sill suites: an earlier, spatially restricted mafic to ultramafic unit termed the Riverdale sill, the predominant Logan sills and Nipigon sills in the northern part of the study area (Hollings et al., 2010). In addition, three predominant dike sets are recognized: the northeast-trending Pigeon River swarm, the northwest-trending Cloud River dikes and the Mt. Mollie dike (Fig. 1).

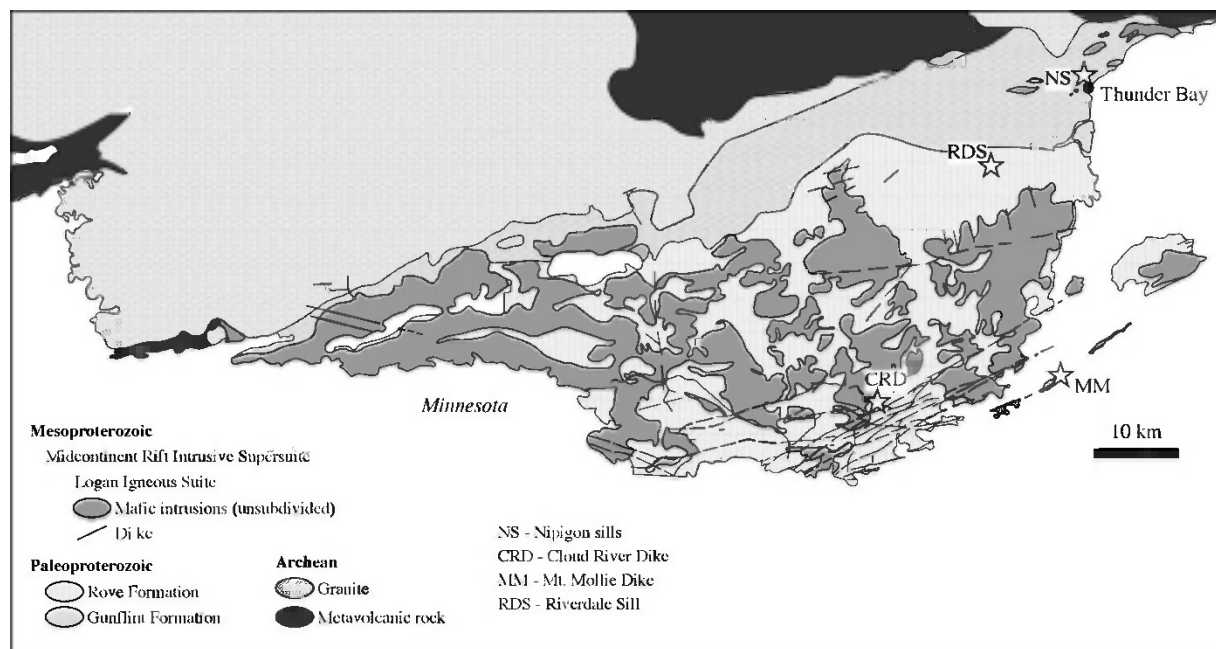


Figure 1: Geological map of the study area showing the location of major intrusive suites. Modified after Pye and Fenwick (1965).

Thirty-four Rb-Sr and Sm-Nd isotope analyses were undertaken on the intrusive units south of Thunder Bay with the full data set reported in Smyk and Hollings (2009). Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Sr_i) for the Logan Sills range from 0.7048-0.7115 and epsilon $\text{Nd}_{(T=1100\text{Ma})}$ from -1.4 to +0.4, whereas the Riverdale Sill is characterised by smaller range of Sr_i (0.7037-0.7055) and more negative epsilon $\text{Nd}_{(T=1100\text{Ma})}$ (-1.6 to -1.9). The epsilon Nd values for both suites are broadly similar to those of the Nipigon sills reported by Hollings et al. (2007) but the Logan sills are characterised by significantly higher Sr_i values (Fig. 2). T_{DM} values for the Logan and Riverdale sills are in the range of 1750-1850 Ma which are considerably younger than the generally Archean T_{DM} values of the sills of the Nipigon embayment. The younger T_{DM} and the elevated

Sr_i of the southern sill suites are consistent with contamination by Rove shales which have Sr_i of up to 0.7207 and epsilon $Nd_{(T=1100Ma)}$ of -9.3 (Fig. 2).

All three dike suites are characterised by highly variable Sr_i and epsilon $Nd_{(T=1100Ma)}$ values with epsilon Nd ranging from positive to negative in all three suites (Fig. 2). Samples with strongly negative epsilon Nd values are also characterised by strongly enriched Th abundances, negative Nb anomalies and older (~2200 Ma) T_{DM} ages, consistent with contamination by a deeper and older source, likely Archean basement. The dikes with less negative epsilon Nd values have similar major and trace element geochemistry to the strongly contaminated samples suggesting they were derived from the same mantle source but were emplaced after limited interaction with the underlying crust. This supports geochronological data presented by Hollings et al. (2010) which suggested that the dike swarms were emplaced over an extended period.

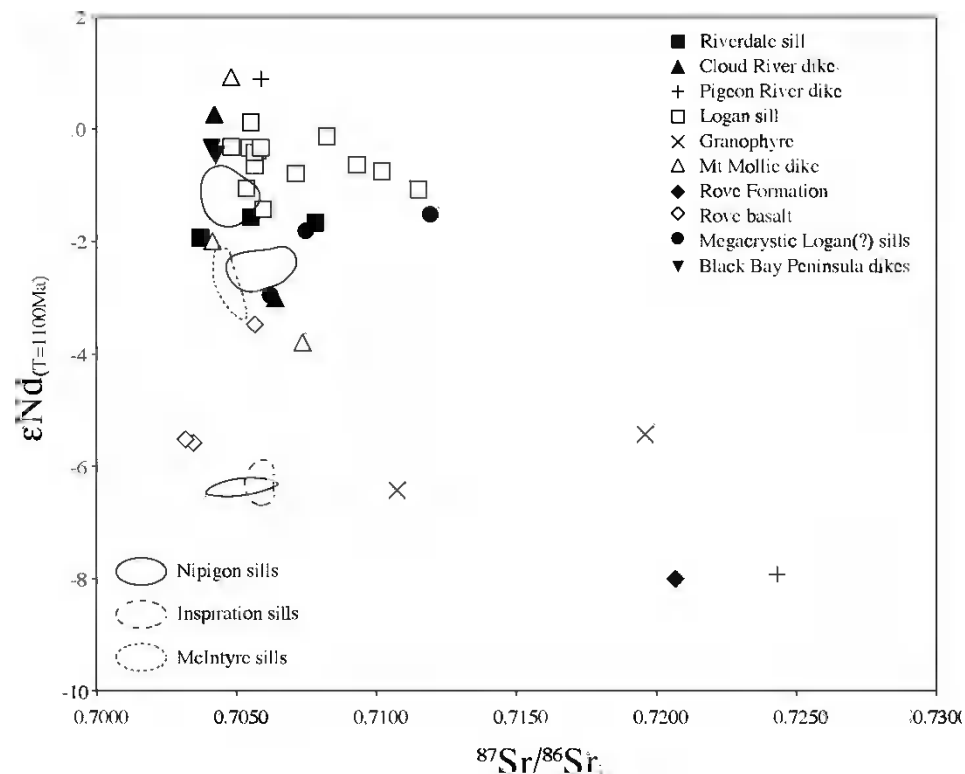


Figure 2: $^{87}Sr/^{86}Sr_i$ and $\epsilon Nd_{(T=1100Ma)}$ for intrusive Midcontinent Rift rocks south of Thunder Bay. Fields from Hollings et al. (2007).

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TACONITE-DERIVED MINERAL DUST IN POPULATION CENTERS ON MESABI IRON RANGE: AN UPDATE

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The Natural Resources Research Institute (NRRI) is conducting a detailed characterization of dust that is produced from mining and processing Biwabik Iron Formation ore. This three-year long study is an effort to evaluate the effects of past and present emissions from taconite mining and processing on air quality throughout the Mesabi Iron Range (MIR). NRRI's research will characterize airborne particulate matter within taconite operations, in communities surrounding taconite operations on the Mesabi Iron Range (MIR) and in population centers in other regions of northeastern Minnesota, as well as particulate matter deposited in lake sediments. NRRI's sampling and characterization work represents the community/environmental component of a larger University of Minnesota (U of M) effort that is addressing long-standing questions regarding the impact of dust derived from mining and processing of taconite (iron ore) on human health. The U of M School of Public Health (SPH), with whom NRRI is collaborating, is responsible for the human health- and exposure-related components of that effort, which include: 1) an occupational exposure assessment; 2) a mortality study; 3) a cancer incidence study; and 4) a respiratory health survey of taconite workers and spouses.

Air sampling is performed within taconite operations and communities by NRRI scientists during both winter and summer seasons. MIR community sampling sites include: 1) Keewatin Elementary School; 2) Hibbing High School; 3) the Virginia Courthouse; 4) the Babbitt Municipal Building; and 5) Silver Bay High School. Population centers in northeastern Minnesota include: 1) the Ely Fernberg site; and 2) the Natural Resources Research Institute in Duluth, MN. Sampling sites within taconite operations include crushers, magnetic separators/concentrators, agglomerators/ball drums, and the kiln/pellet discharge area. Taconite processing plant sites, from west to east, include: 1) U.S. Steel's Keewatin Taconite (Keetac); 2) Cliff's Natural Resources' Hibbing Taconite (Hibtac); 3) U.S. Steel's Minntac; 4) Cliff's Natural Resources' United Taconite (UTAC); 5) ArcelorMittal's Minorca Mine; and 6) Cliff's Natural Resources' Northshore Mine.

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

Additional analyses are completed on relevant metamorphosed and unmetamorphosed Biwabik Iron-Formation diamond drill core. Analyses include: 1) optical and electron microscope studies of polished thin sections; 2) TEM studies of liberated elongated mineral particles produced by the modified elutriator method (Berman and Kolk, 2000); and 3) x-ray diffraction evaluations of crushed material.

The lake sediment component of NRRI's work relies on studying cores collected from the eastern and western regions of the MIR to offer insights into historic production of mineral dust in the MIR. Core samples obtained from "North-of-Snort" Lake near Babbitt and Silver Lake near Virginia are being analyzed for elongated mineral particles and are being age dated utilizing the ^{210}Pb method to ensure that the oldest sediment samples pre-date MIR mining activities.

The NRRI has completed numerous study tasks over the past year-and-a-half. Community air sampling is nearly completed and includes forty-eight sampling events in MIR communities and seven sampling events in the NE Minnesota communities. All operating taconite processing facilities are being sampled, and additional sampling events are planned for the mid-2010, including taconite mine road dust, drilling dust, and mine blasts.

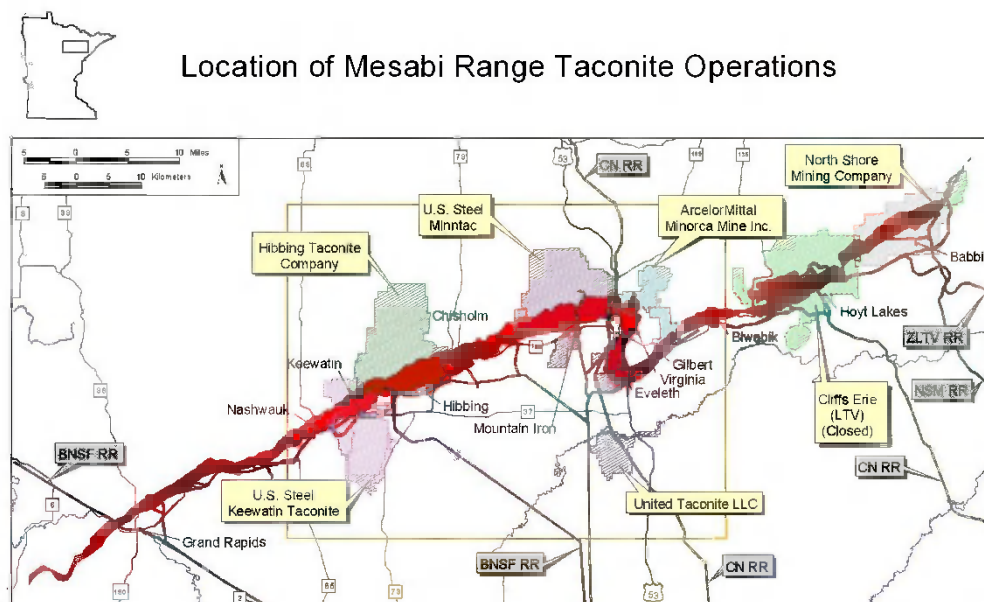


Figure 1: Locations of taconite processing plants on the Mesabi Iron Range being sampled during this study (after Oreskovich and Patelke, 2006)

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STRATIGRAPHY OF SUDBURY “IMPACTITE” NEAR GUNFLINT LAKE, NE MINNESOTA

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The impactite near Gunflint Lake is sandwiched between underlying, gently dipping, parallel-bedded Gunflint Iron Formation (~1878 Ma), and overlying slate and siltstone of the Rove Formation. The term “impactite” is a very general one used informally here to include all facies of sedimentary rocks inferred to have been formed or deformed in response to the ca. 1850 Ma Sudbury meteorite impact. By that definition, it includes autochthonous material interpreted to be seismically folded and shattered iron-formation (ejecta-absent), and overlying strata composed largely of allochthonous material derived from the impact site (ejecta-bearing) (Fig. 1). This discussion uses stratigraphic observations from recent mapping to devise a sequence of depositional events that is consistent with experimental and empirical evidence of impact processes (e.g., www.lpl.arizona.edu/impacteffects). It builds on—and in some cases should supersede—preliminary results presented in 2008 by Jirsa and others (ILSG v. 54). The impactite locality at Gunflint Lake is one of several similar exposure areas in the Lake Superior region (see Fralick and others, and Cannon and Slack; this volume). All of these deposits exhibit extreme lithologic variability from place to place within each exposure area, and between exposure areas, which is not surprising given the chaotic nature of impact processes. It should not be inferred, therefore, that the interpretations presented here necessarily apply to successions in other areas.

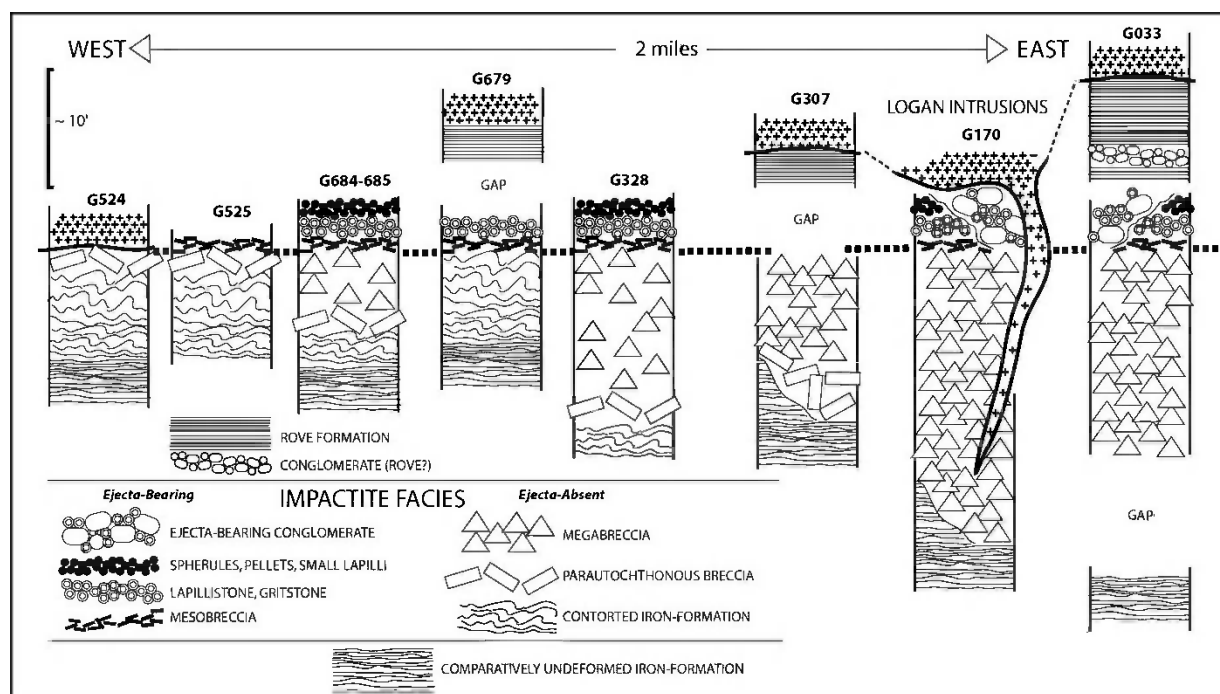


Figure 1. Stratigraphic framework derived from 8 exposures along a 2 mile strike-length near Gunflint Lake; hung from the contact between ejecta-bearing and ejecta-absent facies of the impactite horizon (bold dashed line).

Because the impactite deposits near Gunflint Lake lie within the contact metamorphic aureole of Mesoproterozoic intrusions, much of the original mineralogic features are obscured (see Weiblen and others, this volume). Despite this, macroscopic textures and sedimentological details are sufficiently preserved to convey information about protolith and depositional mechanisms. Figure 1 depicts the apparent stratigraphic relationships. In no single outcrop are all facies present; nevertheless, an approximation of temporal relationships can be inferred from the juxtaposition of two or more facies in individual outcrops. In the following section, facies are described in apparent stratigraphic order from oldest to youngest:

Ejecta-Absent

Contorted iron-formation facies: The uppermost layers of iron-formation are chaotically folded and exhibit both ductile and brittle behavior in close proximity at the scale of individual outcrops. The rheologic response depends on the apparent rigidity of material at the time of deformation. Silica-rich layers display brittle, shattered to semi-ductile, boudinage-like textures. By contrast, much of the iron-silicate mudstone layers behaved in a ductile fashion, locally showing evidence of fluidization and injection into superjacent strata. Folds are non-systematic in trend and style, and multiple hinge detachments occur. These attributes counter-indicate a regional tectonic origin, and instead are best viewed in the context of impact as the result of impact-generated seismicity imposed on semi-lithified substrate.

Parautochthonous breccia facies: At several locations, straight-bedded iron-formation passes laterally along strike into irregular zones in which the silica-rich layers have been broken and disheveled, while still retaining some semblance of jigsaw-puzzle fit.

Megabreccia facies: This term is used for breccia composed of unsorted slabs (as large as 5 m), blocks, and smaller fragments of iron-formation. The fragments are angular and in most places have random orientations. Fragments of iron-silicate mudstone typically show some evidence of semi-ductile behavior, and locally this material was fluidized to form irregular matrix.

Ejecta-Bearing

Mesobreccia facies: This is fragmental rock containing angular, subrounded, and amoeboid clasts (up to 5 cm long) of dark green material and scattered accretionary lapilli. Petrography shows that much of the original structure of the clasts has been metamorphically recrystallized and annealed; however, relicts of amygdaloidal and fluid-looking textures remain—implying a glassy protolith.

Lapillistone-gritstone facies: Accretionary lapilli as large as 1.5 cm occur as irregular masses and layers interbedded with sandy to silty gritstone. In areas least affected by metamorphism, several grains of shocked quartz with planar deformation features have been identified in thin section.

Spherule, pellet, small lapilli facies: The upper parts of ejecta horizons locally contain layers, lenses, and interbeds of accretionary or relict glass grains that are smaller than typical lapilli and generally lack concentric zonation. These may represent waning ejecta plume deposition.

Ejecta-bearing conglomerate facies: In a few localities, the uppermost part of impactite deposits consist of conglomerate containing subrounded fragments of iron-formation (in contrast to breccias described above), and matrices containing variably abraded lapilli.

Nearly all contacts between individual facies are gradational, with one very important exception—in all exposures, the boundary between ejecta-absent and ejecta-bearing facies is extremely sharp. This is interpreted to reflect a fundamental shift in geologic process from intense seismic perturbation of uppermost iron-formation represented by the ejecta-absent facies, to deposition by the passing ejecta plume. The uppermost conglomerate facies represents mixing of local and exotic detritus, presumably by tsunamis or post-impact fluvial or marine processes.

This interpretation was strongly influenced by field discussions with William Cannon, William Addison, Phillip Fralick, and Christian Koeberl, and the pioneering work of Bevan French.

GEOCHEMICAL CHARACTERISTICS OF CADMIUM-RICH SOILS OF THE PEMBINA ESCARPMENT, NORTH DAKOTA

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Investigations of topsoils in northeastern North Dakota (Hopkins et al., 1999) revealed that trace element levels of cadmium (Cd), are 10 to 20 times higher than the baseline level of 0.3 mg/kg total Cd established by Garrett (1994) for northern prairie soils of Canada and the adjoining states of United States. North Dakota produces 96% of the nation's flaxseed, 50% of all durum wheat, and is the top U.S. producer of confectionary sunflower (NDASS, 2008). All these crops are known to bioaccumulate Cd.

Naturally occurring Cd concentrations were determined for soils on the Pembina Escarpment in Cavalier County, NE North Dakota. These soils overlie the Cretaceous Pierre Formation and the glacial till parent materials include considerable shale lithic fragments. Surface and core sampling locations from both residual and transported soils included an active agricultural field, a field currently in the Conservation Reserve Program (CRP), and former agricultural fields that are now grassland fields in a North Dakota State Wildlife Management Area (WMA). Samples were analyzed for Cd and other trace elements using nitric acid digestion followed by ICP-OES at NDSU. Results revealed marked differences in measured Cd values between different sampling sites, e.g., values for WMA fields range from 0.3 mg/kg to 7.0 mg/kg (n=139) for the 0-30 cm depth, whereas values for the agricultural field and CRP area range from 3.0 mg/kg to 16.4 mg/kg (n=25), for samples ranging in depth from surface soils to 1.5 m. Values for core samples from the WMA measured at 15 cm intervals down to 225 cm depth range from 0.01 mg/kg (detection limit) to 1.9 mg/kg (n=188). The measured values for Cd concentrations in several samples in this study confirm earlier results showing significantly higher concentrations of Cd compared to the 'environmental baseline' value of 0.3 mg/kg reported by Garrett (1994).

Chemical analyses for cores were grouped by soil horizon and lithology and correlation matrices were calculated for each class. A subset of results illustrates the correlation of Cd concentrations with other analytes for each sample class (Table 1).

In bedrock material, the highest positive correlations for Cd are with Ca, Fe, Mn, organic matter, and electrical conductivity, while a weaker positive correlation is seen for Cd-Ni. Cd-pH shows a weak negative correlation. In sand and silt layers, Cd is strongly positively correlated with As. Interestingly, most of these Cd-analyte pairs (with the exception of organic matter) are negatively correlated in topsoil.

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Table 1. Correlations of Cd with other analytes in soil horizons and lithologic units of cores taken from formerly cropped fields on the Pembina Escarpment in eastern Cavalier County, ND. Top value: Pearson correlation coefficients; second value: Prob > |r| under H0: Rho=0. Analyte pairs with p < 0.05 are in bold. EC: Electrical Conductivity; OM: Organic Matter; n: no. of observations.

	Topsoil	Sand & Silt	Argillic	Shale/ Claystone Contact	Shale	Bedrock	Carbonate
Al	0.5223 0.0671	-0.4520 0.1401	-0.0024 0.9872	-0.0332 0.9273	-0.0270 0.8076	0.2902 0.5769	-0.7948 0.0588
As	0.4462 0.1265	0.8443 0.0006	0.0029 0.9848	-0.3489 0.3231	0.2248 0.0398	0.2970 0.5677	-0.5338 0.2754
Ca	-0.7071 0.0069	-0.0559 0.8630	-0.0596 0.6940	0.2294 0.5239	-0.1151 0.2970	0.9326 0.0067	0.6525 0.1602
Co	-0.0347 0.9103	-0.4021 0.1951	-0.0232 0.8781	-0.0143 0.9688	-0.2762 0.0110	0.4110 0.4183	-0.2300 0.6610
Cr	-0.4866 0.0917	0.3111 0.3250	-0.0537 0.7231	-0.1552 0.6685	-0.0036 0.9739	-0.5916 0.2161	-0.8484 0.0327
Cu	-0.5146 0.0720	0.5872 0.0447	0.1572 0.2968	-0.2217 0.5382	0.1411 0.2004	0.5623 0.2454	-0.6847 0.1335
Fe	0.0130 0.9664	-0.0642 0.8430	0.0677 0.6549	-0.2225 0.5367	0.2971 0.0061	0.9542 0.0031	-0.8845 0.0192
Mn	-0.5024 0.0802	-0.3479 0.2679	-0.3838 0.0085	0.0972 0.7894	-0.3030 0.0051	0.9724 0.0011	0.3275 0.5264
Mo	0.0323 0.9165	0.7907 0.0022	0.1808 0.2292	-0.2604 0.4675	0.0565 0.6099	0.2543 0.6267	-0.5448 0.2636
Ni	-0.4427 0.1298	-0.3163 0.3165	0.0312 0.8372	0.21408 0.5526	-0.3201 0.0030	0.7446 0.0895	-0.5448 0.2636
Zn	-0.3397 0.2562	-0.2677 0.4003	0.5441 <.0001	-0.08486 0.8157	-0.0158 0.8863	0.4436 0.3783	-0.9208 0.0092
OM	0.3361 0.2615	0.4367 0.1558	0.4244 0.0033	0.1346 0.7109	0.3723 0.0005	0.8919 0.0169	-0.9449 0.0045
pH	-0.4932 0.1231	-0.4500 0.1177	0.0225 0.8876	0.5565 0.0948	-0.1676 0.1324	-0.9958 0.0587	0.9069 0.0126
EC	-0.7882 0.0040	0.4638 0.1508	-0.2525 0.1067	0.2002 0.5791	-0.2152 0.0521	0.9976 0.0441	0.4759 0.3400
n	13	12	46	10	84	6	6

Support from NIH grant P20 RR016471 from the INBRE program of the National Center for Research Resources is gratefully acknowledged.

A MICROSTRUCTURAL STUDY OF GOLD MINERALIZATION AT MUSSELWHITE MINE AND HAMMOND REEF SHEAR-ZONE-HOSTED GOLD DEPOSITS

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Musselwhite Mine and Hammond Reef are shear-zone-hosted gold deposits located in the Western Superior Province of the Canadian Shield. Like other “lode-gold” or “orogenic gold” deposits these two deposits are proximal to major regional shear-zones. Musselwhite Mine is located adjacent to the North Caribou-Totogan Lake shear zone, while Hammond Reef is adjacent to the Marmion shear zone.

The importance of deformation and metamorphism in shear-zone-hosted gold systems is investigated by comparing microstructures associated with gold mineralization from two very different gold deposits. Musselwhite Mine is hosted by amphibolite facies metamorphosed banded iron formation while Hammond Reef is hosted by greenschist facies metamorphosed tonalite.

For both deposits gold mineralization can be seen associated with deformational structures where nearby minerals demonstrate very different responses to strain due to differing competency. Examples include brittle failure of competent minerals while matrix minerals deform ductilely, as well as strain shadows formed around these competent minerals

Strain shadows around garnet crystals are commonly observed at Musselwhite Mine. At Hammond Reef gold mineralization is often associated with strain fringes around pyrite crystals. These strain fringes show varying degree of recrystallization due to ductile deformation after formation. Quartz textures observed within these recrystallized strain fringes are consistent with textures observed in quartz within the greenschist facies of metamorphism.

Gold inclusions have been seen within the metamorphic minerals grunerite and garnet at Musselwhite Mine as well as muscovite at Hammond Reef. This demonstrates that gold mineralization occurred during or before metamorphism. Gold mineralization is also commonly associated with sulphide minerals in both deposits (pyrrhotite at Musselwhite Mine and pyrite at Hammond Reef).

Many similar microstructures host gold mineralization at Musselwhite Mine and Hammond Reef. Finding gold mineralization within common structures indicates the importance of deformation and metamorphism in the formation of shear-zone-hosted gold deposits. Textures and mineral assemblages observed in this study support the interpretation that gold mineralization occurred as an ongoing event for both Musselwhite Mine and Hammond Reef.

ASSIMILATION AND PETROGENESIS IN THE NAVILUS AND TERRY FOX SILLS, THUNDER BAY, ONTARIO

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The numerous diabase sills in the Thunder Bay area were called the Logan sills by A.C. Lawson at the end of the 19th century. They were first studied in detail by Blackadar (1956), particularly with regard to the pink granophyre associated with some of the sills. He attributed this pink granophyre, especially in the case of the Navilus sill, located immediately east of Thunder Bay, to in situ assimilation of granitic rock. Differentiation of diabase was not considered capable of producing the large volumes of granophyre present in some of the Logan sills.

Textural evidence suggests, as discussed by Philpotts (1978), that on cooling, the magma separated into two immiscible liquids, one iron-rich and one silica-rich. This has resulted in a zone of quartzo-feldspathic granophyre containing minute hematitic inclusions, which produces the pink colour seen in hand sample. However, some reaction with xenoliths is also present as seen in the rounding of immiscible carbonate xenoliths and the formation of granophyric zones surrounding quartzo-feldspathic xenoliths.

Geochemical evidence indicates that late-stage differentiation by fractionation is the primary cause of variation within the Navilus sill. The uppermost samples of the Navilus sill, which typically contain xenoliths, display this late fractionation through enrichment of light REEs and depletion of heavy REEs (Figure 1a). A Nb-Ta trough on the chondrite-normalized spider diagram, as well as enrichment in LILs, indicates assimilation of crustal material has most likely occurred.

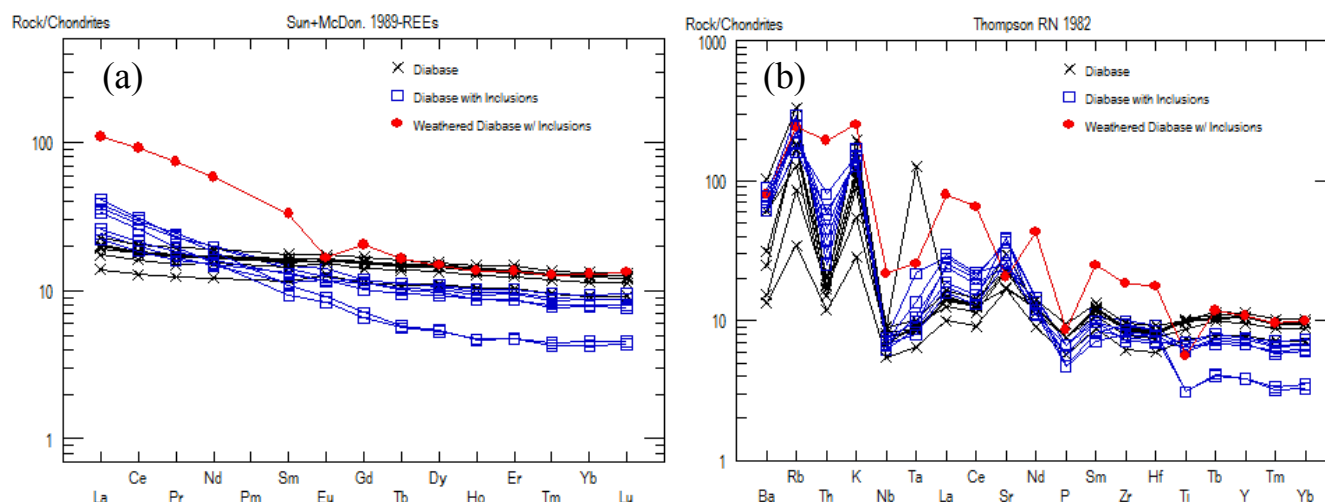


Figure 1 – Chondrite-normalized REE diagram (a) and chondrite-normalized spider diagram (b) for the Navilus Sill. Note the clockwise rotation of uppermost samples (squares) due to fractionation.

The Terry Fox sill, located 4 km west of the Navilus sill, shows REE and Spider patterns almost identical to the normal diabase in the Navilus sill. Although the sample of the basal contact between the Terry Fox sill and Rove shale shows some variability in the REE and Spider diagrams, a more detailed analysis is required to determine whether they are the effects of in-situ assimilation or fractionation.

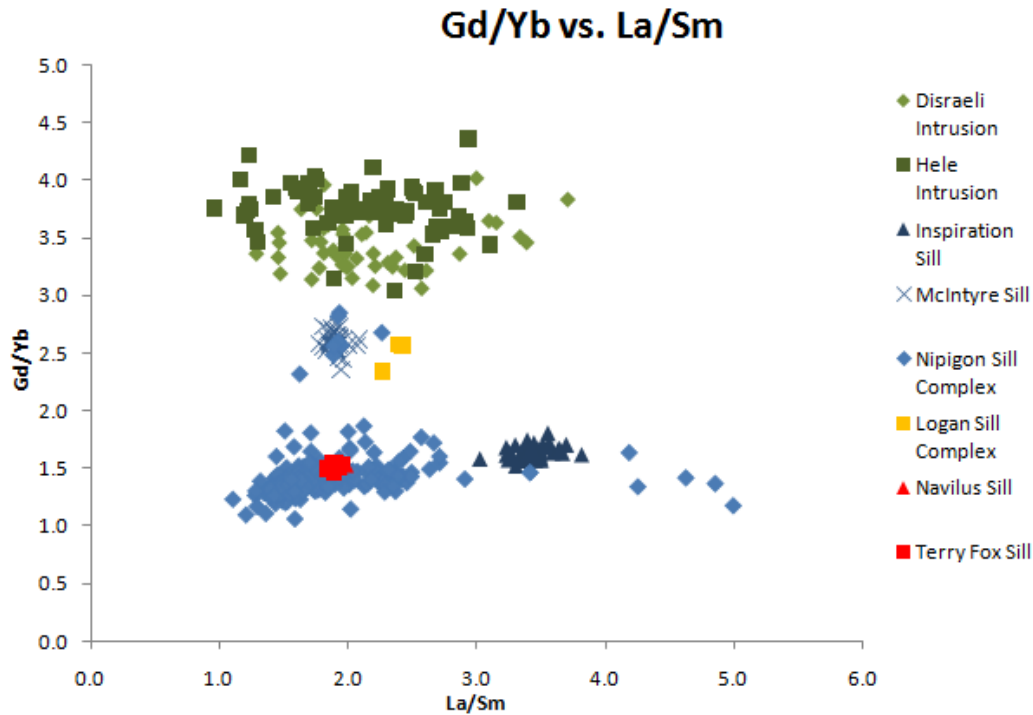


Figure 2 – Plot of Gd/Yb vs La/Sm for several Keweenawan Intrusive Suites, with data from Hollings et al. (2007) and Hart (2002). Note that the Navilus and Terry Fox samples plot within the Nipigon Sill Complex samples.

Comparison of the Navilus and Terry Fox sills to other Keweenawan intrusions and intrusive complexes in the Thunder Bay area using trace-element discrimination diagrams (Figure 2) indicates that these sills are grouped with the Nipigon sills.

In summary, textural evidence has shown that assimilation of granitic xenoliths is not likely the cause of the formation of the pink granophyre, but the development of magmatic immiscibility has produced this feature. Geochemical evidence indicates that assimilation of crustal material has most likely occurred, though chemical variations seen within the sills appear to have been caused by in-situ fractionation. A more detailed study on the possible effects of assimilation at the base of the Terry Fox sill is required, although assimilation of xenoliths has possibly contributed to geochemical differences as seen in the Navilus sill spider diagram (Figure 2).

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TEXTURAL ANALYSIS OF A SIMPLE IGNEOUS INTRUSION, NIPIGON, ONTARIO

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In this study, I examined the textural variations in a small (1.4 m) diabase sill from Nipigon, Ontario, which was apparently formed by a single, instantaneous injection event, in order to develop a baseline to test against other sills with unknown injection histories. With an understanding of the textural characteristics of a simple intrusion, we can recognize the variations in more complex intrusions with complicated thermal histories and make comparisons between observed textural variations and the predictions of theoretical models. Such textural criteria are particularly important when the magma composition remained constant through several injections, in which case reinjection events would not be reflected in the chemical composition or modal mineralogy of the rocks.

Petrographic examination of the rocks in this sill focused on opaque oxides, as they can be characterized easily using automated image processing techniques. Samples were collected from a 1.4 meter thick diabase sill in Nipigon, Ontario spanning the entire vertical cross-section of the sill. Thin sections were prepared at 5 cm intervals throughout the sill, yielding 28 thin sections between chill margins. Randomly oriented test lines were used to determine mean crystal length using the intercept method discussed by Higgins (2006): $L_{\text{mean}} = V_v / P_L$, where V_v is the modal fraction of the mineral of interest, as determined by automated image analysis, and P_L is the number of crystals intersected along the test line. To determine P_L , a hundred test lines were randomly oriented in the field of view of a petrographic microscope for each sample and grain intersections along the test lines were averaged. To determine V_v , digital thresholding was used to determine the average area of opaque minerals present in each sample and divided by the entire area of the slide. Once V_v and P_L are known, L_{mean} can be determined for any position in the sill. Figure 1 shows the modal abundance of opaque oxides with varying position in the sill and Figure 2 shows the variations in L_{mean} through the sill.

Based on the observed textural variations, namely a smooth transition from smaller grains at the chilled margins to larger grains in the sill's center, this sill was almost certainly emplaced in a single injection event. However, questionable data points and the large statistical uncertainties in calculate mean lengths prevent us from using this intrusion as a baseline for confidently identifying complex injection histories. Further investigation and refinement of this textural profile could ultimately make it useful as a null hypothesis for testing formation history: unless the textural profile in the intrusion of interest differs significantly from the profile in this sill, we must assume that it was formed as a single injection.

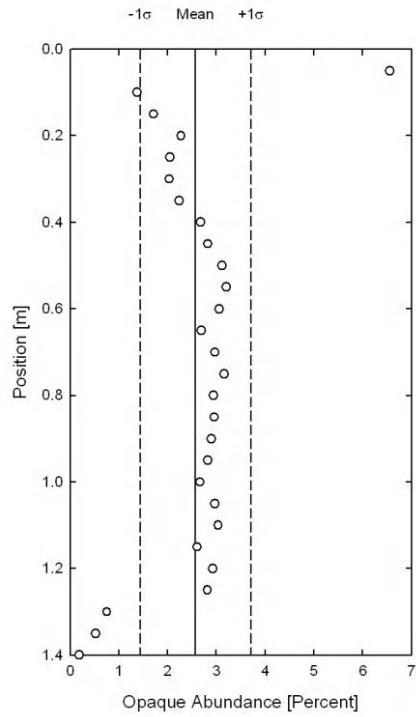


Figure 1: *Modal abundance of opaque minerals.*

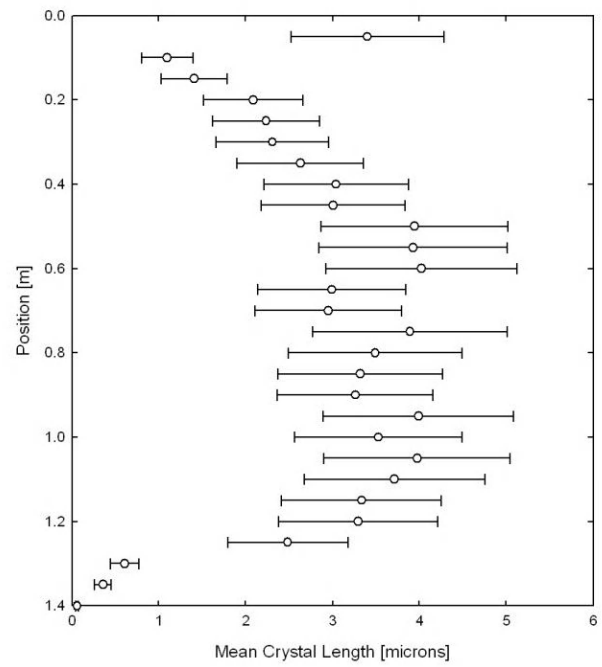


Figure 2: *Mean crystal lengths of opaque minerals.*

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BEDROCK GEOLOGIC MAP OF THE DISAPPOINTMENT LAKE AREA, LAKE COUNTY, NORTHEASTERN MINNESOTA

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The “capstone” project for the Precambrian Research Center (PRC) summer field camp encompasses one week of detailed field mapping in small groups with faculty from the field camp. During the fifth and sixth weeks of the 2009 field camp, seven students mapped Neoproterozoic and Mesoproterozoic rocks in the vicinity of Disappointment Lake (located in the Boundary Waters Canoe Area Wilderness) under the direction of PRC faculty Dr. Dean Peterson and Dr. George Hudak. Geological maps of this area were originally published by Van Hise (1901) and Gruner (1941). This capstone mapping project sought to: 1) define and characterize the nature of the contact between the Mesoproterozoic Duluth Complex and Neoproterozoic supracrustal strata; 2) to better understand the lithological components of the Duluth Complex and the Neoproterozoic supracrustal strata in this area; 3) to obtain a better understanding of geological structures and their orientations within the Neoproterozoic supracrustal strata; and 4) to identify and map out regions of Mesoproterozoic (Duluth Complex associated) and Neoproterozoic (Snowbank Lake Granite-associated (Miller et al., 2001; Jirsa and Miller, 2004)) contact metamorphism within Neoproterozoic strata. Field mapping was completed at 1:5,000 scale, with the final map being published at 1:10,000 scale. Mapping was completed by means of lakeshore mapping from canoes and traverses through the bush.

The north-central and northeastern regions of the field area are composed principally of Neoproterozoic intrusive and supracrustal strata. The Neoproterozoic supracrustal sequence is interpreted to represent the Knife Lake Group (Jirsa and Miller, 2004), and is composed, from oldest to youngest units, of: a) massive and pillowed basalt lava flows; and b) thick-bedded to massive rhyodacitic to dacitic tuffs locally interbedded with matrix- to nearly clast-supported, medium-bedded to massive polymict volcaniclast-dominated epiclastic deposits. Regional D₂ deformation led to the development of localized west-northwest – east-northeast-trending chlorite schist zones which can be traced for at least 300 meters. Southwest of the chlorite schist zones, greenschist facies metamorphosed Timiskaming-type interbedded polymict conglomerates, conglomeritic sandstones, and mudstones interpreted as the Ogishke Conglomerate (Jirsa and Miller, 2004) appear to unconformably overlie the mafic lava flows and felsic volcaniclastic rocks and associated epiclastic sedimentary rocks described above. These sedimentary strata have been deformed into a series of relatively tightly folded anticlines and synclines characterized by moderately- to steeply- dipping (60°-90°) fold limbs with west-northwest – east-southeast trending fold axes. Folding predated the intrusion of medium- to coarse-grained granite and hornblende granite (the Snowbank Lake Granite (Jirsa and Miller, 2004) and associated aplitic to pegmatitic dikes which occur in the westernmost one-third of the field area. Locally, xenoliths of sedimentary rocks, and sedimentary rocks along the margin of this intrusion, have been recrystallized into fine-grained to medium-grained granoblastic to granular hornblende hornfels.

The southeastern one-third of the field area comprises Mesoproterozoic intrusive rocks that comprise the Duluth Complex. A marginal phase composed of medium- to coarse-grained oxide gabbro and poikilitic olivine gabbro transitions into medium- to coarse-grained troctolite that locally displays modally-layered subhedral olivine crystals and ophitic augite crystals. In the northeastern part of the field area, a southeast- northwest-trending wedge-shaped marginal phase of diorite and hornblende diorite occurs in an area roughly 1.5 km long by 1.0 km wide.

Three distinctive zones of Mesoproterozoic thermal metamorphism have also been identified and mapped in the field area. Neoarchean sedimentary strata have been thermally metamorphosed to the pyroxene hornfels facies for up to 250 north of the Duluth Complex contact to produce fine- to coarse-grained norite. Basalt hornfels xenoliths are locally present in the troctolitic phase of the Duluth Complex. In the east-central region of the field area, approximately 1 to 3km northwest of the contact between the Duluth Complex and Neoarchean supracrustal strata, a southeast - northwest-trending 1.5km by 2.0km zone of hornblende hornfels facies metamorphosed Neoarchean conglomerate, sandstone, and mudstone occurs. This southeast – northwest-trending zone has the same orientation as the wedge-shaped zone of marginal diorite and hornblende diorite phase of the Duluth Complex. The spatial distribution of the hornblende hornfels facies metamorphosed rocks, as well as the marginal hornblende diorite phase of the Duluth Complex, suggest the former presence of a shallowly-dipping southeast- northwest trending sill of Duluth Complex that has subsequently been eroded away.

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FERROMAGNESIAN MINERALS IN THE STETTIN SYENITE COMPLEX, MARATHON COUNTY, WISCONSIN: COMPOSITIONS AND CONTRASTS WITH THE WOLF RIVER BATHOLITH

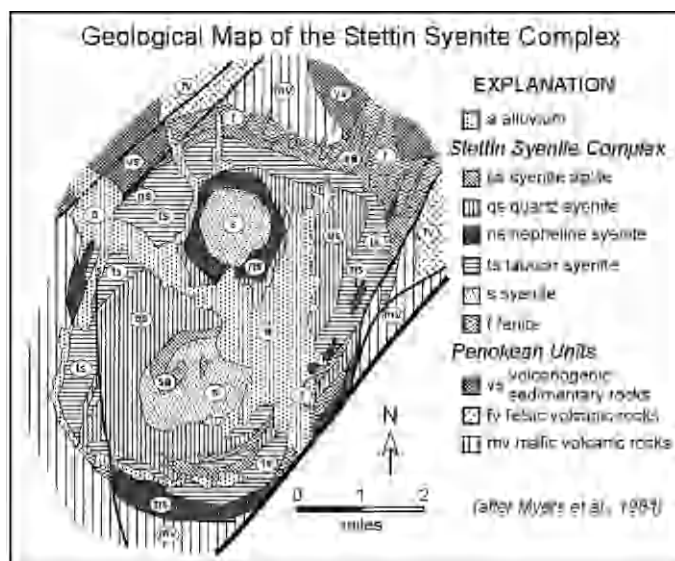
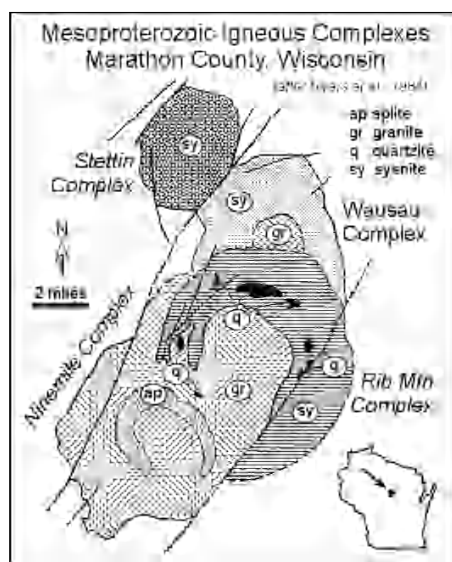
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The Stettin syenite complex is the northernmost of four overlapping, concentric intrusions, which are located immediately west of Wausau in central Marathon County, Wisconsin (Myers *et al.*, 1984). The intrusions decrease in age from north to south, with zircon U-Pb ages of 1565 ± 4 Ma in the Stettin complex, 1522 ± 6 Ma in the Wausau complex, and 1506 ± 3 Ma in the Ninemile complex (Van Wyck *et al.*, 1984; Dewayne and Van Schmus, 2007). Previously, these intrusions were thought to be associated with geon 14 Wolf River magmatism, but their ages are significantly older than the 1468-1484 Ma Wolf River batholith and preclude a cogenetic relation between them.



The Stettin complex consists of concentrically arranged syenite bodies, the most important of which are syenite, tabular syenite, nepheline syenite, and quartz syenite (Myers *et al.*, 1984). The latter two units illustrate the divergent silica differentiation trends in the complex, *i.e.* silica undersaturation in nepheline syenite and silica oversaturation in quartz syenite. Values for the Thornton-Tuttle Differentiation Index (normative $qtz+or+ab+ne$) range from 71 to 94 in nepheline syenite and from 82 to 87 in quartz syenite. The complex is markedly Fe-rich, with Fe#s ranging from 89.3 to 99.8. Stettin syenites are more alkaline than Wolf River granites, $A/CNK = 0.84 \pm 0.08$ ($n=10$) vs. 1.00 ± 0.08 ($n=38$), have higher Al-pairing Indices, $(Na+K)/Al = 1.44 \pm 0.10$ vs. 1.21 ± 0.10 , and are more sodic, $Na/K = 1.77 \pm 0.15$ vs. 0.88 ± 0.22 (Myers *et al.*, 1984; Anderson and Cullers, 1978). Another important distinction is the presence of titaniferous magnetite in the Stettin complex and ilmenite in the Wolf River batholith.

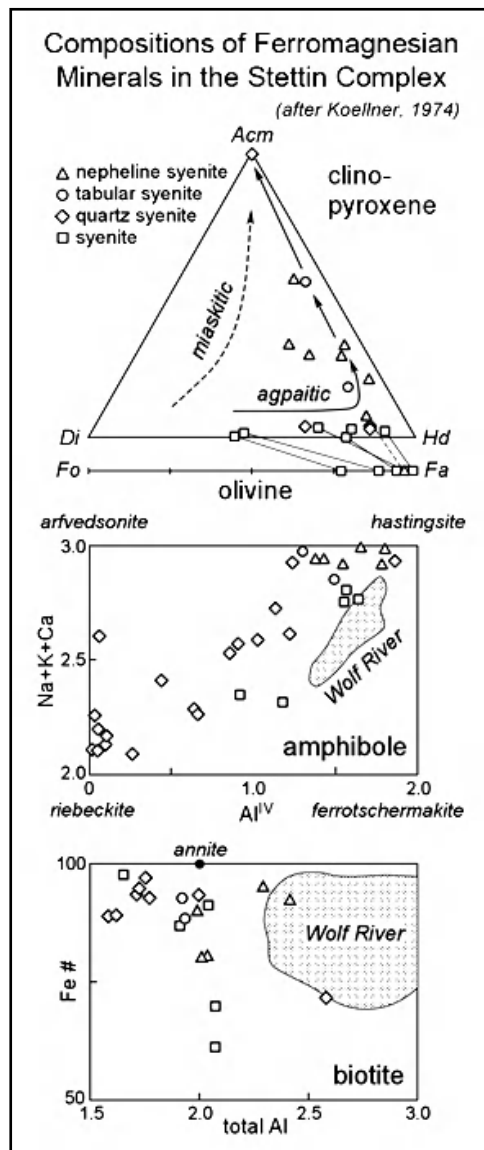
Clinopyroxene occurs in all four major syenite units in the Stettin complex, ranging in composition from $\text{Di}_{55}\text{Hd}_{44}\text{Acm}_1$ to $\text{Di}_8\text{Hd}_{90}\text{Acm}_2$ in syenite, from $\text{Di}_{12}\text{Hd}_{70}\text{Acm}_{18}$ to $\text{Di}_6\text{Hd}_{39}\text{Acm}_{55}$ in tabular syenite, from $\text{Di}_{11}\text{Hd}_{81}\text{Acm}_8$ to $\text{Di}_{10}\text{Hd}_{35}\text{Acm}_{55}$ in nepheline syenite, and from $\text{Di}_{32}\text{Hd}_{64}\text{Acm}_4$ to end-member acmite in quartz syenite. Overall, clinopyroxene in the Stettin complex displays one of the most pronounced agpaitic compositional trends reported among alkaline complexes worldwide.

Olivine occurs in syenite and nepheline syenite, ranging in composition from Fa 77 to 97, and having a consistently higher Fe# than coexisting clino-pyroxene.

Amphibole in syenite, nepheline syenite, and tabular syenite is largely hastingsitic, but in quartz syenite reaches near end-member riebeckite, which has been stabilized under igneous conditions by the presence of F (>2 wt.%). Amphibole in the Wolf River batholith consists of ferroedenite to hastingsite (Anderson, 1980), devoid of the marked alkaline trend in Stettin amphibole.

Biotite approaches annite (or ferriannite) in composition and is relatively poor in Al. Many samples contain insufficient Si+Al to fill the tetrahedral position, which is a common feature in biotite from alkaline rocks. Wolf River biotite is also relatively Fe-rich, but is more aluminous than Stettin biotite (Anderson, 1980).

The compositions of Stettin and Wolf River ferromagnesian minerals are dependent in part on intensive crystallization conditions, *e.g.* relatively reducing conditions, at or below that of the FMQ buffer, allow the crystallization of hedenbergite and fayalite. However, the occurrence of sodic pyroxene and amphibole in the Stettin complex, as in many other alkaline complexes, is more a function of bulk composition, *i.e.*, a relative increase in Na, combined with an increase in $\text{Fe}^{3+}/\text{Fe}^{2+}$, during differentiation. The contrasts in Stettin and Wolf River amphibole and biotite compositions are also due to differences in bulk composition between the two bodies, reflecting their different degrees of alkalinity.



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CYCLICAL PHASE LAYERING IN THE DULUTH COMPLEX AT DULUTH – EVIDENCE FOR PERIODIC MAGMA VENTING FROM A SHALLOW STAGING CHAMBER?

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Igneous layering is an almost ubiquitous feature in mafic intrusive bodies and yet remains an enigma. One of the more intriguing forms of layering in the 1.1 Ga Duluth Complex of NE Minnesota is cyclical phase layering exhibited by the Layered Series at Duluth (DLS). The DLS is a well-exposed, well-differentiated, north-south striking, eastward-dipping, sheet-like intrusion. Its cumulate stratigraphy ranges from troctolite (Pl+Ol) upward to olivine oxide gabbro (Pl+Cpx+Ol+Ox) and ultimately to intermediate and felsic rock types as final differentiates. Detailed field mapping by Miller and Green (2008) separated the DLS into five distinct zones: the basal contact zone, the troctolitic zone, the cyclic zone, the gabbroic zone, and the upper contact zone. The cyclic zone is composed of at least 5 macrocycles wherein troctolitic (Pl+Ol) cumulates grade upward into olivine gabbroic (Pl+Aug+Ol+Ox) cumulates. The 4-phase gabbros are then abruptly overlain by troctolitic cumulate marking the base of the next macrocycle. A conventional interpretation of such layering may be that it formed by progressive differentiation followed by magma recharge. However, cryptic layering of olivine and pyroxene across the cumulate regressions marking each macrocycle boundary show no significant increase in mg#, which such a model would predict. Instead, Miller (Miller and Ripley, 1997; Miller et al., 2002) proposed that decompression due to magma venting at shallow depths might better explain this layering by significantly changing phase equilibrium without changing magma composition.

Exposed in the Spirit Mountain ski area and within the second macrocycle of the cyclic zone is a large outcrop exhibiting meter-scale mesocyclic layering that mimics the textural and mineralogical changes seen in the larger scale macrocycles (Fig. 1A & B). Detailed field, petrographic, and geochemical studies of these mesocycles were performed to further test the plausibility of magma recharge as the mechanism responsible for the cyclic phase layering. Analyses of olivine and augite revealed that mg# ($=\text{Mg}/(\text{Mg}+\text{Fe}) \times 100$) remained within 2% of the mean throughout individual cycles and throughout the entire mesocyclic system of 16 cycles (Fig. 2). Despite this minor variation, there is a systematic difference in the mg# of olivine, such that the olivine in troctolite cumulates is consistently more fosteritic than gabbroic cumulates. Some cycles show a similar shift in augite, though this is less consistent. This may at first glance seem to argue for recharge of more primitive magma as the cause for the phase layering. However, the shift in mg# in olivine may also reflect a shift in the Fe-Mg equilibrium between melt and olivine when augite becomes a cumulus phase. Trace element data, particularly REE, show a significant difference between the troctolite and gabbro layers, but this can be attributed to differing partition coefficients for the main cumulate phases.

In conclusion, the field, petrographic, mineral chemistry, and lithochemical attributes of the mesocyclic layering observed at Spirit Mountain does not unambiguously favor either a magma recharge or decompression venting model for its origin. More data and evaluation are needed to definitely determine the origin of the mesocyclic and larger macrocyclic layering of the Cyclic Zone of the Duluth Layered Series.

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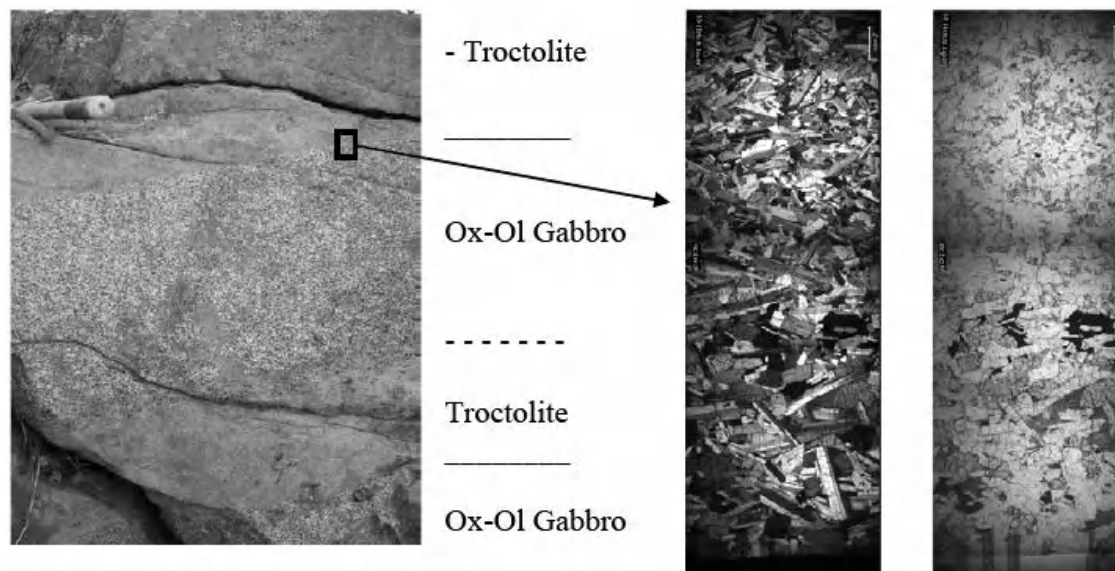


Figure 1. Mesocyclic layering of troctolite (Ol+Pl) and Ox-Ol gabbro (Pl+Cpx+Ol+Ox) cumulates in outcrop (A) and in thin section (B).

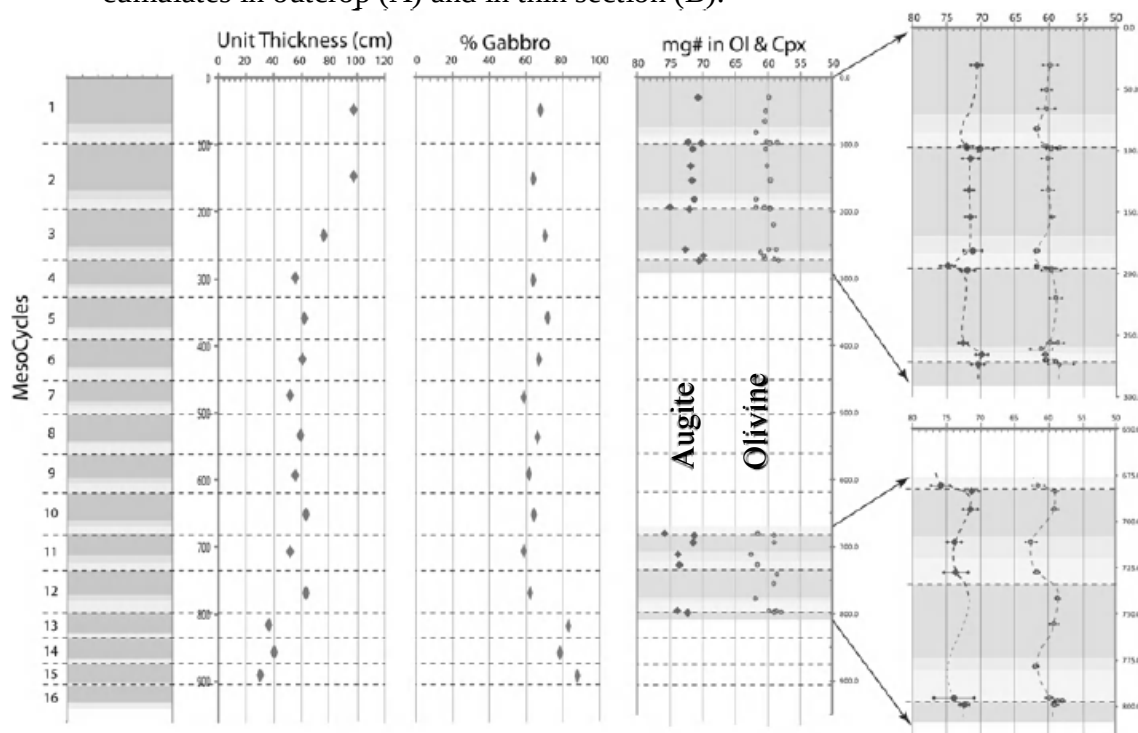


Figure 2. Stratigraphic changes in the physical and compositional characteristics of mesocycles in the Spirit Mtn area.

MESOPROTEROZOIC BEDROCK GEOLOGY OF THE HOMER LAKE – VERN LAKE AREA, COOK COUNTY, NORTHEASTERN MINNESOTA

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As one of the capstone mapping projects for the 2009 Precambrian field camp, a crew of four students (Blakely, Brown, Foley, and Rowland), a teaching assistant (Stifter), and an instructor (Miller) conducted five days of field mapping bedrock geology of the Homer Lake and Vern Lake areas of northeast Minnesota. This area comprises intrusive and volcanic rocks formed during the 1.1 Ga Midcontinent Rift in northeastern Minnesota. This mapping project expanded on a capstone mapping project conducted in 2007 (Frost et al., 2007). A 1:12,000-scale bedrock geologic map that integrates the previous mapping and new mapping from last season will be displayed as a poster presentation. A pdf version of this and other Precambrian field camp capstone geologic maps can be downloaded from the PRC website: www.d.umn.edu/prc/fieldcamp/capstone.

Prior to the detailed mapping conducted by the PRC field camp students, the general geology of the Homer Lake area was poorly known. Township-scale mapping by Grout et al. (1959) showed the area to be dominantly composed of gabbroic to felsic intrusive rocks, mafic volcanic rocks and minor volcanoclastic sedimentary rocks. They noted that the gabbroic rocks are well layered and portions are particularly rich in Fe-Ti oxide. Curiously, Davidson and Burnell (1977) did not integrate Grout et al.'s (1959) mapping into their reconnaissance geologic map of the Brule Lake 7.5' quadrangle, which contains Homer Lake. Showing only one outcrop on Homer Lake, they portrayed the geology as being composed of exclusively gabbroic and anorthositic rocks. The regional geologic map of northeastern Minnesota focused on the geology of the Duluth Complex (Miller et al., 2001) incorporates Davidson and Burnell's (1977) interpretation, which current mapping shows to be largely incorrect. In fact, Grout et al.'s (1959) mapping has been shown to be quite accurate.

Capstone mapping in August of 2007 by Shelby Frost, Natalie Juda, and Jim Miller and reconnaissance mapping in 2006 by Miller resulted in a geologic map of the Homer Lake area (Frost et al., 2007). This map interpreted the area to be composed of two main gabbroic suites separated by a thin screen of basaltic and sedimentary hornfels that runs along the north shore of Homer Lake (and noted by Grout et al., 1959). The gabbroic suites and the hornfels units have an east-west strike and gentle (15-25°) dips to the south. The basaltic hornfels has some remnant volcanic features such as flow top breccias and amygdaloidal zones and the sedimentary hornfels commonly displays cross-bedding. These units are interpreted to be basalt flows and interflow sediments of the North Shore Volcanic Group. Gabbroic rocks north of (below) this hornfels screen include olivine diabase, oxide gabbro, ferromonzodiorite, and granophyric gabbro, which were collectively termed the Axe Lake gabbroic sequence. South of the hornfels units are a series of oxide gabbros that were termed the Homer Lake gabbroic sequence. Two textural variants of the oxide gabbros were distinguished – a medium-grained, well-foliated and intergranular rock type and a coarse-grained, poorly foliated, and ophitic to intergranular lithology that can locally contain up to 25% interstitial granophyre. These two variants were found to be interlayered in 4-5 cycles over a stratigraphic thickness of about 600 meters.

Capstone mapping during the 2009 field camp extended the mapping of Frost et al. (2007) to the south and west of Homer Lake. This mapping expanded the total map area from 3 square miles to about 10 square miles. The screen of volcanic and sedimentary hornfels was traced across the map area, though at its western extent where it crosses Vern Lake, the hornfels occurs as inclusions in the base of the Homer Lake sequence. The Axe Lake sequence was traced to the west and east of Axe Lake. The more intermediate lithologies recognized in the Axe Lake area during 2007 mapping were found to persist to the east, but were not observed to the west. West of Axe Lake, the main rock type observed is olivine

gabbro to augite troctolite. Exposures along Vern Lake at the western extent of the map area, troctolite and olivine gabbro contain abundant inclusions of anorthositic gabbro.

Mapping to the south of Homer Lake to East Pipe and Pipe Lakes revealed that the oxide gabbros that compose most of the Homer Lake gabbroic sequence grade upward into an apatitic oxide gabbro, a ferromonzonite, and then into a granophyric leucogranite. In addition to recognition of these new map units, the 2009 map simplified the multiple coarse and medium grained oxide gabbro units of Frost et al. (2007) into two main alternating cycles. Also, the lowermost coarse oxide gabbro unit of Frost et al. (2007) was renamed as the heterogeneous oxide gabbro to highlight the variable texture and granophyre content of this unit. One of the more interesting discoveries was the occurrence of nearly pure layers of Fe-Ti oxide in the upper oxide gabbro cycle in the vicinity of Vern River. Grout (1949-50) noted such layers of nearly pure ilmenite in this area and to the west, which he speculated may be an economic Ti resource.

Although too little of the Axe Lake sequence has been mapped to adequately speculate as to its petrogenesis, the Homer Lake sequence has been revealed as a rather complete mafic to felsic differentiated sequence. In contrast to other mafic layered intrusions in the Duluth and Beaver Bay complexes, however, the differentiation of the Homer Lake sequence appears to start from a very evolved oxide gabbro (Pl+Cpx+Ox) cumulate rather than more primitive troctolitic (Ol+Pl) cumulates. Moreover, granophyre capping the Homer Lake sequence is part of the massive Eagle Mountain granophyre (Miller et al., 2001). Therefore, this much granophyre could not have fractionated from the oxide gabbro. Rather, as found with other granophyre masses in the Duluth and Beaver Bay complexes, the felsic rocks likely served as a density barrier to the mafic magmas of the Homer Lake sequence. Underplating of the Eagle Mountain granophyre by the Homer Lake mafic magmas would have caused partial melting of the lower part of the granophyre, which may have assimilated with the upper part of the Homer Lake sequence to create the ferromonzonite unit. If this scenario is correct, then the recent U-Pb age of 1098.6 ± 3.6 Ma reported by Vervoort et al. (2007) for the Eagle Mountain granophyre gives a maximum age for the Homer Lake sequence. A geochemical study through the Homer Lake sequence into the overlying Eagle Mtn granophyre is necessary to discern the extent to which this apparent differentiation sequence is the result of fractional crystallization or contamination by the granophyre.

Plans for the 2010 capstone mapping project in this area are to follow the stratigraphy of the Homer Lake sequence to the west. Aeromagnetic data indicates that the sequence should not only persist to the west, but should also thicken.

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SEDIMENTOLOGICAL STUDY OF THE GLACIOGENIC BRUCE FORMATION, HURONIAN SUPERGROUP, IN THE NORTH SHORE AREA, ONTARIO

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The Bruce Formation is a diamictite succession located in the lower-most portion of the Paleoproterozoic Quirke Lake Group, of the Huronian Supergroup. The Formation is exposed on the north shore of Lake Huron, and covers an area east of Sault Ste. Marie to east of Sudbury, Ontario, Canada. This assemblage of rocks represents deposition on a passive margin after initial rifting and volcanism at approximately 2450 Ma (Fralick and Miall, 1989). The passive margin succession is composed of three glaciogenic cycles beginning with outwash sandstones, which are overlain by glacial diamictites and capped by marine deposits. The Bruce Formation is situated above the Mississagi Formation, which commonly shows evidence of extensive soft sediment deformation of its cross-stratified sandstones (Fig. A). These are also more rarely intruded by clastic dykes (Fig. B), orientated perpendicular to bedding and filled with diamictite. The upper contact with the Espanola Formation is sharp and conformable. The Espanola represents the oldest cap carbonate known in the worldwide geologic record and may be evidence of a snowball Earth event. The Bruce Formation was studied in detail in an attempt to understand the ambient conditions that were present at the time of its deposition. The study included measuring and describing 16 detailed sections in the field, plus petrological and geochemical analysis of samples collected from the field areas.

Glaciogenic deposits can be either terrestrial or marine and marine deposits can be further divided into three lithofacies zones: 1) the grounding ice line zone, 2) the floating ice-shelf zone, and 3) the proximal iceberg zone. Deposits in each of these environments have distinctive characteristics that, where present, can be used to identify the depositional setting. Most outcrop areas in the sections studied consisted of massive diamictite that contained considerable quantities of sand and only scattered pebbles and cobbles. The thickness of the assemblage of diamictites making up the Formation varied drastically from section to section, with three less than 10 meters thick and others hundreds of meters in thickness. Within these massive diamictites are areas with more distinctive features. Lenses and layers of moderately well-sorted sandstone are not uncommon. In other portions of the section mud layers and mud wisps highlight layering in the diamictite, and at one location a fine-grained succession within the diamictite contained a dropstone (Fig. C). If other dropstones exist in areas of the diamictite they are commonly impossible to recognize without layering to deform. However, where clay-rich layers and wisps are present in the diamictite they can be seen to bend under and be terminated by penetration of dropstones. Layers of pebbles and cobbles in clast support were more rarely present (Fig. D). These represent deflation lags produced by current activity removing the fine-grained material. Rarest of all were flat bottomed and convex-up mounds of pebbles and cobbles in clast-support approximately one meter across, although a larger deposit of this type may also have been present in one section. Similar features are produced in modern environments by uneven melting of icebergs causing flipping and dumping of melt-out debris on their surface. In Pleistocene successions diamictite deposited near the grounding ice line commonly contains subaqueous outwash sand layers and lenses. The diamictite deposited below floating ice shelves is generally massive but has features, such as mud-rich layers and sand-rich layers, which indicate current activity. Dropstones and deflation lag layers can also develop in this zone. The

proximal iceberg zone can also be dominated by massive diamictite, which has a lower clast concentration, and also contains dropstones. The most conclusive evidence of the iceberg zone is the presence of mound shaped iceberg dumps, which are created when an iceberg overturns. This implies that large segments of the glaciogenic succession were deposited under floating ice with open water present in the basin. The open water is necessary to develop current activity. Although this data does not negate the development of a snowball earth at some point during this glacial period it does not support it.



Fig. A Soft sediment deformation of bedding in Mississagi Sandstone.



Fig. C Mud layers deformed and truncated below dropstone in Bruce Diamictite.

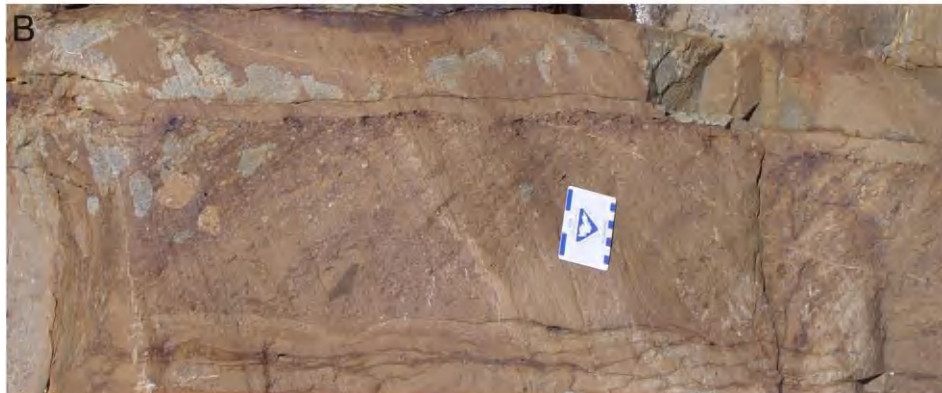


Fig. B Medium-coarse-grained clastic dyke cutting through Mississagi Sandstone. The orientation of the dyke in relation to the Mississagi and Bruce Formations contact is roughly perpendicular.



Fig. D Deflation lag layer in Bruce Diamictite. Arrow showing loonie marker.

VIRGINIA FORMATION OUTCROP (New Outcrops Versus Old Concepts)

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In their 1983 study of Virginia Formation stratigraphy, Lucente and Morey noted the absence of natural exposures of the formation and the temporary nature of a few Virginia Formation exposures related to iron mining. Their stratigraphic study was based solely on four deep core holes that were drilled as part of the “Mesabi Deep Drilling Project.” The statement (taken on faith?) that the Virginia Formation doesn’t outcrop is a truism that may actually have discouraged geologists from looking for outcrop. However, several areas of actual outcrop have been found in the last 15 years.

While not technically on the Iron Range, there are long known exposures of weakly to strongly partially melted Virginia Formation in close proximity to the Duluth Complex at Linwood Lake (Severson 1995). These particular outcrops were originally found by a minerals exploration company in the 1970s and their rumored occurrence was eventually followed up.

As part of a mapping project for the Minnesota Geological Survey, Severson and Miller, (1999) routinely visited areas as part of outcrop searches and recorded a small area of Virginia Formation outcrop in the area of the Siphon Fault (related to structure) at the east end of the LTV taconite mine in the Allen Quadrangle. Recent low water in that same area has expanded the outcrop area to about 200 ft. by 1200 ft of scattered exposure, ranging from intact outcrop, in-place blocks, and a large area of frost shattered angular blocks.

About one and a half miles east of this location, along the Dunka Road, is another area of frost shattered angular boulders of Virginia Formation that was discovered in early April, 2010. Again, these subcrops were recently exposed by low water and presumably represent outcrop.

In the fall of 2009, upon the insistence of some of PolyMet employees, who are residents of Hoyt Lakes and Aurora, we canoed into an area on the St Louis River, just south of Whitewater Lake, that the locals call “The Slates”. Here we found flaggy outcrop of Virginia Formation in floor of the river, exposures up to 12 ft. high at the riverside, and exposures in the woods near the river. The area extends about 750 ft. along the stream. Unlike the other areas of outcrop, metamorphism is not readily apparent. Sedimentary features include bedding, cross-bedding, ripple marks, and load casts. Rock types are siltstones intermixed with graywackes. Compass issues precluded quality measurements, but overall strike is SW to NE, with gentle dips to the southeast. Sulfide (pyrite) is present, but rare, in these exposures. Another area to the south of Hoyt Lakes reported by the same locals has yet to be visited. This experience would indicate the value of pursuing that lead.

In summary, a reported paucity of outcrop of any unit should never be taken at face value. Outcrops can be found in some of the most unlikely areas if enough effort is expended in systematic searches. This search should also include conversations with local outdoor enthusiasts, woodsmen, loggers, and hunters.

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HYDROTHERMAL OVERPRINT BY GREENSTONE SILLS WITHIN THE TILDEN PIT, MICHIGAN

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The Negaunee Iron Formation in the Paleoproterozoic Marquette Range Supergroup contains numerous greenstone sills and dykes. Relict gabbroic textures within these bodies identify their mafic igneous origin. Direct dating has been unsuccessful due to the pervasive retrogression of the primary silicate mineralogy. Schneider et al., (2002) suggests the Negaunee and ~1.8 Ga Hemlock volcanics interfinger and therefore date the Negaunee between 1880 and 1860 Ma. However, Hans and Runnegar (1992) consider the Negaunee to be 2.1 Ga based on Sm-Nd isotopes and identification of fossils. The lowest greenstone sill exposed in the Tilden Pit is termed the “Pillar Intrusive” and this separates the Martite Domain from the overlying Hematite Domain (Lukey et al., 2007).

Three strategic drill cores have been studied to document detailed petrography from the base of the pillar to the lowest Negaunee clastics. Microscopic examinations supported by microprobe analyses reveal that primary iron formation textures have been hydrothermally overprinted up to 100 meters below the pillar. The chilled margin of the pillar is mineralogically complex and comprises chlorite, sericite, albite and veinlets of carbonate, quartz, minor rutile and apatite; Fe-oxides are absent. Proximal to the chilled margin, iron formation textures are overprinted by massive recrystallized quartz with trace to minor disseminated Fe-oxides and K-feldspar. Vugs, occasionally filled with specularite and commonly associated with goethite patches, increase towards the sill contact. With increasing depth away from the sill, Fe-oxides increase in size and abundance whereas the goethite patches decrease in size and abundance.

Within the sill chilled margin chlorites are fine grained and show moderately high iron content (Figure 1A). Chlorite and carbonate are absent in the recrystallized quartz zone and reappear in veinlets cross-cutting the primary oolitic-chert textures 100 meters below the pillar. Below the recrystallized aureole the chlorite shows progressive increasing iron content from low iron in the oolitic-chert lithologies to higher iron contents in the lower iron formation bands and basal clastic units (Figures 1B-D). Carbonate shows a similar compositional trend as chlorite. Within the chilled margin the carbonate is fine grained calcite (Figure 2A), while ankerite-dolomite species occur in distal oolitic-chert. Within the lower iron formation bands and basal clastic lithologies the iron content of the carbonate increase dramatically to form siderite-magnesite species (Figures 2B-D).

The emplacement of greenstone sills and related dykes was accompanied by hydrothermal overprinting of the enveloping iron formation as well as the mafic intrusions. The intense chloritization of the sills and dykes suggest they intruded into still hydrous sediments and auto-hydration resulted in near-complete chlorite replacement of the chilled margins. Domains of chlorite schist that develop along the contact clearly demonstrate hydrothermal alteration predated Penokean folding. The recrystallized massive quartz aureole, with vuggy textures, represents a dehydration zone that underwent loss of iron and CO₂. The increase in porosity and permeability proximal to the sill allowed ingress of cooler fluids, giving rise to the goethite patches. Evidence for direct involvement of dehydration of enveloping sediments and pervasive retrogression of the greenstones indicates the sills are likely of similar age to the deposition of the Negaunee Iron Formation.

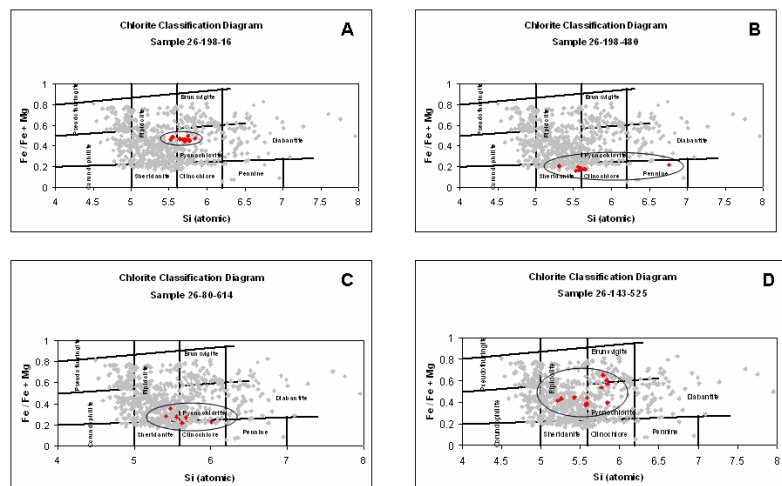


Figure 1: Chlorite chemistry of grains defined by ellipses: A) the chilled margin; B) oolitic-chert unit; C) chert-carbonate- banded unit; D) clastic unit.

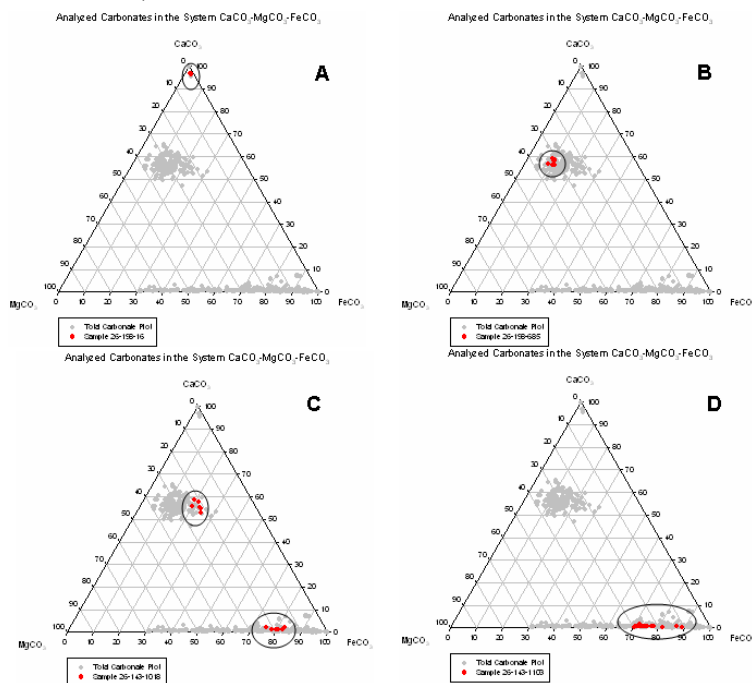


Figure 2: Carbonate chemistry defined by ellipses from: A) the chilled margin; B) oolitic-chert unit; C) chert-carbonate banded unit; D) clastic unit.

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THE RARE EARTH ELEMENT AND YTTRIUM COMPOSITION OF ARCHEAN AND PALEOPROTEROZOIC IRON FORMATIONS REVISITED: A NEW PERSPECTIVE ON SIGNIFICANCE AND MECHANISMS OF IRON FORMATION DEPOSITION

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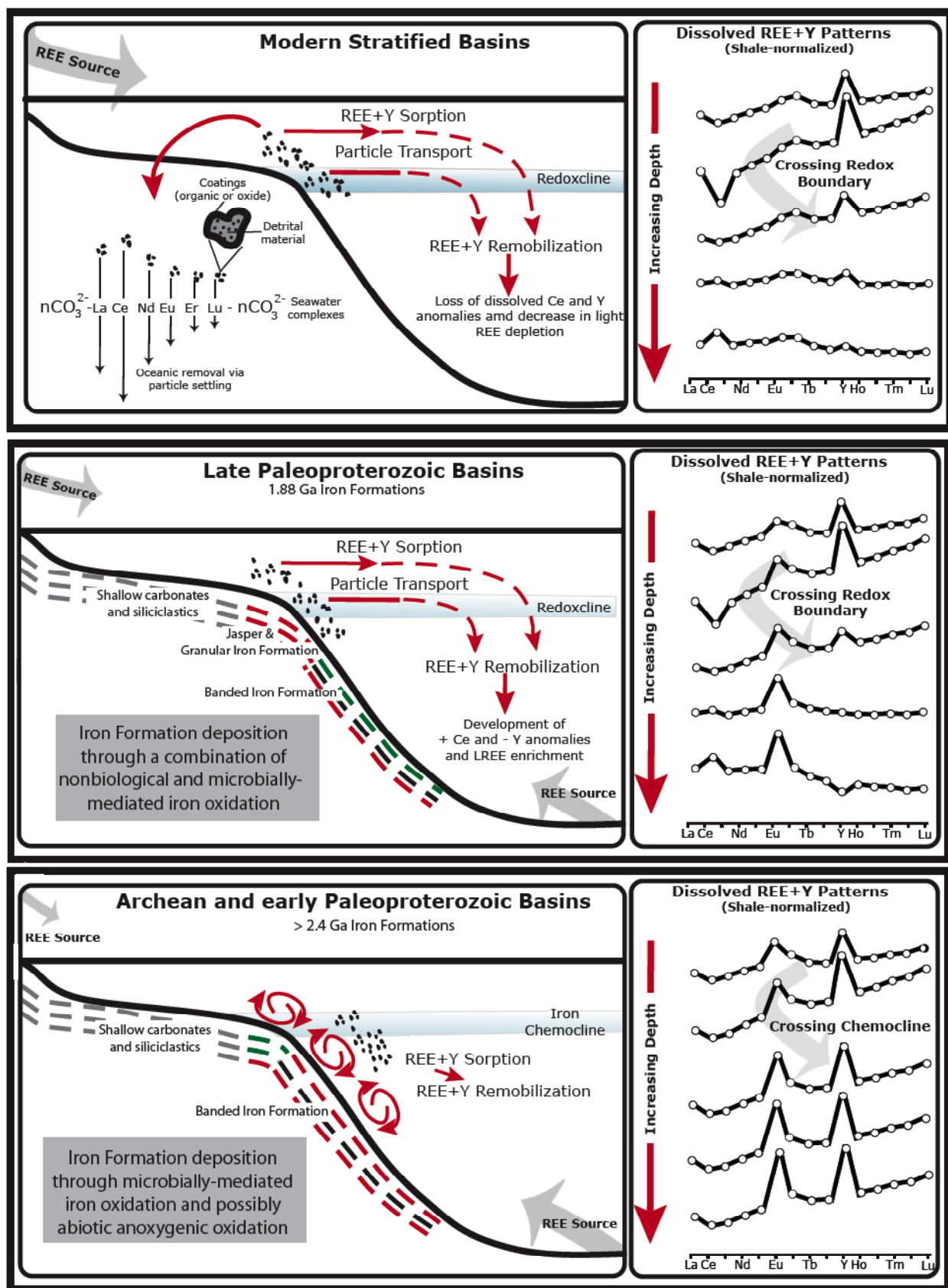
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The ocean and atmosphere were largely anoxic in the early Precambrian, which dictated a dramatically different iron cycle than today. Extremely iron-rich sedimentary deposits, iron formations, are the most conspicuous evidence of a disparate iron cycle in the early oceans. Rare Earth Element (REE) systematics have long been used as a tool to understand the genesis of iron formations and the chemistry of ancient oceans. However, many earlier REE studies of iron formations have drawn ambiguous conclusions, partially due to analytical limitations and sampling from severely altered formations. We present new chemical analyses of iron formation samples from 18 units, but with a focus on Lake Superior iron formations. These new analyses allow a reevaluation of the mechanisms and significance of Precambrian iron formation deposition. There are several temporal trends in our REE and Y dataset that we propose to reflect shifts in marine redox conditions. In general, Archean iron formations do not display significant shale-normalized negative Ce anomalies and only iron formations younger than 1.9 Ga display prominent positive Ce anomalies. Low Y/Ho ratios and high shale-normalized light to heavy REE (LREE/HREE) ratios are also present in ca. 1.9 Ga and younger iron formations but are essentially absent in their Archean counterparts. These marked differences in REE+Y patterns of late Paleoproterozoic and Archean iron formations can be explained in terms of varying water column REE cycling. Similar to modern redox-stratified basins, the REE+Y patterns in late Paleoproterozoic iron formations record evidence of a shuttle of metal and Ce oxides across the redoxcline from oxic shallow seawater. Oxide dissolution—mainly of Mn oxides—in an anoxic water column lowers the Y/Ho ratio, raises the light to heavy REE ratio, and increases the concentration of Ce relative to neighboring REE (La and Pr) values/concentrations. In contrast, Archean iron formations do not display REE+Y patterns indicative of an oxide shuttle, which implies an absence of a distinct Fe-Mn redoxcline prior to the rise of atmospheric oxygen in the early Paleoproterozoic. These results question classical models for deposition of Archean iron formations that invoke oxidation at or above a redoxcline. In contrast, we suggest that metabolic iron oxidation is a more likely oxidative mechanism for these iron formations, implying that the iron distribution of Archean oceans could have been controlled by microbial iron uptake and ecosystem stratification rather than the oxidative potential of shallow-marine environments.



THE PETROLOGY AND GEOCHEMISTRY OF THE RIVERDALE SILL

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The Riverdale Sill is located within the southern city limits of Thunder Bay. Although the sill consists mainly of gabbronorite, olivine gabbro can be found in a number of localities. The intrusive contact between the sill and the Paleoproterozoic Rove Shale is sharp and the chilled margins are only a few centimetres thick. The sill is exposed over an area approximately 6 km long and 2 km wide but the true thickness is unknown because the upper contact is not visible.

In comparison to other Midcontinent Rift-related intrusions, the Riverdale Sill is geochemically similar to ultramafic intrusions such as the Hele and Disraeli (Hollings et al. 2007). Although it is found south of Thunder Bay it most closely resemble the Jackfish Sill of the Nipigon Embayment rather than the Logan and Nipigon Sills which surround it.

The Riverdale Sill crops out in a quarry on West Riverdale Road where it has an exposed thickness of 10 m. Detailed sampling was carried out every metre up through the cross section of the sill to investigate geochemical variations within it. There is no geochemical evidence for fractionation within the sill (Fig. 1) which is supported by the absence of cumulate textures.

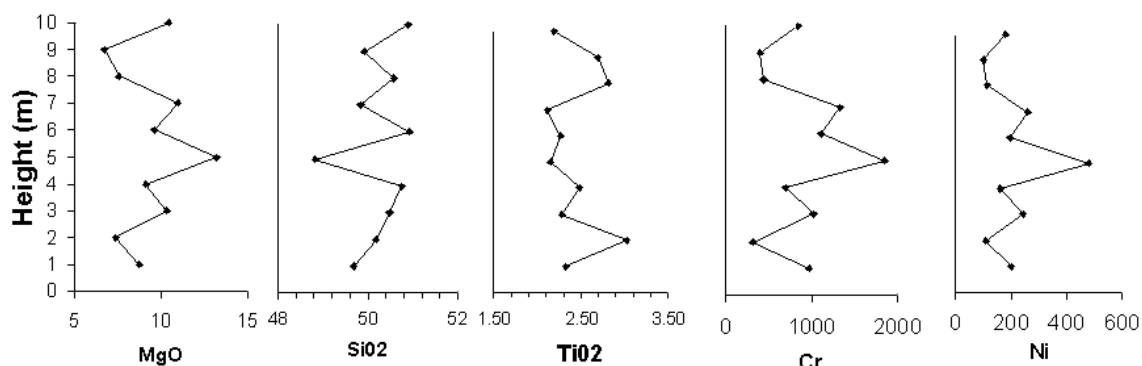


Fig. 1 Geochemical data from a transect through the Riverdale Sill. SiO₂, TiO₂ and MgO in weight percent Cr and Ni in ppm.

Geochemical evidence for contamination of the sill is localized to within less than 1m of the contact with Rove Shale, as shown by the higher SiO₂ values in the gabbronorite at the contact (Fig. 1).

On a primitive mantle-normalised plot, a number of samples of the Riverdale Sill broadly resemble Ocean Island Basalts (OIB; Fig. 2). However, some samples within the sill have negative niobium anomalies which are best interpreted to be the result of crustal contamination at depth. The less-contaminated samples are typically found towards the center of the sill. The geochemistry of the center of the sill varies slightly from that near the sill margins. Samples of gabbronorite taken adjacent to a shale xenolith within the sill do not display a negative Nb

anomaly. The lack of this anomaly, combined with the lack of contamination above the contacts in the sill at the quarry, supports a model in which contamination is occurring at depth rather than during emplacement. $\text{CNd}_{(T=1100\text{Ma})}$ values of -1.6 to -1.9 for the Riverdale Sill are consistent with this model (Smyk and Hollings, 2009).

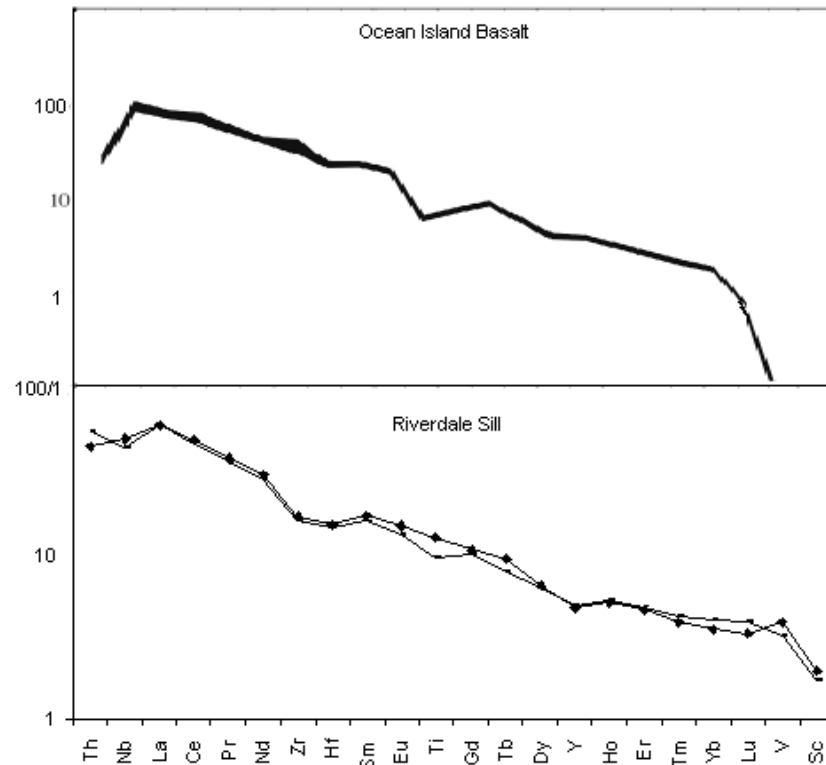


Fig. 2 Rare earth element primitive-mantle normalised plot (Modified after Hollings et al. 2007 and Sun et al.1989)

Geochemical variations within the sill can be interpreted as the result of two pulses of magma, with the first more-contaminated pulse intruded by the second, less-contaminated magma shortly after the emplacement within the shale. The less-contaminated magma may have pushed the contaminated magma to the edges of the sill, leaving a less-contaminated core.

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PETROGRAPHIC AND GEOCHEMICAL ANALYSIS OF A NIPIGON DIABASE SILL

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In this study, we present preliminary results of a detailed stratigraphic analysis of a Nipigon diabase sill. This sill has been sampled in a drill core (BSE-07-01) that has been made available for study by RPT Uranium Corp and is archived by the Ontario Geological Survey. The sill is intersected over 266 m in the core. In this preliminary investigation, we report on the stratigraphic variations in modal mineralogy (by point counting), geochemical composition (by XRF), and plagioclase composition (by optical methods).

The ultimate goal of this study is to examine the relationships between mineralogical, chemical, and textural variations in mafic sills as indicators of emplacement and differentiation processes. In a companion study (Markwood and Zieg, this volume), textural and mineralogical variations are examined in a much smaller (~1.5 m) sill. The small sill was emplaced in a single injection event, while we are hypothesizing that the larger (266 m) sill was emplaced in a series of smaller injections (as was originally proposed for the petrographically similar Logan sills by Blackadar, 1956). By comparing the variations in these two sills, we hope to develop techniques to better recognize reinjection events and characterize the petrologic evolution of mafic intrusions.

Of particular interest in the differentiation of this sill is the evidence for post-injection settling of entrained olivine phenocrysts. The settling of phenocrysts to form discrete olivine-rich horizons is well-known from, e.g., the Palisades sill (Gorring & Naslund, 1995). In this sill, the distribution of olivine-rich zones (Fig. 1) is similar to the variation trends in plagioclase composition (Fig. 2), for example between 75 and 110 m above the basal contact. Based on this petrographic evidence, it is proposed that this sill is a composite intrusion, built up by a sequence of at least three separate injections. This type of composite intrusion has been recognized in the Beacon sill of Antarctica (Zieg, 2007) that was emplaced without phenocrysts, and in this study we are specifically interested in examining the additional effects of phenocryst settling on the geochemical and textural variations. Future work will focus on further refining the spacing and timing of these reinjection events through additional sampling of olivine-rich zones and textural analysis of potential reinjection horizons.

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Figures

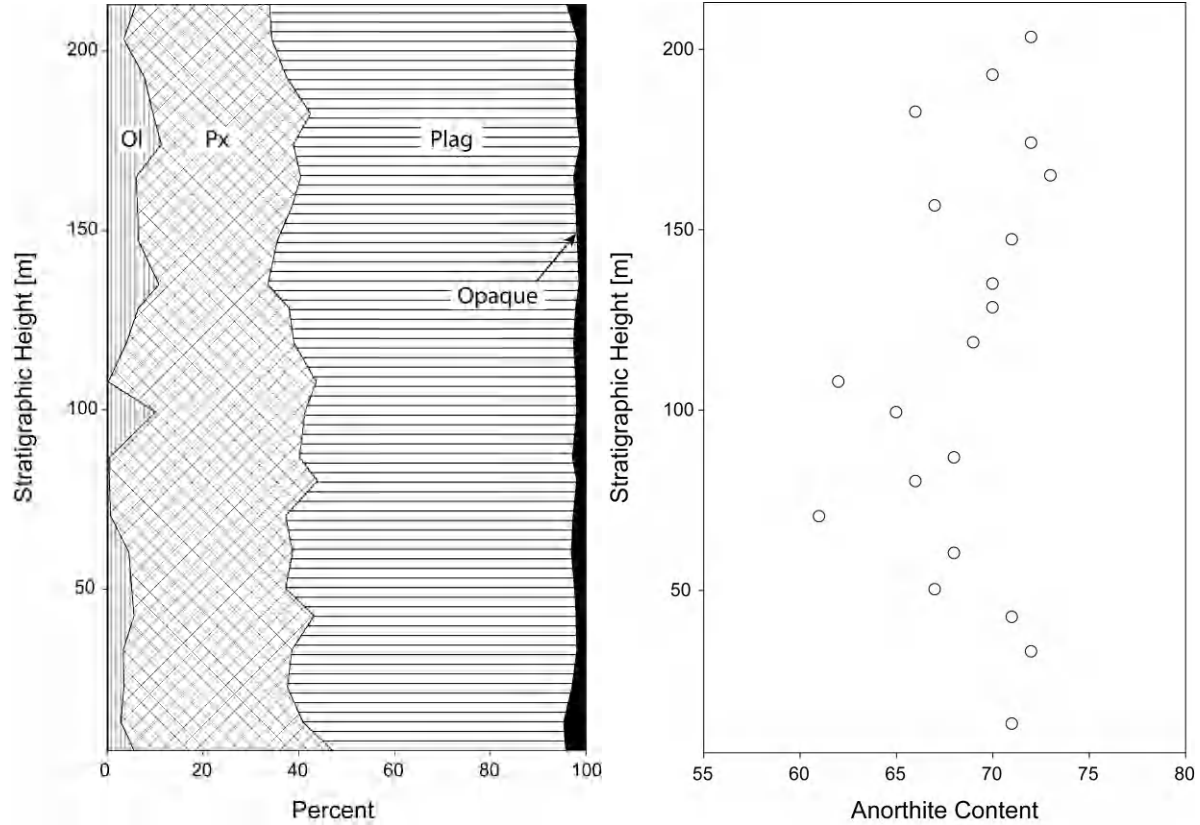


Figure 1. Stacked modal abundances of major minerals at ~10 m intervals in stratigraphic height. Abundances determined by 1000-1100 grain point count, yielding maximum error of $\sim \pm 3\%$ (van der Plas & Tobi, 1965).

Figure 2. Plagioclase composition as a function of stratigraphic height in sill, determined using Carlsbad-Albite method.

QUARTZ “EYES” OF THE MOOSE LAKE PORPHYRY COMPLEX, HEMLO, ONTARIO

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The Hemlo gold deposit, Ontario, Canada is located in the Archean Schreiber-Hemlo greenstone belt, Wawa subprovince, of the Superior Province. The deposit has been subjected to a complex history of deformation, metamorphism and intense hydrothermal alteration.

The host lithology to most of the gold at Hemlo is the Moose Lake Porphyry Complex (MLPC), a felsic orthogneiss, characterized by the occurrence of quartz “eyes”. These quartz “eyes” are actually deformed quartz porphyroclasts. The matrix of the MLPC is mylonitic, composed of quartz, microcline, minor biotite and white mica. The micas define the weak to strong foliation. Other minerals present are calcite, plagioclase, and pyrite, with trace gold, sphene and tourmaline. The porphyroclasts of quartz range in size from 1mm to 5mm and are typically elongated to form the characteristic eye shape. Rarely, feldspar porphyroclasts are present in addition to quartz porphyroclasts.

Although common in association with gold deposits, quartz “eyes” are generally rare. These occurrences of quartz porphyroclasts in a mylonitic quartz/feldspar matrix is curious and challenging to explain. Microscopic observations reveal the brittle deformation and alteration of feldspar porphyroclasts in spatial association with ductile deformation of quartz porphyroclasts. The existence of quartz porphyroclasts in a mylonitic matrix could be dependent on the protolith of the MLPC, which is the subject of some debate. Was the protolith a volcanic rock with quartz phenocrysts or is the MLPC a deformed mylonitized granitic intrusive rock?

GOLD IN THE WABIGOON SUBPROVINCE – GIS-BASED MINERAL POTENTIAL MAPPING

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Using a Geographical Information System (GIS) it is possible to analyze multiple large datasets to identify and quantify spatial relationships. The rationale behind this project is to identify areas of potential gold mineralization in the Wabigoon Subprovince using automated empirical and conceptual techniques in a GIS environment. Specific objectives include defining empirical gold associations in the Wabigoon Subprovince; creating a template for conceptual gold exploration using a mineral systems approach; and generating empirical and conceptual maps of gold mineralization potential.

While referred to as the traditional Wabigoon Subprovince, the chosen study area was defined as being the Archean rocks between the English River and Quetico sedimentary basins. The study area excludes the Proterozoic rocks of the Nipigon Basin, and is bounded on the west by the Manitoba border and on the east by the Paleozoic rocks of the James Bay Lowlands (Figure 1).

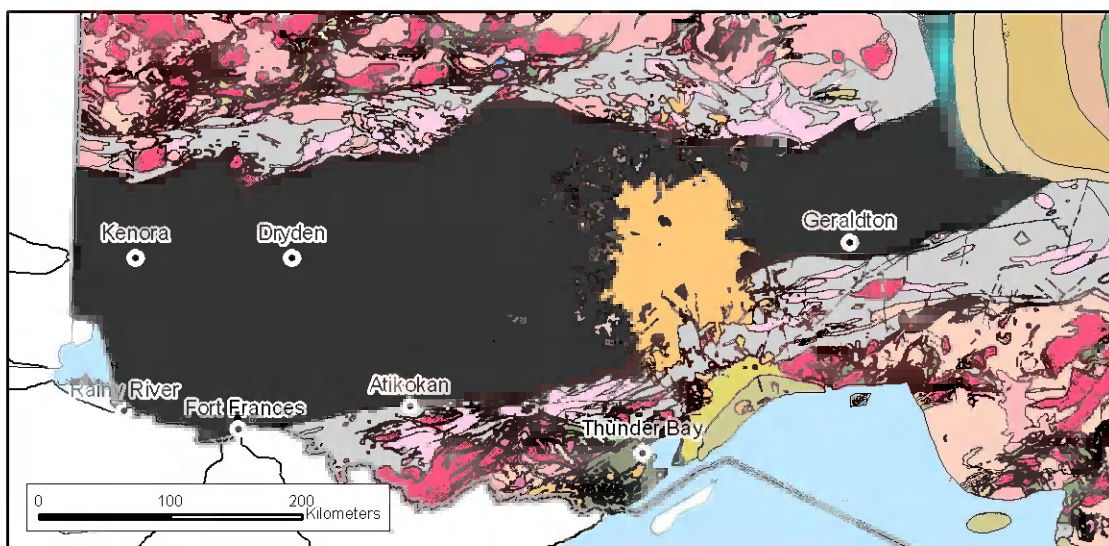


Figure 1: 1:250,000 bedrock geology with study area shaded in black. (Modified from Ontario Geological Survey, Miscellaneous Release Data 126 – Revised)

Mineral potential mapping is applied using either empirical (data driven) or conceptual (knowledge driven) techniques. Recent developments in mathematical geological modeling are beginning to combine the benefits of both techniques but are outside the scope of this project. Weights of Evidence (W of E) and Neural Networks will be used to perform the empirical analyses, with fuzzy logic being the technique applied to do the conceptual targeting.

The mineral systems approach that will be used to do the conceptual targeting allows for expert input into both defining the critical and constituent processes in gold mineralizing environments and their subsequent ranking. The mineral systems approach to characterizing ore deposition processes stems from the oil and gas industry and the widely applied source rock-migration-trap-seal methodology in petroleum exploration plays. Applied to gold mineralization, this would translate to source-active pathway-physical trap-chemical trap. While many small low-grade small-tonnage gold deposits exist, it is believed that each of the above 4 processes (source-active pathway-physical trap-chemical trap) must be present and active to generate a large gold deposit.

At the scale of the Wabigoon Subprovince it is important to select datasets that have relatively uniform coverage across the study area so as to not introduce bias. To achieve this goal, publically available geosciences datasets were examined and various layers representing proxies to critical gold mineralization processes were determined with a mineral systems framework in mind. Once the data compilation and generation stage is complete, data analysis and mineral potential mapping can begin.

It is important to realize that these techniques will not provide drillable targets, but rather allow for a quantifiable and justifiable means to examining multiple geosciences datasets in a common framework. Mineral potential mapping forces the examination of the spatial relationships between objects, documents the reasoning behind expert opinions and helps to eliminate “arm-waving” in the decision making process. Useful not only in mineral exploration, mineral potential mapping and the techniques used during its application can be useful in environmental risk assessments, land-use planning, and many other related disciplines.

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THE RING OF FIRE: AN OVERVIEW OF THE GEOLOGY, MINERAL DEPOSITS AND EXPLORATION HISTORY OF THE McFAULDS LAKE AREA

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The McFaulds Lake area of northern Ontario has been the focus of intense exploration activity since 2002, already resulting in the discovery of a remarkable number of varied metallic mineral deposits, including:

- Volcanogenic massive sulphide (VMS) copper-zinc-silver;
 - e.g. McFaulds #3 deposit (Indicated: 802 000 t @ 3.75% Cu, 1.1% Zn)
 - e.g. McFaulds #1 deposit (Inferred: 839 700 t @ 1.03% Cu, 2.38% Zn)
- Orthomagmatic copper-nickel-PGE;
 - e.g. Eagle's Nest deposit (Indicated: 6.9 Mt @ 2.04% Ni, 0.95% Cu, 1.3 g/t Pt, 3.4 g/t Pd; Inferred: 4.3 Mt @ 1.42% Ni, 0.87% Cu, 0.8 g/t Pt, 3.4 g/t Pd)
- Orthomagmatic chromium ± iron ± vanadium ± titanium ± PGE;
 - e.g. Black Thor deposit (Inferred Mineral Resource: 69.5 Mt @ 31.9% Cr₂O₃ ; 25% Cr₂O₃ cut-off); and
- Lode gold
 - e.g. Triple J occurrence: (>1.0 km strike length, depth >300 m.; grades ranging from 0.3 to 30.0 g/t Au)

The arcuate area termed the “Ring of Fire” is underlain by the folded Neoarchean McFaulds Lake greenstone belt and subvertically dipping mafic to ultramafic intrusions, at least some of which are layered and crosscut the western portion of the belt. An altered, feldspar-phyrlic dacite associated with the VMS mineralization returned an age of 2737 ± 7 Ma (Rayner and Stott 2005).

Limited radiometric dating, field constraints indicate that there might be at least two main ages of layered intrusions preserved in this region: an older, Mesoarchean suite, *ca.* 2808 Ma (e.g. Highbank Lake intrusion), close to the southwestern boundary of the Oxford-Stull domain, and a younger, Neoarchean suite of intrusions (e.g. Ring of Fire Intrusion, 2735 Ma; Gowans *et al.* 2010) hosting the copper-nickel-PGE and chromite deposits. This latter intrusive event is synchronous with local VMS mineralization and may represent the synvolcanic heat source for the VMS system.

Over 40 companies have been involved in exploration in the Ring of Fire, spending approximately \$100 million since 2002. Approximately 32 000 claim units, totaling over 5000 km², were staked. The scarcity of outcrop and Paleozoic cover in the eastern portion of the area have created a reliance on detailed geophysical surveys and diamond drilling to identify exploration targets, delineate deposits and elucidate Archean basement geology.

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STRUCTURAL CONTROL AT HAMMOND REEF GOLD DEPOSIT NORTH OF ATIKOKAN, ONTARIO

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Hammond Reef is located 22km north of Atikokan, Ontario, within the Marmion Lake batholith adjacent to the Finlayson Lake greenstone belt. Gold mineralization at Hammond Reef is commonly found associated with sulphides, such as pyrite, and in its native form. The main ore zones, and historical mine workings, are primarily composed of muscovite schist with greater than 20cm quartz veins within a northeast trending shear zone. The main ore zone exhibits ductile, brittle-ductile, and brittle deformation, chloritization, sericitization, and carbonitization. Intensely sheared muscovite schist hosts gold when adjacent to lithons which provide competency contrasts.

Areas outside of the main ore zones also show prospect for mineralization as they too underwent similar deformation, metamorphism, and alteration histories. In granitoids the pyrite mineralization is found most abundantly in areas of rheological contrast, such as adjacent to competent lithons. The areas with the greatest amount of pyrite and gold mineralization have the largest and most intense ductile shear zones and the greatest abundance of lithons. In pegmatites the sulphide mineralization and alteration is generally absent but gold is found within structures similar to the gold-bearing granitoid.

In the field, areas of highest competency contrast that are the most prospective for gold can be identified based on intensity, size, and spacing of ductile shear zones and lithons. At Hammond Reef there is a correlation between width of shear bands and intensity of ductile strain. Strain can be described as weak if shear bands are greater than 5cm wide, moderate with shear bands 5 to 2cm wide, strong with shear bands 2cm to 2mm wide, and intense with shear bands less than 2mm wide. Lithons are described based on size, lithology, composition, and characteristics which make the rock more competent than the surrounding shear zone, such as differing lithology, composition, folding, increased quartz veins, etc.

Where outcrop is scarce, or pyrite is absent in areas of intense deformation adjacent to lithons, it is difficult to locate mineralized zones and other structures are required to locate areas of highest strain. Structures to be noted in the field which indicate high strain ductile and brittle-ductile deformation, and therefore the greater potential for mineralization, are pinch-and-swell, boudinage, foliation, lineation, pressure shadows of amphibole, quartz, and pyrite, drag and sheath folds, lithons, and S-C fabrics. Low-lying areas and rivers are also geomorphological indicators of eroded shear zones at Hammond Reef.

Structures that have undergone the greatest amount of deformation, and therefore areas that have a history of deformation in a ductile, brittle-ductile, and brittle manner, have the greatest potential for mineralization at Hammond Reef when formed adjacent to a competent lithon. Long deformation histories result in the greatest amount of porosity and permeability, however brief, and therefore gold mineralization. Ductile structures which have been crosscut by brittle-ductile and brittle structures are the best indicators for mineralization as they have been reopened repeatedly through time. Prospecting along the splays of the regional shear zone utilizing knowledge of competency contrasts that have undergone brittle-ductile and ductile deformation histories should be noted in the Finlayson Lake greenstone belt and Marmion batholith area.

IDENTIFICATION AND CHARACTERIZATION OF FIBROUS ZEOLITES IN WESTERN NORTH DAKOTA

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The naturally occurring, non-asbestos, fibrous zeolite mineral erionite is a concern due to its potential for causing pleural malignant mesothelioma (PMM) in humans (Baris et al., 1987). PMM is a rare cancer usually associated with exposure to fibrous asbestos minerals. Studies have shown that low-level environmental exposure to erionite-bearing altered volcanic bedrock may be the explanation for a high PMM rate in certain locations (Metintas et al., 1999). Epidemiologic studies suggest erionite could potentially be more active and more toxic than some forms of asbestos (Metintas et al., 1999).

The presence of erionite in North Dakota was reported by Forsman (1986) as occurring in the Killdeer Mountains (KDM), one of a number of buttes in western North Dakota. It was discovered in volcanic tuffs of the late Oligocene to early Miocene Arikaree Formation. Other formations throughout western North Dakota, South Dakota, and Montana have been recognized as erionite-bearing (Goodman and Pierson, 2010).

Due to the possible health risks associated with inhalation of the fibers, hazard mapping (Forsman, 2006) was undertaken by the North Dakota Department of Health (NDDoH), in cooperation with the North Dakota Geological Survey (NDGS) and the Environmental Protection Agency (EPA). These investigations led to gravel quarry restrictions, gravel use restrictions, dust control measures, and guidance plans to control and reduce the overall exposure by businesses and private landowners working in close proximity to the bedrock formations and/or gravel quarries which potentially contain erionite (NDDoH 2009).

For the study reported here, samples were collected from regions in ND where erionite is known or suspected to be present. A total of 37 rock and/or soil samples were taken from North and South Killdeer Mountains in Dunn County, West and East Rainy Buttes in Slope County, and White Butte, also in Slope County.

Sample preparation consisted of breaking down each sample and placing it in a water column to separate any zeolite fibers from larger size fractions. Suspended materials, including the zeolite fibers, were collected from the water column and vacuum filtered. All 37 filtered samples were analyzed using powder X-ray diffraction (XRD). Of those, the 8 which showed the strongest zeolite patterns were analyzed using scanning electron microscopy (SEM). Visual inspection of the samples was conducted (Fig. 1), as well as determination of a preliminary chemical composition of the suspected zeolite fibers using SEM/EDS. The remaining 29 samples, which did not show as strong XRD indications of erionite or offretite, were also scanned by SEM to identify any other potential zeolite containing samples. The SEM/EDS chemical composition data of fibers were plotted for comparison with data from Forsman (1986) and Passaglia et al. (1998) (Fig. 2).

The results of this study are consistent with those of Lowers and Meeker (2007), who analyzed fibers separated from ND soil and roadbed samples. SEM/EDS data plot in both regions of erionite and offretite. Ongoing and future work includes stratigraphic correlation, additional powder XRD and SEM analysis, and electron microprobe analysis.

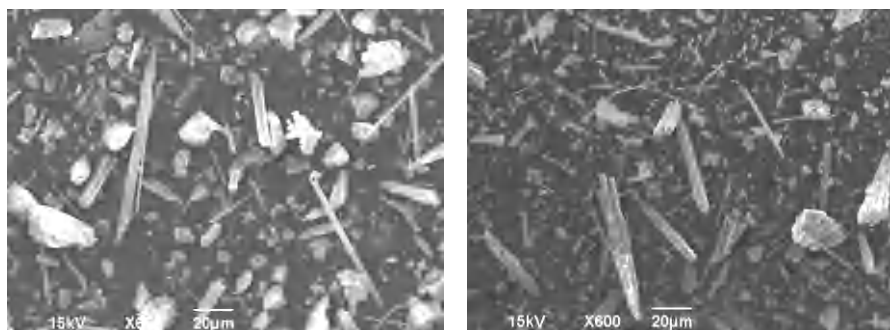


Figure 1: Concentrated zeolite fibers from South KDM. Left: sample jwt080602-01. Right: sample jwt080603-03

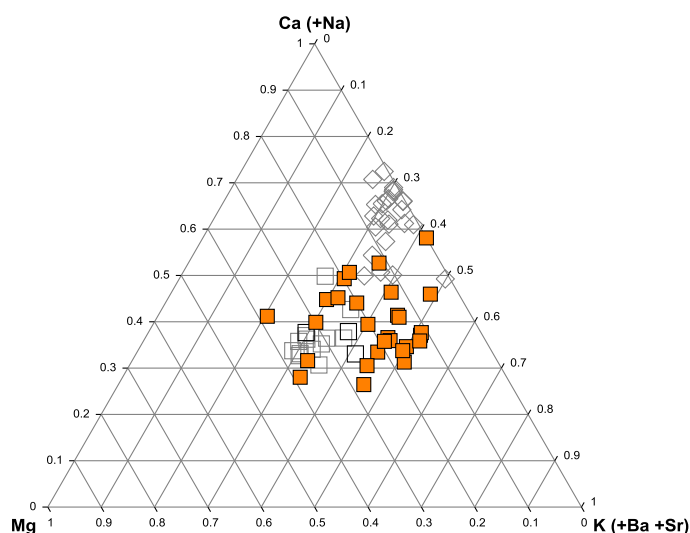


Figure 2: Comparison of SEM/EDS analyses. Passaglia et al. (1998): erionite (open diamond) and offretite (open box). Forsman (1986): erionite (bold, open box). This study: erionite/offretite (filled box).

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REVISITING THE BARABOO BRECCIAS

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Many outcrops of Baraboo-interval quartzites in Wisconsin contain brecciated zones with angular quartzite fragments in a network of quartz veins. The formation of the breccias has generally been assumed to coincide with the folding and deformation of the quartzite at 1630 Ma (Holm et al 1998), but muscovite in some of the quartz veins yields well-defined $^{40}\text{Ar}/^{39}\text{Ar}$ ages of ~1450-1460 Ma, approximately coeval with the emplacement of the Wolf River Batholith (Medaris et al 2002; 2003). By re-examining the textures in the breccias, we seek to resolve some of the ambiguity about their formation.

Samples of breccia and quartz veins were collected from five sites: three in the Baraboo Syncline itself (Ableman's Gorge and Williams Quarry on the north limb; Devil's Lake on the south limb); and two from other Baraboo-interval quartzites (Necedah Mound and Waterloo). Muscovite grains in samples from Williams Quarry, Devil's Lake and Waterloo have yielded 'Wolf River' ages (Medaris et al. 2002; 2003). Dateable muscovite is not found in the veins at Ableman's Gorge and is present but has not been analyzed at Necedah Mound.

The outcrop-scale geometry of the breccias and veins is not the same at every site, and their relationship to other structures is not always clear. The brecciated zone at Ableman's Gorge is tens of meters thick, traceable for km along strike, and generally bedding-parallel. The breccias from Williams Quarry and Devil's Lake, in contrast, are relatively localized and have more complex geometries not obviously related to bedding or to other secondary structures. The breccias at Necedah and Waterloo are meters thick and can be traced for up to 100 m, but their relationship with primary layering, which is difficult to discern in the massive quartzite, is not known.

Internally, the breccias are quite similar to each other. The breccia fragments are angular and appear to be purely dilational, since there is no evidence for cataclasis or shear offset. The fragments of quartzite have a 'jigsaw' appearance and seem to have been separated almost isotropically through the growth of vein materials. The breccia vein material is composed primarily of coarse-grained quartz with small amounts of muscovite and/or kaolinite. Primary void space is present in some of the breccias. Several types of textural evidence point to multiple stages of mineral growth in the veins. Pronounced differences in the size and shape of quartz grains within individual samples suggest distinct episodes of growth, and the coarsest, commonly euhedral, quartz crystals are optically zoned, with growth bands marked by planes of fluid and mineral (mainly quartz and muscovite) inclusions. In optical cathodoluminescence microscopy, the zoned vein quartz, as well quartz grains in the host rock, are entirely dark, indicating either that all of the quartz is compositionally uniform and/or that no 'activator' trace elements are present. The muscovite grains from which Ar ages have been obtained have generally grown epitaxially on the vein quartz although in some cases (e.g., Devil's Lake) the textural relationships point to multiple, possibly alternating, episodes of quartz and muscovite growth.

In samples from all localities, some or most of the vein quartz exhibits undulose extinction and quasi-ductile microfractures, indicating that it was subjected to significant deviatoric stress ($\geq \sim 100$ MPa), but small finite strains, some time after its formation.

Provisional Interpretations: The dilational nature of the breccias and textural evidence for multiple, distinct episodes of mineral growth points to a sustained period of elevated fluid pressures that transiently and repeatedly reached supralithostatic values. While the vein quartz could easily have formed from locally derived silica-rich fluids, there is no source of potassium in the mineralogy of the supermature host rock (Medaris et al, 2003) to allow formation of the observed muscovite. This indicates that some of the fluids responsible for the veining came from a remote source. Although some of the breccias do occur along layer-parallel zones, this is unlikely to reflect fluid flow along primary, stratigraphically controlled channels of high permeability since the breccias formed during or after the folding event. It is more likely that flexural slip between stratigraphic layers during folding created layer-parallel zones of increased permeability that provided channels for vein-forming fluids.

The textural and deformational observations in combination with the tectonic history of the Midcontinent provide several possible interpretations. One is that the breccias and most of the vein fillings formed during the Baraboo event at 1630 Ma, and that the plastic deformation in the vein quartz represents stresses late in the orogenic cycle. In this interpretation, the muscovite must have formed later, probably from fluids related to the emplacement of the Wolf River Batholith (WRB). This scenario requires some mechanism for generating elevated and fluctuating fluid pressures, and large fluid pressure gradients, to create a pervasive 'Wolf River' signature in Baraboo-type quartzites (including the Sioux Quartzite of SW Minnesota; Naymark et al., 2001). Another permissible (if radical) interpretation is that the Baraboo deformation occurred at 1450 Ma, and that the WRB was not 'anorogenic' as traditionally believed, but emplaced at the end of an orogenic cycle. This is consistent with evidence for a 1.4 Ga tectonic event in New Mexico (Daniel and Pyle, 2006) and would provide a source for both the K-rich fluids and the larger deviatoric stresses needed for deformation of the vein quartz. A third possible interpretation is that the vein-forming fluid flow events occurred in Wolf River time but that the vein quartz was deformed by far-field stresses from the Grenville orogeny at ca. 1 Ga.

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POST PENOKEAN AGE OF MINERALIZATION ON THE MARQUETTE RANGE, MICHIGAN

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The Champion Mine located on the south limb of the Marquette Syncline in Western Marquette County, Michigan is noted for the diverse hydrothermal mineral assemblage that includes molybdenite, native gold, boron and bismuth. The molybdenite is found associated with greisen and with the magnetite ore. Moly occurs as coarse flakes and books that can be readily separated from the gangue. Test work was conducted under contract by David Selby in England at Durham University. The technique utilized is found in the reference listing below.

With the advent of the age determination technique using isotopic Rhenium (Re) and Osmium (Os) it was natural that molybdenite would be tested as it contains an abundance of both. The decay constant of ^{187}Re to ^{187}Os is the key to the age determination. Re-Os date delineation utilizes the isochron dating method assuming ^{187}Os did not exist at the time of emplacement. The isochron plots the ratio of radiogenic ^{187}Os to non-radiogenic ^{188}Os against the ratio of the parent isotope ^{187}Re to the non-radiogenic isotope ^{188}Os .

It was long suspected the alteration minerals were emplaced at the end of the Negaunee iron formation ~1874 Ma or at least no younger than the Humboldt granite (~1760 Ma) located five miles to the southeast of the Mine. It then came as some surprise when the molybdenite associated with the greisen showed an age of 1672±7 Ma and the molybdenite in the magnetite yielded an age of 1570±7 Ma. It may be that a continuum of geological events is present in the Superior Province of the Canadian Shield. Further age dating of the sulfides associated with the hard ores on the Animikie Basin will help further define the hydrothermal events.

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NEW WAYS TO STUDY OLD PROBLEMS

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This poster shows how two recently developed instruments, the Electric-Pulse Disaggregator, and the Tabletop scanning electron microscope, provide new methods to characterize the textures, minerals, and mineral compositions of rock samples. See <http://www.marinereef.com> and http://www.ndsu.edu/pubweb/~sainieid/PPD/Curator_ms.shtml. Samples from the Paleoproterozoic Sudbury Ejecta Layer are used as examples.

The scanning electron microscope (SEM) and the electron microprobe (EMP) are widely used to augment the petrographic microscope as tools to characterize rocks. The tabletop scanning electron microscope (TSEM) provides a new and simpler tool than the SEM for obtaining images and energy dispersive x-ray (EDX) spectra (including more accurate analyses of Carbon). Since it is not necessary to evaporate a carbon film on polished thin sections or mineral grains, samples can be transferred directly from a binocular, or petrographic microscope. The convenience and time saved is significant when studying many samples (Figs. 1 and 2).

Electric pulse disaggregation (EPD) provides a mechanism for liberating individual mineral grains while preserving their three dimensional surfaces. This method of mineral separation has several additional advantages over conventional mineral separation methods. First, the separated grains provide clean samples (Figs. 3 and 4) for energy dispersive x-ray, electron microprobe and bulk chemical analysis (for the two first methods boundary effects of adjacent phases in polished thin sections are eliminated). Secondly, EPD products provide samples in which interesting minerals of low concentration, e.g., zircon, and platinum group minerals can be efficiently concentrated and recovered for further study. Thirdly, concentrates of EPD products can provide samples of minerals of very low concentration or small grain size that may not be recognized in thin section or only postulated on the basis of bulk chemistry.



Fig. 1. Photomicrograph of Sudbury Ejecta containing glassy fragments and spherules in a carbonate matrix. Cross polarized transmitted light.

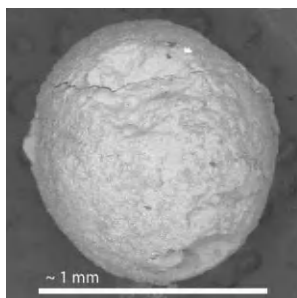


Fig. 3. EPD products of sample OB KS GTP. Note the glass spherules are cleanly separated from the carbonate matrix.

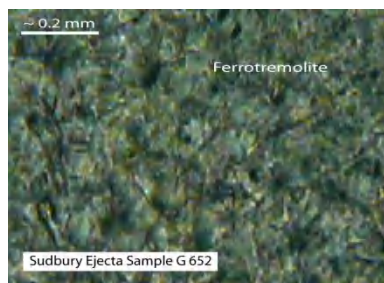


Fig. 2. Photomicrograph of fine-grained matrix in iron formation breccia, that cannot be resolved optically. Plain polarized light.

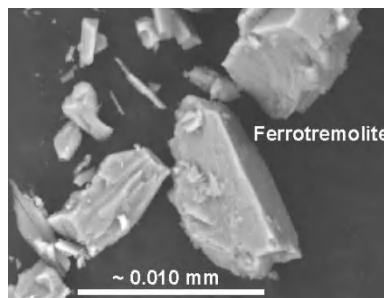


Fig. 4. EPD Products of Sample G 652. The fine-grained matrix actually consists of euhedral crystals. Some as small as 0.050 mm.

SUDBURY IMPACT EJECTA – AMPHIBOLES IN SAMPLES FROM THE VICINITY OF THE GUNFLINT TRAIL, MINNESOTA

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Over two dozen outcrops of Sudbury Meteorite Impact Ejecta have been found and mapped in the vicinity of the Gunflint Trail in Minnesota (Fig. 1). A generalized stratigraphic column has

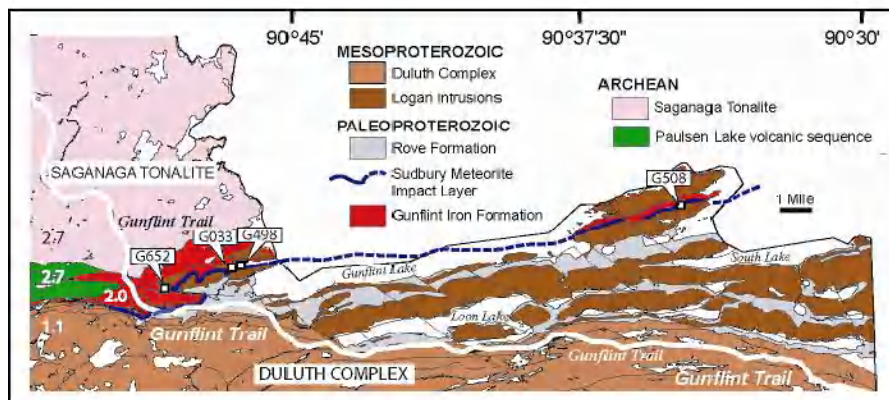


Fig. 1. Geologic map depicting the Sudbury Meteorite Impact Layer, in the Gunflint Trail area. The layer lies within the contact aureole of the Mesoproterozoic intrusive rocks. Hence contact metamorphism combined with weathering (See Figs. 4 and 7) make comparison of mineral assemblages, textures, and compositions with Sudbury ejecta elsewhere problematic.

been derived from these exposures (See Jirsa, this volume). The complete column is not exposed at any of the exposures. We have studied the occurrence of amphibole in the four samples noted on Fig. 1. See Figs. 2 -4 for photos. These samples provide a first look at differences in occurrence, textures, and compositions of amphibole in the basal breccia (G652), the zone of cm-sized accretionary lapilli (G033 and G498, same outcrop). and an upper zone of smaller (< 3mm), pellets (G508) that are generally not zoned except for finer-grained outer rims. Optical and scanning electron microscopy (SEM), electron microprobe analysis (EPA), x-ray diffraction (XRD), and electric-pulse disaggregation (EPD) (See Weiblen this volume) have been used to characterize textures and mineral compositions. Chemical analyses have been obtained on select samples. A sampling of the results thus far is presented in Figs. 5-11.



Fig. 2. Outcrop photo G 652.



Fig. 3. Outcrop photo G033

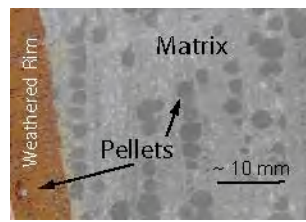


Fig. 4. Sample photo G508

The photomicrographs below are all cross polarized light images.

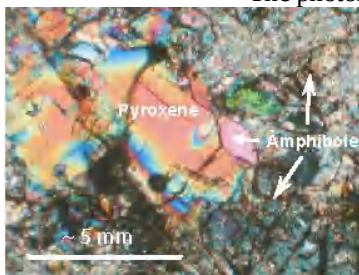


Fig. 5. G652Z-Porphyroblast

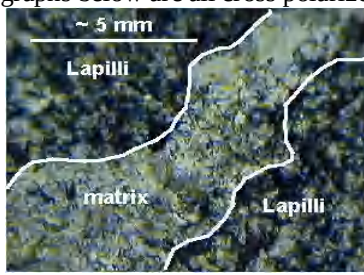


Fig. 6. G498-Lapilli Matrix interface

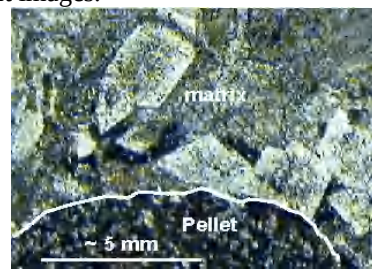


Fig. 7. G508A-Pellet in Matrix

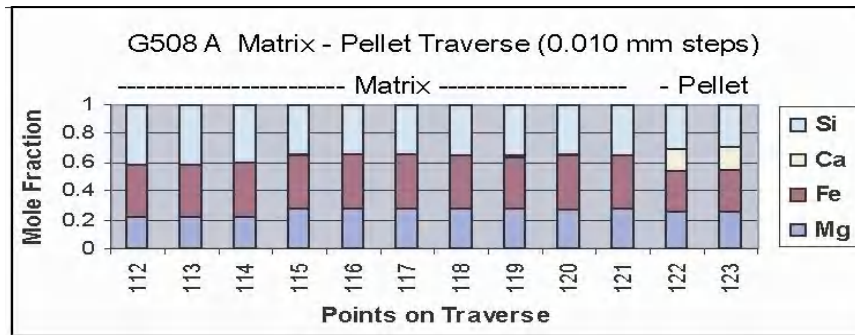


Fig. 8. A portion of a 1.5 mm electron microprobe traverse across a matrix pellet interface in G 508A.. See text for discussion.

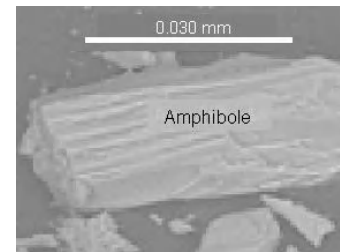


Fig. 9. Back Scatter Electron Image of EPD products from G498 Z. Euhedral crystals as small as 0.005 mm are found.

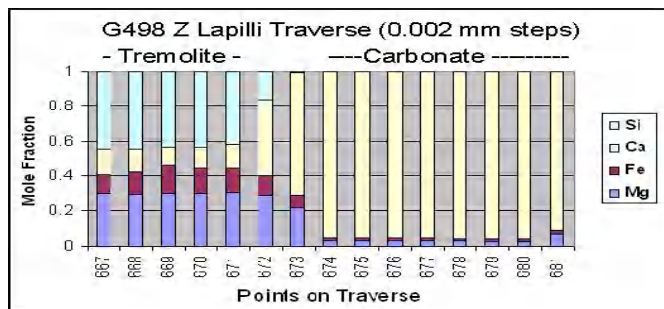


Fig. 10 A portion of a 1.5 mm electron microprobe traverse from the center of one accretionary lapilli across matrix into the center of an adjacent lapilli in G 498Z.. See text for discussion.

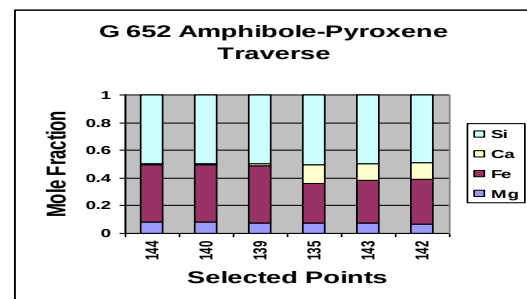
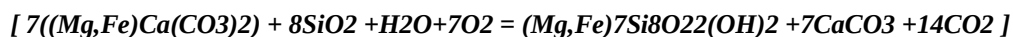


Fig. 11 Selected analyses across the Amphibole (144-139)-Pyroxene (135-142) interface shown in Fig. 5.

We have found it useful to distinguish the small $\sim < 3\text{mm}$, generally unzoned “lapilli” with the term “pellet” (Figs. 4, 7 & 8). *Unaltered/weathered* pellets are just discernible in the *altered-weathered rim* of sample G508 A (Fig. 4). We have separated *intact pellets* from the matrix of *altered-weathered* rims by EPD. Since the pellets and the matrix have the same quartz-carbonate-amphibole mineral assemblage, it is curious that the pellets have remained impervious to *alteration-weathering* in contrast to the matrix. The data in Fig. 8 indicates negligible Ca in *matrix* amphibole in contrast to the Ca bearing *pellet* amphibole. Is this difference a metamorphic or an *alteration-weathering* effect?

EPD traverses across accretionary lapilli indicate the zoning is defined by variations in quartz, carbonate, and amphibole. If amphibole formed from a Mg,Fe carbonate as found in lapilli elsewhere, we thought it remarkable that the original zoning would be preserved. However we find that the reaction products are fine-grained euhedral crystals (Fig. 8) and the zoning is preserved on a scale of 0.010-0.030 mm! The products of the reaction Mg carbonate + quartz + water + oxygen are Mg,Fe amphibole + calcite + carbon dioxide.



This reaction could be the origin of some of the relatively pure calcite found in Gunflint ejecta samples (Incidentally, thermodynamic data indicate that dolomite + quartz + water break down to tremolite + calcite at $\sim 190^\circ\text{C}$ and 1 atm.). Another example of contact metamorphism in the Gunflint area is the occurrence of porphyroblasts in some samples (Fig. 5). This preliminary data indicates that the ejecta samples contain much information on the contact aureole in the Gunflint area. For further examples of how our studies augment petrographic examination (Figs.2-4) are presented in an accompanying poster session (See Weiblen, this volume).

GEOLOGIC MAP OF THE CENTRAL SEINE BAY/ BAD VERMILION LAKE INTRUSION WITH ACCOMPANYING AIRBORNE GEOPHYSICS, RELATING TO NUMAX RESOURCES, INC., MINE CENTRE PROPERTY, MINE CENTRE, ONTARIO

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Numerous massive oxide (Fe-Ti-V) outcrops were discovered in 2004 by Numax Resources, Inc. on their Mine Centre property, which is located in northwestern Ontario. This was followed up by prospecting, mechanical trenching, channel sampling, two ground geophysical surveys (walking magnetic and VLF electromagnetic), and three diamond drill holes over the next five years. Numerous channel and drill core samples assayed greater than 60% Fe₂O₃, 15% TiO₂, and 3000 ppm V. This encouraging data prompted Numax Resources, Inc. to requisition a detailed (1:5000 scale) geologic map of the property. Along with the property map, ten previously excavated trenches were mapped in greater detail (1:400 scale).

Numerous 1 to 30 m-wide continuous to semi-continuous, massive to semi-massive oxide layers (Figs. 1 and 2) trend in an east-west to northeast-southwest orientation across the 12.5 km-long Mine Centre property (Bernatchez, 2009). These massive and semi-massive oxide layers correlate well with magnetic highs discovered during the Ontario Geological Survey airborne geophysical survey (OGS, 2009). The massive oxide layers are bound and interlayered with various medium- to coarse-grained mafic intrusive rocks consisting of gabbro, pyroxenite, and anorthosite (Albers and White, 2010).

In the western portion of the property, the rocks are subvertical and dip steeply to the north. In the eastern part of the property, the rocks dip 30-60 degrees to the northwest. Tops are interpreted to the north based on graded modal layering of silicates. The northern contact of the Seine Bay/Bad Vermillion Lake intrusion is bound by felsic intrusive rocks consisting of granodiorite, quartz diorite, tonalite, and trondhjemite; while the southern contact consists of mafic volcanic rocks including massive, amygdaloidal, and plagioclase-phyric basalt. Locally, subvertical shear zones are adjacent to major lithologic contacts and massive oxide layers, though individual massive oxide layers appear to be largely undeformed.

Upcoming work includes systematically-spaced diamond drilling of high grade Fe-Ti-V layers, petrographic analysis through numerous sections of the mafic intrusion, electron microprobe study of the massive oxide mineralization, 3D geologic modeling, and continued detailed geologic mapping.



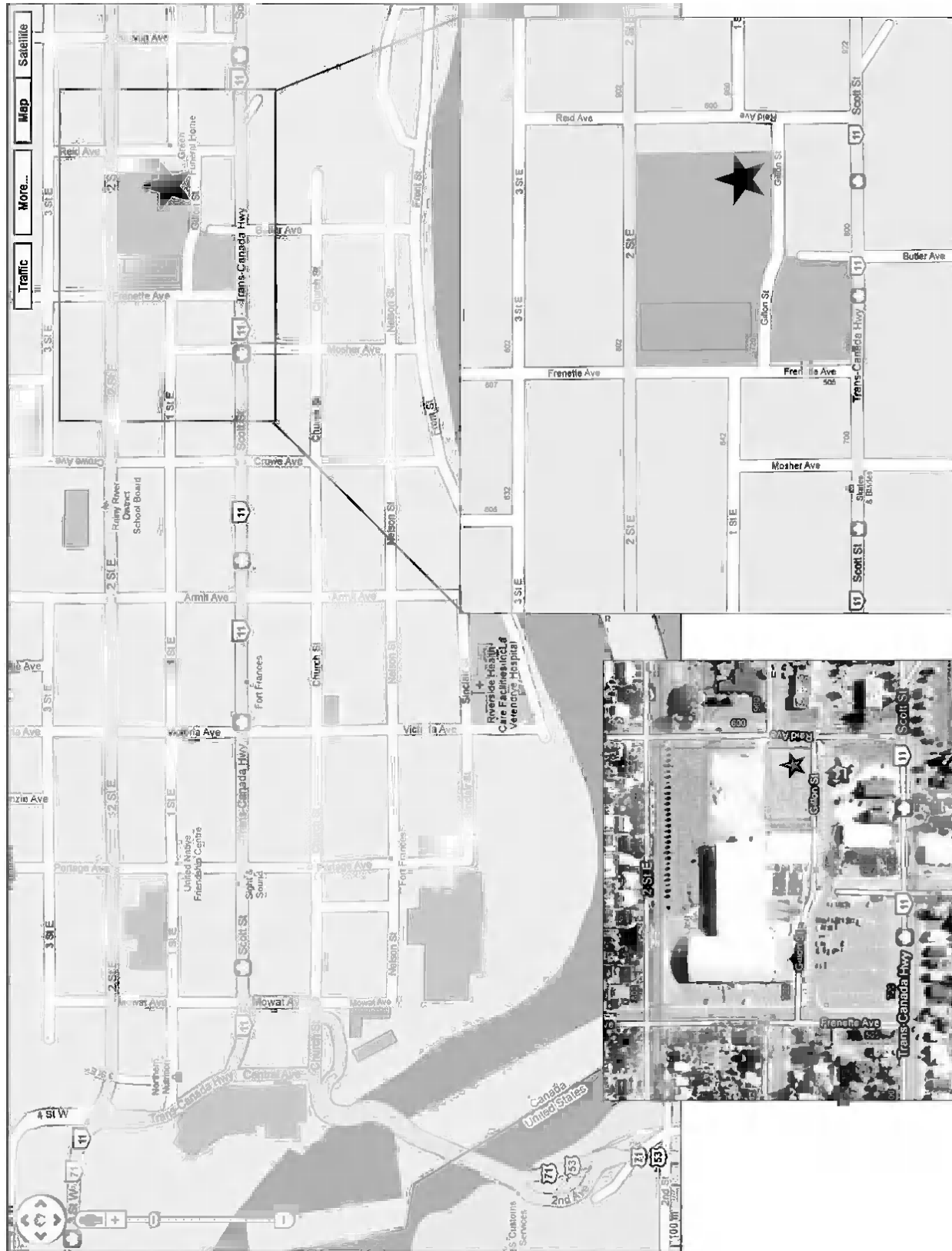
Figure 1. One of numerous massive oxide outcrops (1.5 m wide) within sheared and/or lineated gabbro in Trench L28.



Figure 2. Hematite alteration of massive oxide in Turtle Trench.

Selected References

- Albers, P.B., and White, C.R. 2010. Report on the Geology and Mineral Potential of the Seine Bay/Bad Vermilion Lake Intrusion, Mine Centre Property, Mine Centre, Ontario. Unpublished report prepared for Numax Resources, Inc.
- Bernatchez, R.A. 2009. A Report on the Fe-Ti-V and Cu-Ni-PGM and other Mineral Potential for the Mine Centre Property. Unpublished report prepared for Numax Resources, Inc.
- Poulsen, H.K. 2000. Precambrian Geology and Mineral Occurrences, Mine Centre – Fort Frances area; Ontario Geological Survey, Map 2525, scale 1:50,000.
- Ontario Geological Survey. 2009. Ontario airborne geophysical surveys, Magnetic and Electromagnetic Data, Grid and Profile Data (ASCII and Geosoft formats) and Vector Data, Mine Centre Area; Ontario Geological Survey. Geophysical Dataset 1061a ISBN 978-1-4435-0854-4 [DVD] ISBN 978-1-4435-0855-1 [ZIP FILE].



Map showing location of Frances Memorial Sports Centre, starting point for several of the field trips.



Map showing location of Backus Community Center in Relation to the Rainy River Inn (formerly the Holiday Inn). The banquet will be at the Community Center, located at 900 5th Street, International Falls.