

58th ANNUAL MEETING
INSTITUTE ON LAKE SUPERIOR GEOLOGY
Thunder Bay, Ontario - May 16-20, 2012

Part 1 – Proceedings and Abstracts





58th ANNUAL MEETING

INSTITUTE ON LAKE SUPERIOR GEOLOGY



May 16-20, 2012

Thunder Bay, Ontario

HOSTED BY:

Pete Hollings

Chair

Lakehead University

Proceedings - Volume 58

Part 1 – Proceedings and Abstracts

Edited by Pete Hollings (Lakehead University)

Cover Photos: Top - Lac des Iles open pit, Middle - Kakabeka Falls in flood, notice light coloured tuff units on right, Bottom - the Sea Lion in 1985, Silver Islet (photos courtesy of Al MacTavish and Bill Addison).

58th INSTITUTE ON LAKE SUPERIOR GEOLOGY

VOLUME 58 CONSISTS OF:

PART 1: PROGRAM AND ABSTRACTS

PART 2: FIELD TRIP GUIDEBOOK

TRIP 1 & 13: SUDBURY IMPACTOCLASTIC DEBRISITES AT THUNDER BAY

TRIP 2: GEOLOGY OF THE SIBLEY PENINSULA

TRIP 3: LAC DES ILES MINE

TRIP 4: SHEBANDOWAN MINE AREA

TRIP 5: GEOLOGY OF THE THUNDER BAY AREA

TRIP 6: THUNDER BAY AMETHYST MINE

TRIP 7: BUILDING STONE TOUR OF DOWNTOWN PORT ARTHUR, THUNDER BAY

TRIP 8: HIGHWAY 527 TRANSECT

TRIP 9: REHABILITATION OF THE PAST-PRODUCING SHEBANDOWAN AND NORTH
COLDSTREAM MINE SITES

TRIP 10: GEOARCHAEOLOGY OF THUNDER BAY

TRIP 11: MIDCONTINENT RIFT INTRUSIONS

TRIP 12: MUSSELWHITE MINE

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

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Institutes on Lake Superior Geology, 1955-2012

#	Date	Place	Chairs
1	1955	Minneapolis, Minnesota	C.E. Dutton
2	1956	Houghton, Michigan	A.K. Snelgrove
3	1957	East Lansing, Michigan	B.T. Sandefur
4	1958	Duluth, Minnesota	R.W. Marsden
5	1959	Minneapolis, Minnesota	G.M. Schwartz & C. Craddock
6	1960	Madison, Wisconsin	E.N. Cameron
7	1961	Port Arthur, Ontario	E.G. Pye
8	1962	Houghton, Michigan	A.K. Snelgrove
9	1963	Duluth, Minnesota	H. Lepp
10	1964	Ishpeming, Michigan	A.T. Broderick
11	1965	St. Paul, Minnesota	P.K. Sims & R.K. Hogberg
12	1966	Sault Ste. Marie, Michigan	R.W. White
13	1967	East Lansing, Michigan	W.J. Hinze
14	1968	Superior, Wisconsin	A.B. Dickas
15	1969	Oshkosh, Wisconsin	G.L. LaBerge
16	1970	Thunder Bay, Ontario	M.W. Bartley & E. Mercy
17	1971	Duluth, Minnesota	D.M. Davidson
18	1972	Houghton, Michigan	J. Kalliokoski
19	1973	Madison, Wisconsin	M.E. Ostrom
20	1974	Sault Ste. Marie, Ontario	P.E. Giblin
21	1975	Marquette, Michigan	J.D. Hughes
22	1976	St. Paul, Minnesota	M. Walton
23	1977	Thunder Bay, Ontario	M.M. Kehlenbeck
24	1978	Milwaukee, Wisconsin	G. Mursky
25	1979	Duluth, Minnesota	D.M. Davidson
26	1980	Eau Claire, Wisconsin	P.E. Myers
27	1981	East Lansing, Michigan	W.C. Cambray
28	1982	International Falls, Minnesota	D.L. Southwick
29	1983	Houghton, Michigan	T.J. Bornhorst
30	1984	Wausau, Wisconsin	G.L. LaBerge
31	1985	Kenora, Ontario	C.E. Blackburn
32	1986	Wisconsin Rapids, Wisconsin	J.K. Greenberg
33	1987	Wawa, Ontario	E.D. Frey & R.P. Sage

#	Date	Place	Chairs
34	1988	Marquette, Michigan	J. S. Klasner
35	1989	Duluth, Minnesota	J.C. Green
36	1990	Thunder Bay, Ontario	M.M. Kehlenbeck
37	1991	Eau Claire, Wisconsin	P.E. Myers
38	1992	Hurley, Wisconsin	A.B. Dickas
39	1993	Eveleth, Minnesota	D.L. Southwick
40	1994	Houghton, Michigan	T.J. Bornhorst
41	1995	Marathon, Ontario	M.C. Smyk
42	1996	Cable, Wisconsin	L.G. Woodruff
43	1997	Sudbury, Ontario	R.P. Sage & W. Meyer
44	1998	Minneapolis, Minnesota	J.D. Miller & M.A. Jirsa
45	1999	Marquette, Michigan	T.J. Bornhorst & R.S. Regis
46	2000	Thunder Bay, Ontario	S.A. Kissin & P. Fralick
47	2001	Madison, Wisconsin	M.G. Mudrey & Jr., B.A. Brown
48	2002	Kenora, Ontario	P. Hinz & R.C. Beard
49	2003	Iron Mountain, Michigan	L. Woodruff & W.F. Cannon
50	2004	Duluth, Minnesota	S. Hauck & M. Severson
51	2005	Nipigon, Ontario	M. Smyk & P. Hollings
52	2006	Sault Ste. Marie, Ontario	A. Wilson & R.Sage
53	2007	Lutsen, Minnesota	L. Woodruff & J. Miller
54	2008	Marquette, Michigan	T. Bornhorst & J. Klasner
55	2009	Ely, Minnesota	J. Miller, G. Hudak & D. Peterson
56	2010	International Falls, Minnesota	M. Jirsa, P. Hollings, T. Boerboom, P. Hinz & M. Smyk
57	2011	Ashland, Wisconsin	T. Fitz
58	2012	Thunder Bay, Ontario	P. Hollings

Sam Goldich and the Goldich Medal

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

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

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

Reference:

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

Prepared by various Goldich Medal Awardees, 2007



Institute on Lake Superior Geology Goldich Medal

Goldich Medal Guidelines

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

Preamble

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

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

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

Award Guidelines

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

Nominating Procedures

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

Selection Guidelines

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

Goldich Medalists

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

2012 Goldich Medal Recipient

Jim Miller

University of Minnesota Duluth, Duluth, Minnesota

Goldich Medal Committee

Serving through the meeting year shown in parentheses

Mary Louise Hill (2012) Lakehead University

Laurel Woodruff (2013) United States Geological Survey

Graham Wilson (2014) Turnstone Consulting

Mary Louise Hill, as out-going senior member of Institute Board of Directors, is liaison between Goldich Medal Committee and the Board through the 2012 meeting.

Citation for Goldich Medal Recipient

Dr. Jim Miller is indeed a worthy recipient of the 2011 Goldich Medal. Jim exemplifies the best of what this award represents on the basis of his contributions to our understanding of Lake Superior geology and his long-standing involvement with the Institute on Lake Superior Geology.

Most of us know Jim for his work in the Midcontinent Rift in Minnesota over more than 25 years. The major emphasis of Jim's research with the Minnesota Geological Survey and the University of Minnesota since 1985 has been field, petrologic, and metallogenic studies of the igneous rocks of this 1.1 billion-year-old rift. His work has focused on producing bedrock geologic maps of the Duluth Complex and related intrusive terranes of the Rift in northeastern Minnesota and on studying the petrology and crystallization history of various intrusions within it. Jim has authored or co-authored dozens of peer-reviewed reports, papers and maps and is regarded world-wide as an expert in the Duluth Complex and the Midcontinent Rift. He has 54 contributions in ILSG publications, including both abstracts and field trip guidebooks.

Jim's work is not purely academic, however, his research and mapping has led to the evaluation of the copper-nickel-platinum group element potential of many Midcontinent Rift intrusions. One of the first collaborations that Jim and I worked on was a field trip for the International Geologic Correlation Program looking at mafic intrusions in Ontario and Minnesota, a trip that we reprised in 2002 and 2010 for the International Platinum Symposium. Jim has had a long-standing history with this symposium, presenting papers, workshops and field trips on the economic potential of the Lake Superior region. Jim is highly regarded by geologists in the mineral exploration industry and frequently takes the opportunity to present his research and ideas at industry-based symposia.

From 1989 to 2005, Jim was the principal investigator for a series of six biennial grants from the Minnesota State Legislature's Minerals Coordinating Committee. Specific projects included:

- Shallow drilling project, central Duluth Complex;
- Geologic mapping in the Duluth area;
- Petrology and metallogensis of the Duluth Complex at Duluth;
- Geologic mapping in the Allen quadrangle;
- Digital geologic mapping of the central Duluth Complex;
- PGE potential of the Sonju Lake Intrusion;
- Geology and mineral potential of the Duluth Complex;
- Geology and PGE potential of the Greenwood Lake Intrusion and PGE evaluation of mafic intrusions outside the Duluth Complex.

Jim's research, as well as that of the many undergraduate and graduate students he has supervised, has contributed to the understanding of the general tectonic and magmatic history of the Midcontinent Rift and its mineral deposits. This has led to new ideas in rift development and metallogeny. Jim's ideas and discoveries have led to industry interest and investment, including the drilling of a recently discovered PGE-bearing reef in the Sonju Lake intrusion.

In addition to his research, Jim has also worked with the Minnesota Department of Natural Resources to produce geological displays for North Shore State Parks. He continues to be an advocate of public education and works with researchers in different disciplines such as health, public policy and the environment in making informed decisions involving geology and mineral development.

Another major focus of Jim's work involves educational outreach. Jim frequently speaks to school groups, teaches non-credit classes and leads field trips in an attempt to introduce Minnesota geology to non-geologists. He has been actively involved in planning and implementation of workshops for kindergarten to Grade 12 earth science teachers for many years. Jim has taught Compleat and Practical Scholar Courses, non-credit classes on Minnesota's geology sponsored by the University of Minnesota's General College. Course offerings have included:

- Drifting Continents/Expanding Oceans: An Introduction to the Dynamic Earth (1994-98);
- The Making of Laurentia – Minnesota's Geologic History (1994-99);
- What's this Rock? An Introduction to the Geology of Minnesota's North Shore (2003-05).

Since 2006, Jim has taught non-credit, one-day summer field classes at the University of Minnesota's College of Continuing Education's Curiosity Camp entitled "A Geology Tour of the Twin Cities".

The Teacher Inquiry-based Minnesota Earth Science (TIMES) Project was a federally funded program sponsored by Hamline University that organized two week-long summer field courses for middle school earth science teachers in Minnesota. Jim served as guest lecturer and assisted on field trips for projects between 2000 and 2009 and was the lead instructor for the 2008 program. The Minnesota Mineral Education Workshop began in 1997. Jim served as an instructor, field trip leader and program coordinator for this annual three-day workshop for K-12 earth science teachers that offers short courses and field trips on the geology and mineral resources of Minnesota. He has also lectured on the geology of Minnesota for the national Elderhostel Program since 1986.

Jim, now a professor at the University of Minnesota-Duluth, continues to enthusiastically teach geology and encourage students. He is a staunch advocate of economic geology and tirelessly lobbies administration, government and industry for their ongoing support of the geology program. Most recently, Jim has spearheaded the creation and administration of the Precambrian Research Center (PRC), which was established to satisfy an urgent, long-term need for geologists trained in the mapping and study of Precambrian rocks and their mineral deposits. As a director, Jim continues to canvass the mineral industry for sponsorships, thesis support and ideas on maintaining the relevance of the PRC. The PRC organizes professional workshops and is planning to take a major role in managing the popular Minnesota Minerals Education Workshop for teachers.

Jim is a member of the Geological Society of America (GSA), Prospectors and Developers Association of Canada (PDAC), Society for Mining, Metallurgy, and Exploration (SME) and the Society of Economic Geologists (SEG). He served in 1995 as Co-chair of UNESCO-sponsored International Geologic Correlation Program (IGCP) Project 336 on the topic of mineral deposits associated intracontinental rift systems. From 2003 to the present, Jim has served as principal investigator for one-year grants from the U.S. Geological Survey's EDMAP program, which go toward funding student field research. He is currently Vice Chair of Operations, Minnesota Center for Minerals Resource Education and was Field Trip Chairman for the 2011 Geological Society of America meeting in Minneapolis.

Jim has co-chaired the annual meeting of the Institute on Lake Superior Geology three times and has remained a staunch supporter of the Institute for over 30 years (1979-present). His numerous contributions to our understanding of Lake Superior geology are well-regarded by colleagues, peers and clients alike. He is a vocal advocate of education in the earth sciences. He continues to be captivated by the geology and mineral potential of the Lake Superior region. He exemplifies the dedication and enthusiasm that are the hallmarks of previous Goldich Medal recipients. Jim is indeed a worthy addition to this list.

Submitted by Mark Smyk, P.Geo.

Ontario Geological Survey, Thunder Bay

Eisenbrey Student Travel Awards

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

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

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

Successful applicants will receive their awards during the meeting.

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:

- 1) The contribution must be demonstrably the work of the student.
- 2) The student must present the contribution in-person.
- 3) The Student Paper Committee shall decide how many awards to grant, and whether or not to give separate awards for poster vs. oral presentations.
- 4) In cases of multiple student authors, the award will be made to the senior author, or the award will be shared equally by all authors of the contribution.
- 5) The total amount of the awards is left to the discretion of the meeting Chair in conjunction with the Secretary, but typically is in the amount of about \$500 US (increase approved by Board, 10/01).
- 6) The Secretary maintains, and will supply to the Committee, a form for the numerical ranking of presentations. This form was created and modified by Student Paper Committees over several years in an effort to reduce the difficulties that may arise from selection by raters of diverse background. The use of the form is not required, but is left to the discretion of the Committee.
- 7) The names of award recipients shall be included as part of the annual Chair’s report that appears in the

next volume of the Institute.

Student papers will be noted on the Program.

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 the researcher's supervisor.

In 2011 the ILSG Board of Governors awarded two \$500 awards from the Student Research Fund. The winners were Evgeniy Kulakov from the Department of Geological and Mining Engineering and Sciences, Michigan Technological University for his work on the "Paleomagnetism of the Geordie (Coubran) Lake Basalts" and Ernest Thalhamer from the University of Wisconsin - Milwaukee for his work on "Shear Zones and Strain in the Rainy Lake area".

Student Paper Awards Committee

Ryan Weston - Magma Metals (Canada) Ltd.

Gordon Medaris Jr. - University of Wisconsin – Madison

Michael Easton - Ontario Geological Survey

Session Chairs

Mary Louise Hill - Lakehead University

Mark Severson - Natural Resources Research Institute

Ann Wilson - Ontario Geological Survey

George Hudak - Precambrian Research Centre

Mark Smyk - Ontario Geological Survey

Laurel Woodruff - US Geological Survey

Board of Directors

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

Mark Smyk - General Chair 2012 meeting (2015)

Tom Fitz (2014) - Northland College, Ashland, Wisconsin

Peter Hinz (2013) - Ontario Geological Survey

George Hudak (2012) - NRRI, Duluth

Pete Hollings - Secretary (2013) - Lakehead University, Thunder Bay, Ontario

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

Local Committee

Chair

Pete Hollings - Lakehead University, Thunder Bay, Ontario

Volume Editors

Pete Hollings & Bill Addison - Lakehead University, Thunder Bay, Ontario

Allan MacTavish - Magma Metals (Canada) Ltd., Thunder Bay, Ontario

Organising Committee

Bill Addison - Thunder Bay, Ontario

Dorothy Campbell - Ontario Geological Survey, Thunder Bay, Ontario

Peter Hinz - Ontario Geological Survey, Thunder Bay, Ontario

Al MacTavish - Magma Metals (Canada) Ltd.

Mark Smyk - Ontario Geological Survey, Thunder Bay, Ontario

Banquet Speaker

Dr. David Overstreet

Human Adaptation to Late Pleistocene Landscapes - A View from Southeastern Wisconsin

Study of mammoth bone piles in Kenosha County Wisconsin has provided evidence of human-mammoth interaction between 13,500-12,500 radiocarbon years before present. Chipped stone tools in association with two of the bone piles and micro-wear analyses support the thesis that the carcasses were butchered. Bone modification analyses also support this conclusion. Whether or not the mammoth remains represent active or moribund prey is open to debate and thus the results do not speak to the role of human predation in Late Pleistocene extinctions.

Report of the Chair of the 57th Annual Meeting

Ashland, Wisconsin

The 57th ILSG was held in Ashland, Wisconsin on May 18-21, 2011. Hosted by Northland College and chaired by Tom Fitz, the meeting was attended by a total of 247 people, with most people also attending field trips. Seventy-one students attended, 30 of who received financial support through the Eisenbrey scholarship fund.

The two-day technical session began on Thursday morning with oral presentations on regional geology and then proceeded in chronological order from Archean topics through Friday afternoon's presentations on Quaternary geology. A total of 30 talks were given, 16 of which were presented by students. The poster sessions were also arranged chronologically from Archean through recent, with a total of 24 posters, 18 of which were presented by student authors. The 2011 Goldich Medal was awarded to Dean Rossell of Kennecott Exploration Company. Doug Duskin presented the award during the annual banquet and supplied numerous examples of how Dean's research has expanded our understanding of ore deposits in the region. Huifang Xu of the University of Wisconsin – Madison gave the keynote address, talking about the origin of banded iron formations by interaction between komatiite and seawater.

The meeting offered nine field trips that highlighted the geology of the southwestern Lake Superior region. Three pre-meeting trips were run on Wednesday, including Jim Miller's trip "Igneous Stratigraphy of the Layered Series at Duluth – Type Intrusion of the Duluth Complex"; Marcia Bjørnerud and Bill Cannon's "Midcontinent Microcosm: Geology of the Atkins Lake – Marengo Falls Area"; Dick Ojakangas, Drew Cramer, and Tom Fitz's trip "Geology of the Bayfield Peninsula: Keweenaw Bayfield Group and Pleistocene Deposits". Friday's technical sessions and the presentation of student awards were followed by three late-afternoon field trips: "Geology and Remediation at the Ashland/Northern States Power Site" led by Jamie Dunn; "Bad River Watershed Culvert Restoration Program" led by Michele Wheeler and Cassandra Bodette; and "Geology of Copper Falls State Park" led by Allison Mills, Drew Cramer, and Tom Fitz. Three field trips were run on Saturday: "Geology of the Montreal River Monocline" led by Bill Cannon; "The Archean/Paleoproterozoic Unconformity near Denham, Minnesota" led by Terry Boerboom; and "Granitic, Gabbroic, and Ultramafic rocks of the Keweenaw Mellen Intrusive Complex" led by Tom Fitz.

On Friday evening Northland College hosted a beer and barbeque social event for ILSG participants outside the college's student center. A variety of door prizes were given away and a good time was had by all.

The Institute's Board of Directors met on May 19, 2011 to discuss business and preliminary plans for future Institutes. The meeting was attended by Ted Bornhorst, Peter Hinz, George Hudak, Mark Jirsa (Treasurer), Pete Hollings (Secretary), and Tom Fitz (2011 Chair).

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

1. Accepted report of the Chairs for the 56th ILSG, International Falls, Minnesota; as printed in the Proceedings Volume (Hinz), and minutes of last Board meeting, May 20, 2010 (Hollings).
2. Received, discussed, and accepted 2010-2011 ILSG Financial Summary (Jirsa).
3. Received, discussed, and accepted 2010-2011 report of the Secretary (Hollings).
4. Approved Jirsa to continue as Institute Treasurer until 2014 (this was later presented to the membership and approved).

5. Approved Tom Fitz as on-going ILSG Board member.
6. Approved Thunder Bay, Ontario at the site for the 58th annual ILSG meeting. The meeting will be hosted by Pete Hollings with help from Mark Smyk and Peter Hinz. Ted Bornhorst offered to host the 59th Annual Meeting in Houghton.
7. Discussed and approved replacing Al MacTavish as the “member from industry” on Goldich Committee (end of term 2011) with Graham Wilson.
8. There was some discussion as to whether or not presentations from the meeting should be posted on the ILSG web site or included on a CD given to participants.
9. It was agreed that a copy of the DVD with all proceedings to date would be included with the volumes mailed out to our standing orders.

The Chair would like to thank the student committee made up Northland College students Kristi Wilson, Allison Mills, Cassie Bodette and Drew Cramer for their hard work in organizing and running the meeting. Appreciation also goes to the field trip leaders and session chairs, to the sponsors of the meeting, to the ILSG Board and the many people who worked to make the 2011 Institute a successful, educational, and enjoyable meeting.

Respectfully submitted,

Tom Fitz

Chair, 57th Institute on Lake Superior Geology

Sponsors

The following organizations made generous contributions to the 58th Annual Meeting. We thank them for their commitment to the Institute on Lake Superior Geology. For the past 50 years this organization has thrived as a result of the interest of individuals, corporations, universities and government agencies. The dedication to an exchange of scientific ideas and a passion for field trips has enabled the Institute to provide one of its primary objectives – to promote better understanding of the geology of the Lake Superior region.



RioTinto



Program

Wednesday May 16

- 7:30 a.m. **Field Trip 3:** Lac des Iles Pd mine
Leader: John Corkery (North American Palladium Ltd.)
- 8:00 a.m. **Field Trip 1:** Sudbury Impactoclastic Debrisites at Thunder Bay
Leaders: Bill Addison and Greg Brumpton
- 8:00 a.m. **Field Trip 2:** Geology of the Sibley Peninsula
Leaders: Dr. Philip Fralick (Lakehead University) Mark Smyk & Riku Metsaranta (Ontario Geological Survey)
- 8:00 a.m. **Field Trip 4:** The Shebandowan greenstone belt
Leaders: Alan Aubut (Sibley Basin Group Geological Consulting Services Ltd.) and Dorothy Campbell (Ontario Geological Survey)
- 6:00 p.m. **Return of Trips 1-4**
- 4:00 p.m. - 8:00 p.m. **Registration** (Barcelona Room, Travelodge Airline)
- 7:00 p.m. - 9:00 p.m. **Ice Breaker Social** (Barcelona Room, Travelodge Airline), **Poster Setup** (Tiberio Room, Travelodge Airline) **and Core Shack** (Courtyard, Travelodge Airline)

Thursday May 17

- 7:30 a.m. - 4:00 p.m. **Registration** (Barcelona Room, Travelodge Airline)
- 8:20 a.m. - 8:30 a.m. **Introductory Remarks - Peter Hollings, Chair**

Technical Session I

NOTE: Asterisk * denotes a student eligible for a Best Student Paper Award

Session Chairs: Ann Wilson (Ontario Geological Survey) and Mary Louise Hill (Lakehead University)

- 8:30 a.m. **Gilbert, H.**
Stratigraphy and tectonic setting of Neoarchean arc volcanic rocks in the Bird River Belt, Manitoba, Canada
- 8:50 a.m. **Chaffee, M.*, Miller, J., Hollings, P., Heggie, G., MacTavish, A., and Bandli, B.**
Petrographic and geochemical study of the hybrid rock unit associated with the Current Lake Intrusive Complex, Magma Metals' Thunder Bay North Property
- 9:10 a.m. **Brooker, B.* and Miller, J.**
Geology and petrology of a Mesoproterozoic layered mafic intrusion in portions of the Brule Lake and Cherokee Lake 7.5' Quadrangles, northeastern Minnesota
- 9:30 a.m. **Good, D., McLean, K., Epstein, R., Linnen, R., and Samson, I.**
Geology of the Layered Series, Coldwell Alkaline Complex, Ontario
- 9:50 a.m. **Cundari, R.*, Hollings, P. and Smyk, M.**
Petrogenesis and crustal contamination of the Nipigon sills: a geochemical and spatial re-evaluation
- 10:10 a.m. - 10:40 a.m. **Coffee Break, Poster Session and Core Shack**

- 10:40 a.m. **Rousell, D., Petrus, J., Easton, R., Tinkham, D. and Napoli, M.**
The tectonometamorphic, magmatic and mineralization history of the Wanapitei Complex, Grenville Front tectonic zone, Ontario
- 11:00 a.m. **Berkley, J.**
New York's Adirondack Mountains: Window to the Mesoproterozoic Grenville Orogen
- 11:20 a.m. **Van Lankvelt, A.*, Schneider, D., Hattori, K. and Biczok, J.**
Anatomy of a Mesoarchean batholith
- 11:40 a.m. **Kuzmich, B.*, Hollings, P. and Campbell, D.**
Geochemistry and petrology of the Dog Lake Granite Chain, Quetico Basin, Northwestern Ontario
- 12:00 p.m. - 1:30 p.m. **Lunch Break, Poster Session and Core Shack (ILSG Board Meeting by invitation)**

Technical Session II

Session Chair: Mark Severson (Natural Resources Research Institute) and Laurel Woodruff (USGS)

- 1:30 p.m. **Horner, S.* and Fralick, P.**
Chert stromatolites in the basal Gunflint Formation, Kakabeka Falls: Primary precipitation or silicification?
- 1:50 p.m. **Phillips, B., Dean, F. and Zaniewski, K**
A catastrophic breach and inter-lake flow through the Marks Moraine via Brule Creek and Cedar Creek, Thunder Bay Region, Ontario. A small but significant detail of the eastern outflow history of Lake Agassiz
- 2:10 p.m. **Beh, B.* and Fralick, P.**
Depositional processes operating on the Paleoproterozoic Gowganda ice margin: an example from the Espanola area, Ontario
- 2:30 p.m. **Kerkermeier, L.* and Fralick, P.**
Ferromanganese precipitates in lacustrine environments of Northwestern Ontario and Nova Scotia: Effects on arsenic concentration
- 2:50 p.m. - 3:20 p.m. **Coffee Break, Poster Session and Core Shack**
- 3:20 p.m. **Frederiksen, A., Deniset, I., Bollman, T., Van der Lee, S. and Darbyshire, F.**
Erosion of Archean lithosphere by subduction and rifting: a tomographic image of central North America
- 3:40 p.m. **Pesonen, L. and Veikkolainen, T.**
Supercontinents during the Proterozoic – A paleomagnetic view with Keweenaw data (Lake Superior) as an example
- 4:00 p.m. **Swanson-Hysell, N., Burgess, S., Maloof, A., and Bowring, S.**
Temporal context of the Mamainse Point succession: a record of magmatic activity and fast plate motion across the “latent stage” of Midcontinent Rift development
- 4:20 p.m. **Easton, R.M.**
The source of the Elliot Lake uranium ores: The neodymium isotope story
- 4:40 p.m. **Medaris, G., Driese, S., Boerboom, T. and Jirsa, M.**
Granitic saprolites in the Lake Superior region: K-metasomatism, intensity vs. magnitude of weathering, and estimates of atmospheric pCO₂

7:00 p.m. **Annual Banquet and Award Presentation** (Barcelona Room, Travelodge Airline)

Announcement of 59th Annual Meeting Location

2012 Goldich Award Presentation to Jim Miller

2012 Banquet Address - Dr. D. Overstreet

Meeting participants not registered for the banquet are welcome to attend the address

Friday May 18

9:00 a.m. - 12:00 p.m. **Registration**

Technical Session III

Session Chairs: George Hudak (Precambrian Research Centre) and Mark Smyk (OGS)

8:30 a.m. **Stinson, V.* and Hill, M.L.**

Regional to microstructural control of gold mineralization along the Quetico-Wabigoon subprovince boundary

8:50 a.m. **Thalhamer, E.* and Czeck, D.**

Analyzing ductile shear zone network geometries in the Grassy Portage Sill, Rainy Lake Region, Northwestern Ontario, Canada

9:10 a.m. **Heggie, G., MacTavish, A., Johnson, J., Weston, R. and Ma, L.**

Structural control on the emplacement of the TBN-Igneous Complex

9:30 a.m. **Bailes, A., Galley, A., Paradis, S. and Taylor, B.**

Using large synvolcanic alteration zones to explore for VMS deposits at Snow Lake, Manitoba, Canada

9:50 a.m. **Scott, G., Karakus, M., Shinkle, D. and Mitchell, A.**

Exploration history, mineralogy and genesis of the Black Thor chromite deposit, Ring of Fire Intrusion, Northwestern Ontario

10:10 a.m. - 10:40 a.m. **Coffee Break, Poster Session and Core Shack**

10:40 a.m. **Bornhorst, T. and Williams, W.**

The Copperwood sediment-hosted stratiform copper deposit, Upper Peninsula, Michigan

11:00 a.m. **Blaske, A., Braun, G., Leier-Engelhardt, P., Mottl, R., Anderson, D. and Bornhorst, T**

Glacial geology of the Copperwood Project, Gogebic County, Michigan, and environmental and engineering implications for site development

11:20 a.m. **Waggoner, T and Karakus, M.**

The Little Commonwealth exploration - an example of a SEDEX Deposit

11:40 a.m. **Mikkelsen, L. and Conly, A.**

Predictive water level and preliminary hydrodynamic models of Caland and Hogarth pit lakes, Atikokan, Ontario

12:00 p.m. **Presentation of Best Student Paper Award and Eisenbrey Awards**

1:00 p.m. **Field Trip 5:** Geology of the City of Thunder Bay

Leader: Mark Smyk (Ontario Geological Survey)

1:00 p.m. **Field Trip 6:** Panorama Amethyst Mine

Leader: Steve Kissin (Lakehead University)

- 1:00 p.m. **Field Trip 7:** Port Arthur building stone walking tour
 Leader: Peter Hinz (Ontario Geological Survey)
- 6:00 p.m. **Return of Trips 5-7**
- 7:00 p.m. **BBQ** (Whitewater Golf Club - bus service provided leaving from the Travelodge Airline
 beginning at 6.30 p.m.)

Poster Presentations

Baumann, S. and Cummings, K.

Bedrock Geology of Copper Falls State Park, Ashland County, Wisconsin

Boerboom, T.

Bedrock geologic map of Morrison County, Central Minnesota

Bollmann, T.*, Van der Lee, S., Frederiksen, A., Lou, X.

Preliminary results of P- and S-wave delay times in the Superior Region from transportable array and SPREE stations

Buchholz, T., Falster, A. and Simmons, W.

Accessory minerals of a roadside pegmatite, Orr, Minnesota

Craddock, S.* and Craddock, J.

Strain variations in carbonates across the Proterozoic Grenville Orogen

Cundari, R.*, Hollings P., Scott, J. and Campbell, D.

Geology and geochemistry of the Coubran Lake Basalts, a Midcontinent Rift-related sequence within the central Coldwell Complex, Marathon, Ontario

Gaspar, B*, and Hill, M.L.

The black line faults of the Red Lake gold mines, Ontario

Gasparotto, M.*, and Hill, M.L.

A microstructural study of the Otjikoto Deposit, Namibia: Inferences from gold mineralization in the Superior Province

Goscinak, C.* and Hansen, V.

Quartz Fabric analysis of the Kawishiwi Shear Zone, NE Minnesota

Heim, N., Scott, H., Kilduff, R., Rahtz, C., Vial, A., Young, S., Mahr, C., and Hudak, G.

Preliminary bedrock geology map of the Eastern part of Lake Vermilion State Park, St. Louis County, NE Minnesota

Hudak, G., Monson Geerts, S., Zanko, L., Severson, A., Severson, A. and Bandli, B.

The Minnesota Taconite Workers Health Study: Environmental Study of Airborne Particulates - 2012 Update

Jirsa, M.

Bedrock geologic map of the Crane Lake and Brule Narrows 30'X60' quadrangles, Quetico subprovince, northern Minnesota

Jirsa, M., Baggetto, L., Eliason-Johnson, G., Hansen, D., Hoxsie, E., Kilpatrick, K.

Reconnaissance geologic mapping of Neoproterozoic rocks in the central Boundary Waters Canoe Area Wilderness by students of the Precambrian Research Center's 2011 field camp.

Johnson, T.*, Shannon, J., Boerboom, T., Wendlandt, R.

Geochemistry of mafic dikes from the Carlton Dike Swarm in Minnesota

Kern, A.*, Kulakov, E., Smirnov, A. and Diehl, J.

Paleomagnetism of the alkaline Coldwell Complex: New Results, new Insights.

Koroscil, J.*, Hill, M.L. and Fralick, P.

Thrust faulting in the Gunflint Formation north of Lake Superior

Kulakov, E.*, Smirnov, A. and Diehl, J.

Paleomagnetism of the Geordie Lake and Silver Mountain basalts

Lee, A.*, Albers, P., Miller, J., Severson, M. and Deen, T.

Bedrock Geologic map of the Seine Bay/Bad Vermilion Lake intrusion, Mine Centre, Ontario

McCormick, K. and Paterson, C.

Mafic intrusions along the southern boundary of the Superior Craton, SD: What is their potential for Ni-Cu-PGE mineralization?

Miller, J., Brooker, B., Asp, K., Leu, A., Parisi, A. and Sletten, D.

2011 Precambrian Field Camp Mapping in the Sawbill Lake Area, Cook County, Northeastern Minnesota

Pietrzak-Renaud, N.

A Metallogenic Model and Geometallurgical Treatment of the Basal Iron Ores within the Negaunee Iron Formation, Tilden Mine, Michigan

Piispa, E.*, Smirnov, A., Pesonen, and Diehl, J.

Paleomagnetic, rock magnetic and geochemical data from the Keweenawan dykes and baked rocks from the Little Mountain and Sugar Loaf areas, Michigan, USA

Roe, C.*, and Bjørnerud, M.

The ca. 1650 Ma Freedom Formation, Baraboo Range, Wisconsin: A late iron formation in the Lake Superior Region

Santaguida, F., Lappalainen, M., Jones, S., Voipo, T., Siikaluoma, J. and Ylinen, J.

Geologic Setting of the Kevitsa Ni-Cu-PGE Deposit, Central Lapland Greenstone Belt, Finland

Selagi, J.*, and Hill, M.L.

Microstructural analysis of porcellaneous nepheline syenite, Coldwell Complex, Ontario

Shahabi Far, M.*, Samson, I., Gagnon, J., Linnen, R., Good, D.

Textural and compositional variation in apatite and plagioclase in the Marathon PGE-Cu deposit, Northwestern Ontario; implications for fluid-rock interaction

Taylor-Hollings, J.

Quartz quarry sites in northwestern Ontario: A new 'prospect' for geoarchaeologists investigating lithic raw material sources

Van der Lee, S., Frederiksen, A., Bollmann, T. and Spree Team.

SPREE: Field experiment to study deep structure of the Midcontinent Rift

Vaughan, A.*, Swanson Hysell, N. and Feinberg, J.

Paleomagnetic data in stratigraphic context from 1.1 Ga Osler Group basalt flows on Simpson Island, Ontario: Evidence for rapid plate motion of Laurentia in the late Mesoproterozoic

Wilson, G. and McCausland, P.

The curious meteorite harvest of the Lake Superior Region, I. Overview.

Wilson, G. and Kissin, S.

The curious meteorite harvest of the Lake Superior Region, II. Gems in the Rough

NOTE: Asterisk * denotes a student eligible for a Best Student Paper Award

Saturday May 19

6:00 a.m. **Field Trip 12:** Musselwhite gold mine (participants should check in at the Wasaya Airlines counter at Thunder Bay Airport by 6 AM for a 7 AM departure)

Leaders: John Biczok (Musselwhite Mine)

8:00 a.m. **Field Trip 8:** Highway 527 Transect

Leaders: Mark Smyk (OGS) and Philip Fralick (Lakehead University)

8:00 a.m. **Field Trip 9:** Rehabilitation of the Past-Producing Shebandowan and North Coldstream Mines

Leader: Mark Puumala (OGS)

8:00 a.m. **Field Trip 10:** Geoarchaeology of Thunder Bay

Leaders: Scott Hamilton (Lakehead University)

8:00 a.m. **Field Trip 11:** Midcontinent rift intrusions

Leaders: Rob Cundari & Pete Hollings (Lakehead University) and Mark Smyk (Ontario Geological Survey)

8:00 a.m. **Field Trip 13:** Sudbury Impactoclastic Debrisites at Thunder Bay

Leader: Greg Brumpton

6:00 p.m. **Return of Trip 8 to Armstrong, overnight there**

6:00 p.m. **Return of Trips 9-11 & 13**

7:45 p.m. **Return of Trip 12 to Thunder Bay Airport**

Sunday May 20

8:00 a.m. **Field Trip 8:** Highway 527 Transect

Leaders: Mark Smyk (OGS) and Philip Fralick (Lakehead University)

6:00 p.m. **Return of Trip 8**

Using large synvolcanic alteration zones to explore for VMS deposits at Snow Lake, Manitoba, Canada

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Due to its rich mineral endowment, excellent outcrop exposure and large domains of hydrothermally altered rocks, the juvenile 1.89 Ga Snow Lake arc volcanic assemblage is an important natural laboratory for applying modern volcanic massive sulphide theories to ancient deposits that are well exposed in cross section. For 25 years, a series of multidisciplinary investigations have examined regionally metamorphosed products of sub-seafloor hydrothermal events at Snow Lake (Galley, 1993; Galley et al, 1993; Bailes and Galley 1996, 2007; Galley et al., 2002). This presentation will summarize some of the important findings of these studies and place the VMS mineralization, including the recently discovered 30 million tonne Au-rich Lalor Lake VMS deposit, into a stratigraphic-hydrothermal model.

Alteration zones at Snow Lake are characterized by extensive zones with anomalous 1.82 Ga metamorphic mineral assemblages, including porphyroblasts of garnet, staurolite, amphibole, biotite, gahnite and/or kyanite, produced from altered rocks created during pre-metamorphic, 1.89 Ga, synvolcanic, hydrothermal, fluid-rock interaction. Three separate episodes of hydrothermal alteration (Fig. 1) are recognized that span evolution of the host volcanic rocks from a primitive (Anderson sequence) to mature arc (Chisel sequence) geotectonic setting.

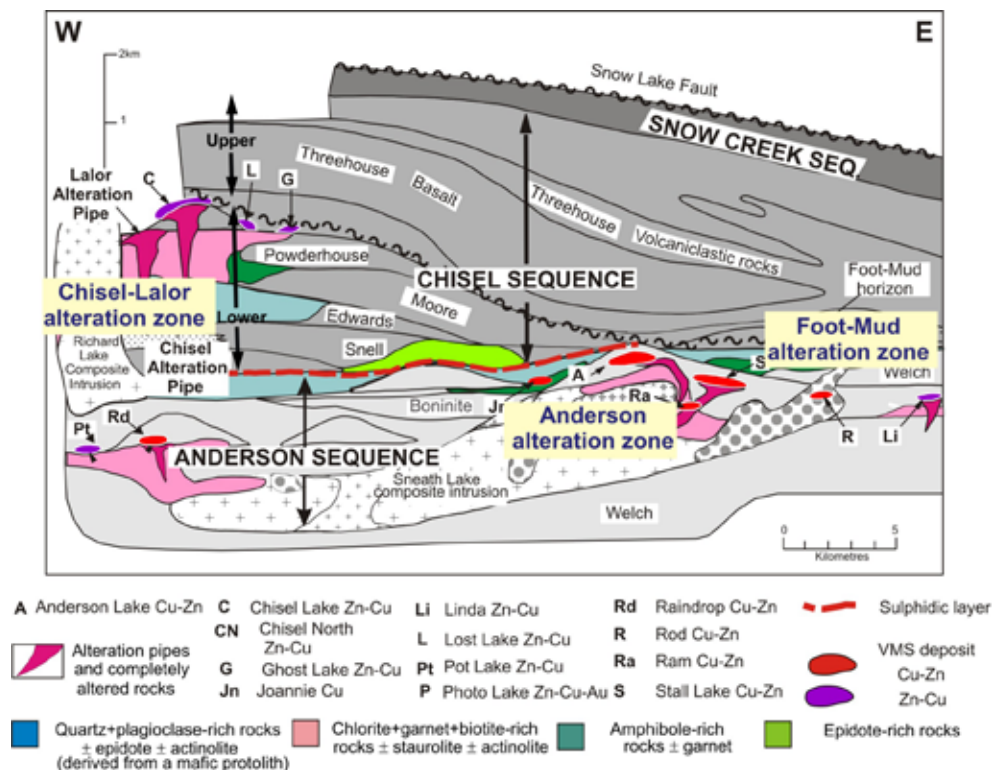


Figure 1. Schematic cross section of large-scale zones of alteration affecting rocks of the Snow Lake arc assemblage. The alteration zones comprise those associated with the Anderson sequence VMS deposits (Anderson alteration zone), those associated with a formational pyrrhotite-pyrite zone (Foot-Mud alteration zone) and those associated with the Chisel-Lalor VMS deposits (Chisel-Lalor alteration zone). The alteration pipe west of Chisel Lake VMS deposit (C) is the footwall pipe for the Lalor Lake VMS deposit (not shown).

The geological, geochemical, mineralogical and isotopic attributes of the zones indicate that they include VMS-related and VMS-unrelated, and were produced at high- and low- temperatures and in seafloor and sub seafloor (intra-stratal) environments.

Semi-conformable alteration zones at Snow Lake are up to 20 km in strike length and 0.8 km wide. Their large exploration 'footprint' compared to associated 'pipe-like' alteration zones and VMS deposits means that such zones provide a useful target to 'vector-in' exploration to VMS depositional settings within volcanic belts. The VMS-related semi-conformable alteration zones at Snow Lake display diagnostic variations in intensity and style of alteration along strike towards VMS deposits, are stratigraphically underlain by altered portions of synvolcanic intrusions, are cut by discordant zones of more intensely altered rocks, and can be demonstrated to have formed by interaction with high temperature(>350°C) hydrothermal fluids.

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Bedrock Geology of Copper Falls State Park, Ashland County, Wisconsin

BAUMANN, Steven D.J. and CUMMINGS, Katy E., Midwest Institute of Geosciences and Engineering,
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The geology of Copper Falls State Park in Wisconsin has been a point of geologic and economic interest since the 19th century. The Park contains both Precambrian sedimentary rocks that have been tilted vertical and Precambrian igneous intrusions. The sedimentary rocks are comprised of the Oronto Group and are about 1060 Ma to about 1088 Ma. Beneath the sedimentary rocks are the basalt and andesite flows of the Powder Mill Group, which includes the local “Sheep Farm Rhyolite”. The Powder Mill Group ranges in age from about 1100 Ma to 1109 Ma old. The Powder Mill Group is intruded by the 1102 Ma Mellen Intrusive Complex which is a mix of granites, ferrodiorites, gabbros, and granoporphyries.

In June of 2011, the authors mapped the Park at a scale of 1:14,400 and an area of about 6 mi². The result was a bedrock geology map with new information on the structure and geologic history of the Park. If you tour the Park you will see yellow signs depicting a fault between the Powder Mill and Oronto Groups. The Powder Mill Group does show signs of breccia within, but this is more likely the cause of “reworked” igneous flows. Plus there is no evidence for faulting anywhere else in the Park. If faulting had occurred, it most likely would have affected the softer Oronto Group sediments. There is evidence on top of the Sheep Farm Rhyolite of a thin “weathered” zone. The field evidence suggests that the Powder Mill-Oronto Group contact is erosional and not faulted.

There are four distinct alternating flows of basalt and andesite of the Powder Mill Group within the Park. The individual flows were not named but contain an andesite at the base and basalt at the top and are part of the Kallandar Creek deposits. These four main flows show internal signs of brecciation and minor sedimentary deposits. There are likely more flows within the four larger flows, but their lateral extent is difficult to determine with the existing exposures in the Park.

The Oronto Group shows some internal variations previously unnoted. The Freda Sandstone exhibits an intertonguing relationship between sandstone and shale, with two large sandstone tongues. The Sandstone facies also exhibits sharp glauconitic contacts with the finer shale facies at the Horseshoe Outcrop (Fig. 1A). The two basal Oronto Formations, the lower Copper Harbor Conglomerate and the younger Nonesuch Shale show a complex intertonguing relationship at Devil’s Gate, where they are excellently exposed (Fig. 1B). The two basal formations are also at their thinnest in the park and pinch out near the west center of the Park. This is due to their deposition on significant paleotopography of the Powder Mill Group.

The overall structure of the geologic units in the Park is vertical bedding from Brownstone Falls to Devil’s Gate. As you head north the beds begin to deviate from the vertical and dip about 80° to the northwest and the finer facies of the Freda Sandstone dominates. The Powder Mill and Oronto Groups were deposited nearly flat and deformed into their near vertical position by the Mellen Creek Intrusions to the south and southeast. Like the Copper Harbor Conglomerate and Nonesuch Shale, the Sheep Farm Rhyolite pinches out within the Park (Fig. 1C).



Figure 1. A) Contact between the sand and shale facies at the Horseshoe Outcrop. B) Inter tonguing beds within the Nonesuch Shale at Devil's Gate. C) The Sheep Farm Rhyolite on the east cliffs near Devil's Gate

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Depositional Processes Operating on the Paleoproterozoic Gowganda Ice Margin: An example from the Espanola Area, Ontario

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Glacial sediments of the Huronian Supergroup outcrop along the north shore of Lake Huron and were likely deposited on what is thought to have been a divergent continental margin (Fralick and Miall, 1981; 1989). The rocks of the Gowganda Formation record one of three glacial events preserved in the Supergroup and are therefore of interest for developing further glaciomarine models (Puffett, 1974) and furthering understanding of this early stage in Earth's history. Data has been collected in five main study areas in an attempt to cover as much of the ancient continental margin as possible. The Espanola study area consisted of the most extensive and well exposed outcrops of the Gowganda Formation, with more than a kilometer of nearly continuous exposure, therefore it will be used as an example to show how the depositional history can be interpreted.

Two metamorphosed stratigraphic sections were logged on McGregor Bay and one on Iroquois Bay, which are located near Espanola, Ontario. The logged sediments were grouped into six lithofacies associations: 1) Planar Cross-Stratified Sandstone Lithofacies Association, 2) Diamictite Lithofacies Association, 3) Interlayered Siltstone and Fine-Grained Sandstone Lithofacies Association, 4) Slump Lithofacies Association, 5) Fine- to Coarse-Grained Sandstone Lithofacies Association and 6) Quartz-Rich Sandstone Lithofacies Association. These lithofacies associations (LA) likely represent a sequence of depositional environments on a shallow continental shelf. Initially, the shelf was dominated by what were likely large-scale, low-angle sandwaves (Fig. 1A) interbedded with successions of wavy bedding and possible hummocky cross-stratification indicating an

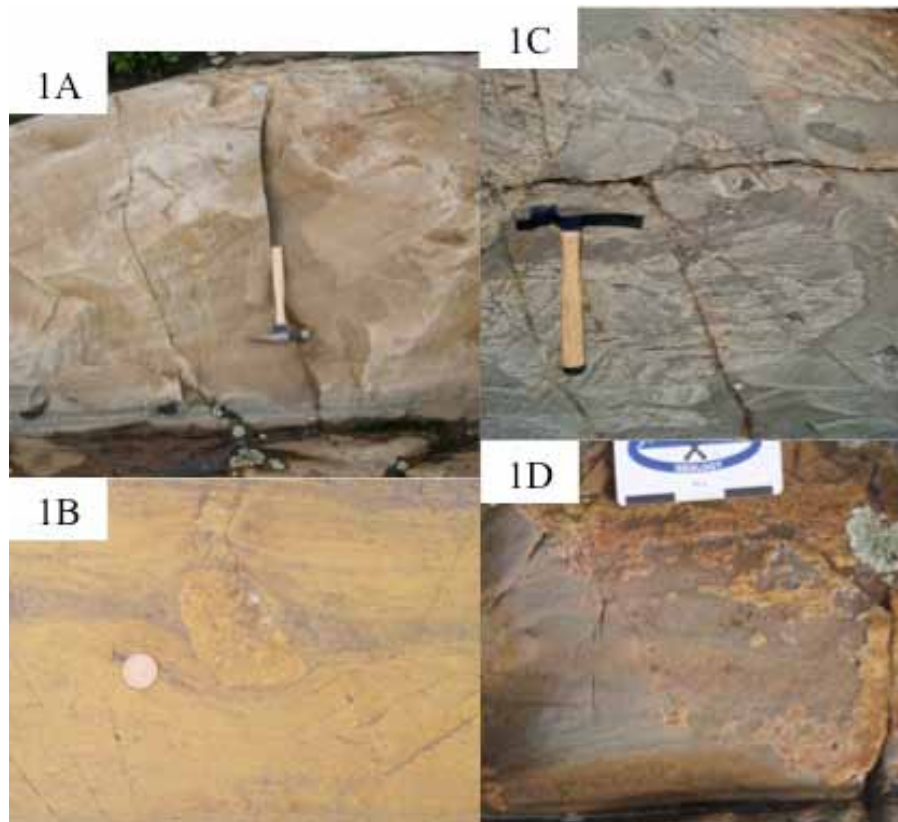


Figure 1. A) Large-scale, low-angle planar cross-stratified sandstone. B) A dropstone compressing underlying laminations. C) A mud-block conglomerate of slumped prodelta deposits. D) Herringbone cross-stratified sandstone.

open-water setting with tidal and storm processes reworking the sediments. The shelf then gradually evolved into an environment dominated by diamictite layers. The diamictite layers have dropstones as well as evidence of current activity indicating outsized clasts were likely being introduced into the environment as ice-rafted debris (Fig. 1B). Resedimentation events in the form of debris flows are thought to account for conglomeratic layers that are common in the Diamictite LA. The Interlayered Siltstone and Fine-Grained Sandstone LA, along with the Slump LA (Fig. 1C), closely resemble deposition from suspension in a prodelta setting where large slump events are common. The gradual transition into a more sandstone dominated LA, with an abundance of current related sedimentary structures, is indicative of the shallowing and coarsening upwards succession common to deltaic deposits. A final transition into the Quartz-Rich Sandstone LA indicates a return to a sandy, current-dominated open continental shelf environment with abundant tidally generated sedimentary structures such as herringbone cross-stratification (Fig. 1D). The southernmost sections contain only mass-flow diamictite with no massive diamictite. Thus, the likelihood of an ice shelf in this area is remote indicating the Gowganda Formation does not represent snowball Earth conditions.

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New York's Adirondack Mountains: Window to the Mesoproterozoic Grenville Orogen

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The Adirondack Mountains occupy most of the northeastern lobe of New York State, with associated Grenville metamorphic rock exposures and structures extending north through the Laurentian Lowlands and into Ontario, Canada (Fig. 1). Isotopic data give whole-rock ages of roughly 1.3 to 0.9 Ga corresponding to the late Mesoproterozoic, thus are generally coeval with the Midcontinent Rift system exposed prominently in the Lake Superior region. Orogenic evolution of the Grenville Orogeny was complex, and arose from at least two major continent-continent collisions producing the eastern (including the Adirondacks) and southern chains (including Texas and Mexican exposures) during the assembly of the supercontinent Rodinia. The Adirondack region reveals evidence for Himalayan-magnitude mountains that were part of a nearly continuous chain stretching from present-day Scandinavia through North America, Africa, Australia and Antarctica. Major Grenville exposures in North America include the (1) Grenville Province (Labrador-Quebec-Ontario), which includes the Adirondack-NY-Laurentian Lowland region, (2) inliers within the Green, Taconic, Blue Ridge Appalachian chain, (3) the Llano County, Texas granite-gneiss/schist terrain, and (4) the Oaxacan Complex, southern Mexico.

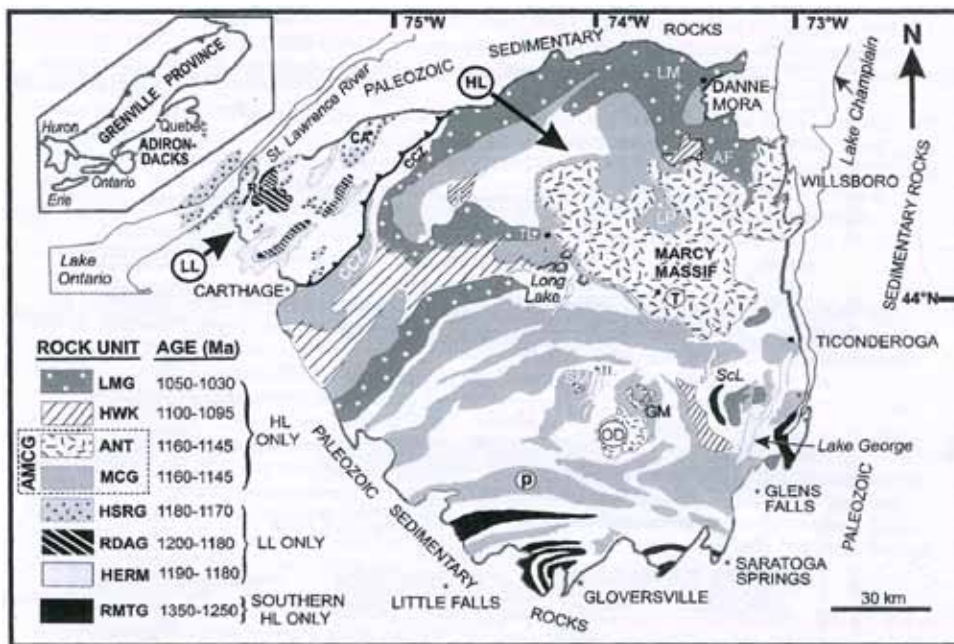


Figure 1. Generalized geology of the Adirondacks with ages of principal units. ANT-anorthosite; HSRG-Hyde School & Rockport granites; HWK-Hawkeye granite; LMG-Lyon Mtn. granite; MCG-mangerite, charnockite, granite; RDAG-Rossie diorite & Antwerp diorite; RMTG-Royal Mtn. tonalite & Granodiorite; CCZ-Carthage-Colton mylonite shear zone; HL-Highlands; LL-Lowlands. After McLelland, 2008

The overall timeframe of Grenville deformation, metamorphism and plutonism began with the Elzevirian Orogeny (from 1240-1220 Ma), followed by the Shawinigan event (1190-1140 Ma), the Ottawan (1090-1020 Ma), and the 1010-980 Ma Rigolet Orogeny (Rivers, 2008). Grenville tectonic history – as exemplified in the Adirondacks – consisted of major convergent folding events (Shawinigan and Ottawan) with intermittent relatively quiescent periods featuring rifting episodes and erosion-deposition of sedimentary units in rift basins and shelf areas. These quiet spans also spawned the extensive intrusion into countryrock of AMCG (anorthosite-mangerite-charnockite-granite) plutonic suites, well-represented in the Adirondacks. Evidence gleaned from extensive modern studies, including recent data from TIMS and SHRIMP single-grain isotopic determinations (e.g., McLelland, 2008) shows that subduction with formation of island arcs long preceded collision events, with magmatic arc intrusive and volcanic rocks eventually riding over continental margins on overlying NW-vergent thrust sheets. The closing of the Iapetus seaway during the Neoproterozoic-Paleozoic Appalachian orogenies some 700 million years later presents parallels to Grenville tectonic mechanisms.

Exposed areas in the Grenville orogen consist of three litho-structural “belts”, the Gneiss Belt, Metasedimentary Belt, and the Granulite Terraine. Relatively narrow shear zones separate each belt. In the Adirondacks the Metasedimentary Belt occupies most of the Laurentian Lowlands terrain consisting of marble, calcsilicates, rare gypsum-anhydrite layers (mostly in mine excavations) along with various gneiss and amphibolite terrains. The Carthage-Colton shear zone separates the Metasedimentary Belt from the Granulite Terrain, which makes up the bulk of geology within the Adirondack State Park. As its name implies, most rocks in the Granulite Terrain are assigned to the granulite metamorphic facies, while Metasedimentary Belt assemblages predominantly plot in the amphibolite facies. Greenschist and lower P-T assemblages are absent in the Adirondacks.

Various models have been advanced seeking to establish a genetic and regional kinematic connection between the Grenville orogen and the Midcontinent rift system (for a synopsis, see Hauser, 1996). Early ideas postulated dextral strike-slip movement along the Grenville front causing opening of the Midcontinent rift (e.g., Anderson and Burke, 1983), however, these models were fraught with problems. Principal among these is that isotopic dates along the Canadian Grenville front are consistently younger than Keweenawan terrains, also shown by cross-cutting truncation of the eastern rift arm by the Grenville front near Detroit.

Current thinking posits a primary role of an uprising mantle plume in producing the midcontinent rift at around 1.10 Ga (e.g., Nicholson and Shirey, 1990), but with some interplay with the Grenville belt. For example, creation of horst ridges during later convergent rift inversion may have been influenced by Grenville shortening during early Ottawan times, around 1.08 Ga (McLelland, 2008). Also, strike-slip offsets along the southern extent of the western rift arm may be influenced in some manner by the southern (Texas-Mexico) Grenville front (Hauser, 1996).

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Glacial Geology of the Copperwood Project, Gogebic County, Michigan, and Environmental and Engineering Implications for Site Development

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The Copperwood Project is located in the northwestern portion of Gogebic County, Michigan, between the Black River and the Presque Isle River, on the west side of the Porcupine Mountains. In 2008, Orvana Minerals Corporation began development of a stratiform copper deposit at the base of the Nonesuch Shale in the Western Syncline. Data on the glacial overburden were collected through rotosonic soil borings, monitoring well installations, test pits, grain size analyses, and hydrogeological testing methods. AECOM collected data necessary for an Environmental Impact Assessment pursuant to Michigan's Non-Ferrous Metallic Mining Regulations (Part 632) funded by Orvana Minerals Corporation. The broader context of the data provided here is provided in the publically available Part 632 Mine Permit application for the Copperwood Project.

Research regarding the glacial deposits in the western Upper Peninsula of Michigan is generally scattered and not especially detailed. Most available information is on the regional scale, rather than a local scale. Farrand and Bell (1982) mapped the area west of the Porcupine Mountains as "lacustrine clay and silt." Hack (1965) described the Ontonagon Plain (east of the Porcupine Mountains) to be underlain by reddish-brown glacial lake sediments and till. He described three units within the glacial deposits – lower, intermediate, and upper units. Thin lacustrine deposits related to Glacial Lake Duluth are described as a veneer of strongly-laminated clay, silt and sand of variable thickness. More recently, Petersen (1985 and 1986) described the glacial deposits of the area as thin drift over bedrock, generally less than 30 feet thick, composed of calcareous red till of fine sand, silt, and clay with a small percentage of angular clasts.

Detailed investigation at the Copperwood site indicated the unconsolidated materials consist primarily of a reddish-brown glacial till. The glacial section most closely matches that described by Hack (1965). The overburden material was interpreted as subglacial till based on the following evidence:

- Uniform composition and consistently found to be massive, matrix-supported diamicton with little evidence of interbedded sorted sediments;
- Little structure and no observed stratification, lamination or fining upward or downward trends;
- The material is widespread and consistent over several square miles of the project area;
- Grain-size distribution curves are typical of those associated with subglacial tills; and
- The matrix is uniform based on USDA grain size distribution plots.

The average composition of the cohesive (silt/clay) samples encountered at the site was found to be approximately 50% silt, 20% clay, and 30% sand. The gravel/cobble portion of the material was approximately 10 to 20% and consisted primarily of dark reddish-brown sandstone (Freda Sandstone). The fine fraction (<200 sieve size) were determined to be predominantly quartz, with very minor amounts of clay minerals. The matrix also contains carbonate (fizzes when exposed to dilute hydrochloric acid).

Layers of coarser (non-cohesive) material were observed throughout the site in various borings. These soil types generally consisted of fine to medium-grained sand with varying amounts of silt and clay. Granular deposits are thin and isolated, with none greater than 10 feet thick. These deposits are not laterally extensive, and for the most part cannot be correlated between adjacent borings. They are interpreted to be lacustrine, intra-till sands, or subglacial meltwater deposits. These deposits are typically stratigraphically between the upper and lower till

units, but some are located at the base of the overburden, lying directly on the top of the bedrock surface.

Thin, surficial, lacustrine deposits related to Lake Duluth are present across the site, as wave-cut benches and beach deposits. The beach deposits are generally less than 10 feet thick and less than 200 feet wide. These beach deposits consist of sand and gravel deposits adjacent to the wave-cut bluffs that parallel topography.

The unconsolidated overburden at Copperwood is interpreted to be the result of least two advances of the Ontonagon lobe. The first advance moved south out of the Lake Superior basin, and deposited the lower till unit, as well as the granular deposits on the bedrock surface. The ice then retreated, depositing the lacustrine/subglacial meltwater deposits which are located between the upper and lower till units, where present. The youngest glacial advance occurred as the ice moved out of the western Lake Superior basin and overrode previous deposits, and influenced the orientation of surface drainage features. Glacial Lake Duluth occupied the area after final retreat of the Ontonagon lobe. This lake had an elevation as high as approximately 1,200 feet msl. Drainage of this lake continued as ice continued to retreat. Several Lake Duluth shorelines are present across the site between elevation 650 feet msl and 1,125 feet msl. The Lake Nipissing shoreline (elevation 615 feet msl) is not present at the site and likely has been destroyed by erosion along the current Lake Superior shoreline.

The characteristics of the glacial material have significant implications for site development. The very low hydraulic conductivity of the till limits surface water infiltration producing streams that are runoff-dominated and flashy. Streams are present in deeply incised, closely-spaced parallel valleys, impacting space for site development. Abundant wetlands are present across the site, due to the poor infiltration, and are not hydraulically connected to groundwater. The very low hydraulic conductivity also leads to very slow movement of groundwater. Hydraulic testing and migration modeling suggests that a tailings disposal facility can be constructed in the clay till soil thus using a native material as natural liner.

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Bedrock Geologic map of Morrison County, Central Minnesota

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Morrison County, located in the center of Minnesota, has recently been remapped with help from the USGS STATEMAP mapping program, and eventually it will become integrated into the MGS County Atlas Program. Although the basic geologic framework was well established prior to this mapping effort, much has been learned by logging of all available drill cores, integration of old exploration data, and outcrop examinations. Scattered bedrock outcrops are present throughout the southern two-thirds of the county, and more than 200 drill holes targeted at iron ore were placed in the northern part of the county prior to the 1960's. Although the core from many of these was not preserved, drill logs, including iron assay data, locations, and some cross-sections, are available for all. The only iron mine to come out of this effort was the tiny Gorman mine (U of M 1954 Mining directory reports operation from 1951-1952, with 116,000 tons shipped). More recently, about 100 drill holes were placed into other parts of the county; these are a mixture of diamond and mineral exploration, scientific research, and other borings. About 50 of these have useful core or cuttings available and the rest have descriptions deemed reliable for use. In total 85 cores and cuttings were logged. In areas between drill holes and bedrock outcrops, the bedrock geology is inferred, with varied degrees of confidence, from geophysical data.

Morrison County is located along the southern Margin of the Superior Province – Wawa subprovince, and also straddles the Penokean Orogen (Fig. 1). Archean bedrock is inferred to be primarily felsic gneisses and metamorphosed supracrustal rocks intruded by felsic to mafic plutons. The rest of the county is composed of Paleoproterozoic bedrock that includes, from north to south, basal quartzite and turbidites of the Animikie basin, the Cuyuna North and South Ranges (external and medial zones of the fold-and-thrust belt, Fig. 1), the Little Falls Formation, and the east-central Minnesota batholith (both within the internal zone; Fig. 1).

The external and medial zones of the Penokean fold-and-thrust belt are composed of phyllitic muddy to quartzose sedimentary rocks interbedded with mafic flows and sills and thin iron-formations, all metamorphosed under lower greenschist-facies conditions. In contrast, the Little Falls Formation, within the internal zone, is composed only of turbidites metamorphosed under amphibolite-facies conditions, and ultramafic to felsic intrusive plugs and plutons. The break between low-grade and high-grade rocks, the Malmo structural discontinuity

(MSD), is modeled as a south-dipping thrust fault. The MSD is clearly recognizable on aeromagnetic data, where sharp linear magnetic trends associated with iron-formations to the north are truncated by low, uniform aeromagnetic patterns to the south. South of the MSD, the metamorphic grade of the Little Falls Formation increases in proximity to the ECMB, from biotite at the northwest, through a narrow band of garnet, into a wide zone of sillimanite-garnet-staurolite to the southeast. Cordierite occurs around the margins of what are inferred to be gneiss domes. Adjacent to mafic intrusions staurolite has been thermally metamorphosed to an

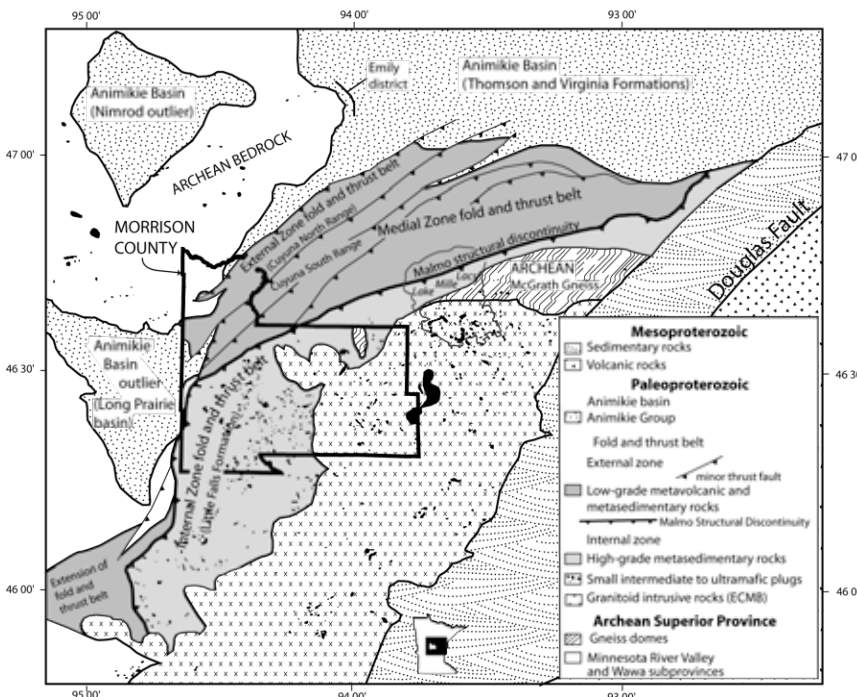


Figure 1. Simplified geologic map of east-central Minnesota showing the major structural elements of Paleoproterozoic rocks of the Penokean orogen, and Archean Superior Province.

assemblage of hercynite and corundum.

The ECMB batholith is composed of several separate intrusions that range from tonalite to granite. Some of these include the approximately 1,800 Ma Hillman tonalite, the Pierz granodiorite (1796±19 Ma), the Foley granite (1779±4 Ma non-magnetic phase and 1774±1 Ma moderately magnetic phase), the Freedhem granodiorite (ages of 1775±3 to 1776±7 Ma; intruded by 1773±2 granite dike) and unnamed granites, one of which is 1766±8 Ma and another that is 1784±8 Ma (all U-Pb zircon ages reported in Holm et al., 2005).

Small dominantly mafic to ultramafic, but also felsic, plug-like intrusions are abundant. Fourteen of these have either been drilled or are exposed, and the rest are mapped on the basis of small, sharp aeromagnetic anomalies. Those drilled or exposed consist predominantly of porphyritic gabbro to norite, and others include ultramafic olivine-pyroxene hornblende, hornblende, hornblende gabbro, and diorite to tonalite.

The gabbro contains euhedral phenocrysts of augite, variably altered olivine, and rare plagioclase in a fine-grained, weakly trachytoid groundmass composed of lath-shaped plagioclase, intergranular bronzite, hypersthene and varied proportions of augite, and lesser poikilitic biotite/phlogopite, interstitial alkali feldspar, and apatite. One of these bodies gives an Ar-Ar plateau age of 1791±8 Ma (Jirsa et al., 2006). Only two of the intrusions sampled are ultramafic; these are coarse-grained, phlogopitic pyroxene-olivine hornblende with 30-40% poikilitic, pargasitic Mg-hornblende, 30-35% variably altered olivine, 15-20% augite, 2-10% phlogopite, 1-15% secondary actinolitic amphibole, 3-6% secondary oxides, and minor chlorite, chromite, and apatite. These intrusions contain high Cr, Ni, and MgO. A second distinct type of hornblende is dark green, medium-grained, and composed mainly of deep green equant hornblende. This unit forms plugs, is observed as a 3m-wide dike that cuts the Little Falls Formation, and as local phases in the gabbro intrusions. A third distinct type of hornblende-rich intrusion is composed medium- to coarse-grained, strongly prismatic-foliated (magmatic), weakly plagioclase-phyric, hornblende gabbro. This intrusion is substantially larger than the other plug-like bodies and yields an Ar-Ar plateau age of 1770±6 Ma (Jirsa et al., 2006). Thin sills of dioritic rocks within the Little Falls Formation wallrock adjacent to the mafic rocks, as well as irregular zones within the mafic and ultramafic intrusions, are identical to small, discrete dioritic plugs. These felsic members contain strongly zoned plagioclase phenocrysts, and petrographic textures indicate that they are likely the product of contamination by melting of the adjacent Little Falls Formation.

Geochronological studies show that supracrustal rocks in the Penokean fold and thrust belt were metamorphosed as recently as 1,760 – 1,770 Ma, which compares with emplacement ages of 1,800 – 1,776 Ma for the ECMB, indicating that the metamorphism may be attributed to widespread crustal thickening and heating related to pluton emplacement. These metamorphic and pluton emplacement ages correspond to the Yavapai Orogeny (e.g. Holm and others, 2007, and references therein). Intrusions within the ECMB show mafic/felsic magma mingling textures, and the ECMB is likely related to the small outboard plugs but emplaced at a deeper crustal level in the heart of the orogenic belt where there was greater crustal thickening and wholesale crustal melting.

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Preliminary results of P- and S-wave delay times in the Superior Region from transportable array and SPREE stations

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The Superior Province is cut by a Proterozoic structure named the Midcontinent Rift (MCR). It is one of the most striking gravity anomalies in North America on account of its length and height in mgals. The anomaly is caused by large masses of mafic/ultra mafic rock deposited along the rift axis around 1.1. Ga. To investigate the deep structure of this region we measured delay times of teleseismic waves recorded at 242 seismic stations from the Earthscope Transportable Array (TA) and the Superior Province Rifting Earthscope Experiment (SPREE). To date, 6144 P-wave and 3013 S-wave delay times were measured from 33 teleseismic earthquakes. Using a new, interactive automated delay time assessment interface, we could measure absolute delay times, relative to global seismic velocity model iasp91.

Interesting features found by mapping the average delay times are: a region of negative delays around Lake Nipigon and regions of positive delays in central Minnesota into Wisconsin, and in south-central Iowa (P-wave only). These delay times are most affected by the structures in the upper mantle due to the fact that the lithospheric portion of the delay time is less than 5 percent of the whole delay time. Since deeper structures cause larger variations with distance and azimuth it is not a surprise that the delay times vary between individual events. Looking at delay time maps of individual events show patterns of planar wave arrivals. These patterns will be investigated to discern their origins and if they are related to their azimuth or distance. More measurements will be added as new TA data is downloaded from the IRIS Data Management Center and as SPREE servicing runs are completed in the next 1.5 years.

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The Copperwood Sediment-Hosted Stratiform Copper Deposit, Upper Peninsula, Michigan

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The Copperwood copper deposit is located in Gogebic County, Upper Peninsula, Michigan within the Porcupine Mountains sediment-hosted copper district. It was discovered in 1956 by United States Metal Refining Company. In 2008, Orvana Minerals Corporation began exploration and development work at Copperwood. The company is planning first production in 2014, which would be the first Upper Peninsula copper mine since 1996.

The copper mineralization occurs as very fine-grained chalcocite hosted by siltstones and shales of the lowermost Nonesuch Formation, which is underlain by red-bed sandstones, conglomerates, and minor siltstones of the Copper Harbor Formation. The mineralized beds are stratigraphically equivalent to the lower copper mineralized units at the now closed White Pine Mine about 30 kilometers to the northeast. These rocks are part of a thick section of clastic sedimentary rocks that comprise the upper fill of the Mesoproterozoic (1.1 to 1.0 Ga) Midcontinent rift.

The copper deposit is a tabular body averaging 2.5m thick, lacks significant basal undulations, and dips 8° to 12° northward on the southwest limb of the Western Syncline, an open fold with a shallow plunge to the northwest. Copper mineralization occurs as 5 to 50 micron disseminated grains of chalcocite and as concentrations along laminations. The deposit is relatively undeformed with only one shallow, north-dipping reverse fault recognized; its displacement is as much as 7m. Gangue minerals in the ore body are quartz, clinoclase, muscovite/illite, plagioclase, K-feldspar, calcite, and hematite. Reported Canadian National Instrument compliant Proven and Probable Reserves, fully diluted, are 27.42 million metric tonnes averaging 1.41 % Cu and 3.6 ppm Ag for contained metal of 852 million pounds of copper and over 3.2 million ounces of silver.

A model for sedimentation and mineralization was based on the logging of core from nearly 200 drill holes at Copperwood and over another 100 drill holes throughout the Western Syncline. The host rocks were likely deposited under mostly anoxic conditions along the margins of a lake. In these conditions, reduced organic carbon-bearing muds with very fine-grained, syngenetic pyrite were deposited in the copper-bearing sequence. Red intervals within the otherwise black to gray sequence suggest periodic oxic conditions. During diagenesis and incipient lithification, copper-bearing, saline basinal fluids passed vertically through the sequence and formed chalcocite after pyrite; copper was likely leached from the underlying red-bed paleoaquifer. The stratigraphic sequence was folded during the Grenvillian compression of the rift strata long after lithification. In addition to the formation of the Western Syncline and recognized reverse faulting, calcite veinlets were emplaced at Copperwood.

The Copperwood deposit has the characteristics of a reduced-facies, sediment-hosted stratiform copper deposit, or Kupferscheifer-type. Although the mineralized sequence is stratigraphically equivalent to that of the White Pine deposit, it lacks the structural complexity and hydrothermal overprint characteristic of that deposit. The simple mineralogy and geochemistry, single copper-mineralizing event, and minimal deformation distinguishes the Copperwood deposit from other more complex, reduced-facies sediment-hosted stratiform copper deposits throughout the world.

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Geology and petrology of a Mesoproterozoic layered mafic intrusion in portions of the Brule Lake and Cherokee Lake 7.5' Quadrangles, northeastern Minnesota

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The Duluth Complex and related Mesoproterozoic intrusions of northeastern Minnesota comprise one of the largest igneous complexes on Earth (Miller and Severson, 2002). These intrusions, and the comagmatic volcanics into which they were emplaced, are part of the 1.1 Ga Midcontinent Rift (MCR). Many areas of northeastern Minnesota have sufficient bedrock exposure to be mapped at a detailed scale (e.g., 1:24,000). Some areas, however, are underlain by the Duluth Complex and related MCR rocks, particularly those contained within the Boundary Water Canoe Area Wilderness, have been only cursorily investigated or mapped at a reconnaissance-scale. One such area of incomplete mapping, which has been a particular curiosity since the acquisition of high resolution aeromagnetic data over northeastern Minnesota (Chandler, 1983), is located in the Sawbill Lake area of Cook County. Part of what is generalized as the Brule Lake-Hovland gabbro on the M-119 map of NE Minnesota (Miller et al., 2001) is characterized by a strongly banded, tightly curved anomaly pattern.

Reconnaissance mapping in the anomaly area by Grout et al. (1959) and Davidson (1977; Davidson and Burnell, 1977) indicates a predominance of well foliated and locally layered, oxide-rich olivine gabbro. Recently, several areas of the gabbro were mapped in detail by PRC field camp students (Frost et al., 2007; Blakely et al., 2009; Brooker et al., 2010; Asp et al., 2011). For the first author's MS thesis project, he is focused on integrating this previous mapping with his own bedrock mapping to establish the geology of a previously unrecognized, well differentiated mafic layered intrusion, which we have named the Sawbill Lake intrusion (SLI).

The detailed mapping of the SLI indicates that it is composed of troctolitic cumulates in its lower section, oxide gabbro cumulates in its medial section, and apatite ferrogabbro cumulates to ferromonzonite in its upper section. The footwall of the SLI is composed of a mix of intermediate to gabbroic rocks, anorthositic gabbros, and Pl-porphyrific diabase. The hanging wall is composed of leucogranites of the Eagle Mountain granophyre. The gradational nature of the contact between SLI ferromonzonite and Eagle Mtn granophyre implies that the SLI underplated and partially melted the granophyre body, as found elsewhere throughout the Duluth Complex (Miller and Severson, 2002). Petrographic analysis of samples collected along multiple profiles through the intrusion confirmed the cumulate stratigraphy of the SLI implied from field mapping, namely $PO \Rightarrow PCF \Rightarrow PCFOA$. The majority of samples collected were concentrated along three main profile lines in different areas of the intrusion. One set of profiles was in the west end, one in the central, and the other in the eastern end of the SLI.

One of the more striking features within the intrusion is the presence of an interval rich in subconformable blocks of basaltic and sedimentary hornfels, which were first recognized by Grout et al. (1959). The interval is located immediately above the transition between troctolite and oxide gabbro cumulates. Although the cumulate stratigraphy of the SLI shows a typical progression that could be related to progressive differentiation of a tholeiitic mafic magma, the presence of a persistent volcanic screen at the major transition in cumulate mineralogy suggests that this intrusion probably did not form by uninterrupted closed system fractional crystallization. Possible explanations for these relationships are 1) the hornfels interval separates two distinct intrusions, 2) the onset of oxides becoming cumulus caused the liquid in the magma chamber to become less dense and allowed volcanic rocks in the hanging wall to fall to the cumulate floor of the chamber, or 3) the hornfels blocks mark a significant venting event that depressurized the magma chamber and triggered the saturation (cumulus arrival) of pyroxene and oxide. To determine which of these scenarios is most likely, EDS analyses of olivines and pyroxenes were collected from the samples profiling the intrusion with the intention of evaluating whether the abrupt mineralogical change marked by the hornfels interval also corresponds to a compositional break.

The mineral chemical data collected from over 68 samples does not unequivocally support any one theory for the emplacement and crystallization history of the SLI, but it does seem to favor the venting model best. Perhaps

the most significant result of the mineral chemical data is that it shows a smooth cryptic variation throughout the entirety of the intrusion in both the olivine and pyroxene. The lack of any significant chemical break at the hornfels interval would seem to indicate that the SLI fractionally crystallized in situ from one major pulse of magma, thus supporting the density inversion and venting models. The problem with the density inversion model is that one would expect that if hornfels blocks fell to the crystallized floor due to the cumulus crystallization of oxide, one would expect to find inclusions of the volcanic rocks throughout the upper oxide gabbroic part of the intrusion. This is not the case. Alternatively, the singular occurrence of volcanic hornfels at horizon marked by the abrupt change in pyroxene habit from subophitic-ophitic below to granular above, but no significant mineral chemical change, seems more consistent with a significant venting model. While decompression attending a venting event could have a profound affect on the phase equilibrium of the system to where augite and oxide may become cumulus, it should have a minimal effect on the chemistry of the magma system. The presence of high density subophitic-ophitic pyroxenes below the screen indicate that the magma was very close to becoming saturated in augite such that venting could have triggered the cumulus arrival of augite and oxide.

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Accessory minerals of a roadside pegmatite, Orr, Minnesota

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While returning from ILSG 2010, the first author took some samples from a pegmatite exposed on the west side of US 53 just north of Orr, MN. Interesting results from heavy mineral separates prepared from the samples encouraged a return visit in August 2011, in which samples were taken from discrete zones of the pegmatite. Heavy mineral separates were prepared at the University of New Orleans, mounted in epoxy, and examined under SEM/EDS. Selected grains were analyzed with the electron microprobe.

Rock units in the vicinity of the pegmatite were mapped by Jirsa (2011) as Neoarchean biotite schist-rich migmatite intruded by Lac La Croix granite. The pegmatite is zoned, roughly horizontal, and with multiple alternating zones of aplite and pegmatite. The footwall is granitic with scattered pegmatite stringers, but the hanging wall is not well exposed; rafts or screens of biotite-rich schist in the uppermost pegmatite exposure suggest close proximity to the top of the dike. Zones are not continuous, but pinch and swell laterally. No discrete massive quartz core such as frequently observed in pegmatites is present, but pegmatite zones do have distinctive mineralogy, exhibiting varying degrees of fractionation; hence a more highly fractionated, core zone can be distinguished. Aplite zones throughout the dike are generally lacking in HFSE-bearing mineralization, though zircons are present in all phases.

Lower pegmatite zones adjacent and near the lower contact carry Mn and Zn-bearing ilmenites, along with Th-rich allanite. Nb-rich titanite in these zones appears to accommodate Nb by charge balance using $Al+Fe^{3+} \rightarrow Nb^{5+}+Ta^{5+}$. Magnetite is common in all pegmatite zones, and carries significant Zn and some Mn, reflecting pegmatite enrichment in these elements.

The third pegmatite zone is perhaps the most highly fractionated, and is thusly considered to correspond to the core zone of the pegmatite. Mn-rich almandine garnet, magnetite, Th-rich monazite, possible chevkinite-(Ce), and columbite-Fe have been noted. Sparse zircons exhibit significant Hf enrichment, ranging from about 2.1 wt% to about 5.3 wt% HfO_2 . Sparse columbite-Fe is somewhat enriched in Ta, with up to almost 16 wt% Ta_2O_5 . Notably, detectable Sc is present, ranging from 0.021 to 0.031 Sc_2O_3 . Some grains of columbite-(Fe) were found embedded in magnetite grains, and detectable Nb (in the range of 0.0X to 0.00X wt%) was found in the adjacent magnetite. Since Nb cannot be reasonably incorporated in the magnetite structure it is likely present as minute grains of Nb-bearing minerals, most likely columbite-(Fe).

Heavy mineral separates from the biotite-rich metamorphic rock rafts in the upper portion of the pegmatite exposure carry abundant titanite and sparse zircons. The titanites carry Nb just barely above detection limit and exhibit variable composition suggesting alteration, likely the result of metasomatism via pegmatite fluids that introduced the Nb.

Since it is generally accepted that pegmatites form from a single injection of relatively volatile-rich, fractionated melt, the interlayered aplite and pegmatite suggest fluctuating conditions of crystallization, from nucleation-suppressing volatile-rich conditions facilitating coarse pegmatite formation, to nucleation-enhancing less volatile-rich conditions facilitating aplite formation. The low abundance of volatile-rich phases, with the exception of biotite in pegmatite layers, suggests a relatively “dry” melt; pegmatite phase formation proceeded until volatile levels decreased to the point that mica formation and volatile-induced nucleation-inhibition ceased, and aplite formation proceeded until buildup of volatiles again inhibited nucleation and allowed pegmatite formation to resume.

It is interesting to note that Grout (1926) noted abundant magnetite in pegmatites of the Vermillion Batholith, now the Lac La Croix granite. Evidently few analyses of the magnetite were made, but the one analysis included

by Grout (magnetite in border phases of the Vermillion Batholith: 0.26 % Mn, p. 74) notes significant Mn contents. There is no evidence that Zn was looked for by these researchers, but it is possible that Zn-rich magnetites, noted in our study, may be more common in these pegmatites than has been recognized.

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Petrographic and geochemical study of the hybrid rock unit associated with the Current Lake Intrusive Complex, Magma Metals' Thunder Bay North Property

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The Current Lake Intrusive Complex (CLIC) is one of several recently discovered ultramafic to mafic intrusions associated with the Midcontinent Rift (MCR) that host Ni-Cu-PGE deposits (Heggie, 2005; Ware et al., 2008; Rossell, 2008; Ding et al., 2010; Goldner, 2011; Foley, 2011). Largely unexposed in the Current Lake area about 50 kilometers northeast of Thunder Bay, Ontario, the CLIC was discovered when glacially transported ultramafic boulders containing disseminated sulfides were located along the shores of Current Lake (MacTavish and Smyk, 2010; Goodgame et al., 2010). Subsequent geophysical surveys and drilling have outlined a 3.6 kilometer long, tubular ultramafic chonolith that is composed mostly of wehrlite to dunite and is intruded into granitic and metasedimentary rocks of the Quetico subprovince. Over the course of drilling, it was discovered that an intensely altered and contaminated heterogeneous rock unit, termed the hybrid rock unit (HRU), commonly occurred at the margins of the CLIC. The focus of this study is to characterize the mineralogical, textural and geochemical attributes of the HRU in order to understand the origin of its heterogeneity and address the question of its petrogenetic relationship to the CLIC.

Ten cores profiling two representative sections across the CLIC were re-logged and sampled. Six cores profile the narrow (30-50m) Current Lake zone where the CLIC intrudes granitic country rocks northwest of the Quetico fault. Four cores profile the wider (up to 600m) Beaver Lake zone southeast of the Quetico fault where the country rock is metasedimentary schists and minor granite. A total of 139 petrographic thin sections that are representative of the various textures and lithologies were studied for this project. 52 samples were submitted to Acme Laboratories in Vancouver, British Columbia for trace element and PGE fire assay analysis. XRF analyses of the ground pulps were conducted in the UMD Research Instrumentation Lab for major element chemistry. Having only recently completed the geochemical analyses, we will focus here mostly on the results of the petrographic study.

Initial core logging conducted by Magma Metals distinguished two types of hybrid lithologies, which they termed red hybrid and grey hybrid by their obvious coloration differences. Typically, the red hybrid occurs on the margins of the CLIC or as narrow offshoots into the country rock. The grey hybrid typically occurs sandwiched between the marginal red hybrid and mineralized wehrlite/dunite. In places, the red hybrid can be missing and the grey forms the CLIC margin in direct contact with the country rock. Like the red, the grey can also occur as isolated offshoots into the country rock.

Core logging and petrography of what has been identified as the red hybrid show it to be an intensely altered and hematized, texturally variable (prismatic to subophitic), fine to medium-grained, quartz-bearing gabbro to quartz diorite, with the dominant lithology being quartz leucogabbro with 2-5% sulfide (mostly iron sulfide). The rock is fine-grained at its contact with country rock, but is medium-fine grained near its abrupt contact with the grey hybrid. Occurrences of this rock type in the Current Lake and Beaver Lake zones are generally similar, with the exception that the Beaver Lake zone contains large, chlorite-mantled quartzite and granitic xenoliths and has more abundant interstitial quartz. A significant discovery is that some of what was logged as grey hybrid because of its color is mineralogically and texturally a quartz leucogabbro that lacks hematization. To steer clear of using secondary coloration as a primary criteria for classifying rock types, we refer to this lithology as the quartz leucogabbro unit (QLG)

Petrographic investigations of rock types that have been logged as the grey hybrid are mineralogically and

texturally distinct from the QLG unit and instead bear more resemblance to the CLIC ultramafic rocks. The average “grey hybrid” rock type is a moderately to intensely altered, fine to medium-fine grained, intergranular to subpoikilitic feldspathic wehrlite to melagabbro with 3-5% Ni-Cu sulfide. As such, we have renamed the grey hybrid, the feldspathic wehrlite (FW) unit. However, significant changes in mode and texture and alteration occur across the 1-3 meter wide FW unit from its outer contact with country rock or the QLG unit inward to the mineralized wehrlite/dunite. Where the FW unit is adjacent to the QLG unit, the contact occurs over several centimeters width and is marked by 1) an abrupt decrease in grain size, 2) a rapid decrease in plagioclase mode and its change from lath shaped to subpoikilitic, and 3) a rapid increase in clinopyroxene mode and its change in habit from subophitic to anhedral granular. Progressing inward from the altered, fine-grained, intergranular melagabbro at the QLG-FW contact, several gradual changes occur within the FW unit: alteration decreases, grain size increases to medium-grained, subpoikilitic plagioclase mode decreases, clinopyroxene mode decreases and its texture changes from anhedral granular to subpoikilitic, and granular olivine quickly appears and become the dominant phase. In one Current Lake zone core where the FW unit is in direct contact with the granitic country rock, the rock grades over 1-3 meter wide interval from a very fine grained (chilled) altered gabbro at the contact to a subpoikilitic feldspathic wehrlite. The modal and textural changes across the FW unit are interpreted as indicating that this unit is a rapidly cooled marginal phase of the mineralized ultramafic intrusion.

The contact relationships between the QLG and mineralized ultramafic intrusion are best explained by a two-stage model of emplacement. The QLG unit was emplaced first, incorporated abundant country rock xenoliths, became strongly contaminated, and extensively hydrothermally altered. This precursor intrusion “set the table” for the main intrusive event by establishing a conduit system and preheating and devolatilizing the country rock. The emplacement of the main CLIC ultramafic magma generally followed the same path as the QLG unit probably by reaming out and inflating the semi-molten core of the precursor intrusion. The incorporation of silica, sulfides, and volatiles residing in the QLG precursor intrusion during the dynamic emplacement of the main chonolithic ultramafic intrusion resulted in high tenor sulfide mineralization.

Preliminary evaluation of lithogeochemical data indicate that despite its intense felsic contamination and hydrothermal alteration, the trace element characterisitic of the QLG unit are consistent with its having similar parent magma as the ultramafic rocks of the CLIC. These results also indicate that the granitic and metasedimentary rocks of the Quetico subprovince are a reasonable source of contamination. Further geochemical modeling is underway in order to confirm the apparent genetic relationship between the QLG and the mineralized ultramafic CLIC.

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Strain Variations in Carbonates across the Proterozoic Grenville Orogen

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The Grenville orogeny involved the accretion of numerous terranes, likely with reversals of slab polarity, adding a width of ~800 km of new crust to Laurentia as part of the supercontinent Rodinia (Easton, 1991; Carr et al., 2000). Top-to-the-northwest thrusting is the common mechanism for accretion but there is a component of post-orogenic collapse (Rivers, 2012) documented by southeast trending kinematic indicators (Carlson et al., 1990).

We report the results of a traverse across the Grenville orogen from Parry Sound, Ontario (NW) to Ft. Ann, New York (SE), including the younger, adjacent Taconic allochthon. Forty three carbonates were collected resulting in 57 strain analyses on mechanically twinned calcite with the following distribution: Parry Sound domain (1), Bancroft domain (20), Harvey-Cardiff domain (1), Belmont domain (4), Marzinaw domain (1), Frontenac domain (1), Adirondack Lowlands (5), Adirondack Highlands (8), and the Taconic allochthon (2). Within the regional sample suite there are two areas studied in detail, the Bancroft shear zone and a roadcut near Ft. Ann, NY. From northwest to southeast, the twinning strain fabric is dominantly a layer-parallel shortening fabric oriented N-S (Parry Sound), then becomes parallel to the Grenville thrust direction (NW-SE) across the Composite Arc Belt (Central Metasedimentary Belt) to the Adirondack Highlands where the sub-horizontal shortening strain becomes margin-parallel (SW-NE). The easternmost Adirondack Highlands preserve a vertical shortening strain in calcite veins that are cross-cut by veins found in the overlying Taconic allochthon; the Ordovician limestones and veins preserve a layer-parallel shortening strain oriented at 330°. Marbles from the Bancroft shear zone contain calcite grains with two sets of twin lamellae (e_1 and e_2). The better-developed e_1 sets (n=406) record a LPS fabric oriented NW-SE whereas the younger e_2 lamellae (n=146) preserve a margin-parallel (SW-NE) LPS fabric. Both the e_1 and e_2 strains record an overprint strain (NEV) that records vertical shortening, perhaps related to the collapse of the Ottawan orogenic lid.

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Petrogenesis and crustal contamination of the Nipigon sills: a geochemical and spatial re-evaluation

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A compilation and re-evaluation of 2397 publically available, spatially referenced samples with associated whole-rock geochemistry has yielded previously unrecognized variation within the Midcontinent Rift-related Nipigon sills of the Nipigon Embayment. Nipigon diabase sills represent the most volumetrically significant Midcontinent Rift-related unit in Canada covering an area in excess of 20 000 km² (Sutcliffe, 1991). 796 Nipigon sill samples have been investigated using Th/Yb_{pm} ratios as a means of evaluating crustal contamination. This investigation revealed three distinct Nipigon sill types comparable to the three distinct suites of sills suggested by Hollings et al. (2007) based on radiogenic isotope data. This discrimination supports the isotopic signatures for each group as higher Th/Yb_{pm} values are consistent with a more negative $\epsilon_{\text{Nd}(t=1000\text{Ma})}$ values. Ranges for the three Nipigon sill types are summarized in Table 1.

Table 1. Summary of geochemical data for the Nipigon sills

	Nipigon I	Nipigon II	Nipigon III
Th/Yb _{pm}	1.97 – 3.4	3.4 – 5.0	5.0 – 6.5
Nb/Yb _{pm}	0.75 – 1.65	1.2 – 1.8	1.5 – 2.2
Nb/Nb*	0.425 – 0.65	0.35 – 0.55	0.3 – 0.5
La/Sm _{pm}	1.2 – 1.8	1.60 – 2.0	2.2 – 2.6
Gd/Yb _{pm}	1.0 – 1.9	1.0 – 1.9	1.0 – 1.9
$\epsilon_{\text{Nd}(t=1000\text{Ma})}$	-0.5 to -1.5	1.5 to 3.0	> 5.0

Populations of more-contaminated samples (Nipigon types II and III) dominantly lie within two areas (Fig. 1); a north-trending, linear group in the southwestern Nipigon Embayment and an arcuate array in northern and eastern Lake Nipigon. Nipigon sill types II and III display higher Th/Yb_{pm} values, lower Nb/Nb* values and more negative $\epsilon_{\text{Nd}(t=1000\text{Ma})}$ values when compared to Nipigon sill type I. These populations appear to be proximal to major structures such as the Black Sturgeon fault, southwest of Lake Nipigon, (Fig. 1). Type I Nipigon sills are located peripherally to Nipigon sill types II and III and display lower Th/Yb_{pm} values, higher Nb/Nb* values and less negative $\epsilon_{\text{Nd}(t=1000\text{Ma})}$. Type I Nipigon sills do not appear to be related to any known major structures.

Preliminary analyses show that Archean rocks of the Quetico Subprovince appear to control the Th/Yb_{pm} values, whereas Sibley Group sedimentary rocks have a stronger control on Nb/Nb*. Type II and III Nipigon sills display higher Th/Yb_{pm} values than type I sills, consistent with the model in which type II and III sills have assimilated metasedimentary rocks of the Quetico Subprovince. The higher Nb/Nb* values of type I Nipigon sills likely reflects a greater degree of interaction with the rocks of the Sibley Group suggesting shallower level contamination (as the Sibley is not present at depth within the Nipigon Embayment). The more crustal-contaminated nature of type II and III sills in conjunction with their proximity to major structures, suggest that magmas feeding these sills ascended through structures that provide more interaction with Quetico rocks at greater depths. This is supported by type II and III samples showing more negative $\epsilon_{\text{Nd}(t=1000\text{Ma})}$ values than

type I samples, a signature that infers interaction with older continental crust. The source magma feeding type I Nipigon sills possibly exploited the same pathways yet had less interaction with continental crust at depth as the system was armoured by previously ascended magmas. As type I melts were laterally emplaced, they were contaminated by Sibley Group sedimentary rocks as displayed by elevated Nb/Nb* signatures.

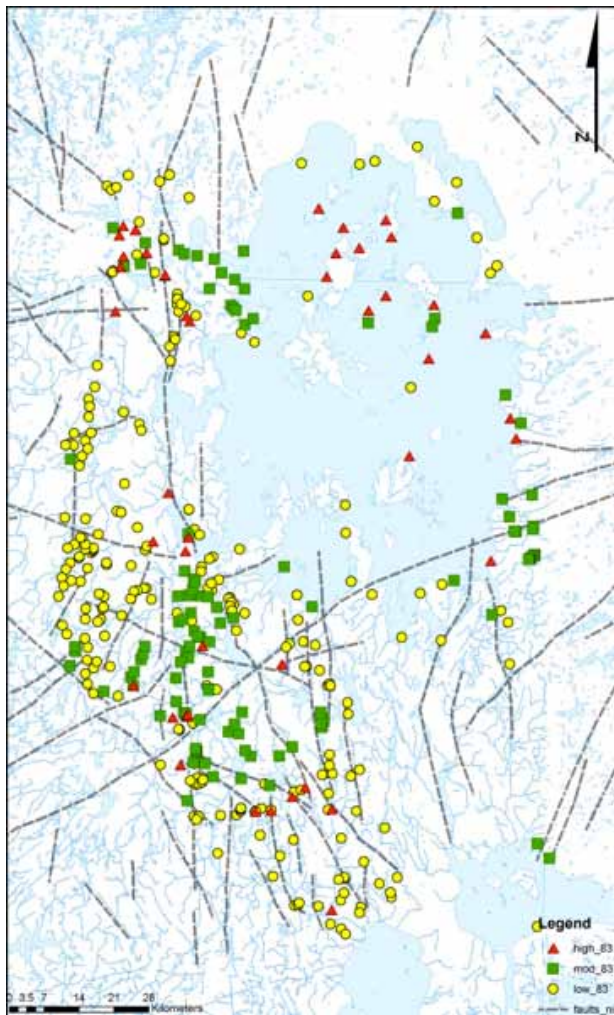


Figure 1. Map of the Nipigon Embayment showing the distribution of Nipigon sill types I (yellow circles), II (green squares) and III (red triangles). Major faults after Hart and MacDonald (2007).

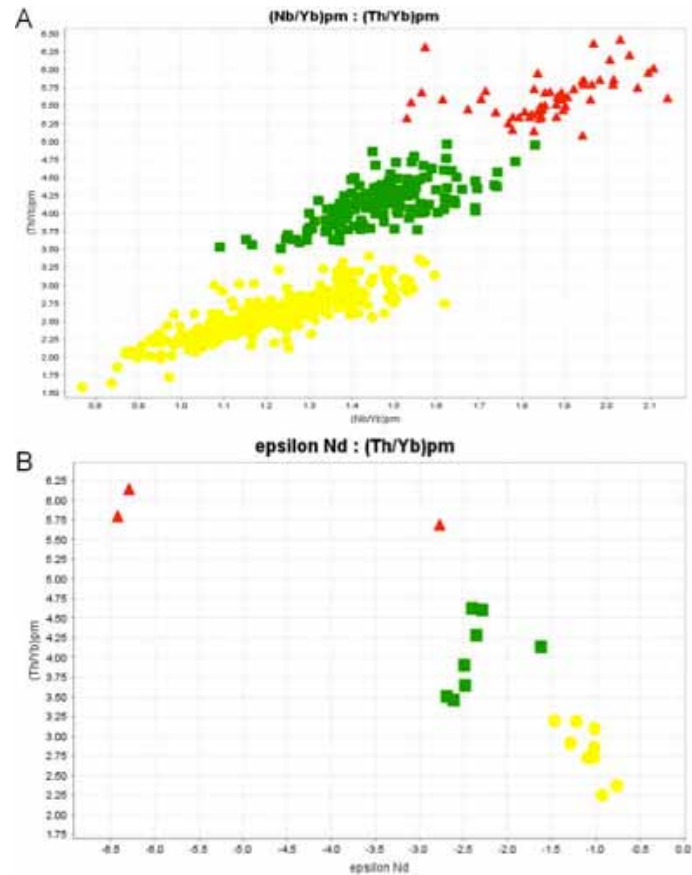


Figure 2. A) Nb/Yb_{pm} vs. Th/Yb_{pm} plot; B) $\epsilon_{Nd(t=1000Ma)}$ vs. Th/Yb_{pm} Nipigon sill types I (yellow circles), II (green squares) and III (red triangles). Radiogenic isotope data from Hollings et al. (2007), Normalizing values from Sun and McDonough (1989).

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Geology and Geochemistry of the Coubran Lake Basalts, a Midcontinent Rift-related sequence within the central Coldwell Complex, Marathon, Ontario

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The Coubran Lake Basalts occur as part of a large, preserved roof pendant of volcanic rocks in the center of the ~28 km diameter Mesoproterozoic Midcontinent Rift-related, alkalic Coldwell intrusive complex near Marathon, on the northern shore of Lake Superior. In one location, basalt is exposed in a 3 to 5 m wide by ~350 m long stripped area. Thin (~2 m), amygdaloidal flows appear to be draped over the side of a hill and exhibit ropy flow tops, suggesting subaerial emplacement (Figs. 1 A and B). The volcanic pile is estimated to comprise five or six individual flows at this locality. The basalts are locally hornfelsed, altered (Fig. 1C) and are intruded by syenite dykes (Fig. 1D). They likely predate the main phase of syenitic magmatism that produced the central part of the Coldwell intrusive complex.

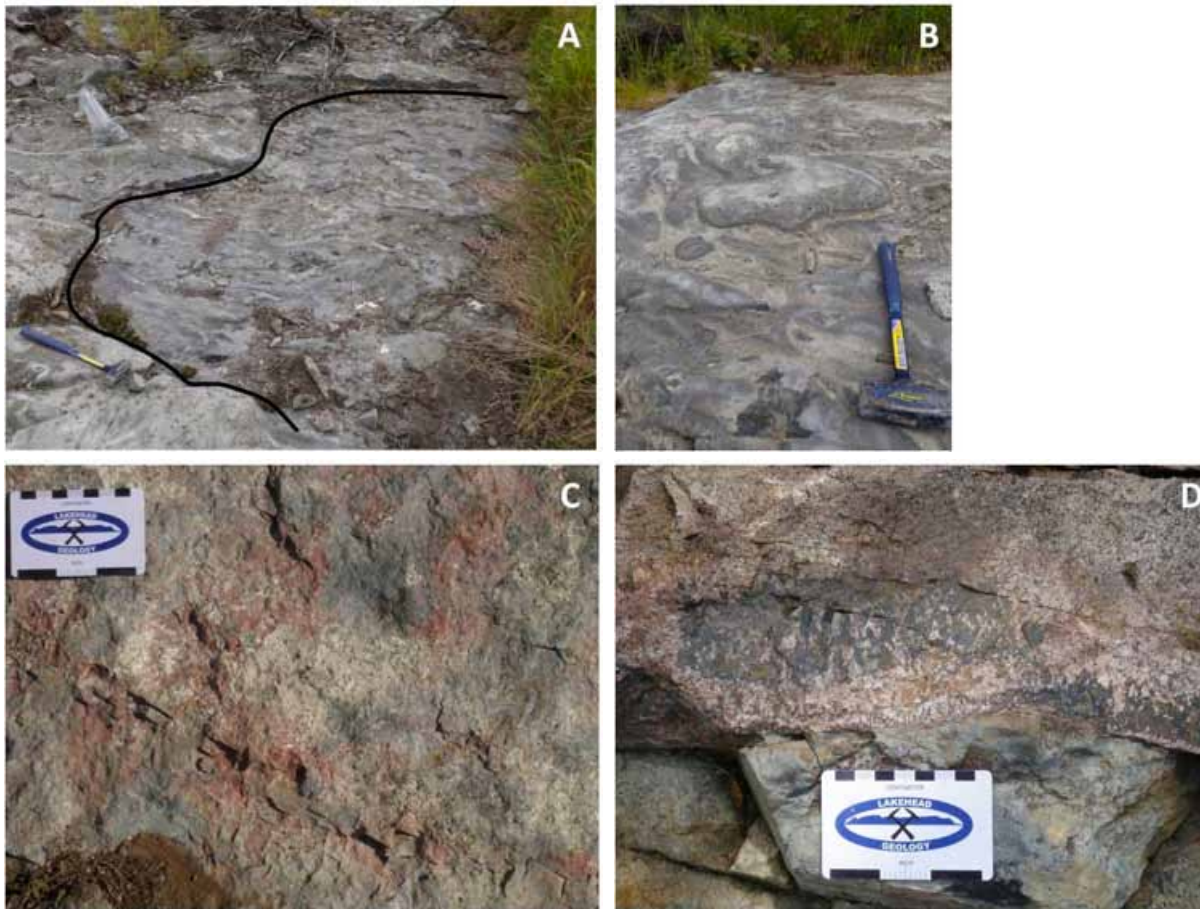


Figure 1. Photos showing characteristic features of the Coubran Lake Basalts.

Major element chemistry for all groups displays very little variation, with SiO₂ values ranging from 49.33 to 51.98 wt%, TiO₂ values ranging from 0.78 to 0.99 wt%, and MgO ranging from 4.77 to 7.34 wt%. However, three groups (types A, B, and C) can be distinguished based on their incompatible element abundances. Basalt type A lies towards the base of the unit, forming the lowermost 10% of the exposed sequence and displays strong LREE enrichment ($\text{La}/\text{Sm}_n = 7.44$ to 9.32) with HREE ratios comparable to that of types B and C ($\text{Gd}/\text{Yb}_n = 2.48$ to 2.52). Basalt type B dominates the succession and displays light rare-earth element (LREE) enrichment ($\text{La}/$

Sm_n = 2.45 to 4.77) and heavy rare-earth element (HREE) fractionation (Gd/Yb_n = 1.96 to 2.39). Basalt type C comprises only three samples sporadically located through the sequence. It is characterised by LREE enrichment (La/Sm_n = 1.99 to 2.94) and HREE fractionation (Gd/Yb_n = 1.97 to 2.10). It is distinguishable from basalt type A and B based on the absence of a negative niobium anomaly and lower abundances of large-ion lithophile elements (LILE). These samples appear to mark the tops of geochemically distinct flows.

Midcontinent Rift-related volcanic rocks have been classified and correlated as five distinct groups (basalt types I through V) based on their major element, trace element and Nd isotopic analyses (Nicholson et al., 1997). Basalt type II represents a reversely polarized group of volcanic rocks deposited during an early phase of magmatism (>1105 Ma). They are characterized by LREE enrichment, HREE fractionation, as well as a negative niobium anomaly (Fig. 2). Primitive mantle-normalized diagrams show the Coubran Lake Basalts to be similar to basalt type II, which includes the upper Siemens Creek Volcanics, the central suite of the Osler Group and the recently recognized Devon Volcanics (Cundari, 2010). Furthermore, the Coubran Lake Basalts may be genetically related to the Two Duck Lake Gabbro of the Coldwell Complex based on preliminary evaluation of trace element abundances. Further correlative work, including radiogenic isotope analysis and paleomagnetism, is ongoing in order to place the Coubran Lake Basalts in context with the Coldwell Complex and other Midcontinent Rift-related volcanic units.

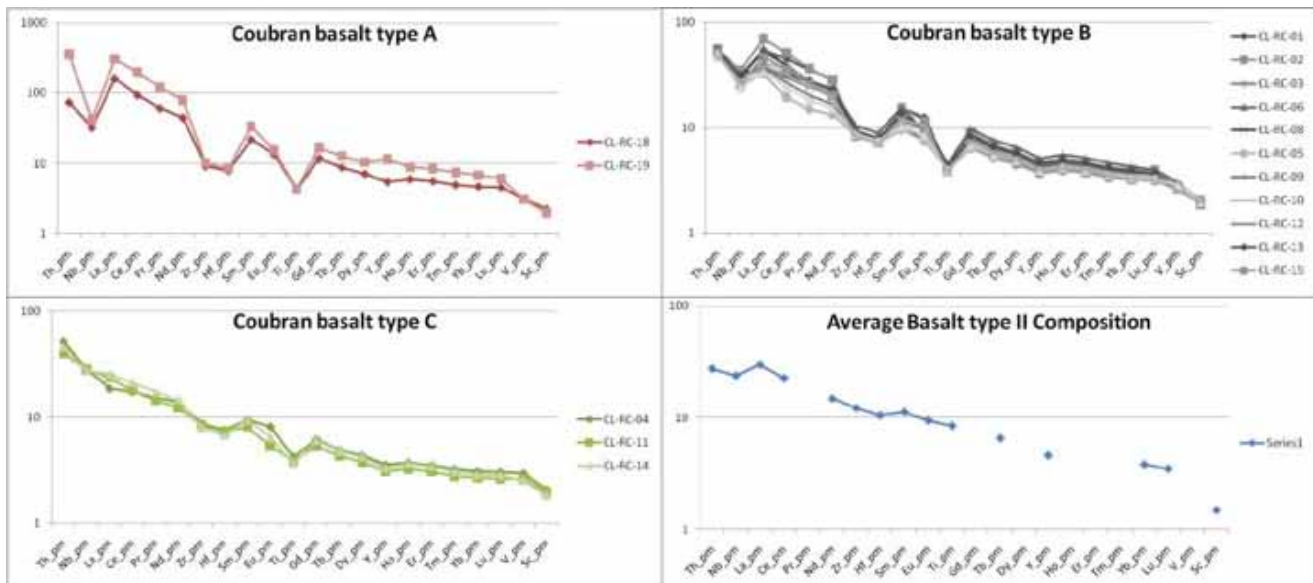


Figure 2. Primitive mantle normalized plots show distinctions between the four Coubran Lake Basalt types. Basalt type II data from Nicholson et al. (1997). Normalizing values from Sun and McDonough (1989).

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The source of the Elliot Lake uranium ores: The neodymium isotope story

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Uranium ore in the Elliot Lake camp is hosted in quartz pebble conglomerate beds within the lower part of the Matinenda Fm near the base of the Paleoproterozoic Huronian Supergroup. The Matinenda Fm is composed mainly of trough and planar cross-stratified, greenish to buff, coarse-grained sandstones deposited in a braded fluvial system (Fralick, 2003). Many workers (see Roscoe, 1969 for list) have suggested a paleoplacer origin for the mineralized conglomerates, but whether the source region was local (cf. Roscoe, 1969) or distal (cf. McDowell, 1969) has remained problematic. Based on a detrital zircon provenance study through the Matinenda Fm, Easton and Heaman (2011) suggested that the Matinenda Fm was locally sourced, especially the basal, mineralized, Ryan Member. This study reports neodymium isotopic data obtained from the Elliot Lake area, including the detrital zircon samples used by Easton and Heaman (2011). This data provides additional insights into the source rocks of the Matinenda Fm.

Neodymium data are presented in Figure 1 and were obtained from the Isotope Geochemistry and Geochronology Research Centre at Carleton University. Archean felsic volcanic and granodiorite samples from the Whiskey Lake greenstone belt (samples -0108, -0180, -0202), all of which have been dated by U-Pb TIMS on zircon, have positive ϵ_{NdT} values close to the depleted mantle evolution curve. Paleoproterozoic rocks of the Thessalon Fm (sample -0042), and the East Bull Lake intrusive suite (sample -0335 and data from Prevec (1993)) have ϵ_{NdT} values ranging from 2.58 to -2.28, suggesting derivation from a primary magma originating from a depleted mantle source, which locally was affected by minor amounts of crustal contamination.

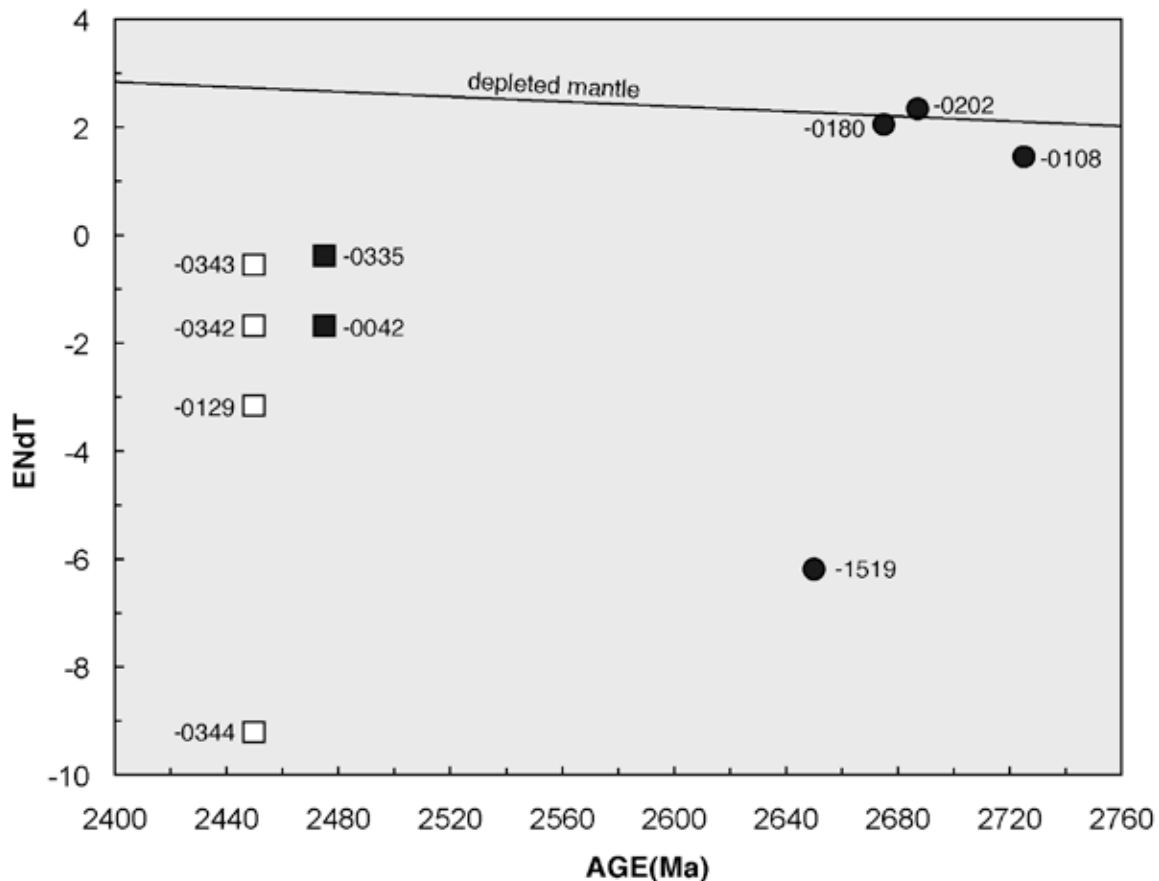


Figure 1. Epsilon neodymium versus age plot for Archean and Paleoproterozoic samples from the Elliot Lake area. Archean rocks indicated by circles, Paleoproterozoic mafic rocks by filled squares, Matinenda Fm samples by open squares. Numbers refer to sample numbers mentioned in the text.

In contrast, the Matinenda Fm. sandstone samples all have negative ϵ_{NdT} , ranging from -0.52 to -9.21. Samples with the highest negative ϵ_{NdT} (-0129, -0344) are also enriched in Th, most likely due to the presence of monazite. The magnitude of the negative ϵ_{NdT} values in the Matinenda Fm indicates a negligible contribution from the volcanic and intrusive rocks of the Whiskey Lake greenstone belt, all of which have positive ϵ_{NdT} . The Matinenda Fm data can be explained if the sandstones contain a significant component derived from a suite of radiogenic granites located 30 to 40 km north and northwest of Elliot Lake which have ϵ_{NdT} of -6.19 (sample -1519). These radiogenic granites typically contain 8 to 33 ppm U and 30 to 50 ppm Th (Easton, 2010), thus they are also a potential source of uranium. In contrast, uranium contents of other Archean felsic intrusions in the Elliot Lake area are 1 to 4 ppm (Easton, 2010). It may be no coincidence that the most negative of the Matinenda Fm samples (-0344) was collected only a few metres below the mineralized Main Conglomerate Bed.

In conclusion, the neodymium data, as well as the detrital zircon and geochemical data reported by Easton and Heaman (2011), are all consistent with a local source region that included radiogenic granites found north and northwest of Elliot Lake. The absence of similar radiogenic granites north of the Huronian Supergroup between Elliot Lake and Sault Ste. Marie may explain why the Matinenda Fm west of Elliot Lake contains no significant uranium occurrences.

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Erosion of Archean lithosphere by subduction and rifting: a tomographic image of central North America

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The core of the North American continent was assembled by Precambrian accretionary processes, which are generally believed to also be responsible for the formation of the underlying continental lithosphere. Signatures of lithospheric accretion are preserved in the lithosphere in a form detectable by observations of seismic velocity and fabric. These signatures, however, are subject to later modification by later tectonic processes, such as orogeny, rifting, and mantle plume impingement. We examine the lithosphere of the region surrounding the southwest portion of the Archean Superior Province using a large teleseismic data set from Canadian and American sources. The western Superior is associated with high seismic P velocity and a strong, consistent east-west pattern of shear-wave splitting. The western edge of the Western Superior velocity and splitting anomalies lies ca. 200 km east of the crustal contact with the Proterozoic Trans-Hudson Orogen, perhaps indicating that Trans-Hudson orogenic processes eroded the Superior lithosphere. To the southwest, the Superior lithosphere is disrupted by a low-velocity lithospheric channel ca. 250 km wide striking northwest through Minnesota and the Dakotas, which is also associated with a sharp weakening of anisotropy. The origin of this feature is enigmatic, as it does not correspond to any known crustal feature, though it appears to be truncated by the Mid-Continent Rift and so may represent a failed rift arm at the lithospheric level. The rift itself is only partially resolved, but shows indications of low velocities; resolution of the Mid-Continent Rift will improve over the next few years due to a combination of the eastward migration of the Earthscope Transportable Array and new data from the temporary Superior Province Rifting Earthscope Experiment (SPREE).

The black line faults of the Red Lake gold mines, Ontario

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Black line faults are a common feature in the Red Lake gold mines. Characterized by their distinctive black color, they are planar structures that cross-cut and displace various lithologies, dykes, and gold-bearing veins. They may have anomalous traces of gold but are usually barren. Although black line faults along the Red Lake mine trend vary in size, geometry and amount of displacement, they all share the same general composition of mostly tourmaline, chlorite, and interstitial quartz. They have previously been interpreted as minor faults associated with brittle late-stage deformation; however thin-section analysis indicates that some are overprinted by ductile deformation. Rather than representing a discrete late-stage event, they are better characterized as compressive shear fractures that formed during progressive high-temperature deformation that was dominantly ductile. Black line faults are significant in that they represent a time of brittle-ductile deformation and the presence of complex hydrothermal fluids, typically related to orogenic gold mineralization.

A microstructural study of the Otjikoto Deposit, Namibia: Inferences from gold mineralization in the Superior Province

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Shear-zone-hosted gold deposits in the Superior province of northwestern Ontario are characterized by heterogeneous deformation in high-temperature brittle-ductile shear zones. Since microstructure is critical to identifying this type of deformation, microstructural analysis may provide a vector to gold mineralization in orogenic gold deposits where scarce outcrop inhibits structural mapping.

The Otjikoto project in Namibia is an example of such an orogenic gold deposit. It is situated in the province of Otjozondjupa, approximately 300 km north of the capital city of Windhoek. A 20-metre-thick layer of calcrete covers the exploration area, making the mapping of structural features difficult. Research for this Lakehead University Honours thesis was carried out through the microstructural analysis of thin sections (obtained from Aurix Gold) that were collected from drill core. The microstructures produced by deformation exhibited in the minerals of this deposit provide information about the relative timing of metamorphism, deformation, quartz veins and gold mineralization of the Otjikoto project.

The metapelitic Okonguarri Formation, host to the Otjikoto gold mineralization, contains evidence for peak metamorphism at the temperatures and pressures of the sillimanite zone of the amphibolite facies. Grain size reduction of feldspar indicates that mylonitization also occurred at amphibolite facies temperatures. The formation also exhibits brittle deformation, specifically in the competent amphibole and garnet porphyroblasts, which occurs during synchronous metamorphism and ductile deformation. The mineralized quartz veins are synorogenic as evidenced by both brittle and ductile deformation under at least greenschist facies metamorphism. In particular, boudins of coarse-grained quartz (interpreted to be boundinaged quartz veins) indicate the mutual overprinting of brittle and ductile deformation which is characteristic of a shear-zone-hosted gold deposit.

Based on evidence for the synchronous metamorphism, brittle deformation and ductile deformation, and the synorogenic mineralized quartz veins, a shear-zone-hosted gold deposit model should be considered for the Otjikoto project.

Stratigraphy and tectonic setting of Neoarchean arc volcanic rocks in the Bird River Belt, Manitoba, Canada.

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The Neoarchean Bird River Belt (BRB) in the western Superior Province is currently the focus of geological and geochemical investigations that have led to a revised interpretation of its tectonic setting and geological history. A collaborative mapping project initiated in 2005 by the Manitoba Geological Survey is currently focused on detailed studies of economically important mafic-ultramafic intrusions and rare-element-bearing pegmatites. The BRB is part of a continental arc, juxtaposed against the north margin of the Winnipeg River Subprovince, which extends east for over 150 km, as far as Separation Lake in Ontario. The stratigraphy of this ca. 2.75 to 2.70 Ga belt documents a history of arc magmatism and associated sedimentation, as well as subsequent deformation that resulted from the convergence and ultimate collision of flanking older cratonic terranes to the north and south: North Caribou Terrane (NCT) and Winnipeg River Subprovince (WRS), respectively. BRB arc activity in the Neoarchean occurred during an interval of widespread magmatism in the central part of the NCT and along its north and south margins (Percival et al., 2006). In many cases the Neoarchean arc assemblages are contiguous with older, Mesoarchean assemblages, but the latter appear to be absent in the BRB. The oldest known rocks in the BRB are mid-ocean-ridge basalt (MORB)-like rocks flanking the arc volcanics along both north and south margins of the belt, and thought to represent back-arc and ocean-floor settings respectively. The northern MORB type is notable for the presence of mafic-ultramafic intrusions (2745 Ma Bird River Sill, Wang, 1993; Mayville intrusive complex), thought to be genetically related to their host rocks, and associated with Cu-Ni-Cr-PGE ore deposits (Meal, 2006).

North (2735-2731 Ma) and south (2725 Ma) panels of arc-type rocks in the BRB (Gilbert et al., 2008) are stratigraphically distinctive but they are probably part of an evolving arc volcanic succession that was associated with subduction of oceanic crust at a continental margin to the north. Sm-Nd isotopic data and crustal residence ages of the arc volcanic rocks indicate the source magma was influenced by older ca. 3.0 Ga continental crust. Crustal assimilation is also indicated by the fact that 70% of the mapped area of BRB arc volcanics consists of felsic to intermediate rock types. Remnants of the cratonic block north of the BRB may be represented by Mesoarchean (2.85 Ga) granitoid rocks within the multiphase Maskwa Lake Batholith, which also contains 2725 Ma granitoid intrusion(s) of synvolcanic age.

Geochemical discrimination of incompatible elements and element ratios in the arc type rocks shows a systematic trend from least evolved compositions in the north panel, towards progressively more evolved compositions in the lower, main and upper parts of the south panel, consistent with a change from arc to arc-rift (extensional) tectonic settings (Gilbert et al., 2008). The upper part of the north panel is a lithologically diverse, mainly volcanoclastic to epiclastic succession (Diverse arc assemblage, DAA), possibly representing an extensional basin. A youngest detrital zircon date of 2706 ± 23 Ma for a turbidite deposit provides a rough estimate for the maximum depositional age of the DAA.

Turbidite deposits (Booster Lake Formation, BLF) in the central part of the BRB are thought to represent an elongate rift basin that extends east between the north and south panels of arc rocks. The turbidites are interpreted as analogous with 2713-2704 Ma orogenic sedimentary rocks and related paragneiss in the English River Subprovince, commonly interpreted as a fore-arc basin that extends for 800 km along the south margin of the Uchi domain (Hrabi and Cruden, 2006). A 2712 ± 17 Ma youngest detrital zircon date provides an approximate depositional age for the BLF. Fluvial-alluvial deposits of slightly younger age (2697 ± 18 Ma) in the eastern part of the BRB structurally overlie the margin of the arc volcanic rocks. The coarse siliciclastic rocks are interpreted as synorogenic, more proximal equivalents of the BLF turbidites. Contacts between the various tectonic components (arc, back-arc and orogenic sedimentary rocks) appear to be invariably faulted.

Synvolcanic granitoid and gabbroic plutons (2723 Ma) intrude the south panel arc rocks, but similar plutons are absent in the north panel that contains, instead, relatively younger sanukitoid rocks. The light-rare-earth-element-enriched and strongly fractionated sanukitoid suite is represented by (1) clasts in DAA conglomerate, (2) dikes and sills in north panel arc volcanic rocks, and (3) minor intrusions in BLF turbidites. The sanukitoid magmatism thus spanned syn- and post-volcanic intervals. Terminal collision of the NCT and WRS resulted in regional folding, faulting and locally tectonic intercalation between BLF turbidites and arc volcanic rocks. Post-tectonic (ca. 2660-2646 Ma) granitoid plutons of probable anatectic origin, and rare-element-bearing pegmatites (e.g. 2640 $\pm$ 7 Ma Tanco pegmatite; Baadsgaard and Černý, 1993) are among the last manifestations of the sequence of events - initiated ca. 3.0 Ga - that were associated with the convergence and collision of Mesoarchean cratonic blocks in the western Superior Province.

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Geology of the Layered Series, Coldwell Alkaline Complex, Ontario

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The Eastern Gabbro forms the outer margin of the Coldwell Alkaline Complex, a large lopolith emplaced during the Mid Continent Rift Event at 1108 Ma (Heaman and Machado (1992) The Eastern Gabbro is up to 1500 meters thick and, as described by Shaw (1997), formed by multiple intrusions of evolved basaltic magma with a subalkaline parentage into a partial ring dike structure that cut the Archean country rock.

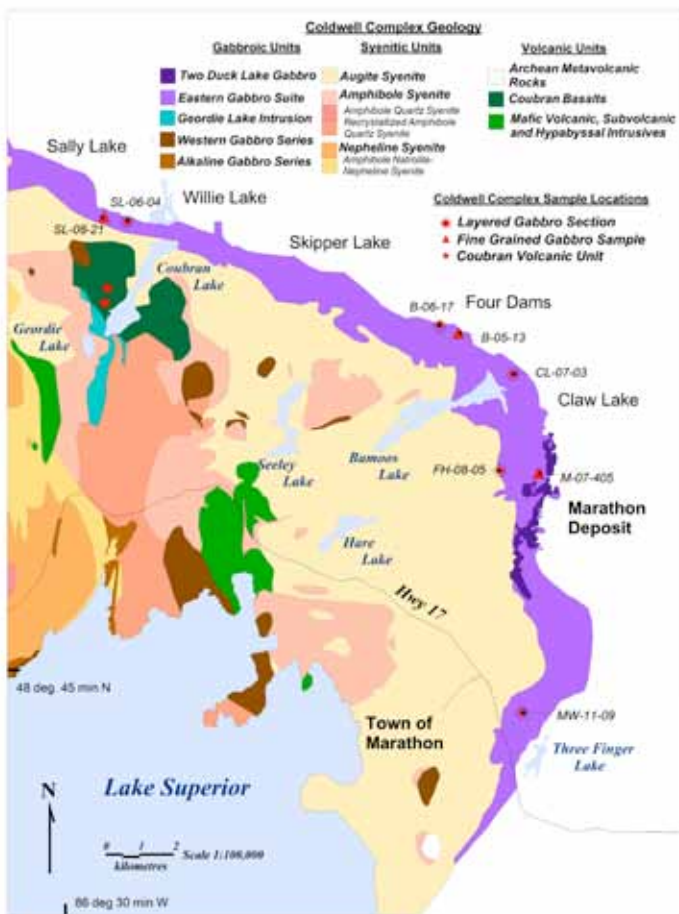


Figure 1. Eastern margin of the Coldwell Complex showing the Eastern Gabbro, Marathon Deposit, and Syenitic Rocks. Geochemical sampling locations are indicated by red symbols.

The Eastern Gabbro is shown to be a composite intrusion made up of at least three distinctive components or gabbroic series including the early Fine Grained Series, the Layered Series and the Marathon Series. This study presents the results of detailed petrography of the Layered Series at five sites covering 24 of the 31 km strike length of the Eastern Gabbro (Fig. 1).

The Layered Series makes up the majority of the Eastern Gabbro and is compositionally, geochemically

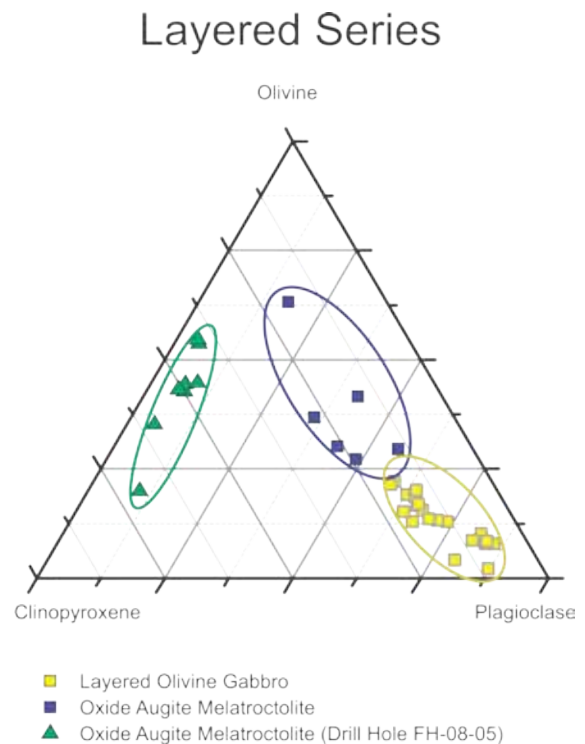


Figure 2. Ternary diagram for CIPW Norm abundances demonstrates the linear modal trends within the layered series. FH-08-05 Fly Hill samples contain a higher proportion of pyroxene and less plagioclase than the typical oxide augite melatroctolites.

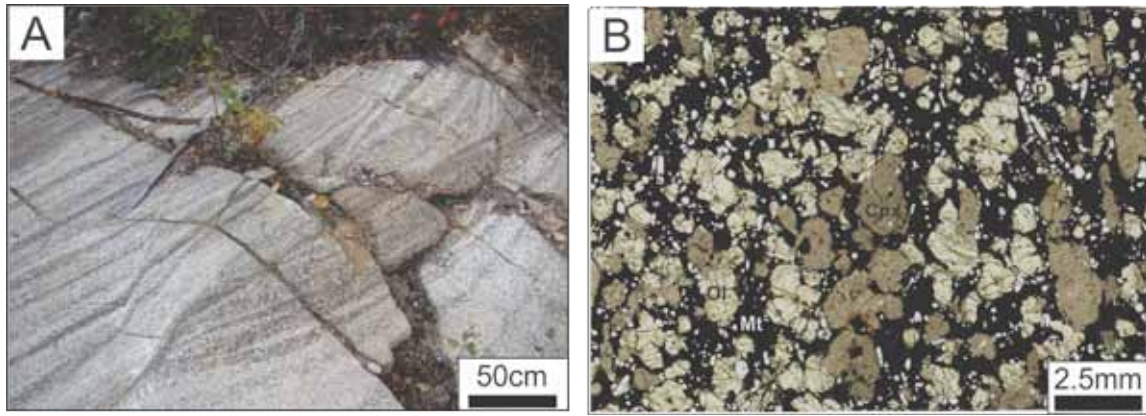


Figure 3. (a) Modal layering in the Layered Series shows cross bedding, gradational variation of plagioclase and clinopyroxene and strong contrast between cyclical layers. (b) Polished thin section of a plagioclase free interval within the oxide augite melatroctolite unit.

and texturally similar for all sample locations. The Layered Series is dominated by massive to modally layered olivine gabbro (Fig. 3a), but also includes relatively thick units of weakly layered oxide augite melatroctolite (Fig. 3b). Contacts between these units are typically gradational. The oxide augite melatroctolite unit at the Fly Hill location contains iron rich clinopyroxene.

CIPW Normative abundance of minerals are plotted on ternary diagrams (Fig. 2) to highlight the sequence of layered rocks that trend from gabbroic anorthosite to olivine melagabbro. The Mg number calculated for olivine gabbro displays a narrow range of values from 35 to 65 and is similar to the results of Shaw (1997). Samples of oxide augite melatroctolite at Fly Hill located near the top of the Layered Series represent the most fractionated rocks with an Mg number of 10 and samples from the Three Finger Lake area represent the most primitive gabbro with Mg numbers up to 65.

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Quartz Fabric Analysis of the Kawishiwi Shear Zone, NE Minnesota

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Structural fabrics within the Vermilion district, NE Minnesota, including metamorphic foliation and mineral lineation are well established and can be summarized as northeast striking, near vertical foliation containing oblique to vertical lineations (Sims, 1972, 1976; Hudleston 1976; Hudleston et al., 1988; Shultz-Ela & Hudleston, 1991; Bauer & Bidwell, 1990; Goodman, 2008; Karberg, 2009; Johnson, 2009; Erikson, 2010). The oblique to vertical lineations are present throughout the Vermilion district, yet areas of subhorizontal lineation orientations are also present locally. Two different interpretations emerge from previous studies: 1) dextral transpression associated with terrane accretion (e.g., Hudleston, 1976; Hudleston et al., 1988) and 2) lineation-parallel shearing consisting of regional dip-slip shearing and later, more focused, strike-slip shearing (e.g., Goodman, 2008; Karberg, 2009; Johnson, 2009; Erikson, 2010). The Kawishiwi Shear Zone (KSZ), one of several Vermilion district shear zones, shows structural relationship particularly well. Foliation consistently strikes east-northeast and dips vertically. Lineations are broadly down-dip with discrete areas of subhorizontal. Goodman (2008) performed a structural and kinematic analysis of the KSZ and interpreted lineation-parallel shearing with dip-slip shearing followed by strike-slip shearing. However, previous studies do not specifically constrain flow within L-S tectonites relative to lineation.

This study aims to characterize the kinematic pattern of flow through use of quartz fabric analysis of c- and a-axis petrofabrics. The data reveal the dominant slip planes and direction of flow during deformation, and also provide deformation temperature and strain geometry information. Oriented samples from the KSZ were analyzed. Sample KS7J contains a vertical lineation and quartz petrofabric data indicate flow nearly parallel to the lineation, thus dominantly dip-slip displacement. Quartz microstructures are consistent with greenschist deformation. Sample KS6UI, collected from a localized zone with strike-parallel lineation, displays Quartz petrofabric data indicative of slip along the prism $\langle a \rangle$ plane with flow parallel to lineation. However, quartz microstructures are inconsistent with this higher temperature slip plane; suggesting another mechanism to activate slip. One such mechanism, orthogonal reactivation, accounts for high temperature slip at lower temperatures due to shearing in two orthogonal directions (Oliver, 1996). In this model, initial shearing produces a crystallographic preferred orientation within quartz. Subsequent orthogonal shearing exploits weaknesses within the aligned quartz lattice and triggers slip along high temperature slip planes. Quartz petrofabrics, in particular a-axis data, support this model.

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Structural control on the emplacement of the TBN-Igneous Complex.

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The Lake Superior area was the focus of extensional and compressional deformation during the development of the Mesoproterozoic Midcontinent Rift (MCR) rift sequence. Age determination carried out around the MCR identify a rift evolution sequence spanning ~60 m.y. and subdivided into 4 stages (Heaman et al., 2007). It is within Stage 2 (1115-1105 Ma) that a series of mafic-ultramafic intrusions prospective for Ni-Cu-PGE were emplaced proximal to the main rift axes (e.g. Seagull, Kitto, Disraeli, Hele, Thunder Bay North, Tamarack and Eagle Intrusions). Pre-existing Archean structures are postulated to be a strong influence on the early rift architecture and are implicated to be a primary control on the distribution of these Stage 2 intrusions (Hollings et al., 2007; 2010).

The Thunder Bay North (TBN)-igneous complex was emplaced during Stage 2 of the rift event. The complex comprises a series of contemporaneous layered intrusions, dykes, sills and chonoliths (Fig. 1). Magma Metals Ltd. has been actively exploring the TBN-complex since 2006 with the discovery of Pt-Pd-Cu-Ni mineralization hosted within the complex. To date the TBN-Complex hosts an indicated resource of 9.8 Mt at 2.34 g/t Pt-Eq for 741 000 contained Pt-Eq ounces and an inferred resource of 0.53 Mt at 2.87 g/t for 49 000 contained Pt-Eq ounces (MMW, Feb. 23, 2012). During the delineation of the mineral resource a number of lines of evidence were observed within the TBN-complex to support the hypothesis that pre-existing Archean structures controlled the spatial emplacement of intrusions, the morphology of igneous bodies, and consequently the distribution of mineralization.

Structural controls on the TBN-complex can be divided into two groups: 1) macro-controls which are evident in the morphology of the intrusion, but not apparent in drill core, and 2) micro-controls which are readily seen

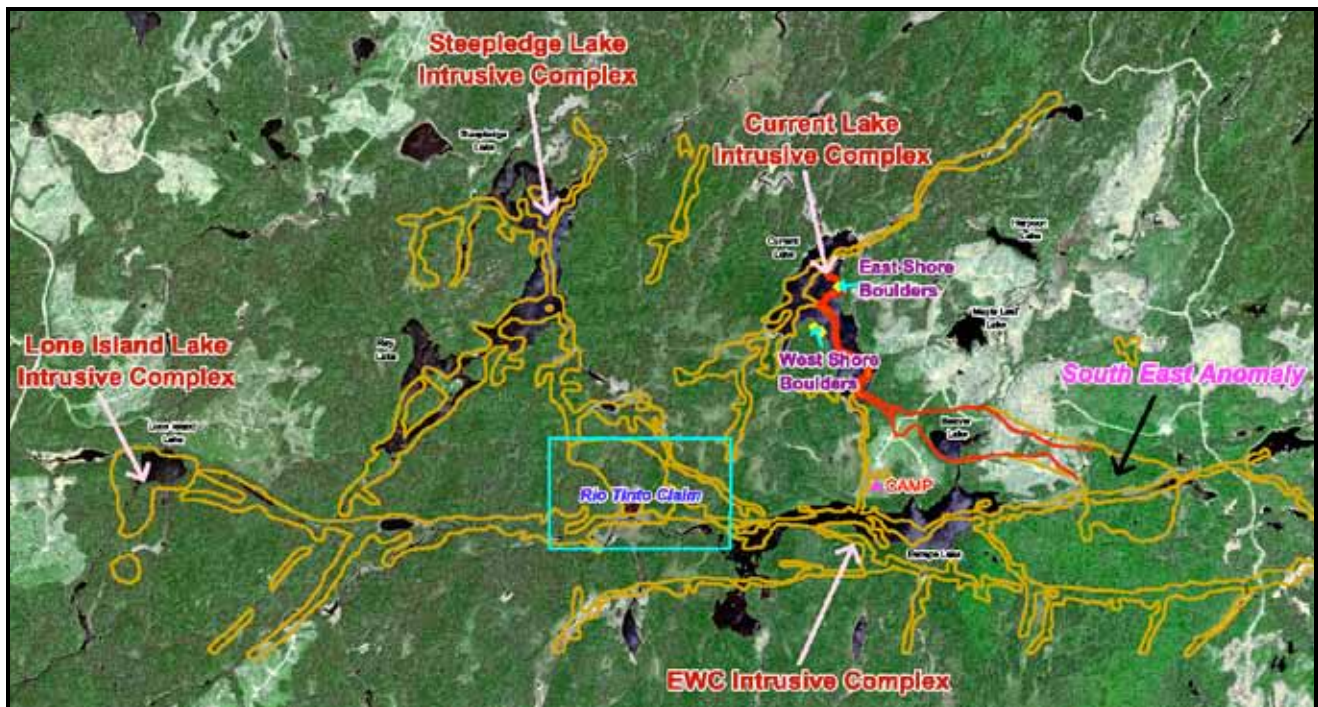


Figure 1. Plan map overview of the TBN-Complex as defined by diamond drilling and airborne magnetics. Outline of the igneous complex shown in orange, mineral resource in red.

in drill core. Macro-structural controls (Fig. 2) include the east-west trending Quetico fault which defines the boundary between Archean metasedimentary rocks to the south and anatectic granites to the north. This structure provides a zone of weakness for the intrusive complex to develop along. Exfoliation and horizontal joints in the Archean rocks provide vertical discontinuities for the lateral development of sills. Regional conjugate joint sets and faults in the texturally homogeneous anatectic granite provide a network of rheological discontinuities that were exploited during the development of chonoliths.

Of the micro-structural controls, fault zones and zones of decreased rock quality are identifiable in the host rocks. The development of invasive magma fingering into these incompetent structural breccias are strong evidence for the influence of pre-existing structure controlling the emplacement, progressive development and final morphology of the intrusions. The progressive development and morphology of the complex influence magma flow dynamics, which in turn effect particle settling and the distribution of fluid load, specifically the distribution of immiscible sulfides and crystal accumulation.

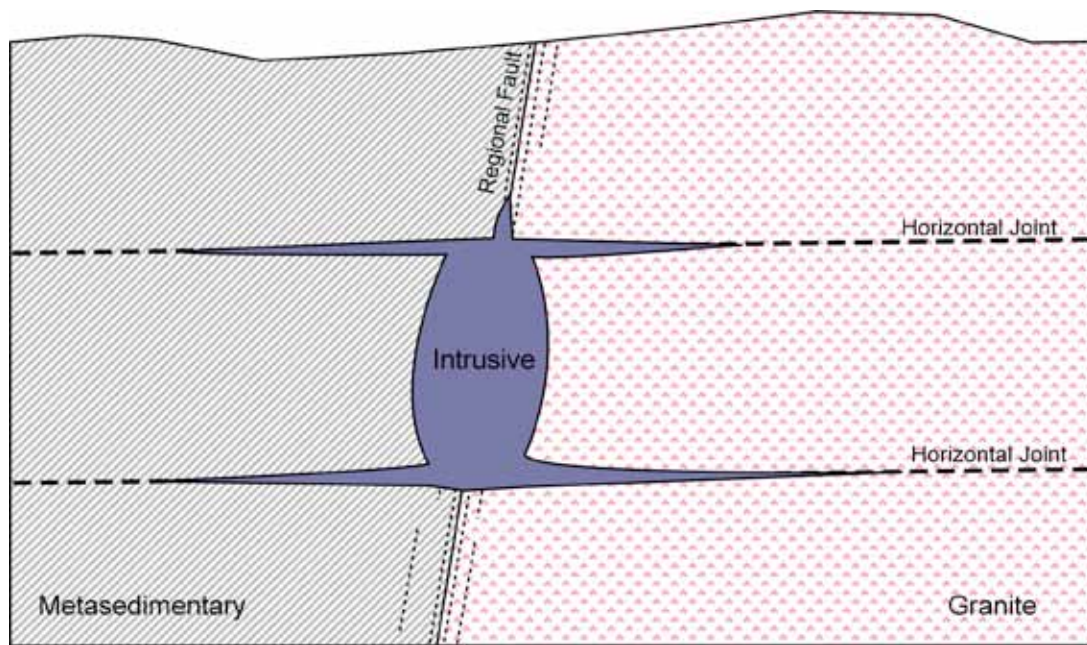


Figure 2. Idealized schematic cross-section showing differing structures controlling the morphology of intrusions.

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Preliminary Bedrock Geology Map of the Eastern part of Lake Vermilion State Park, St. Louis County, NE Minnesota

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Each year, students from the Precambrian Research Center (PRC) geology field camp complete “capstone” projects that encompass approximately one week of detailed field mapping followed by one week of mapmaking and map publishing. During the fifth and sixth weeks of the 2011 field camp, seven PRC field camp students, under the direction of PRC Faculty member George Hudak, mapped Neoarchean rocks in the eastern half of Minnesota’s newest state park, Lake Vermilion State Park (Heim et al., 2011). This capstone mapping project sought to: 1) identify the lithologies and stratigraphy of the Neoarchean supracrustal strata in this area; 2) define and characterize the nature of the contact between various units of the Neoarchean supracrustal strata and intrusive rocks; 3) obtain a better understanding of geological structures and their orientations within the area; and 4) to complete field mapping which will result in a comprehensive bedrock geological map for future use by employees of, and visitors to, Lake Vermilion State Park.

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

In the area mapped, the Neoarchean supracrustal rocks consist of a NE/SW striking, NW facing homoclinal sequence comprising several distinctive volcanic and sedimentary sequences, synvolcanic and post-volcanic intrusive rocks, and sheared rocks adjacent to post-volcanic deformation zones. Up-section, these sequences are:

(1) the Fivemile Lake Sequence of the Lower Member of the Ely Greenstone Formation, which is composed of; a) light bluish green to green, aphyric to sparsely plagioclase-phyric, highly amygdaloidal sheet flow - and pillowed facies andesite and basalt; b) medium-bedded to massive andesite to basalt tuffs and lapilli tuffs; c) grayish-green, aphyric to quartz-phyric coherent rhyolite lava flows and associated flow breccias; and d) green to tan, massive polymict breccias comprising up to 20cm diameter clasts of pumice, scoria, and/or amygdaloidal basalt/andesite;

(2) the Central Basalt Sequence of the Lower Member of the Ely Greenstone Formation, which is composed of medium green to dark green, aphyric to sparsely plagioclase-phyric, sparsely amygdaloidal sheet flow - and pillowed facies basalt lava flows which are locally strongly quartz-epidote altered;

(3) the Soudan Member of the Ely Greenstone Formation, an interbedded sequence comprising: a) laminated to medium-bedded, planar-bedded, locally chaotically folded, dark gray to red-brown, Algoma-type oxide facies iron formation; b) medium- to dark green, aphyric to locally sparsely plagioclase-phyric, massive to moderately amygdaloidal andesite to basalt sheet flow facies lava flows; c) gray to gray green, massive quartz ± plagioclase-phyric rhyodacite tuff; and d) light gray, massive polymict lapilli tuffs comprising up to 5% quartz- and plagioclase-phyric coherent rhyodacite lapilli and 10-15% dark green chlorite-rich lapilli interpreted to be chloritized pumice;

(4) the Gafvert Lake Member of the Lake Vermilion Formation, which is composed of; a) a basal unit

comprising light gray, massive, polymict volcanoclastic conglomerates and sandstones; b) light gray, massive, quartz- and plagioclase-phyric polymict dacite to rhyodacite tuff and lapilli tuff containing up to 20% quartz- and plagioclase-phyric coherent dacite and rhyodacite lapilli and up to 7% locally quartz- and plagioclase-phyric pumice lapilli; c) light gray, massive, quartz- and plagioclase-phyric tuff and lapilli tuff containing up to 15% subangular quartz- and plagioclase-phyric pumice lapilli; d) gray, thinly-bedded to massive tuff breccias with poorly developed graded bedding; e) red to dark gray, laminated to medium bedded oxide facies iron formation; and f) light gray to black laminated to very thinly bedded chert.

Numerous sills and dikes intrude the supracrustal assemblage in the area. Intrusive bodies which appear to be synvolcanic include a) grayish green to black, medium-grained, locally ophitic gabbro; b) gray to gray-green, medium-grained diorite; and c) light gray, massive, quartz- and plagioclase-phyric diorite and quartz-diorite characterized by euhedral blue-gray quartz phenocrysts up to 1cm in diameter. Post-volcanic intrusive rocks identified include: a) pink to green-gray medium-grained hornblende diorite; b) light gray to pale green gray, quartz- and plagioclase-phyric diorite to quartz diorite sills and dikes; and c) light gray, fine- to medium-grained feldspar-phyric diorite. Locally, sericite-dominant schists and phyllites, chlorite-dominant schists and phyllites, and chlorite-rich sheared mafic volcanic rocks occur along discrete ductile to brittle-ductile structures.

Our analysis leads us to interpret the following sequence of events for the development of the bedrock geology visible today in this part of the Vermilion District: 1) deposition of highly amygdaloidal sheet- and pillowed facies andesite and basalt lava flows, felsic lava flows, primary mafic tuffs and lapilli tuffs, and associated resedimented polymict volcanoclastic rocks in a shallow submarine setting (Hudak et al., 2007); 2) deposition of submarine basalt lava flows, comprising both sheet flows and pillowed facies, in a relatively deep water (>500 meters water depth) setting (Hudak et al., 2007); 3) deposition of Algoma-type iron formations of the Soudan Member of the Ely Greenstone Formation as a result of hydrothermal activity during volcanically quiescent periods and deposition of interbedded mafic and felsic volcanic and volcanoclastic strata associated with intermittent volcanism; 4) the onset of voluminous explosive dacitic to rhyodacitic felsic volcanism, alternating with periods of volcanic quiescence characterized by continued chemical sedimentation and localized clastic sedimentation; 5) synvolcanic to post-volcanic intrusion of mafic to felsic sills and dikes; and 4) structural deformation, probably associated with regional D2 deformation (Peterson and Patelke, 2003) that formed the sheared mafic rocks and chlorite schists that occur in the northeastern part of the field area.

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Chert Stromatolites in the Basal Gunflint Formation, Kakabeka Falls: Primary Precipitation or Silicification?

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Modern-day stromatolites primarily form in carbonate-dominated environments through binding particulate matter to the sticky extracellular polysaccharides secreted by the cyanobacteria. Evidence of the operation of this process in constructing stromatolites extends back into the Phanerozoic. However, Precambrian stromatolites do not contain abundant silt- to sand-sized particles characteristic of this process. Instead they are primarily composed of material that has precipitated from seawater. This is commonly a carbonate phase, though chert stromatolites are common in some Proterozoic and Archean sequences. In recent years controversy has developed in the literature as to whether the chert stromatolites in the Gunflint Formation and similar rock units represent silicification of carbonate or are primary silica precipitates (see: Knoll and Simonson, 1981; Simonson, 1985; Knoll, 1985; Siever, 1992; Maliva et al., 2005). Some of this work utilized outcroppings of the Gunflint Formation that are highly diagenetically altered, and thus ambiguous concerning primary mineralogy. Roadwork on Highway 588 near Kakabeka Falls exposed an excellent example of chert microbialites and stromatolites entombed in ankeritic grainstone with a sharp boundary between the two, providing an opportunity to add to the debate on the possible primary origin of the silica in chert stromatolites.

The 1.878 ± 1 Ga Gunflint Formation is a chemical sediment dominated shelf succession deposited on Archean basement. It records a number of transgressive-regressive cycles. Hofmann (1969) and Franklin et al. (1982) described stromatolites occurring at two different stratigraphic levels; at the base of the Gunflint growing on Archean units and the basal conglomerate and secondly, on a hard-ground in the middle of the Formation developed during regression. The basal biogenic sediment at Kakabeka Falls directly overlies Archean granodiorite and consists of a lower one meter thick, continuous chert microbialite. The millimeter-scale, crinkly layering is sub-horizontal, with organic carbon only giving the unit a dark colouration in limited places. A large stromatolitic head develops off the upper microbialite layers. It is the size of a beach ball, with a slightly narrower base. There appears to be a sharp contact between the microbialite-stromatolite and carbonate grainstone, which overlies the microbialite and abuts against the stromatolite. The layering in the stromatolite does not build on top of the lower grainstone laminae, indicating that the stromatolite was fully grown before the grainstone entered the environment.

Samples of all lithologies were investigated with a petrographic microscope, a field emission scanning electron microscope with an energy dispersive spectrometer, inductively coupled plasma atomic emission spectrometry and mass spectrometry.

The diagenetic history is more complex than it appears to the naked eye. The stromatolite contains abundant microquartz, megaquartz, chalcedony, and organic matter. The silica is rather clean and well developed with little to no carbonate inclusions or ghosts. Carbonate present in the stromatolite is seen replacing chalcedony fans. Distinct growth zones can be seen in the outer portions of the carbonate. Rarely, quartz crystals present in the stromatolite show carbonate overprinting, replacing them to varying degrees. Carbonate is visible replacing megaquartz grains and overprinting microquartz as very fine grained specular carbonate. Growth zoning is present in most of the carbonate grains. The carbonate grainstone unit overlying the stromatolite has been highly silicified. The quartz is texturally similar to the quartz in the stromatolite; microquartz and megaquartz are abundant with minor amounts of chalcedony. The megaquartz is seen in the intergranular spaces as space-filling cement. Higher magnification shows extinct carbonate grains that have been silicified with small amounts of carbonate remaining behind. However, further from the contact with the stromatolite the carbonate grainstone unit is silicified to a much lower degree. Some of the carbonate grains have experienced some silicification,

but the rock is mainly composed of carbonate with some organic material. Silica in the form of microquartz is forming within the carbonate grains. A closer observation reveals that the quartz developing in the carbonate grains is itself being over-printed by carbonate growth. The carbonate grains have growth zoning in their outer portions. Rare earth element plots for the ankerite and chert are generally similar, though this probably reflects both inheriting the seawater pattern. The most striking difference between the two lithologies is the Ba/Sr ratio. The stromatolitic cherts have one consistent ratio, whereas the carbonates and known replacement cherts from the area have a different consistent ratio. All of the above is consistent with the microbial and stromatolitic cherts being a primary precipitate, but it is not conclusive. If the silica is primary new models will need to be developed to explain how Precambrian cherty stromatolites form.

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The Minnesota Taconite Workers Health Study: Environmental Study of Airborne Particulates - 2012 Update

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

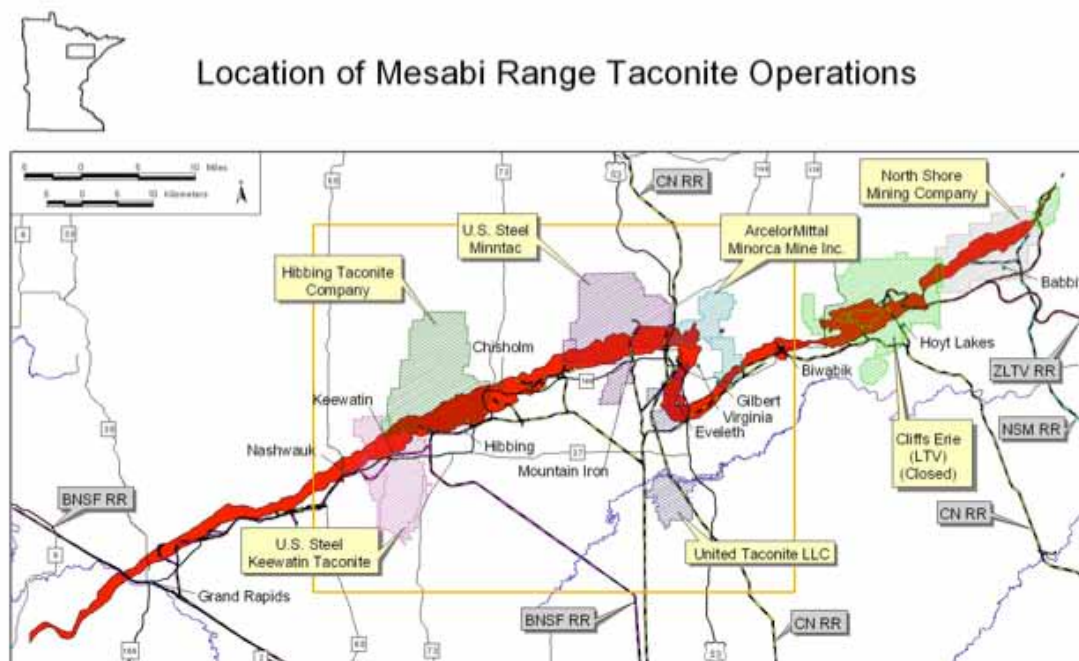


Figure 1. Locations of taconite processing plants on the Mesabi Iron Range being sampled during this study (after Oreskovich and Patelke, 2006)

Air sampling is performed within taconite operations, MIR communities, and non-MIR communities by NRRI scientists during both winter and summer seasons. Sampling at taconite operations takes place at four locations: 1) secondary crushers; 2) magnetic separators/concentrators, agglomerators/ ball drums, and the kiln/ pellet discharge area. Sampling within MIR communities takes place on the rooftops of public buildings, whereas sampling in non-MIR communities occurs on rooftops or in remote locations so that background air quality can be evaluated. Airborne particles are collected using 1) a micro orifice uniform deposit impactor (MOUDI) (Marple et al., 1991), which enables size-fractionated particulate matter collection, and 2) a total suspended particulate filter (TSP). Particulate matter is evaluated via gravimetric analysis and subsequently subjected

to comprehensive particulate matter characterization that includes: 1) scanning electron microscopy (SEM) imaging; 2) energy dispersive spectroscopy (EDS); 3) electron backscattered diffraction (EBSD); 4) proton induced x-ray emission (PIXE); 5) the Minnesota Department of Health's 852 Method Transmission Electron Microscopy (TEM) Analysis for Mineral Fibers in Air; and 6) the International Standard Organization's Method 10312 Ambient air – Determination of Asbestos Fibers – Direct-Transfer TEM Method (ISO 10312, 1995).

Over the past year, the NRRI has completed particulate matter sampling within MIR taconite operations, MIR communities, and non- MIR communities. This includes 14 sampling events at taconite operations and 79 sampling events at locations within communities in northeastern Minnesota (73) and Minneapolis (6), as summarized in Table 1. Continued analysis of lake sediment samples from “North of Snort Lake” indicates collection of sediment dating back to ~1840, which pre-dates iron mining on the MIR. At Silver Lake, logging activities in the early part of the 20th century disrupted the sediments; however, we believe we will have good post-1915 lake sediment data, which will mark the period where the transition from natural ore to taconite mining took place. Continued analysis, interpretation and reporting will take place in 2012.

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

In-Plant Sampling Events			
<i>Taconite Facility</i>	<i>Sampling Events</i>	<i>Taconite Facility</i>	<i>Sampling Events</i>
United Taconite	2 events while active	Keetac	1 event while active, 1 event while inactive
Hibbing Taconite	1 event while active, 1 event while inactive	Northshore	1 event while inactive, 3 events while active
Minntac	1 event while active	Minorca	3 events while active
Community Sampling Events			
<i>Community Sampling Location</i>		<i>Sampling Events and Number per Season</i>	
Keewatin Elementary School		7 Events (3 Winter / 4 Summer)	
Hibbing High School		9 Events (4 Winter / 5 Summer)	
Virginia City Hall		10 Events (5 Winter / 5 Summer)	
Babbitt Municipal Building		16 Events (7 Winter / 9 Summer)	
Silver Bay High School		13 Events (4 Winter / 9 Summer)	
Ely Fernberg Site		6 Events (3 Winter / 3 Summer)	
Duluth NRRI Rooftop		12 Events (7 Winter / 5 Summer)	
UMN Mech. Eng. Rooftop		6 Events (3 Winter / 3 Summer)	

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Bedrock geologic map of the Crane Lake and Brule Narrows 30'X60' quadrangles, Quetico subprovince, northern Minnesota

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The Crane Lake-Brule Narrows map portrays a complex history of sediment deposition, multiple intrusive events, and several periods of deformation and metamorphism. It lies within the Quetico subprovince of the Archean Superior Province (Fig. 1, small inset). The bedrock consists of biotite-plagioclase schist, granitoid and minor mafic intrusions, and complex migmatite containing multiple paleosomatic and neosomatic components. The schist was derived from graywacke and pelitic sediments deposited ~2695 Ma in an accretionary prism during early stages of collision between the Wawa subprovince island arc to the south, and the evolving Superior superterrane to the north. Later stages of this D_1 collisional event produced tilting, broad nappe structures, and

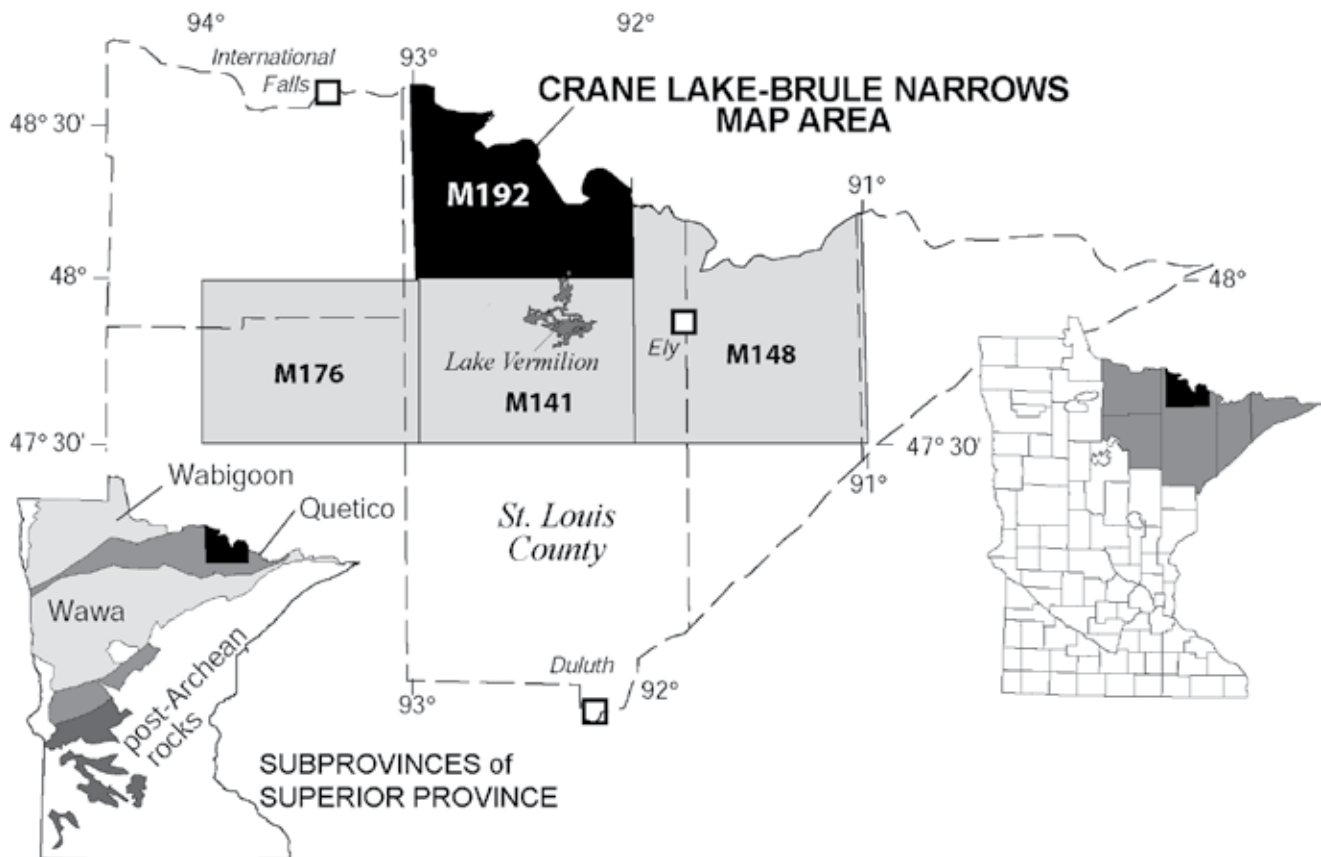


Figure 1. Location and regional geologic setting of Crane Lake-Brule Narrows map (MGS miscellaneous map M-192). Adjacent 1:100,000-scale maps recently published by MGS are numbered: Bigfork (M-176); Vermilion Lake (M-141); Ely-Basswood Lake (M-148).

thrust imbrication of volcanoplutonic rocks in subprovinces north and south of the Quetico subprovince, and recumbent folding within the Quetico. An early suite of leucogranite, granodiorite, trondhjemite, and tonalite is interlayered on all scales with biotite schist. This early suite has compositional and approximate temporal similarities with the 2690 Ma Saganaga Tonalite. A second deformation event (D_2) occurred at about 2680 Ma, and produced regional penetrative fabrics, folds, and prograde metamorphism to greenschist and amphibolite facies. A third deformation event (D_3) is manifest in the Quetico subprovince as broad, east- and west-plunging folds of D_2 fabrics (synforms, antiforms), and by faulting. At least part of this deformation was synchronous with migmatization and emplacement of 2-mica leucogranite and a slightly younger, typically red, variably magnetic biotite granite known as the Lac La Croix granite. A U-Pb zircon age of the latter in adjacent Canada

is approximately 2666 Ma, which is consistent with published ages for metamorphism inferred to be related to D₃. The metamorphic grade is more or less symmetrical along the axis of the Quetico subprovince, with greenschist grade at the margins and middle to upper amphibolite facies near the axis. Metamorphism was generally syntectonic with D₂ and D₃; and a contact metamorphic overprint occurs locally adjacent to the Lac La Croix Granite. Bedrock in the western part of the map area is cut by Paleoproterozoic diabasic dikes that constitute the easternmost extent of the ~2076 Ma, Kenora-Kabetogama dike swarm.

The geologic interpretation is based on archived and newly acquired outcrop and geophysical data augmented with geophysical and digital land surface topographic maps. Nowhere in Minnesota is bedrock so pervasively exposed, and a strong correlation is apparent between topography and the structure and composition of bedrock (Fig. 2). For example, large areas of granitic bedrock in the south and east are topographically higher than areas of migmatitic and schist-rich rocks in the north and west. Differential weathering produced curvilinear topographic relief that crudely depicts foliation trends and reveals complex folding. Prominent fractures and faults in all rock types are manifest in linear topographic lows. The aeromagnetic data similarly reflect foliation, folding, and fracture-controlled oxidation. Ground magnetic susceptibility data acquired from lithologically diverse outcrops indicate that granitic components typically produce higher signatures. The new image created by combining these data sources mimics at the map scale the complex magmatic, migmatitic, deformation, metamorphic, and alteration features observed at the outcrop scale.

Mapping was supported by the U.S. Geological Survey STATEMAP element of the National Cooperative Geologic Mapping Program.

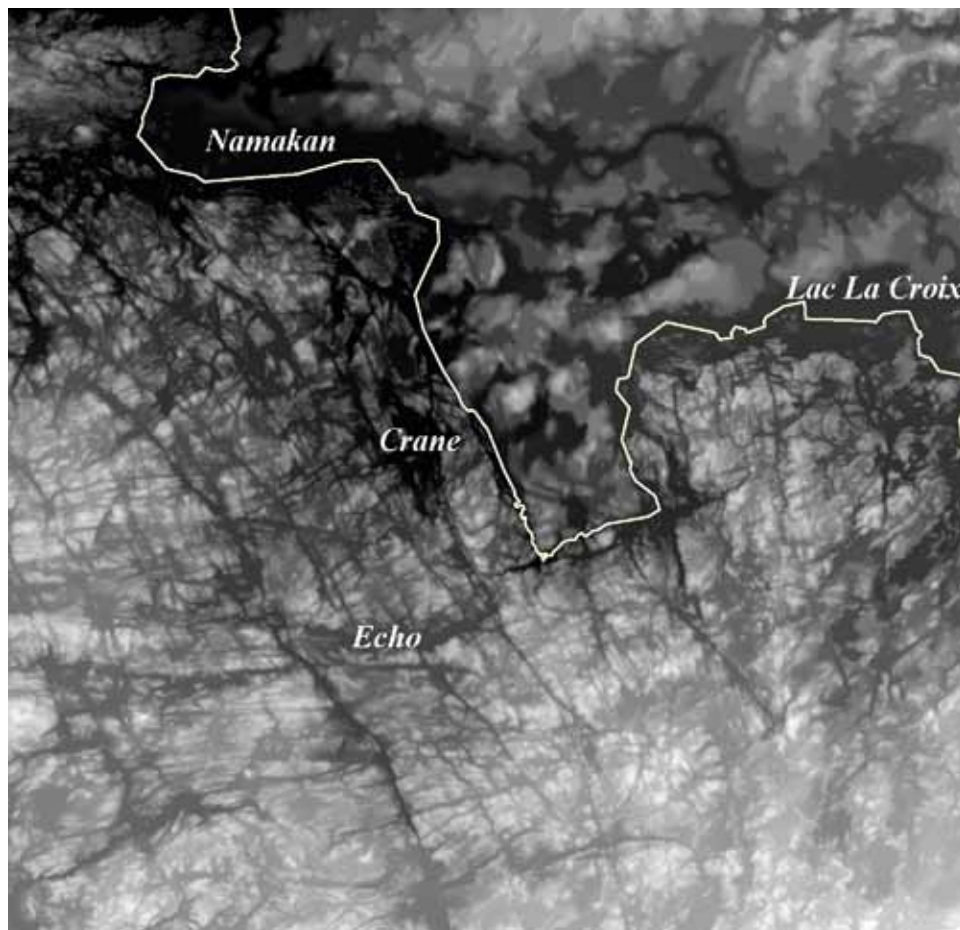


Figure 2. Image of digital land surface topography in the Crane Lake-Brule Narrows area. Highest elevations, international border, and lake names are white.

Reconnaissance geologic mapping of Neoproterozoic rocks in the central Boundary Waters Canoe Area Wilderness by students of the Precambrian Research Center's 2011 field camp.

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The Precambrian Research Center (PRC)—a branch of the University of Minnesota, Duluth—conducted its 5th season of field camp in 2011. The final phase of field training is a “Capstone Project” that provides students an opportunity to create new geologic maps in areas of poorly understood geology. In contrast to detailed mapping that is typical of Capstone exercises, the students in this group were charged with reconnaissance-style mapping in parts of four 1:24,000-scale quadrangles along a 44 mile canoe route in the Boundary Waters Canoe Area Wilderness (BWCAW). The route traversed ~22 lakes (Fig. 1), and a great variety of primarily Archean metavolcanic, metasedimentary, and intrusive rocks. Students mapped shoreline outcrops by canoe, and traced pertinent contacts during short inland traverses and at portages. Much of the area hasn't been mapped in significant detail since J.W. Gruner's work 1927-1938 (published in 1941). Although that work was remarkably detailed for its time, base maps were rudimentary and thus, surface control was uncertain. This project was intended to help place Gruner's work into an accurate geographic context, verify or refute his observations, understand the nature of contacts, and apply modern geological nomenclature and interpretations.

The regional bedrock is part of the Neoproterozoic Wawa subprovince of Superior Province (Fig. 2). Two main suites occur; pillowed volcanic and volcanoclastic rocks of the Newton Lake Formation that are cut by

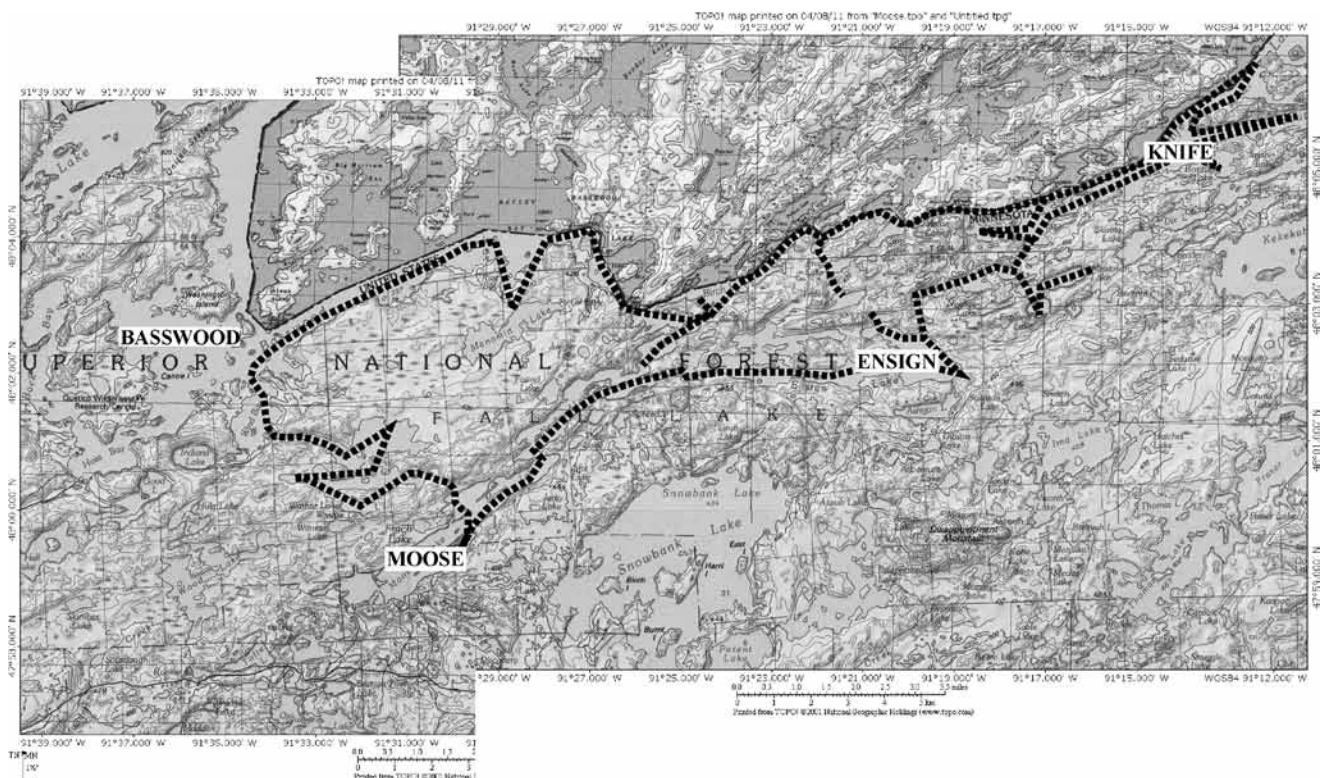


Figure 1. Map of central BWCAW showing route of 2011 geologic mapping (dark dashed line). Some of the larger lakes along the route are labeled.

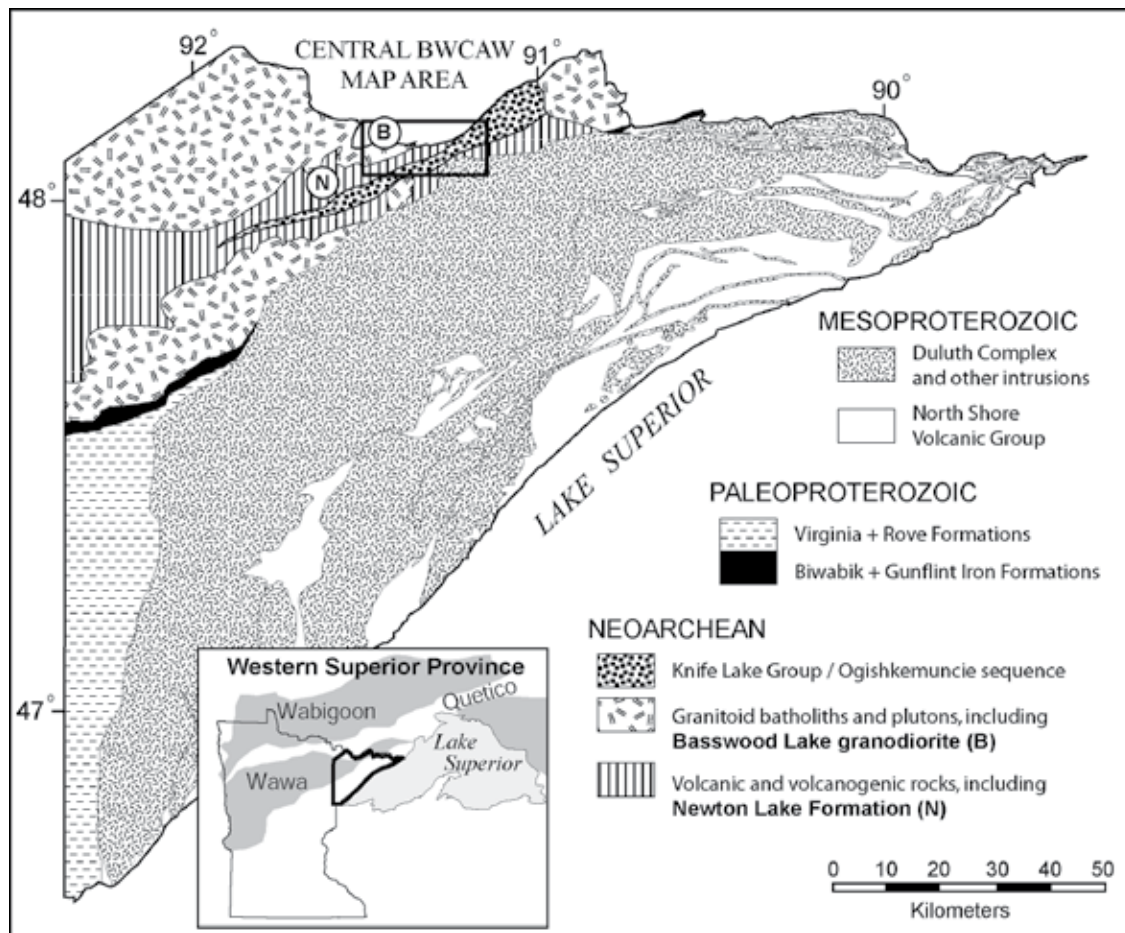


Figure 2. Generalized geologic map of northeastern Minnesota showing map area and geologic entities mentioned in text.

felsic intrusions including the Basswood Lake granodiorite, and sedimentary rocks of the Knife Lake Group that locally contain fragments derived from the Newton Lake and Basswood Lake rocks, and thus are inferred to be younger. The geology is parceled into lozenges of strata having internally consistent stratigraphic relationships, separated by anastomosing shear and fault zones. Offset magnitude on those faults is largely unknown, and correlation of geologic units from one lozenge to another is not always possible. Significant discoveries from the reconnaissance mapping include:

- 1) The presence of iron-formation interlayered with volcanoclastic strata near Moose Lake in a sequence of rocks mapped regionally as the Newton Lake Formation.
- 2) The Basswood Lake granodiorite is compositionally and texturally identical with parts of the 2690 Ma Saganaga Tonalite, and wall-rock relationships are similar, suggesting temporal equivalence.
- 3) Identification of an unconformity and paleosaprolite between metagabbroic rocks likely equivalent to the Newton Lake Formation, and sedimentary strata of the Knife Lake Group.
- 4) Fault-bounded lozenges appear to represent slightly different crustal levels of exposure. For example, the lozenge exposed at Knife Lake was likely uplifted to expose the older, weathered and eroded metagabbroic floor of the Knife Lake Group depocenter.

Geologic maps of all capstone projects can be downloaded or viewed at the PRC website: <http://www.d.umn.edu/prc>.

Geochemistry of mafic dikes from the Carlton Dike Swarm in Minnesota

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The Carlton Dike Swarm (CDS) is a reversely-polarized diabase dike swarm associated with the early-reversal period of the ~1.1 Ga Midcontinent Rift System. The mafic dikes occur west of Duluth centered on Carlton County, MN and are generally oriented rift parallel. Previous characterization of the CDS has been completed by field mapping, petrography, geochemistry and aeromagnetism. Continued characterization of the CDS is being completed to delineate possible subgroups based on structural orientation, mineralogy, texture, geochemistry and geochronology. The four dike subgroups under consideration are (1) the standard CDS diabase dikes described by Green et al. (1987) and Reichhoff (1987), (2) a Ti-enriched set that may be related to the reversely polarized Esko intrusion, (3) an ultramafic-like set described by Boerboom (2009) and (4) the NW-trending orthogonal set. In addition two normally-polarized dikes in Carlton County are included to contrast temporal differences. Detailed characterization studies of rift-related dike swarm intrusions may elucidate temporal-spatial relationships to extrusive and intrusive rocks of the Midcontinent Rift including mineralized, magmatic Cu-Ni chonoliths and Duluth-type intrusions.

Distinct petrographic differences in olivine modes, oxide compositions/modes, phenocryst phases/modes and quench textures are initially being used to delineate subgroups. Based on these criteria, NW-trending dikes have similar petrographic attributes to the standard CDS. The variations of ilmenite and magnetite exsolution and oxidation characteristics are being investigated further to use as a distinguishing factor. Quench textures of chain olivine, Ti-rich augite, plagioclase and ilmenite in the chilled margins of Esko-like dikes are similar to the mineralogy and quench textures found in the upper part of the Esko intrusion. The standard CDS dikes, NW-trending and normally-polarized dikes have chilled margins ranging from glassy to aphanitic. Further comparisons of the chilled margins among subgroups are in progress using whole rock geochemistry and electron microprobe analyses.

Considering the difficulties in age determination for mafic rocks, QEMSCAN[®] is being used to identify possible uranium enriched zirconium minerals. Representative thin sections from each of the proposed subgroups are analyzed at 4 μm intervals with BSE imaging (Fig. 1). Points with a designated brightness (BSE95-150) are further analyzed with EDS to determine the mineralogy. The minerals identified with this technique are zircon, zirconolite, baddeleyite and monazite. For age determination, samples with zirconium minerals greater than 20 μm will be candidates for bulk analysis with ID-TIMS, and samples with grain sizes smaller than 20 μm will be considered for in-situ analysis with SIMS methods designed by Chamberlain et al. (2010). The final selection of grains for in-situ analysis is enhanced by additional high resolution BSE and CL imaging to characterize mineral associations, compositional zoning, intergrowths and overgrowths.

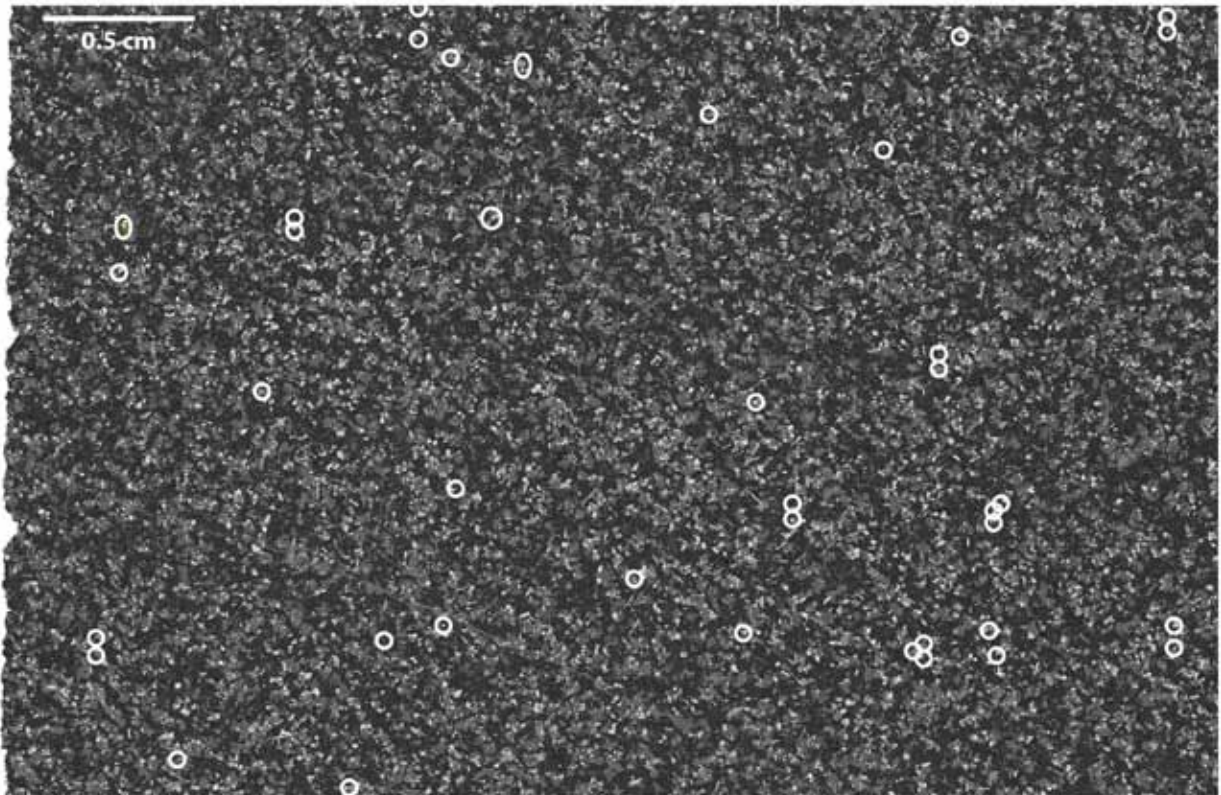


Figure 1. BSE image of NW-trending dike; white circles show locations of zirconium minerals

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Ferromanganese Precipitates in Lacustrine Environments of Northwestern Ontario and Nova Scotia: Effects on Arsenic Concentration

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Freshwater lakes in Northwestern Ontario and Nova Scotia have iron and manganese precipitates growing at the sediment-water interface. The precipitates appear as disc shaped nodules with ringed structures composed of alternating iron- and manganese-rich laminations surrounding a nucleus of a pebble or cobble (Fig. 1). On the surface of some of the structures, micro-columnar stromatolites are formed (Fig. 2). The nodules are often found covered with a thick bacterial mat. Precipitates collected from Lake Shebandowan and Sowden Lake in northwestern Ontario and Lake Charlotte in Nova Scotia have been analyzed. The nodules have revealed extreme naturally concentrated arsenic with values as great as 3500ppm.



Figure 1. A ferromanganese nodule collected from Sowden Lake, Northwestern Ontario



Figure 2. Micro-columnar stromatolites found on the surface of a ferromanganese nodule

To understand such an arsenic concentration, natural environments able to create reduction/oxidation boundaries are being examined. The precipitates are composed primarily of the redox sensitive metals iron and manganese allowing for speculation that arsenic concentration has a relationship with the redox potential of an environment. In a reduced environment, such as some groundwaters, iron and manganese can be transported in solution until reaching an oxidized environment, such as lake water. It is proposed that arsenic will behave similar to phosphorous in a lake environment due to its molecular similarities and valance state, therefore also having an attraction towards metals such as iron (Takamatsu et al., 1985).

Two possible natural redox environments can occur in a lacustrine environment allowing for precipitation of redox sensitive metals. When reduced groundwater comes into contact with oxidized lake water by means of a spring or diffuse flow on a lake bottom, redox sensitive elements can oxidize and precipitate out of solution coating a nucleation point such as a pebble. This is hypothesized to be occurring in the study area in Lake Charlotte and areas of Lake Shebandowan. The concentration of arsenic, by means of this redox method, can be high due to the ability of groundwater to leach a large area and transport ions in solution for long distances, concentrating the dissolved material in the nodules.

The second postulated redox environment involves upwelling of anoxic, deeper lake water carrying redox-sensitive elements to the oxic water in the shallows (Dean et al. 1981). In conjunction with this process, microorganisms concentrate dissolved manganese and iron and upon death are buried in the lake bottom sediment. The anoxic environment in the substrate allows for the reduction of iron and manganese, releasing the soluble reduced forms of these metals into sediment pore waters. These ions then diffuse upward into the lake water, until contact with photosynthetic microorganisms enables re-oxidization and precipitation onto a nucleus, often a pebble (Dean et al. 1981). Continued accretion of iron and manganese will form a nodule. This redox process probably creates ferromanganese precipitates that do not accumulate substantial amounts of arsenic due to lack of a large reservoir that can be leached. It is hypothesized that areas of Shebandowan and Sowden Lake fall into this category.

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Paleomagnetism of the Alkaline Coldwell Complex: New Results, New Insights.

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The alkaline Coldwell Complex is a ≈ 1.1 Ga intrusive complex which is thought to have been emplaced during three different episodes of magmatism. Previous paleomagnetic work by Lewchuk and Symonds (1990) has shown that rocks representing magmatic episodes I and III exhibit reversed (R) magnetizations with mean directions that are significantly different. The rocks representing episode II were characterized by normal (N) magnetizations which are symmetrical with respect to the R magnetizations. Lewchuk and Symonds (1990) interpreted these results as indicating the reversal asymmetry seen in other Keweenawan age rocks is not the effect of a long-standing non-dipole field but the effect of plate motion.

To further investigate the reversal asymmetry question in Keweenawan-aged rocks, we have begun a new paleomagnetic study of the alkaline Coldwell Complex at the Earth Magnetism Laboratory of Michigan Technological University. We are also using the micro-baddeleyite method to refine the ages of the various episodes of Coldwell Complex magnetism, but are only reporting our preliminary paleomagnetic results at this meeting. Six to ten samples were collected from 32 sites along the Trans-Canadian HWY 17 (previously sampled and studied by Lewchuk and Symons (1990)). In addition, we sampled 11 sites north of Marathon and near Middleton.

Characteristic remanent magnetizations (ChRM), in our study, have been isolated by thermal and alternating field demagnetization techniques. Mean paleomagnetic directions have been categorized according to the existing model of the three episodes of magmatism. The mean paleomagnetic directions for episodes I and III have been found to be statistically similar at 95 percent confidence, making these episodes indistinguishable with paleomagnetism unlike the Lewchuk and Symons' study. We will discuss two possible scenarios of the geomagnetic field behavior during the formation of the Coldwell Complex:

1. Multiple reversals $R \Rightarrow N \Rightarrow R$, as recorded consecutively by episodes I, II and III;
2. Single reversal from R to N polarity, where episodes I and III were emplaced at the same time (single episode) or in pulses during a time interval insufficient to result in any difference between the primary ChRM directions.

The normal polarity paleomagnetic direction of episode II appears to be antipodal to both reversed components as well as to the mean direction calculated from all reversely magnetized sites. The reversal test (McFadden, 1990) is positive in classification C for both $R \Rightarrow N \Rightarrow R$ reversals and positive in the same classification for the $R \Rightarrow N$ case.

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Thrust faulting in the Gunflint Formation north of Lake Superior

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New exposure of the Gunflint-Rove contact at the Terry Fox monument north of Thunder Bay reveals several thrust faults that cut through the Sudbury impact layer and into the overlying Rove Formation. This discovery has implications for the timing of thrust-fault deformation here and elsewhere in the area north of Lake Superior. Previously, thrust-fault deformation in the Gunflint Formation was interpreted to be associated with the Penokean orogeny (Hill and Smyk, 2005). However, new observations of thrust faults cutting the impact layer and overlying Rove Formation mean that this deformation is too young to be Penokean.

The thrust faults exposed in this outcrop are mainly small discrete bedding plane faults with few kinematic indicators observed in the hanging wall or footwall. The faults are most visible where they cut across bedding; once identified they can be traced along the outcrop. Thrust faults within the impact layer are identified by slickenlines on fault plane surfaces as well as possible duplication of strata, resulting in localized thickening of the impact layer. The faults can be traced along strike until they are either covered by overburden or cut by a prominent normal fault which displaces all units in the hanging wall down to the south several meters.

The timing of thrust-fault deformation can be constrained based on cross-cutting relationships and published ages of the 1878 Ma Gunflint Formation (Fralick et al., 2002), 1850 Ma Sudbury impact event (Krogh et al., 1984) and the 1832 Ma Rove Formation (Addison et al., 2005).

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Paleomagnetism of the Georgie Lake and Silver Mountain basalts

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A paleomagnetic study of 17 basaltic lava flows exposed in the northern part of the Coldwell Complex, near the Georgie Lake (GL) (Ontario, Canada), and 13 lava flows that crop out on Silver Mountain (SM) (Baraga County, Northern Michigan) has been carried out in order to investigate the paleomagnetic directions of these rocks and to determine their relationship to other rocks of the North American Midcontinent Rift (MCR). The Georgie Lake basalts consist of a series of flat-lying lava flows that overlay gabbros of the northern part of the Coldwell Complex and are assumed to be similar in age (~1108 Ma) to these gabbros. The lava flows at Silver Mountain, a 300 foot-high glacial polished dome-shaped hill, are part of the Siemens Creek volcanics, the lowermost formation of the Powder Mill Group. This sequence of lava flows dip 15 degrees to north-west. Silver Mountain is surrounded by Cambrian and younger sediments as well as glacial deposits.

Six to ten samples were collected from each lava flow at both locations. Well-defined characteristic remanent magnetizations (ChRM) were isolated using thermal demagnetization techniques. Both the GL and the SM CHRM define a reversed (R) polarity magnetization. Mean directions for each flow as well as group means were calculated using standard Fisher statistics. Group mean paleomagnetic directions of GL ($D=109.1^\circ$, $I=-63.1^\circ$, $\alpha_{95}=3.81^\circ$, $K=89$, $N=17$) and SM ($D=107.9^\circ$, $I=-60.4^\circ$, $\alpha_{95}=2.43^\circ$, $K=232$, $N=13$) are statistically indistinguishable after the correction of SM directions for structural tilt. In addition, both the SM and GL mean directions are statistically similar to the published data for reversely magnetized Lower North Shore Volcanics (LNSV) (e.g. Books, 1968; Halls and Pesonen 1982) dated at 1107 ± 1.9 Ma using the U-Pb method (Davis and Green, 1997). Paleomagnetic poles calculated from GL and SM paleomagnetic direction are located at $\text{lat}=42.9^\circ\text{N}$, $\text{long}=206.5^\circ\text{E}$ ($\alpha_{95}=3.6^\circ$) and $\text{lat}=39.8^\circ\text{N}$, $\text{long}=202.8^\circ\text{E}$ ($\alpha_{95}=3.4^\circ$), respectively. These poles fall directly on the eastern arm of the North American Precambrian apparent polar wander path (APWP) (Logan Loop (Robertson and Fahrig, 1971)) and are similar to that calculated for 1107 Ma reversely magnetized LNSV ($\text{lat}=41.5^\circ\text{N}$, $\text{long}=202.7^\circ\text{E}$) at the 95 percent confidence level. Therefore, we conclude that rocks of the Georgie Lake and Silver Mountain represent the earliest stage of rift related volcanic activity. Similarity of paleomagnetic directions and paleomagnetic poles for these sequences suggests no clockwise rotation of Midcontinent Microplate after 1107 Ma, as proposed by Hauser (1996).

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Geochemistry and Petrology of the Dog Lake Granite Chain, Quetico Basin, Northwestern Ontario

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The Dog Lake Granite Chain is composed of six ovoid magnetite-bearing granitic intrusions within the Quetico Basin, Northwestern Ontario (Fig. 1). From east- to west the intrusions have been termed the Penasen Lake, White Lily, Barnum Lake, Trout Lake, Silver Falls, and Shabaqua intrusion. These granites have been mapped previously as syn- to post-tectonic, massive to foliated granite/granodiorites (Ontario Geological Survey, 2006). Of the intrusions, only the Barnum Lake intrusion has been studied in detail and was classified as a homogenous quartz-monzonite with lesser amounts of syenite and gabbroic phases (Steinert, 1975; Kelhenbeck, 1977). The Dog Lake Granite Chain displays a linear trend, which parallels the tectonic boundary between the Wawa-Abitibi terrane to the south, and the Quetico Basin to the north.

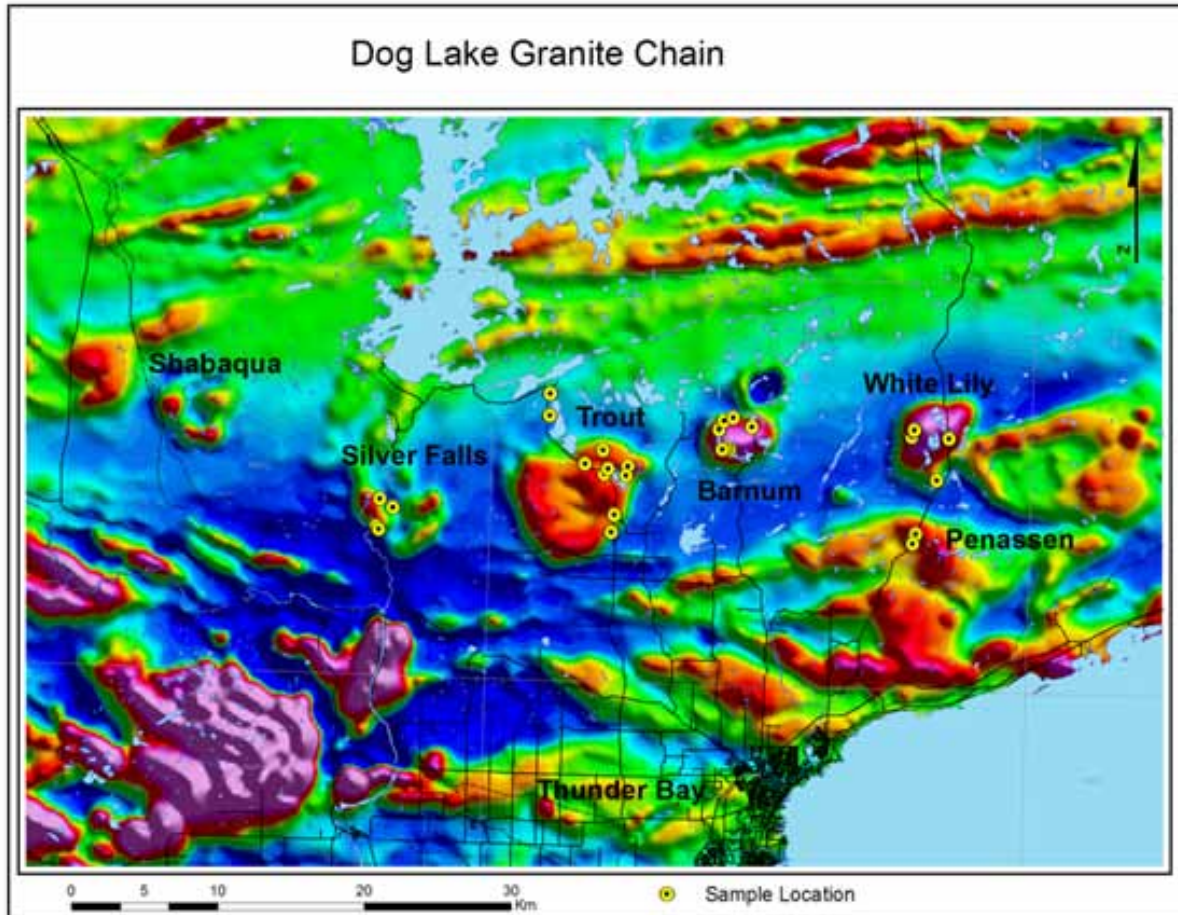


Figure 1. Aeromagnetic map of the Dog Lake Granite Chain (modified from Ontario Geological Survey, 1999)

Petrologic and geochemical data has been used to classify the granites as both I- and S-type. The I-type granites can be classified into three broad groups a microcline-phyric monzonite/quartz-monzonite, syenite/quartz-syenite, and a monzodiorite. These granites are massive, silica poor, largely metaluminous, and characterized by a hornblende+ magnetite+ sphene +/-pyroxene assemblage. The microcline-phyric monzonite/quartz-monzonite and syenite/quartz-syenite groups are characterized by a positive ϵ_{Nd} (+1.44 to +2.11). The I-type granites have

been recognized within the Trout Lake, Barnum Lake, White Lily, and Penasen Lake intrusions.

The S-type granites are typical of the Quetico Basin, and have a largely peraluminous affinity, variable ϵ_{Nd} signatures (-1.44 to +1.09), and are characterized by a muscovite+ biotite+/- garnet assemblage. The S-type granites have been sampled within the Silver Falls, Trout Lake, and White Lily intrusions.

The recognition of I-type granites within the Quetico Basin, which is predominantly composed of S-type granites requires a different model for the formation of this relatively rare rock type. It is suggested that the formation of I-type granites within the Quetico Basin involves the partial melting of the mantle wedge beneath the Wawa-Abitibi island arc. The mafic melt would have underplated the Archean lithosphere possibly near the contact between the Wawa-Abitibi terrane and the Quetico Basin. The mafic melts would then have evolved into granitic melts through fractionation, thus giving rise to the I-type granites. Small volumes of these melts were then emplaced within the Quetico Basin, possibly along weaknesses associated with lithosphere scale structures at the boundary between the Wawa-Abitibi terrane and Quetico Basin. The majority of the underplated melts may also have aided in the production of large S-type granites, which are typical of the Quetico Basin. These S-type melts formed from the melting of sedimentary rocks, and may have interacted with the I-type granites, producing variations in isotopic and geochemical signatures as seen within the S-type granites of this study.

Although magnetite-bearing granitic intrusions within the Quetico Basin are not unique, the identification and classification of I-type granites has not been widely documented. The regional implication of I-type granites within the Quetico Basin is both profound and complex. It is suggested that other magnetite-bearing metaluminous granites within the Basin (e.g., the Vermillion complex, northern Minnesota) may have formed through a similar processes as the Dog Lake Granite Chain.

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Bedrock Geologic map of the Seine Bay/Bad Vermilion Lake intrusion, Mine Centre, Ontario

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The Seine Bay-Bad Vermilion Lake Intrusion (SB/BV) is a layered plutonic sequence of gabbroic rocks exposed along the shores of Seine Bay (Rainy Lake) and Bad Vermilion Lake in Northwest Ontario, Canada. It is approximately 14 km long and 1-3 km wide, stretching along the northern shores of Seine Bay in the southwest and Bad Vermilion Lake in the northeast with the town of Mine Centre marking its northeast tip. The SB/BV lithologically consists of a layered mafic intrusive package of anorthositic to gabbroic to pyroxenitic rocks with layers/lenses of semi-massive and massive oxides that have been significantly altered and possibly metamorphosed. The intrusion occurs between a hanging wall of felsic intrusive rocks at its northern contact and a footwall of mafic volcanic rocks at its southern contact. The nature of these contacts and the relative magmatic history of each unit are currently poorly known.

Although gold has historically been the primary focus of mineral exploration in the Mine Centre area, deposits of iron, titanium, copper, nickel and zinc have been identified in recent years by various junior exploration companies (Hinz et al., 2010). Lode gold, magmatic Cu-Ni-PGE, magmatic Fe-Ti-V, and pyroclastic-hosted diamond deposits in the Mine Centre area are currently being evaluated for economic viability. Numax Resources, Inc. (Numax) holds 45 contiguous mineral claims totaling 5,188 ha in the Kenora Mining Division, covering the length of the SB/BV. While the Mine Centre property was somewhat inactive for decades, Numax's 2004 field season saw a jump in activity including prospecting, diamond drilling, trenching, channel sampling,

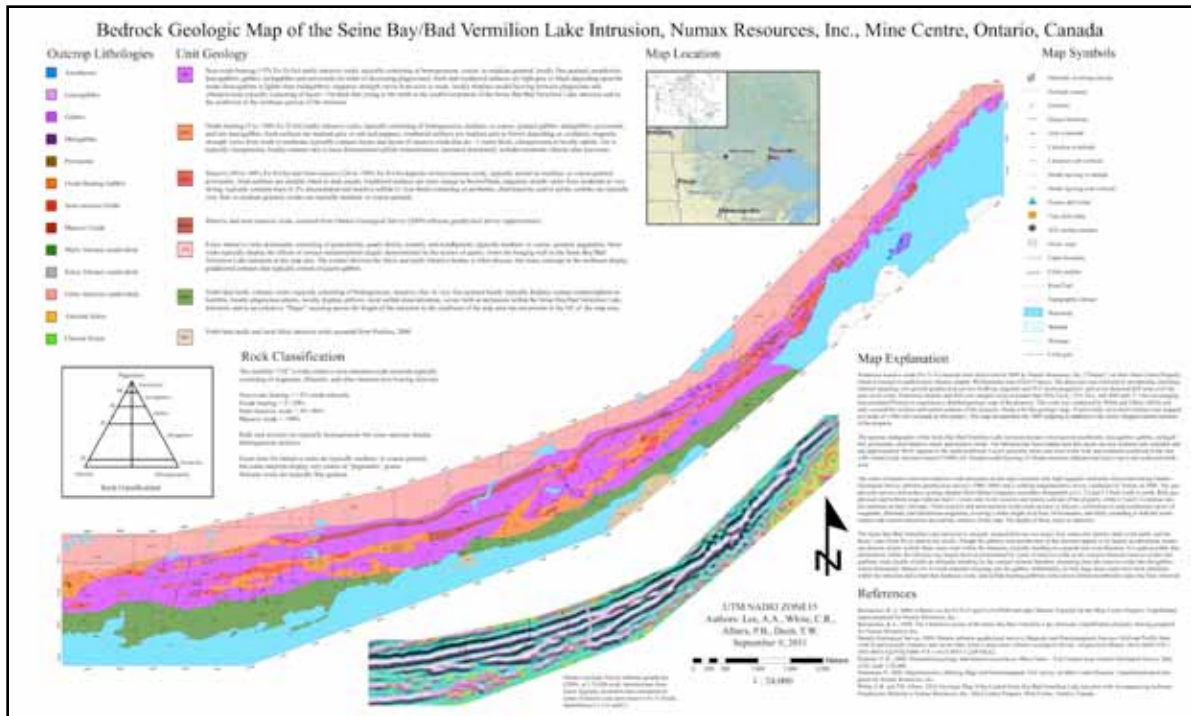


Figure 1. Bedrock Geologic Map of the Seine Bay/Bad Vermilion Lake Intrusion, Numax Resources, Inc., Mine Centre, Ontario, Canada. Compiled and finalized by A. Lee, this map was generated with data collected by A. Lee during the summer of 2011 and by P. Albers and C. White during the summer of 2009. (Lee et al., 2011)

field sampling, and two ground geophysical surveys (magnetic and electromagnetic). In 2009 Numax contracted Paul Albers and Chris White to conduct geologic bedrock mapping at 1:5000 scale and detailed trench mapping at 1:400 scale across the southwest portion of the property (Albers and White, 2010). In the summer of 2011, Aubrey Lee with assistance from Tobin Deen was recruited to map the northeast portion of Numax's property at 1:5000 scale. A total of 83 hand-samples were collected during Lee's mapping and have subsequently been geochemically assayed and cut into thin-sections. This field work and the sample suite constitute the basis for Aubrey Lee's MS thesis at UMD.

Recent geologic mapping of the SB/BV has illustrated that massive, semi-massive and disseminated oxide layers containing significant Fe-Ti mineralization exist within the intrusion (Lee et al., 2011). These layers are generally persistent along the strike of the intrusion, but may anastomose and bifurcate, as indicated by bedrock mapping, magnetic surveys, and drill core. The layers are typically hosted by pyroxenite and contain the oxides magnetite and ilmenite. Titaniferous magnetite may also be present. Oxide-rich layers range in width from a few centimeters to over 20 meters and number dozens. They dip sub-vertically and likely extend along with the host intrusion to a considerable depth. Magnetic surveys of the Mine Centre area reveal three distinct magnetic highs extending the length of the intrusion and merging in the northeast where the exposure of the intrusion narrows along Bad Vermilion Lake. It is also unknown how many massive Fe-Ti oxide-rich layers exist within the intrusion. Drill core from three holes drilled by Numax establish the lateral continuity of the layers along the strike of the intrusion.

The principal objectives of this study are to characterize the lithologic, petrographic, and geochemical attributes of the SB/BV through analyses of hand samples, channel samples, and drill core from three widely spaced traverses across its stratigraphy. The research goals are three-fold: 1) to establish the lithologic and chemical stratigraphy of the intrusion so as to delineate the history of emplacement and crystallization within the magma chamber; 2) to fully characterize the mineralogic, textural, and chemical attributes of the Fe-Ti oxide-rich layers with the goal of documenting their composition and understanding their origin; and 3) to assess the history of sulfide saturation in the intrusion so as to evaluate the potential for precious metal mineralization. More specifically, the research will address the following questions: 1) Recognizing that the formation is a gabbroic layered intrusion that has been significantly altered, deformed, and possibly metamorphosed, what are the original igneous rock types that comprise the intrusion?; 2) How many massive Fe-Ti oxide-rich layers exist within the intrusion, how do they compare in mineralogy, texture and chemistry, what is the nature of lateral and vertical variations of the layers, and which layers contain the highest, most homogeneous Fe, Ti, V, and P content?; 3) Was the cyclically layered gabbroic sequence formed in a closed system or was it affected by multiple magma pulses into the chamber, and what mechanism acted to concentrate multiple layers of massive oxides?; 4) What was the parental magma composition of the intrusion?; 5) What is the nature of the contact between the mafic intrusion and the felsic rocks at its top and the basaltic rocks at its base and what do these relationships reveal about the magmatic history of these rock units?; and 6) What is the potential for PGE reef-style mineralization?

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Granitic saprolites in the Lake Superior region: K-metasomatism, intensity vs. magnitude of weathering, and estimates of atmospheric pCO₂

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Paleosols provide insights into past climates, atmospheric compositions, and the role of terrestrial biomass in weathering processes. A geochemical comparison of nine granitic paleosols in the Lake Superior region (Table 1), ranging in age from 2690 to 100 Ma, has been undertaken to evaluate weathering conditions in the region over time.

Table 1. Characteristics of selected granitic saprolites in the Lake Superior region

Locality	Age, Ma	Overlying Formation	Saprolite Protolith	Saprolite Depth, m	max PIA ¹	max MW ²	K ³	pCO ₂ × PAL ⁴	paleo-latitude
Saganaga	2690	Ogishkemuncie	tonalite	<47.4	70.5	<16	<2.2	<137	25° N
Pronto	2450	Matinenda	granite	13.4	97.7	6.2	2.0	11	40° N
Ville Marie	2450	Lorrain	granite	7.6	99.6	8.6	1.1	4.5	40° N
McGrath	~2200	Denham	gneiss	n.d.	93.0	n.d.	n.d.	n.d.	10° N
Baraboo	1700	Baraboo	granite	7.9	96.5	4.3	0.7	6.4	50° N
Sibley	1500	Pass Lake	granite	5.6	90.3	2.3	1.0	12	25° N
Monticello	500	Mt. Simon	tonalite	2.2	94.9	2.1	0.3	2.5	10° S
EC MN	100	Cenomanian	granite	>34.7	97.9	>36	-2.3	6.8	40° N
SW MN	100	Cenomanian	gneiss	>33.8	98.8	>22	-2.1	6.8	40° N

¹PIA, Plagioclase Index of Alteration: $100 \times (\text{Al}_2\text{O}_3 - \text{K}_2\text{O}) / (\text{Al}_2\text{O}_3 + \text{CaO}^* + \text{Na}_2\text{O} - \text{K}_2\text{O})$

²Magnitude of Weathering: integrated loss of SiO₂+MgO+CaO+Na₂O+K₂O (moles/cm²)

³integrated change in K₂O (moles/cm²); for Precambrian & Cambrian saprolites, relative to estimated weathered material (see text)

⁴partial pressure of CO₂ times pre-industrial level, calculated for 100,000 years of weathering

n.d., not determined

In A-CN-K diagrams (Fig. 1), the compositions of Precambrian and Cambrian saprolites are displaced markedly from a “normal” weathering trend towards the K apex (except for the Barron saprolite), indicating a substantial degree of K-metasomatism. Such metasomatism precludes use of the Chemical Index of Alteration (CIA) as an indicator of the intensity of weathering. Instead, the Plagioclase Index of Alteration (PIA), which is a measure of plagioclase removal, may be used and yields values >90 for all but the Saganaga saprolite (Table 1).

The % change of oxides was calculated for each saprolite relative to its protolith, taking Al₂O₃ as the immobile constituent. For metasomatised saprolites, K₂O loss was taken to be 75% of Na₂O loss, by analogy with the Cretaceous saprolites and modern day weathering profiles. The magnitude of weathering (MW) is a measure of mass removal and is defined as the loss of SiO₂, MgO, CaO, Na₂O, and K₂O, integrated over the depth of weathering. Although most of the saprolites have comparably high intensities of weathering (PIA >90), the Cretaceous saprolites have appreciably larger magnitudes of weathering compared to the Precambrian and Cambrian saprolites, i.e. MW values of 22 to 36 moles/cm² vs. 2 to 9 moles/cm² (Table 1). The Saganaga

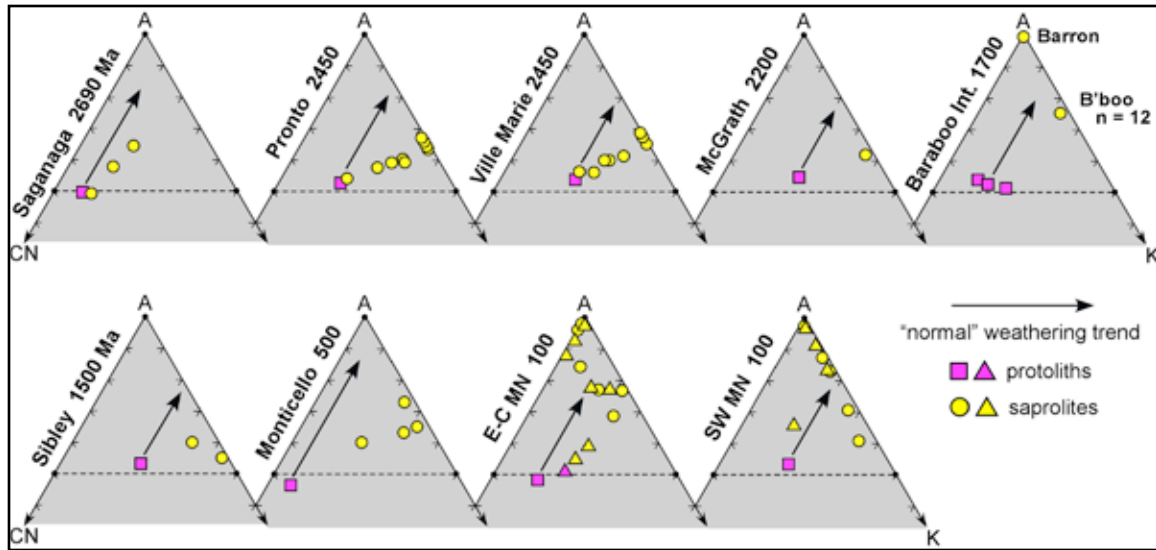


Figure 1. Compositions of protoliths and saprolites in terms of molar Al_2O_3 , CaO^* , Na_2O , and K_2O .

saprolite is an exception to this pattern, most likely due to uncertainty in the depth of weathering.

The mass of K_2O added to the weathered Precambrian and Cambrian saprolites is 0.3 to 2.0 moles/ cm^2 , an amount which is comparable to the mass of K_2O removed by weathering from the Cretaceous saprolites, 2.1 to 2.3 moles/ cm^2 (Table 1).

It is apparent that under high (= modern) atmospheric pO_2 , Fe is retained in most Cretaceous saprolites, whereas in Neoproterozoic and Proterozoic profiles Fe is generally lost, consistent with previous interpretations of lower pO_2 ; the Cambrian Monticello saprolite shows a pattern for Fe loss with depth more like the Precambrian profiles.

Following Sheldon's method (2006, *Precam. Res.*, v. 147, 148-155), pCO_2 has been calculated for the Precambrian and Cambrian saprolites (Fig. 2, Table 1). Among the parameters involved, the MW and duration of weathering are most critical. The uncertainty in duration of weathering may preclude direct comparison of pCO_2 among the individual saprolites, although the results in Figure 2 indicate a generally higher level of atmospheric pCO_2 associated with the Precambrian and Cambrian saprolites compared to the pre-industrial level. Note that the depth of weathering and pCO_2 estimate for the Saganaga saprolite are uncertain.

Despite elevated concentrations of atmospheric CO_2 and low-to mid-paleolatitudes, the Precambrian saprolites have significantly lower MW values than do the Cretaceous saprolites, perhaps reflecting enhanced weathering in Cretaceous time in response to organic compounds contributed by vascular land plants.

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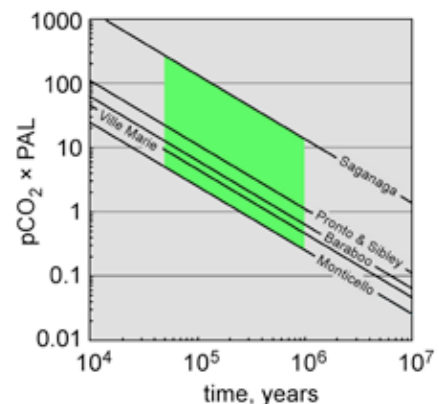


Figure 2. pCO_2 vs. duration of weathering

Mafic intrusions along the southern boundary of the Superior Craton, SD: What is their potential for Ni-Cu-PGE mineralization?

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A significant volume of mafic intrusive rocks is present along the southern margin of the Superior Craton, mainly within the Superior Boundary Zone, in southeastern South Dakota, northeastern Nebraska, and northwestern Iowa (McCormick, 2010). This region of the North America Craton experienced a number of orogenies in the Proterozoic, including the Trans-Hudson, Penokean, Yavapai, and Mazatzal. Most certainly at least three of these have significantly affected the southern margin of the Superior craton in this tri-state region. These intrusions of interest are typically 700 to 900 ft deep. Existing samples of these rocks are limited to the upper few feet of each body with the exception of a fairly well-studied 2890 Ma layered mafic-ultramafic intrusion in northwestern Iowa (Windom et al., 1993), a 1733 Ma metagabbro present just south of the Spirit Lake Tectonic Zone (Van Schmus et al., 2007) in Union County, South Dakota, and an undated mafic intrusion in Clay County, South Dakota near the town of Wakonda. The location of these mafic intrusions along a craton margin, the potentially elevated heat flow over an extended period of time due to the active orogenesis, and the subsequently strong possibility of a mantle contribution to these mafic bodies, suggests the potential for existence of an economic Ni-Cu-PGE deposit within the region. Our objective is to characterize and understand the regional tectonic and metallogenic framework of the southern margin of the Superior Craton in South Dakota and contiguous states in a number of integrated projects focusing on petrologic, geochemical, isotopic, and geochronological studies. We hope to initiate the research through the study of the two 1000 ft cores of the Wakonda intrusion drilled by WMC exploration in 2003/2004.

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Predictive water level and preliminary hydrodynamic models of Caland and Hogarth pit lakes, Atikokan, Ontario.

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Recent limnology studies of the pit lakes on the former Steep Rock Iron Mines property (McNaughton, 2001; Gould, 2008) have shown that Caland and Hogarth pit lakes are meromictic and holomictic, respectively, and that, in general, measured concentrations of sulphate within the lakes are at or above Ontario Drinking Water Standards (ODWS) or Environmental Protection Agency (EPA) Secondary Maximum Contaminant Level (SMCL). Pit lake water quality can be influenced by hydrodynamics. For example, unexpected overturn of a meromictic pit lake can transport dissolved metal laden waters that are toxic to aquatic life to the surface, or where overturn in a holomictic pit lake transports dissolved oxygen down to submerged tailings producing acid mine waters where sulphide minerals exist. Changes in hydrodynamic behavior of Caland or Hogarth will influence whether the water released from the super pit lake will be of good quality or have elevated sulphate concentrations, potentially impacting downstream drinking water sources. Predictions of future water quality in the pit lakes are important to assess the type of rehabilitation efforts, if any, that may be required at the former Steep Rock Iron Mines property with respect to out flowing water quality (Conly et al., 2008; Godwin et al., 2010). This research develops a predictive analytical model of pit lake water level over time that is used to define water volume inputs for the hydrodynamic models. Preliminary hydrodynamic models of Caland and Hogarth pit lakes are designed to assess if the model can accurately simulate current conditions as well as future limnology, as flooding continues and Caland and Hogarth join forming a super pit lake before out flowing into the West Arm Reservoir. Future water quality is assessed by proxy using a linear relationship between water salinity and sulphate concentrations in the Steep Rock pit lakes and data deficiencies with respect to the models are discussed.

The future water levels in the pit lakes are modeled using a void filling approach. The volume of Caland, Hogarth and South Roberts open pits and Fairweather Lake are calculated based on ultimate pit limits and contours based on 1986 aerial photography. The surface area of the pit lakes between the contours is calculated using linear interpolation at a 1 m interval. A water balance for each pit defines the volume of water entering the pits as the sum of precipitation landing on the lakes plus runoff and groundwater minus evaporation from the pit lake surfaces. The surface area of the pit lake and watershed area are variable depending on the accumulated volume in the pit lakes. The model predicts that water from Caland will flow into Hogarth in 2057 and the super pit lake will flow in the West Arm in 2077 or 45 years and 65 years from present day. Compared to the Regional Engineering model for the Steep Rock pit lakes (MNR, 1986), which has proven to be accurate, this study prediction is the same as the Regional Model except this study predicts it will take 8 years longer to completely fill. The methods used to construct the two different models are similar, but this study benefits from a longer data set for meteorological parameters and that the remaining volume capacity of Hogarth pit lake when the two lakes join is taken into account in subsequent water level predictions.

This study was the first hydrodynamic modeling attempted for the Steep Rock pit lakes. The hydrodynamics of Caland and Hogarth are modeled using Dynamic Reservoir Simulation Model (DYRESM) from the Centre for Water Research at the University of Western Australia (www.cwr.uwa.edu.au). DYRESM simulations of current conditions accurately portray the observed limnological characteristics of Caland and Hogarth pit lakes (McNaughton, 2001), including: i) that Caland is meromictic and has a lower salinity relative to Hogarth; and, ii) that Hogarth develops a temporary meromix. Simulations of the two pits joining indicate that Caland's freshwater lens is maintained, but is thinner, and Hogarth pit lake develops a permanent meromix. Simulations of when the pit lakes outflow into the West Arm indicate that Caland maintains its upper freshwater lens and that a fresh water lens is seen in Hogarth is quickly lost when the pit lakes join. In most cases, variations in simulation parameters including additional inflows, alteration of the inflow salinities, and the use of a slower rebound rate to define the

DYRESM water balance only produced minor changes in the simulation.

Based on the linear trend between salinity and sulphate concentrations, the DYRESM salinity profiles suggest that: i) future outflow waters from Caland into Hogarth will have sulphate concentrations ranging from 0 mg/L to 100 mg/L; and, ii) waters that outflow from Hogarth will be toxic with sulphate concentrations ranging from 1700 mg/L to 1900 mg/L. In general, the sulphate concentrations in Caland are below maximum acceptable limit of the ODWS and EPA SMCL, while those in Hogarth exceeded these standards. Simulation results for when the pit lakes outflow suggest that the waters will be toxic. However, results may be influenced by the initial profile used to execute the model due to the short simulation period. Further work will address this issue by lengthening the simulation period and by using different initial profiles of the pit lake water column to assess their influence on the pit lake hydrodynamics. Other limitations to the model that should be addressed in future work include: the ill-defined inflow volumes and chemistry overtime which must be assumed for the length of the simulation period; the availability of information pertaining to site hydrogeology was limited; and, the light extinction coefficient should be measured because the presence of iron oxides influences light absorption in water.

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2011 Precambrian Field Camp Mapping in the Sawbill Lake Area, Cook County, Northeastern Minnesota

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As part of the 2011 Precambrian field camp, a crew of four students, a teaching assistant (Brooker) and an instructor (Miller) conducted five days of field mapping bedrock geology in the Sawbill Lake area of northeast Minnesota. This area is composed of intrusive and volcanic rocks formed during the 1.1 Ga Midcontinent Rift (MCR) in northeastern Minnesota. This year's mapping project expanded on three previous capstone mapping projects conducted to the east (Frost et al., 2007; Blakely et al., 2009; Brooker et al., 2010). These mapping projects have focused on a previously unnamed, well differentiated layered mafic intrusion that forms the western part of the Brule Lake –Hovland gabbro of Miller et al. (2001). This intrusion is now called the Sawbill Lake intrusion (SbLI) since the intrusion is centered and well exposed in and around the large lake. A 1:12,000-scale bedrock geologic map (Asp et al., 2011) generated of a 3 mile by 3 mile area profiles the igneous stratigraphy of the lower two-thirds of the intrusion and the footwall rocks. 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 this intrusion was poorly known. Township-scale outcrop mapping by Grout et al. (1959) showed the area to be dominantly composed of gabbroic to felsic intrusive rocks, mafic volcanic rocks, and minor volcanogenic sedimentary rocks. They noted that the gabbroic rocks are well layered and portions are particularly rich in Fe-Ti oxide. Reconnaissance mapping by Davidson (1972) designated the mafic intrusion as an olivine gabbro unit that he interpreted as an early intrusion relative to granophyric and anorthositic rocks in the area (Davidson, 1977; Davidson and Burnell, 1977). The regional geologic map of northeastern Minnesota, which focused on the geology of the Duluth Complex (Miller et al., 2001), incorporated Davidson's (1972) mapping of the area, but his olivine gabbroic unit is now interpreted to be a relatively late intrusion that is roughly equivalent to the Beaver Bay Complex to the south.

2011 capstone mapping was conducted in the northern half of Sawbill Lake, and reached to the west into Handle and Java lakes and to the north into Ada Lake. Exposures along the shorelines of these waterways provided a nearly complete profile of the lower two thirds of the SbLI as well as a footwall composed of ferrodiorite of unknown affiliation. The internal structure of the SbLI defines a southeast plunging synform with foliation and intermittent layering dipping moderately to the south at the east end and moderately east at the south end.

The igneous stratigraphy of the approximately 1.5 to 3 km-thick intrusion generally defines a progressively differentiated sequence. Unlike the complex mixture of medium-grained, augite troctolite to olivine gabbro and fine-grained, intergranular gabbroic rocks observed at the basal contact during last summer's mapping two miles to the east (Brooker et al., 2010), the basal contact exposed in the Ada Lake area shows well foliated and intermittently layered troctolite and melatroctolite in sharp contact with a well foliated ferrodiorite. This contact is also exposed along the western shoreline of Sawbill Lake, but here melatroctolite is rare. The troctolite grade upward into an medium-grained, moderately foliated augite troctolite (Pl+Ol cumulate) unit which contains 2-3 oikocrysts of ophitic to subophitic augite. Exposed in Ada Creek and through the north central part of Sawbill Lake is the gabbroic unit rich in hornfels inclusions of basalt and volcanogenic sandstone that has been traced over six miles between Sawbill and Homer lakes. This inclusion-rich unit, which is exposed at the north end of Weird Lake, is overlain by a very thick sequence of foliated, intergranular oxide gabbro to olivine oxide gabbro (Pl+Cpx+Ox±Ol cumulate) exposed along the shorelines of northeastern Sawbill Lake. The cm- to m-thick layers in Fe-Ti oxides found in this unit to east are not very abundant in the Sawbill Lake area. Some occurrences of intermingled intrusions of diabase, ferromonzondiorite, and quartz monzonite found to the east were observed in the Sawbill Lake however. that mostly appear to be sill-like. The cumulus arrival of apatite which characterizes

the upper part of the SbLI was not observed in this map area, but was found to the south in the Burnt and Smoke Lake area (see Brooker and Miller, this volume).

Following the 2010 capstone project, Ben Brooker chose to develop an MS thesis project at UMD that would integrated the previous mapping by Grout, Davidson, and the PRC field camp projects and conduct additional mapping to create a complete geological picture of the Sawbill Lake Intrusion. He has conducted petrographic studies of over 200 thin sections to characterize the mineralogic and textural attributes of the main rock types. To document the cryptic variation through the SbLI, he has conducted mineral chemical analyses of olivine and pyroxene from a suite of samples collected along several profiles across the intrusion. As reported elsewhere in this volume (Brooker and Miller, 2012), the main topical objective of this study is to evaluate the genetic relationship between the lower troctolitic cumulates and the upper oxide gabbroic cumulates. Although these rock types could represent the progressive differentiation of a mafic magma, their separation by a screen of volcanic and interflow sedimentary rocks suggests that they may represent two discreet intrusions formed by different parental magmas.

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Supercontinents during the Proterozoic – A paleomagnetic view with Keweenawan data (Lake Superior) as an example.

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The importance of supercontinents in understanding the geological evolution of the Earth has been recently discussed in several articles (e.g., Pesonen et al., 2012, and references therein). Geological processes linked to the existence of supercontinents include concepts such as large igneous provinces (LIPs), mantle superplume events, low latitude glaciations (“Snowball Earth”) and the high obliquity-theory of the rotation axis, carbon isotope excursions, fragmentation of continental dyke swarms, truncations of tectonic belts and major rifts, matching of conjugate orogenic belts, episodic nature of distributions of magmatic activities, discoveries of Precambrian ophiolites and the concept of true polar wander.

Three supercontinent assemblies (Pangaea 350-165 Ma, Gondwanaland 550-400 Ma, Rodinia ~ 1050-750 Ma) have existed during or since the Neoproterozoic. The two younger assemblies have been constructed by sea floor magnetic data (Pangaea), and by palaeomagnetic and biostratigraphic results supported by geology (Gondwanaland). A current debate concerns the relative positions of the continents in supercontinent Rodinia, and the timing of its assembly and breakup. The consequences of supercontinents on geological evolution of the Earth have led some people to look also for pre-Rodinian supercontinents.

In this paper, we use the updated palaeomagnetic database combined with new geological information, to define the positions of the continents during Paleoproterozoic (2.5 - 1.5 Ga) and Mesoproterozoic eras (1.5 - 1.04 Ga). We do the reconstructions relying mainly on isotopically (U-Pb) dated high quality palaeopoles since this method provides strict information of ancient latitudes of the cratons throughout the Proterozoic time. The new database is both geographically and temporally more abundant than any previous database and contains 2813 observations. Before putting the continents to a supercontinent assembly, we have tested the validity of the geocentric axial dipole model (GAD) of the Paleo-Mesoproterozoic geomagnetic field using four methods. The tests yield support to the GAD-model, but do not rule out a ca. 5% non-dipole (octupole) field.

During the Proterozoic, the continents lie predominantly in low to intermediate latitudes. The sedimentological indicators of palaeoclimate are generally consistent with the palaeomagnetic latitudes, with the exception of the Early Proterozoic, when low latitude glaciations took place on several continents. The Proterozoic continental configurations are also in agreement with current geological models of the evolution of the continents. Three large continental landmasses existed during the Proterozoic. The oldest one is the Neoproterozoic Kenorland. The protracted break up of Kenorland during the 2.45-2.10 Ga interval is manifested by mafic dykes and sedimentary rift-basins on many continents. The two Meso- to Neoproterozoic supercontinents are Columbia (known also as Nuna or Hudsonland) and Rodinia, respectively, which were predominantly in moderate to low paleolatitudes during their life span, although during the Paleoproterozoic some parts of Columbia, notably India (Dharwar craton) and Australia (Yilgarn craton), occupied polar latitudes. The pre-Columbia orogenies were due to a complex set of collisions, rotations and transform or strike slip faultings that caused the orogenic belts to appear obliquely. The final amalgamation of Columbia did not happen until ca. 1.53 Ga. Columbia broke up at ca. 1.18 Ga during several rifting episodes, followed by a short period of independent drift of most continents. The youngest assembly is the Meso-Neoproterozoic supercontinent Rodinia, which was formed by continent-continent collisions during ~ 1.10-1.00 Ga and which involved most of the continents. A new model for its assembly and configuration is presented, which suggest that multiple Grenvillian age collisions took place during 1.10-1.00 Ga (Fig. 1). In building up the Rodinia model, the 1.2-1.0 Ga apparent polar wander paths from Laurentia (Keweenawan Lake Superior data), Kaapvaal (Umkondo Igneous Province), Yilgarn (intrusive), dyke data from Baltica and North China, as well data from Siberian sediments are strikingly similar containing a large

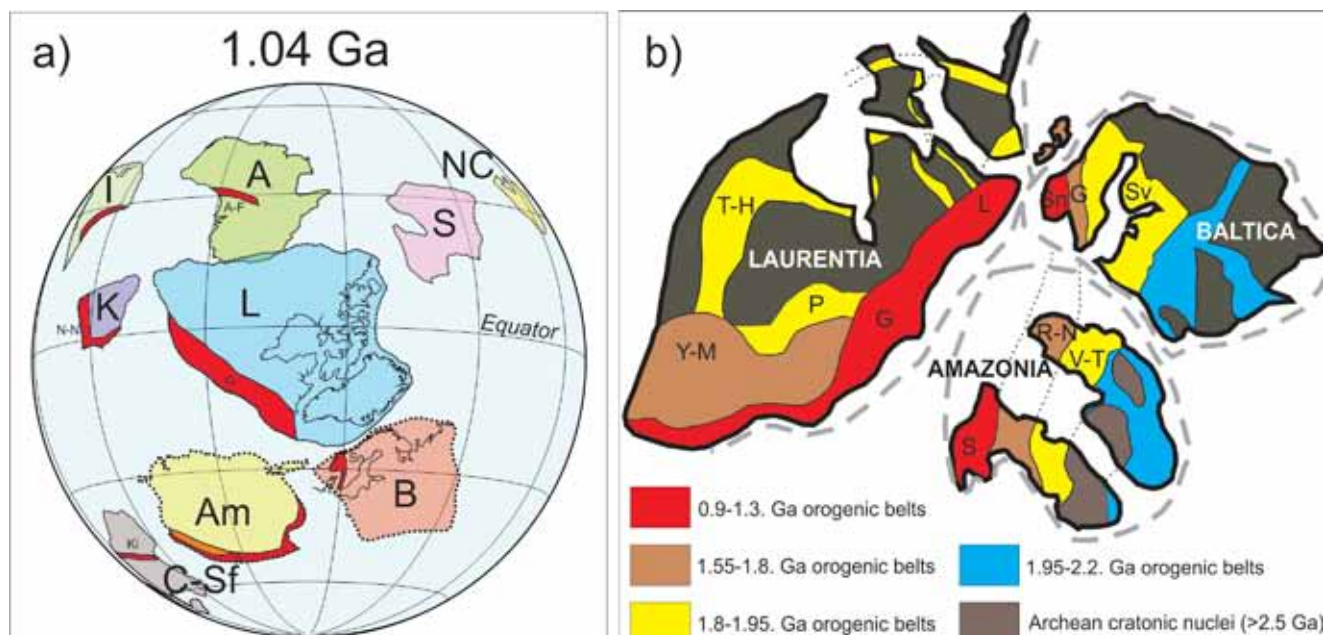


Figure 1. (a) Reconstruction of continents at 1.04 Ga showing the Rodinia configuration. Data available from Laurentia (L), Baltica (B), Amazonia (Am), Australia (A), Congo/São Francisco (C-Sf), Siberia (S), India (I), North China (NC) and Kalahari (K). The Grenvillian age orogenic belts are shown in red. (b) Geologically made reconstruction of Laurentia-Baltica-Amazonia (= the 0.9 Ga SAMBA-assembly by Johansson, 2009).

loop (“the Logan Loop”). The similarity suggests that the various cratons experienced very rapid drift during 1.15-1.10 Ga just before docking to Rodinia, or the whole Earth suffered a true polar wander, or “non-dipole” episode during that time.

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A catastrophic breach and inter-lake flow through the Marks Moraine via Brule Creek and Cedar Creek, Thunder Bay Region, Ontario: A small but significant detail of the eastern outflow history of Lake Agassiz.

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The search for the eastern outlets of glacial Lake Agassiz began with John Elson's pioneering aerial reconnaissance in Northwestern Ontario (Elson, 1957). His air photo interpretation revealed six possible outlets: Brule Creek, Dog River, Kaiashk River, Kaministiquia River, Pitikigushi River and Pillar Lake. Field studies followed in the summer of 1961 (Zoltai, 1963). Stephen Zoltai was tasked with ground truthing Elson's work, a project that would lead to the publishing of "The Surficial Geology of Thunder Bay", Map S265 (1965a, Zoltai, 1965b). Zoltai concluded that two outlets, the Brule Creek spillway and the Kaministiquia River spillway (and the associated Dog River tributary) were not related to glacial Lake Agassiz. He concluded that "the Kaministiquia–Dog River spillway was functioning to carry away meltwater from the area of the Kaiashk Moraine, while the Brule spillway follows closely the outer margin of the Marks Moraine" (Zoltai, 1963 p.110). The remaining spillways would become the well known "Nipigon outlets" (Zoltai, 1965a,b, 1967; Elson, 1967; Teller and Thorleifson, 1983).

Interest in the two all-but-forgotten spillways waned until Thorleifson (1996) brought about their revival in his review of Lake Agassiz history. Work by Minning et al (1994) began to reveal that Lake Agassiz levels were still high south and west of Lake Nipigon and the eastern "Nipigon outlets" could not have been functioning to draw down early Lake Agassiz levels. This led Thorleifson (1996) to propose that the Matawin-Shebandowan outlet (into the Kaministiquia River spillway) and the Savanne River outlet (into the Dog River spillway) were active. Research in the Fort Frances area by Bajc et al (2000) further supported high Lake Agassiz levels along the Ontario/Minnesota border, prompting Teller et al to publish "Alternative Routing of Lake Agassiz Overflow During the Younger Dryas: New Dates, Paleotopography and a Re-evaluation" (2005). This led to renewed interest in Glacial Lake Kaministiquia, the Kaministiquia spillway and the chronology of glacial and deglacial events in the Thunder Bay area (Loope, 2006; Loope et al, 2006).

In 2009, Lowell et al published "Radiocarbon Deglaciation Chronology of the Thunder Bay, Ontario area and Implications for Ice Retreat Patterns", in which a key point made was that ice at the Brule Moraine blocked the Matawin-Shebandowan outlet. The low point between the Arctic and Great Lakes watersheds was determined as between Squeers and Watershed lakes, and since the Brule Moraine was not breached here, they concluded that no overflow had taken place (Lowell et al 2009). However, the conclusion was based on digital elevation maps, and is considered in error by the present authors. Squeers and Watershed lakes lie at the top of Squeers Creek at 484m (1588') ASL, while the Squeers Creek spillway, mapped by Mollard and Mollard (1980), runs at the bottom of the drainage line from 472m to 453m (1550' to 1486') ASL. Bajc (2000) established the level of Glacial Lake Agassiz in this very area, based on the South Burchell Lake delta grading to 472m (1550') ASL. At 472m (1550') there is a 2km (6562') breach in the Brule Moraine, leading to Sawmill Bay on Lake Shebandowan. Mollard and Mollard (1980) mapped the deepest incision of the Squeers Creek spillway to be over 500m (1640') wide.

This breach area was used before and after the Steep Rock readvance (Dean and Phillips, 2011) and flow was through Lake Shebandowan, down the Shebandowan River and into Glacial Lake Kaministiquia, also a part of the Dog-Kaministiquia spillway. Burwasser (1981) determined three distinct levels of Glacial Lake Kaministiquia: 1450' (442m), 1500' (457m) and 1550' (472m) ASL. Earlier, Zoltai (1963) had noted the highest level as 1540' (469m) ASL. With the sill between Kashabowie and Lac de Milles Lac lakes close to this high level, it must be concluded that the 1540-1550' (468-472m) level was during the peak of the Marquette readvance

when ice was holding up Lake Kaministiquia and before breaching the Marks Moraine and ultimately flowing south into a pro-glacial lake.

Phillips and Fralick (1994), determined from a perched delta north of Thunder Bay, that a post Marquette level of Glacial Lake Kaministiquia was 1500' (457m) ASL, and Bajc (2000) noted 1510' (460m) ASL as a Marquette ice held level of Glacial Lake Kaministiquia. This would have been when red clays stopped flowing west out of Glacial Lake Kaministiquia through Lac de Milles Lac to be deposited in front of the Hartmann Moraine (Zoltai, 1965b; Teller and Thorleifson, 1983). Loope (2006) suggested that Glacial Lake Kaministiquia could have drained catastrophically following retreat of Marquette ice. This could have been when the level first dropped to 1500' (457m) ASL (Phillips and Fralick, 1994). This level would have been the start of the Brule Creek spillway (Elson, 1957), running out of the Brule Creek valley, and along the Marks Moraine and the valley of Cedar Creek. There, based on the characteristics of a feature named in this paper as the "Cedar Creek Delta", the authors present evidence of a catastrophic breaching of the Marks Moraine, waters of Glacial Lake Kaministiquia flowing south into "Glacial Lake Cedar Creek", initially at the 442m (1450') level. Subsequently, Glacial Lake Kaministiquia lowered to the 442m (1450') level (Burwasser, 1981), before finally breaching the Marks Moraine along the Kaministiquia River valley at Kakabeka (Phillips and Fralick, 1994; Loope, 2006) and draining away into the Upper and Lower Beaver Bay levels of Lake Superior (Phillips and Fralick, 1994).

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A metallogenic model and geometallurgical treatment of the Basal Iron Ores within the Negaunee Iron Formation, Tilden Mine, Michigan

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The complex paragenesis of the Tilden ores can be tied to the regional tectonic framework. Variable mineral chemistry and textures of basal Negaunee iron ores mined in the Main Tilden Pit have led to metallurgical difficulties. Core-logging and detailed petrography supported by microprobe investigations, identify three upward fining lithofacies within the Main Pit Carbonate and overlying Martite ore domains: 1) Basal Clastics; 2) Medial BIF; and 3) Granular Iron Formation. Growth fault related subsidence controlled deposition of the Basal Clastics, comprised of detrital quartz dispersed in a matrix of chlorite, cemented by initial ferri-hydrate, chert and Mg-siderite. Subsequent starvation of any clastic input led to cyclic iron-silica precipitation throughout the deposition of Medial BIF. Increasing wave action accompanied marine transgression caused deposition of granular rip-up clasts to form the Upper Granular Iron Formation. These domains are cross-cut by numerous chloritized feeder dykes and are capped by a greenstone Pillar, indicating overlapping mafic magmatism.

Low grade regional metamorphism attending the 1850 Ma Penokean arc-continent collision led to magnetite growth, carbonate grain coarsening and chlorite crystallization. Metamorphic fluids facilitated martite replacement of magnetite and deformation led to developing local platy specularite schists. A late retrograde hydrothermal overprint post-dates peak thermal conditions that accompanied the development of the 1750 Ma Republic Metamorphic Node. This is expressed by high-Fe chlorite, Fe-dolomite/ankerite, zoned Mn-rich siderite with associated trace Cu-Fe sulphide and REE bearing fluoro-apatite and monazite, diagnostic of an “IOCG” type signature.

The development of a metallogenic model accounting for the multistage paragenetic sequence has shown that textures and mineral chemistries reflect a complex evolution. Bulk chemical analyses do not always reliably predict concentrate chemistries. Textural variations and mineral speciation of the different lithofacies can affect grinding and liberation and must be taken into account. Therefore, ore treatment processes are more effective when the genesis of the ore deposit is fully understood. This complex paragenetic history accounts for the unpredictable geometallurgical response of the basal Negaunee iron ores. Treatment difficulties relate to: 1) variable silica-iron separation that occurs due to liberation from detrital quartz versus massive mosaic and granular textured chert; 2) the bulk iron content is expressed not only in iron oxide but in iron carbonate and iron chlorite; and 3) the intense late IOCG overprint proximal to the Southern Shear Zone.

Paleomagnetic, rock magnetic and geochemical data from the Keweenaw dykes and baked rocks from the Little Mountain and Sugar Loaf areas, Michigan, USA

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Rock magnetic, paleomagnetic and geochemical data from the Keweenaw diabase dykes from the Little Mountain (Baraga County) and Sugar Loaf (Marquette County) areas are presented. The study areas are located in the Upper Peninsula of Michigan where the dykes intrude metasedimentary and metavolcanic rocks of Animikean age, forming part of the Marquette Range Supergroup. This supergroup unconformably overlies a dominantly granitic basement of Archean age. At least three Keweenaw dyke swarms crop out in the area. Most of the Middle Keweenaw units have dual polarities and there is a tendency of the R polarity units to be slightly older according to radioisotope dating, paleomagnetic studies, and stratigraphic evidence. Previous paleomagnetic studies have shown that the E-W trending Baraga and Marquette dykes are of reversed polarity, with minor but significant differences in their paleomagnetic and physical properties. Our study reveals the presence of normal polarity dykes in the study area. Based on cross-cutting relationships, they are younger than the R-polarity dykes. The top-hill exposure of the Little Mountain, where the cross-cutting of the dykes takes place, is complex: the rocks have been hit by lightning and the dykes and their baked contact rocks are of mixed polarity. In contrast, the down-hill sites, where the N and R dykes are more distant from each other, they reveal either N- or R-polarities (the NE-SW and the E-W trending dyke respectively). The R-polarity and N-polarity dykes have slightly different petrophysical, rock magnetic and paleomagnetic properties. Geochemical signatures of the two dykes are also different: typically the R-polarity dykes have higher Fe- and lower Al- and Mg-values than their N-polarity counterparts. In addition, the R-polarity dykes of the Baraga County are paleomagnetically, petrophysically and geochemically slightly different than the R-polarity Marquette dykes. The same is not true for N polarity dykes from the two areas. The differences between the R polarity dykes may reflect a small difference in age (Baraga dykes being older). The new paleomagnetic and geochemical data together with cross-cutting relationships also hint that an even older N-polarity Keweenaw dyke event is present in the Sugar Loaf area. These older dykes may represent the earliest stage of the intrusive activity associated with the Mid-Continental Rift.

The ca. 1650 Ma Freedom Formation, Baraboo Range, Wisconsin: A late iron formation in the Lake Superior Region

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Iron formation deposition in the Lake Superior region is typically considered to have ceased by about 1850 Ma, with the end of deposition of Animikie Group iron formations including the Gunflint, Biwabik, and Ironwood Formations in western Ontario, northern Minnesota, Wisconsin, and the Upper Peninsula of Michigan. However, a little-known iron formation occurs within the latest Paleoproterozoic (ca. 1650 Ma) Freedom Formation, part of the Baraboo sequence of southern Wisconsin. The Freedom Formation does not occur in outcrop, but was the target of iron mining in the early 1900s, and drill cores taken more than a century ago were recently acquired by the core repository of the Wisconsin Geological and Natural History Survey (WGNHS).

The Freedom Formation, which is at least 300 m thick, lies conformably above the Seeley Slate, which in turn overlies the well-known Baraboo Quartzite (Dalziel and Dott, 1970). According to a 1904 WGNHS report by Samuel Weidman, the Freedom Formation includes interbedded ferruginous slates, ferruginous cherts, and iron-rich dolostones, and is made up almost entirely of quartz, dolomite, hematite, magnetite, kaolinite and chlorite. The lower half of the formation consists mainly of thinly bedded slates and cherts and lesser dolomite, as well as localized stratiform bodies of iron ore (mainly hematite) with up to 65% Fe. The upper half of the formation is predominantly dolomitic.

We studied core samples originally drilled for the Cahoon Iron Mine (43.4470 N, 89.7565 W), on the south limb of the Baraboo syncline about 3 km northwest of Devils Lake. The cores had been stored for at least 80 years in an abandoned mine building before they were obtained by the WGNHS, and no related documents other than depth tags were preserved. As a result, we are not sure of the precise stratigraphic position of the cores we examined, but the lithologies present – primarily ferruginous slate and chert – are consistent with Weidman's (1904) descriptions of the lower half of the Freedom Formation.

Most of the rock in the cores shows clastic textures and mm-cm scale layers of quartz, magnetite, and lesser carbonate. In places, the magnetite is altered to hematite. The layers are somewhat irregular or lensoid, commonly varying in thickness even across the width of the 1.5 cm cores. In thin section, the magnetite is seen to occur in mm-scale clumps or granules that are subspherical but lack any obvious concentric banding that would indicate they formed as ooids. These textures are similar to those observed in classic Lake Superior granular iron formations (GIFs). Unlike banded iron formations (BIFs) *sensu stricto*, which represent laminated chemical muds, GIFs originated largely as well-sorted sands, most likely as a result of intrabasinal erosion and redeposition of pre-existing iron formation, and are younger than most BIFs (Simonson, 2003; Bekker et al., 2010). XRF analysis of trace metals in the Freedom Formation show Fe-normalized concentrations comparable to those in the Ironwood Iron Formation, a GIF-type deposit. In contrast, the chemistry, mineralogy and textures of the Freedom Formation do not resemble Phanerozoic ironstones, which tend to be highly oolitic, with chamosite, glauconite and/or pyrite as major mineral constituents (van Houten and Bhattacharyya, 1982).

The geochemical factors leading to deposition of the Freedom Formation are not clear. The Baraboo Quartzite and Seeley Slate are both supermature sedimentary units deposited in a shallow marine environment adjacent to a rhyolitic/granitic landmass that had undergone intense and sustained tropical weathering (Medaris et al., 2003). The contact between the Seeley Slate and Freedom Formation seems to be conformable and gradational, suggesting that the Freedom Formation was deposited under similar conditions. While Phanerozoic ironstones are also thought to have accumulated in tropical settings with intense chemical weathering, they typically occur at the base of transgressive sequences and represent protracted periods of sea level lowstand (van

Houten and Bhattacharyya, 1982). This does not appear to have been the case for the Freedom Formation, which is underlain by more than 1000 m of uninterrupted marine sediments.

The Freedom Formation therefore seems to be more closely related in genesis to other (earlier) Paleoproterozoic GIFs than to Phanerozoic ironstones. If this is the case, its existence challenges models that point to an end for iron formation deposition at ca. 1850 Ma as a result of deep ocean euxinia (Canfield, 1998), the Sudbury impact (Slack and Cannon, 2009) or cessation of komatiitic volcanism (Wang et al., 2009). Instead, we suggest with Planavsky et al. (2011) that ferruginous ocean conditions and GIF deposition may have persisted well after early Paleoproterozoic time.

Remaining questions about age of the Baraboo Sequence and the timing of its deformation are relevant to understanding the significance of the Freedom Formation. The youngest detrital zircons in the Baraboo Quartzite indicate that it can be no older than 1710 Ma (Medaris et al., 2003). There are, however, no direct constraints on the ages of the overlying units nor on the timing of the Baraboo folding event, although indirect arguments suggest that it occurred at ca. 1630 Ma (Holm et al., 1998). ⁴⁰Ar/³⁹Ar analyses of muscovite in breccias within the Baraboo quartzite consistently yield ages in the range of 1470-1450 Ma (Medaris et al., 2003), and it is possible that the deformational event could have occurred as late as this time (van Lankvelt and Bjørnerud, 2010). If so, the Freedom Formation could be as young as Mesoproterozoic and may indicate that Paleoproterozoic-type ocean chemistry prevailed much longer than previously thought.

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The tectonometamorphic, magmatic and mineralization history of the Wanapitei Complex, Grenville Front tectonic zone, Ontario

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This presentation summarizes the results of new fieldwork and U-Pb geochronology from the Wanapitei Complex (WC), located 13 km ESE of Sudbury (Fig. 1). The WC is elliptical in plan view (6 x 2.5 km) and is located 400 m SE of the Grenville Front (Fig. 1). The WC is surrounded by a variety of gneissic rocks of the Grenville Front tectonic zone, including orthogneiss, paragneiss, amphibolite, migmatite, mylonite and breccia. All marginal contacts of the WC are sheared and no chilling is present near the margins. All new U-Pb data reported herein were obtained from the laser-ablation -ICP-MS facility at Laurentian University.

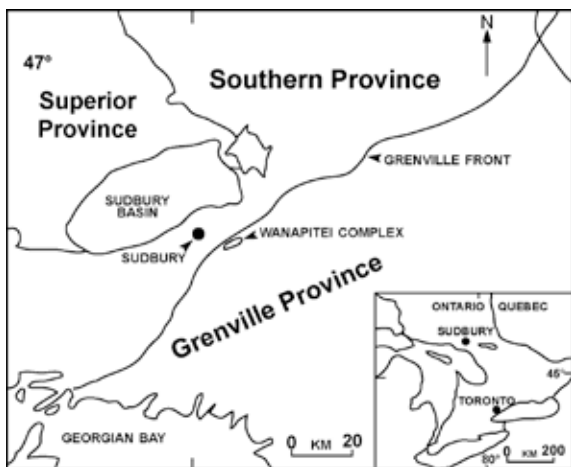


Figure 1. Regional setting of the Wanapitei Complex

The WC is divided into three segments each separated by a covered interval: a large NW and smaller SE and NE segments (Fig. 2). The WC was intruded twice by felsic dikes and twice by mafic dikes, subsequently underwent local folding and shearing, and finally was cut by late NW-trending pegmatite dikes (Napoli, 2003). The latter, dated regionally at 979 ± 3 Ma (Easton et al., 1999), strike parallel to a major joint set and cut all rocks of the WC as well as a hornblende-plagioclase gneiss body in the SE segment.

Within the SE segment a deformed, sill-like, hornblende-plagioclase gneiss body (4.4 x 0.36 km) trends NE and is in sheared contact with the WC (Fig. 2). A cluster of concordant zircons from it yields a Concordia age (Ludwig 1998) of

2377 ± 4 Ma (site 2, Fig. 2), similar to the age of the Creighton granite (Smith, 2002). This age represents a minimum age for emplacement of the body. The WC in the SE segment consists of olivine norite, norite and hornblende gabbro. Olivine and plagioclase occur as phenocrysts enclosed by hypersthene and augite, suggesting that the former two minerals are cumulates, subsequently enclosed in post-cumulus pyroxene. The olivine norite is also characterized by coronas around olivine and hypersthene, resulting from the reactions (1) olivine + plagioclase $\Rightarrow$ bronzite + pargasite-spinel; (2) olivine + pyroxene $\Rightarrow$ bronzite; and (3) pyroxene + plagioclase $\Rightarrow$ pargasite-spinel. Other mafic rocks include norite and gabbro with varied amounts of secondary hornblende. Discordant zircon from a hornblende norite yielded an upper intercept age of $1747 \pm 12/-6$ Ma (Prevec, 1993). In the NE segment of the WC, toward the margin of the complex, gabbro grades into recrystallized gabbro and then into a breccia containing clasts of garnetiferous gabbro and infolded boudins of country rock.

The bulk of the NW section of the WC consists of gabbro which was intruded by porphyritic quartz monzonite emplaced as large dikes and anastomosing vein systems which form an intrusion breccia. A sample of one of these dikes yielded a single population of concordant zircons with a Concordia age of 1707 ± 4 Ma (site 1, Fig. 2), slightly younger than the age of $1747 \pm 12/-6$ Ma from the same unit reported in Easton et al. (1999). To the NE, the breccia passes into garnet metagabbro, which has a Concordia age of 1735 ± 3 Ma (site 4, Fig. 2). Fine-grained mafic dikes ($68^\circ/90^\circ$), typically 1 m wide with non-chilled contacts, are widely distributed in the WC. Locally garnetiferous mafic dikes with chilled margins cut injection breccia in the WC, and a sample yielded 2

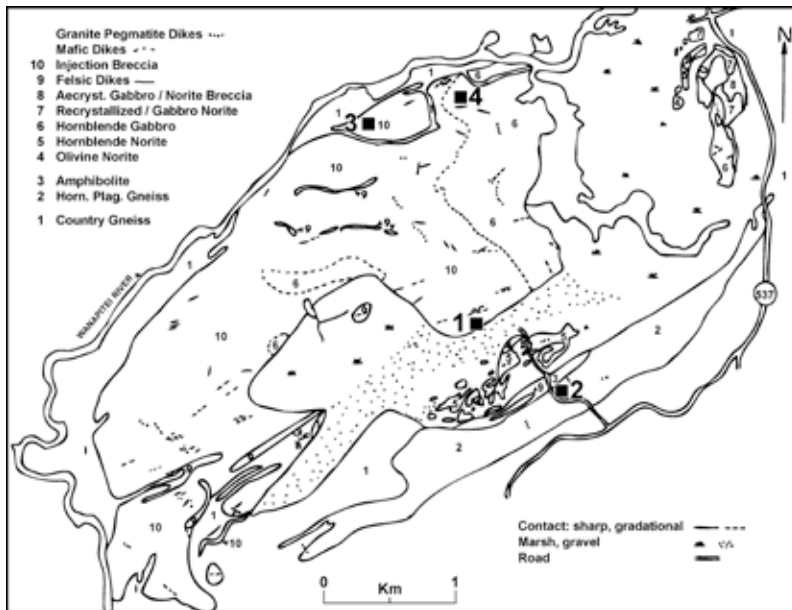


Figure 2. Geological map of the Wanapitei Complex showing the location of new U-Pb sample locations (sites 1 to 4). Map modified from Rousell and Trevisiol (1988).

clusters of concordant zircons, with Concordia ages of 1694 ± 7 Ma and 1640 ± 10 Ma, respectively (site 3, Fig. 2). Discordant zircons from the same sample define a Pb loss line trending toward 1000 Ma.

Mineral exploration in the WC began in the 1940s, and is ongoing. The SE and NE segments of the WC contain 17 occurrences of sulphide mineralization (pyrrhotite, chalcopyrite, pentlandite, pyrite) all hosted by norite. The sulphide minerals are interstitial to the silicates, are inter-cumulus, and of primary magmatic origin. Although not all rocks of the WC are deformed, all are metamorphosed to upper amphibolite facies, with the possible exception of the olivine norite (do the coronas reflect subsolidus reactions or metamorphic overprinting?). Based on new and previous geochronology, the WC likely crystallized deep in the crust from multiple magma injections between 1747 and 1707 Ma during Killarney Belt magmatism. It was subsequently emplaced into its current position, in the solid state, along shear zones near the end of the Grenville Orogeny. During this emplacement, it was dismembered into three segments, with later independent tilting and/or rotation, and may be the remnant of a much larger intrusion.

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Geologic setting of the Kevitsa Ni-Cu-PGE Deposit, Central Lapland Greenstone Belt, Finland

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The Kevitsa Ni-Cu-Pt-Pd Mine is a new operation in northern Finland commencing full production in 2012. The current measured and indicated mineral resource (NI 43-101 compliant) for the deposit is 240Mt @ 0.30% Ni, 0.41% Cu, 0.21 gpt Pt, 0.15 gpt Pd, 0.11 gpt Au using a 0.1% Ni cutoff value. Additionally, an inferred resource of 34.7 Mt exists with comparable grade.

The deposit is located within the Central Lapland Greenstone Belt; a Paleo-Proterozoic volcano-sedimentary sequence. Ultramafic intrusive and volcanic rocks are widespread and occur at several stratigraphic levels within the greenstone belt sequence (Hanski et al., 2001). The host ultra-mafic intrusion at Kevitsa has been dated at 2058 ± 4 Ma and is considered in general to be 2050 Ma in age based on dates from other cross-cutting dykes (Mutanen and Huhma, 2001).

Mineralization consists largely of disseminated sulphides defined as Regular Ore, False Ore, Ni-PGE Ore and Contact Ore. Sulphide minerals are dominantly pyrrhotite, pentlandite, and chalcopyrite; although pyrite is also locally present. The Regular Ore constitutes approximately 95% of the resource.

The deposit is hosted within a thick (> 1km) peridotite rock unit segregated as olivine pyroxenite, websterite and plagioclase-bearing pyroxenite (Figure 1). A ubiquitous amphibole overprint has replaced the primary minerals, affecting mainly clino-pyroxene, making rock identification locally impossible in hand specimen and in drill core. A crude internal layering is evident within the peridotite highlighted by horizons of sulphide mineralization. Individual sulphide lenses are 10s to 100s meters in thickness typically associated with the olivine pyroxenite layers, suggesting emplacement of magmas as pulses. Olivine-rich, “dunite”, xenoliths occur locally and are aligned within discrete zones discordant to the internal layering. In places, the dunite is seen as irregular-shaped masses intercalated with the peridotite groundmass. The Ni-PGE Ore is spatially associated with these dunite zones. Dunitic rocks also occur below the peridotite unit, but are poorly defined. The peridotite unit is overlain by gabbro which forms a comparatively thin lithologic unit (typically < 200m) in the SW portion of the intrusion. The dunite, peridotite and gabbro geochemically occur as a fractionation series. A large, discrete, serpentinized dunite body exists within the central portion of the intrusion that is geochemically distinct from the main Kevitsa body and is un-mineralized. Presently, this body is not well understood, but is considered to cut the Kevitsa peridotite unit. The immediate country rocks surrounding the Kevitsa Intrusion consist of mafic volcanic flows and tuffs interlayered with clastic metasediments and sulphide-rich carbonaceous schists.

Continuing exploration to depth has improved the 3D geologic model of the deposit and of the intrusion. Both 2D- and 3D-seismic surveys have been utilized to delineate regional- and mine-scale structures as well as to define the basal Kevitsa Intrusion contact in un-drilled areas. Several new research initiatives have commenced recently to aid the exploration effort and in general will better position the Kevitsa deposit within the current Ni-Cu-PGE genetic models.

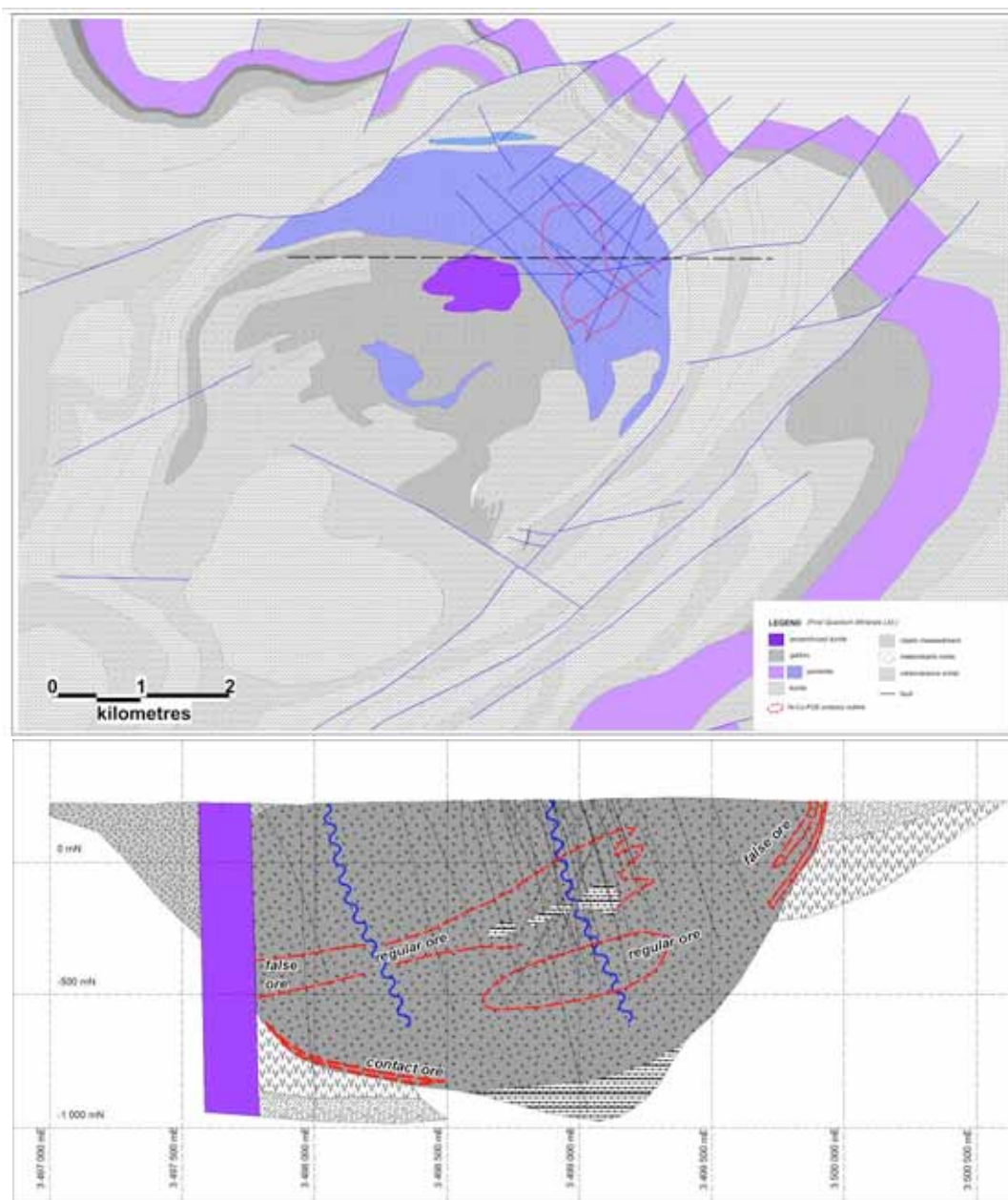


Figure 1. Bedrock geology of the Keivitsa Intrusion area defined by surface mapping and diamond drilling. The surface projection of the complete Ni-Cu-PGE orebody is shown by the dotted line. The geologic cross-section is drawn along the dashed line (drill section 12150N); note: the cross section is an expanded scale from the map.

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Exploration history, mineralogy and genesis of the Black Thor chromite deposit, Ring of Fire Intrusion, Northwestern Ontario

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The McFaulds Lake Black Thor chromite deposit, an emerging world class chromite deposit, is located in northwestern Ontario approximately 550 km north of the City of Thunder Bay in the Ring of Fire greenstone belt. The initial discovery of the deposit was made by Freewest Resources Inc. in 2008 when a diamond drill hole intersected approximately 100 m of massive chromitite. Subsequent geophysical surveys and drilling have outlined a deposit amenable to open pit mining 400 m deep with a strike length of approximately 3 km, occurring in vertically dipping, sheet-like zones with mineable widths between 50 and 100 m. Chromite mineralization has been confirmed beyond the open pit zone to a depth of approximately 700 m and remains largely open down-dip. Cliffs Natural Resources (CNR) acquired Freewest in 2010, and is currently proceeding with a definitive feasibility study and environmental assessment for the project.

The chromite mineralization is hosted by a multi-phase layered ultramafic intrusion (Ring of Fire Intrusion or RFI) consisting of: peridotite, olivine cumulates, pyroxenite and gabbro occurring in three discrete fault bounded domains: the Southwest Domain, the Central Domain and the Northeast Domain. All domains feature some degree of layering and repetition of massive chromitite horizons. These features may be attributed a combination of primary magmatic and structural origins. Magma mixing, sulphide removal and sialic crustal contamination are possibilities with respect to the saturation of the magma in chromium. The volume of chromite mineralization in the deposits does not balance with the magma volume of the delineated extent of the RFI. Emplacement in a magma conduit has been proposed as a possible physical mechanism for the concentration of chromite mineralization of the magnitude represented by the deposits.

Samples from drill holes in the Northeast Domain and from the Southwest Domain were studied at Cliffs Technology Laboratories to determine the bulk chemical composition, chemical composition of chromite, typical chromite textures, free magnetite content and gangue mineralogy. The Cr_2O_3 content of chromite grains increases from 45% in disseminated mineralization to over 52% in massive chromitite. Similarly, Cr/Fe ratio of chromite grains increases from 1.45 in disseminated mineralization to 1.96 in massive chromitite. Chromite mineral content ranges from as low as 7.8% in disseminated to more than 88% in massive chromitite. Semi-massive mineralization contains 35-63% chromite. The gangue minerals in disseminated mineralization are primarily sjoegrenite, lizardite and to a lesser extent antigorite, whereas clinocllore was the primary gangue mineral in massive chromitite. Disseminated mineralization zones were also characterized by the presence of magnetite and absence of talc-carbonate veins.

Several distinct types of chromite textures are recognized. They are (#1) un-deformed and unaltered chromite, (#2) un-deformed chromite with slight surface alteration, (#3) deformed and fractured chromite but with preserved grain outline, (#4) intense cataclastic textured chromite, (#5) completely silicate altered chromite, (#6) chromite with many gangue or sulfide inclusions, and (#7) very fine precipitated chromite with very high chromia content. Types #1-#5 are the most common textures and can occur within the same drill core. The mean grain size of chromite grains in the massive type is slightly larger (200-220 μm) than in semi-massive (~160-167 μm) and in disseminated samples (180-190 μm).

Microstructural analysis of porcellaneous nepheline syenite, Coldwell Complex, Ontario

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The Coldwell Complex is a large Proterozoic alkaline igneous complex on the north shore of Lake Superior west of Marathon, Ontario. From east to west across the complex, three distinct magmatic centres form an overlapping sequence; Center 2 is characterized by biotite-bearing alkaline gabbro and nepheline syenite (Mitchell and Platt, 1982). Within Center 2, a fine-grained porcelaineous variety of nepheline syenite is recognized as being chemically equivalent to the more typical coarse-grained nepheline syenite. This porcelaineous nepheline syenite outcrops in a narrow arcuate zone along the western shore of Redsucker Cove. Microstructural evidence for dislocation creep indicates that the porcelaineous syenite is a mylonite formed by localized solid-state deformation. As the Coldwell Complex has not been subjected to regional metamorphism, the high temperature required for ductile solid-state deformation in the porcelaineous syenite must be related to the magmatic activity. Localized high-temperature ductile strain within this arcuate zone could have led to catastrophic brittle failure along ring faults culminating in caldera collapse. This discovery may have implications for understanding the processes associated with caldera collapse in large alkaline igneous complexes.

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Textural and compositional variation in apatite and plagioclase in the Marathon PGE-Cu deposit, Northwestern Ontario: Implications for fluid-rock interaction

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The Marathon PGE-Cu deposit is hosted within the Two Duck Lake gabbro (TDLG) of the Mesoproterozoic (1108 ± 1 Ma) Coldwell alkaline complex. Three zones of mineralization with different textural, mineralogical and geochemical characteristics have been identified: Footwall Zone, Main Zone, and W-Horizon. The relative roles of magmas and volatiles in Cu and PGE enrichment in this deposit remain a point of debate.

The TDLG is coarse-grained to pegmatitic, and comprises plagioclase with variable amounts of interstitial ophitic clinopyroxene, olivine, and magnetite. Apatite, biotite and amphibole are common accessory minerals. Hydrothermal alteration is a common feature, especially in the Main and Footwall Zone, and is dominated by replacement of primary igneous minerals by amphibole, chlorite, biotite, and serpentine. Epidote and carbonate are also present as alteration minerals in some samples.

Preliminary petrographic studies and SEM-CL imaging have revealed complex textures in both plagioclase and apatite, including evidence of dissolution and replacement, normal or reverse zoning, oscillatory zoning, and patchy zoning in plagioclase. Preliminary LA-ICP-MS analyses of various textural types of plagioclase and apatite have been conducted to evaluate any relationship between textural complexities and chemical variations. Magmatic plagioclase is characterized by a strong positive Eu anomaly, and has higher REE concentrations in the rims relative to the cores. Plagioclase with replacement rims occurs in the vicinity of quartz-feldspar granophyre patches, suggesting alteration by fluids exsolved from the granophyric melts. This is supported by the lower An content (An_{33-50}) of the replacement plagioclase compared to the magmatic plagioclase that was replaced (An_{60-75}). These rims also contain higher concentrations of Cu and Pb compared to magmatic plagioclase.

Apatite occurs as euhedral to subhedral acicular and tabular prisms, and as anhedral crystals hosted by both altered and un-altered minerals. SEM-CL imaging shows that apatite crystals can exhibit growth (oscillatory) and replacement zoning, and EDS analyses indicate that the F and Cl contents are variable. In different rocks, apatite either predated (early apatite) or postdated plagioclase crystallization (late apatite). Apatite crystals from mineralized Main and Footwall Zone samples generally have high Cl contents, whereas apatite from the W-Horizon has low Cl contents, and generally have fluorapatite end-member compositions. Apatite crystals from the Footwall Zone (the lowest stratigraphic zone) have the highest Cl/F values, whereas those from the W-Horizon (the highest stratigraphic zone) show the lowest Cl/F. In addition, zoning, re-crystallization textures, and the presence of primary fluid inclusions are more common in apatite crystals from Main and Footwall Zone samples compared to the W-Horizon. Apatite consistently has a strong negative Eu anomaly, and early apatite has higher REE concentrations in the rims compared to the cores. The magnitude of the negative Eu anomaly, however, increases from core to rim. Late apatite has a REE abundance between that of the core and rim of early apatite. This suggests that late apatite probably crystallized from a new influx of magma rather than from continued crystallization of a resident, more fractionated magma. Replacement rims of apatite crystals show lower Σ REE, higher Cl, and higher transition metal (e.g., Ti, Fe, Cu) contents compared to early apatite. The similar REE core to rim evolution of the apatite and plagioclase suggests that early apatite and plagioclase co-precipitated; similarly, the sequestration of Eu by plagioclase resulted in the decrease in Eu* in apatite from core to rim.

The observed spatial changes in Cl/F in apatite can be explained by compositionally distinct magma pulses, responsible for each mineralized zone, as most apatite crystals are euhedral to subhedral, formed early in the paragenetic sequence, and are magmatic. Intracontinental basaltic melts, however, (cf. Bushveld, and Stillwater complexes) are reported to be poor in Cl. Thus, apatite crystallizing from such a melt is expected to

be fluorapatite. Much of the chalcopyrite in the Main Zone is reported to replace pyrrhotite and is intergrown with hydrous silicate minerals, which suggests that Cu was introduced into the system by fluids. This observation can be explained by a process in which fluids flux through the Footwall Zone, and transport Cu to the Main Zone during its upward migration. Therefore, a zone-refining process in which volatiles, derived from footwall country-rock dehydration, migrated up through the crystallizing gabbros is an attractive alternative by which Cl could be added to the system. The low Cl contents of apatite in the W-horizon can be explained if these fluids did not migrate upward into the W-Horizon, or the W-Horizon represents late-stage magma infiltration. Thus, the alteration of the primary igneous minerals, the re-crystallization textures, high Cl/F exhibited in apatite within the Footwall and Main Zones, and higher Cl and transition metal contents of the apatite replacement rims can be attributed to the interaction of a fluid phase at suprasolidus and/or subsolidus conditions.

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Regional to microstructural control of gold mineralization along the Quetico-Wabigoon subprovince boundary

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Gold occurrences in Greenstone, Ontario are located along major regional shear zones, along the Quetico and Wabigoon subprovince boundary within the Superior province. On the regional scale, gold mineralization occurs within anastomosing ductile to brittle-ductile shear zones in pressure shadows around competent plutons or in ductilely deformed fractures within the plutons. In outcrop and drill core gold mineralization is observed in areas of heterogeneous deformation, especially at rheological or lithological contacts, such as along an amphibolite-granodiorite contact within the Klotz Lake shear zone east of Longlac, Ontario. Microstructure mimics the regional structure, as gold is found in fractures in competent minerals as well as in pressure shadows around the competent minerals, such as the gold found in fractured garnet west of Caramat, Ontario.

The regional shear zones in Greenstone are transcurrent, ductile to brittle-ductile shear zones that typically trend east-west, parallel to the Quetico-Wabigoon subprovince boundary. Deviations from this east-west trend occur where shear zones anastomose around older, competent granitoid plutons, like the Elmhirst meta-granodiorite pluton north of Jellicoe. Areas of highest strain along the pluton margins exhibit evidence of dislocation creep, such as quartz ribbons and grain size reduction, and host sporadic gold mineralization. No gold mineralization is present in the interiors of the plutons where strain fabric is minimal or absent. The highest gold mineralization is present immediately adjacent of the zones of highest strain and within the competent plutons, usually in ductilely-deformed fractures or along rheological contrasts. Significant gold mineralization is also present in pressure-shadows around the deformed plutons, where complex folding is typically located.

Pressure shadows that host gold are present on all scales, including the microscopic scale. Gold is commonly found in pressure shadows around garnet, plagioclase, hornblende, and pyrite throughout the Quetico-Wabigoon subprovince boundary.

Heterogeneous deformation on the microscopic scale hosts gold mineralization within fractures of competent minerals, such as pyrite and garnet, while the less competent matrix minerals, like quartz, deform more ductilely. Gold is typically located at the grain boundary between competent and less competent minerals.

Fractured meta-granitic plutons adjacent to shear zones that host gold are analogues to gold found in fractured garnet within a schistose fabric, although on much different scales. Exploration for gold mineralization along the Quetico-Wabigoon subprovince boundary should continue west of Lake Nipigon and east of Longlac and focus on heterogeneous deformation within shear zones on all scales. Heterogeneous deformation continues north into the Quetico and south into the Wabigoon and so should the exploration for new gold occurrences.

Temporal context of the Mamainse Point succession: a record of magmatic activity and fast plate motion across the “latent stage” of Midcontinent Rift development

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A popular model for the development of the Midcontinent Rift (MCR) proposes that there were four stages of magmatism: Early Stage (>1109-1106 Ma), Latent Stage (1106-1100 Ma), Main Stage (1100-1094 Ma) and Late Stage (1094-1086 Ma) (Miller and Vervoort, 1996; Vervoort et al., 2007). U-Pb dates of both extrusive (Davis and Green, 1997) and intrusive (Paces and Miller, 1993; Vervoort et al., 2007) sequences in the western part of the Lake Superior basin largely fall within either the early or main magmatic stages—leading to the interpretation that the period between them was a latent stage characterized by minimal eruptive activity. The early stage of MCR volcanism is characterized by magnetizations of reversed polarity while the main stage of MCR volcanism is characterized by magnetizations of normal polarity. In the Powder Mill Group and the North Shore Volcanic Group (NSVG), U-Pb dates on extrusive felsic units (Davis and Green, 1997, Zartman et al., 1997) reveal condensed stratigraphy during the time period of the latent magmatic stage accompanied by the switch from reversed to normal magnetizations.

In contrast, the succession in the eastern Lake Superior basin exposed at Mamainse Point has been interpreted to represent a much more continuous record spanning nearly the entire duration of rift volcanism (Klewin and Berg, 1990). This interpretation of more continuous eruption in the eastern Lake Superior basin has stemmed, in part, from the presence of multiple geomagnetic reversals in the Mamainse Point succession (R-N-R-N; first identified by Palmer, 1970) that have not been recognized in other extrusive successions in the rift. These reversals suggest that eruptive activity continued locally, albeit with some shorter duration lulls marked by conglomeratic units, while there was the hiatus of the latent magmatic stage elsewhere in the rift.

Due to the large change in paleomagnetic inclination throughout the development of the MCR (Davis and Green, 1997, Swanson-Hysell et al., 2009), paleomagnetic data can be used to provide rough chronostratigraphic constraints through comparison of undated paleomagnetic poles to those with age control. Applying this approach with the paleomagnetic data set we have developed at Mamainse Point, we find that the lowermost flows at Mamainse Point correlate to those from the lower northeast sequence of the NSVG (the early magmatic stage with a U-Pb crystallization age of 1107.9 ± 1.8 Ma determined from the intercept of a linear regression with the concordia curve; Davis and Green, 1997) and that the upper normal flows correlate with the upper southwest sequence of the NSVG (the main magmatic stage with concordia intercept U-Pb crystallization ages of 1096.6 ± 1.7 Ma and 1098.4 ± 1.9 Ma; Davis and Green, 1997). This result implies that the intervening stratigraphy at Mamainse Point spans the latent magmatic stage during which there were at least three reversals of the geomagnetic field.

A U-Pb crystallization age of 1096.2 ± 1.9 Ma for a felsic unit within the lower reversed zone at Mamainse Point was presented in an ILSG abstract and tentatively interpreted to be extrusive (Davis et al., 1995)—although the unit was mapped as a felsic intrusion by Giblin (1969). An extrusive interpretation implies that all the geomagnetic reversals within the succession occurred during the main magmatic stage—in conflict with the consistently normal magnetostratigraphy of the upper sequence of the NSVG and the Portage Lake Volcanics as well as the comparative analysis of paleomagnetic poles. New field observations document that this fine-grained unit with quartz phenocrysts has a cross-cutting relationship with the basalt flows such that the felsic unit both overlies and underlies the pahoehoe flow top of a single basalt flow. These observations indicate the unit is

intrusive with its age providing a minimum rather than absolute age constraint on the lower reversed polarity zone at Mamainse Point.

During a field season when fortuitously low lake levels led to excellent exposure of the stratigraphy in Flour Bay, we collected a crystal-rich tuff in close stratigraphic proximity to the base of the “Great Conglomerate” within the upper reversed polarity zone. We will present a new chemical abrasion TIMS U-Pb date from euhedral prismatic zircons from this tuff that anchors the Mamainse Point stratigraphy in absolute time and demonstrates that the record does indeed span much of the latent magmatic stage. These results strengthen the temporal framework of the Mamainse Point succession and allow for refined stratigraphic correlations across the rift. Furthermore, these results along with an expanded paleomagnetic data set support the interpretation that significant plate motion of North America was ongoing between the early and main magmatic stages that led to the decrease in the paleomagnetic inclination.

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Quartz quarry sites in northwestern Ontario: A new ‘prospect’ for geoarchaeologists investigating lithic raw material sources

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Flintknapping is the process of creating stone tools by utilizing percussion and pressure flaking techniques on siliceous minerals. Preservation of lithic materials in the archaeological record provides some of the best evidence for reconstructing past human activities. In the boreal forest of northwestern Ontario, Aboriginal people began flintknapping about 9500 years ago, as evident from dated contexts of stone tools, cores, and resultant flaking debris (debitage). Despite this lengthy time frame, there is limited knowledge of archaeological sites in general and even less information about primary, secondary, or tertiary sources that Aboriginal people accessed to obtain useable siliceous material for stone tool manufacturing. Archaeological quarries are typically large sites with dense clusters of tools,debitage, and diverse processing areas. However, few quarries sites have been found in the Canadian boreal forest.

Over the last seven years, rare opportunities enabled eight brief archaeological surveys to take place on the Bloodvein River in Ontario’s Woodland Caribou Provincial Park (now enlarged into a Signature Site); these projects are part of ongoing collaborations with Ontario Parks as well as Pikangikum, Lac Seul, and Little Grand Rapids First Nations in their traditional territories (e.g., Taylor-Hollings, 2006). The Ontario portion of this Canadian Heritage river is about 106 km long and all projects required fly-in transportation to this remote area. These surveys enabled data collection for the author’s PhD research as well as park and community-based land use planning. The first survey indicated that the most common lithic artifacts in that area consisted of various forms of quartz: rock crystal, white, yellow, and smoky. However, it was unknown where this quartz was sourced. As Bakken (2011:124) suggests, “quartz is a complicated issue in regional raw material studies, and one that remains to be resolved”. Thus, while looking for archaeological sites, it was decided to look for quartz sources, such as vein quarries or pebbles and cobbles, since the latter forms are known from northern Minnesota sites (Bakken, 2011).

As part of the larger Canadian Shield, the Bloodvein River lies within the North Caribou Terrane, a collage of ~3-2.8 billion years old diverse lithotectonic assemblages within the northern Archean Superior Province (Thurston et al., 1991; Corfu and Stone, 1998). This part of the terrane was formerly known as the Berens River subprovince as defined by Corfu and Stone (1998). Geological mapping (Rickaby, 1923; Corfu and Stone, 1998) and research has been minimal in the Bloodvein River area. Published data is available for only one sample of a biotite tonalite from along that river system in Ontario (Corfu and Stone, 1998:2985). This is likely explained by the Bloodvein River being part of the Woodland Caribou Signature Site, where mineral prospecting has not been allowed since at least the 1980s, although possibly as early the 1940s when it first became a protected area (OMNR, 2004). Underlying most of the Bloodvein River in Ontario is a biotite granite suite consisting of a massive granodiorite to granite unit generally containing tonalite inclusions (Corfu and Stone, 1998). Within these types of bedrock outcrops along the river, there are a large number of quartz veins available for quarrying stone tool materials. However, sources of the most common quartz artifacts were previously unknown until this study.

Although few archaeologists have looked for quartz vein quarrying previously in the boreal forest, the Woodland Caribou Signature Site presented an opportune locale to look for these sites where there was minimal mineral sampling known or evident. Due to the extensive amount of prospecting in northwestern Ontario since the last century, particularly in the nearby Red Lake area, it is important to consider carefully the evidence for precontact quartz quarrying as opposed to quartz sampled for mineral exploration. Three types of evidence for Aboriginal quarrying activities were found along the Bloodvein River during these surveys: (1) quartz veins

located adjacent to other types of archaeological sites typically with quartz artifacts (n=9); (2) quarried quartz veins with artifacts found beside or in them (n=5); and (3) mined quartz veins with evidence of non-recent quarrying (n=7). All of the places considered to be the result of ancient quarrying activities were weathered and had lichen developed on them, sediments deposited and/or soil development, which had been disturbed to reveal the quartz vein. No pebble or cobble based quartz sources were found, but they may be present in the tills found in the Lac Seul moraine to the east of the park.

Since locally derived quartz is evidently the most commonly found raw material in the Bloodvein River area, Aboriginal people from this region were selecting reliable, nearby quartz vein sources more often than typically higher quality exotic types from afar. There is a specific Ojibwe word for white quartz, *wiininwaabik* (fat rock), whereas most other minerals and rocks are generically known as *asin*. Perhaps this distinction stems from the longstanding importance of this material in lithic technology within *Anishinaabeg* territories. In addition, the Bloodvein River examples indicate that geoarchaeologists do need to search for these types of small-scale quartz vein quarry sites in the boreal forest where quartz artifacts are typically prevalent.

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Analyzing ductile shear zone network geometries in the Grassy Portage Sill, Rainy Lake region, Northwestern Ontario, Canada

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The Grassy Portage Sill (GPS) is a ~2.7 Ga metagabbroic sill located in the Rainy Lake region of northwestern Ontario (Fig. 1). The Rainy Lake region is located in the Superior Province between the metavolcanic Wabigoon subprovince to the north and the metasedimentary Quetico subprovince to the south (Card and Ciesielski, 1986). Two regional faults bound the region and intersect to the east, forming a wedge which defines the Rainy Lake zone (Poulsen, 1986). This area was regionally deformed due to dextral transpression resulting from the Kenoran Orogeny (~2.7 Ga) (Poulsen et al., 1980; Davis et al., 1989; Czeck and Hudleston, 2003; Druguet et al., 2008).

The GPS is approximately 20 km long and 1-2 km wide, and has undergone heterogeneous strain along its length. This strain variation is a function of the competence contrast between the GPS, the gneissic Rice Bay Dome to the west, and the metavolcanic and metasedimentary units between the two (Druguet et al., 2008; Carreras et al., 2010). The GPS has a higher competence than the adjacent metavolcanic and metasedimentary units, but all have a lower competence than the Rice Bay Dome.

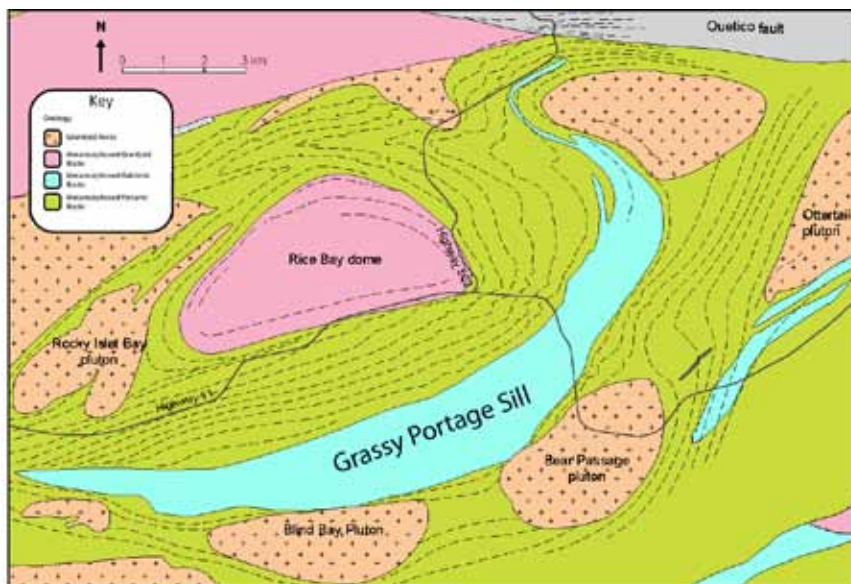


Figure 1. Geologic map of the Grassy Portage Sill and surrounding region with regional foliations indicated by dashed lines. Modified from Druguet et al. (2008) from mapping by Poulsen (2000).

Within the GPS, anastomosing ductile shear zone networks accommodated the bulk of deformation within the largely competent sill (Fig. 2; Carreras et al., 2010), although a penetrative foliation also formed locally. The network geometries vary along the length of the sill, apparently related to strain variations. At nearly all locations, steeply dipping dextral and sinistral sets of shear zones formed, presumably simultaneously as evidenced by mutually offsetting cross-cutting relationships where present. Conjugate shear zone sets initiated at a near perpendicular orientation, and through progressive deformation have rotated towards one another.

At the least strained sites, the gabbro has a pervasive foliation, but few, if any, shear zones. The varying responses of the GPS to deformation may be explained by lithological heterogeneity. Where grain size is coarse, the rock is likely stronger and deformation is localized into discrete shear zones. Where grain size is fine, the rock is generally weaker and pervasive foliation forms.

Regionally the bulk shortening direction is oriented NW-SE, due to the N-S oriented shortening accompanied by dextral transpression. Estimates of bulk shortening direction based on shear zone geometries within the GPS indicate wide variation along the length of the unit, but outcrops can be grouped into three general clusters. In

the north, bulk shortening is predominantly oriented NE-SW. In the central part, shortening is oriented between N-S and NW-SE. In the south, the shortening direction is oriented NW-SE.

Overall the shortening direction appears to “wrap” around the GPS, which is similar to the trend of the foliation variation within surrounding units. The variations seen at the unit scale can be attributed to a regional scale “strain shadow” imparted by the highly competent Rice Bay gneissic dome.



Figure 2. Photograph of the anastomosing shear zone network within metagabbro at a highly strained outcrop. Shear zones have been traced, and are defined by narrow zones of intense foliation surrounding undeformed or less deformed lozenges. They define an anastomosing network pattern.

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SPREE: Field experiment to study deep structure of the Midcontinent Rift

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By about 1 Ga North America's midcontinent region completed a formation process broadly similar to the current American west, with convergence along the Grenville Orogeny and extension along the contemporaneous Mid-continent Rift (MR). Now buried under platform sediments, more than a half million cubic km of dense igneous rock was deposited in the MR. These rocks generate an elongated 60+ mgal Bouguer gravity anomaly and a correlated magnetic anomaly, which cuts curiously through major geologic units such as the Superior and Yavapai Provinces. Although the MR is the most striking surface geophysical anomaly in the midcontinent, no evidence has yet been found for current geologic activity or correlated anomalies in the mantle lithosphere. The installation this year of the first swath of Earthscope-USArray stations east of the Mississippi River allows us to shed light on this enigmatic anomaly. Specifically, our seismic field experiment SPREE (Superior Province Rifting Earthscope Experiment) aims to uncover important details such as the depth and lateral extent of crust and mantle structures related to rifting, rift cessation/inversion, or post-rift stabilization. In addition, SPREE can answer questions about the longevity and healing ability of Proterozoic continental lithosphere.

SPREE is a collaboration between Canadian and US universities. Eighty-three Flexible-Array (FA) seismic stations were installed between April and June this year on and near the MR. The array configuration includes an extension of the US-based Transportable Array (TA) into Ontario north of Lake Superior as well as three lines of 10-km spaced stations along and across the MR west and east of the northern Mississippi.

SPREE recorded the M2.5 western Minnesota earthquake (April 29), the M7.3 Fox Islands earthquake (June 24), the M5.8 Virginia earthquake, and an unusually high number of moderate earthquakes in the relatively stable continental interior, from eastern Ontario to Oklahoma. We aim to use the recorded earthquakes and ground motion noise to detect microseismicity as well as to construct a multi-scale, three-dimensional image of the seismic velocity and discontinuity structure of the study region's lithosphere and underlying mantle. These investigations will reveal the deep structure of the mid-continent rift. Moreover, the central location of SPREE with respect to North America's seismically active plate boundaries contributes optimally to the seismic imaging of the sub-continental mantle elsewhere in stable North America.

Anatomy of a Mesoarchean Batholith

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The North Caribou greenstone belt (NCGB) lies in the North Caribou Terrane (NCT) of the Superior Province at the northeastern boundary of the North Caribou Core and the Island Lake Domain (Stott et al. 2010). The NCGB hosts the Musselwhite gold mine, a banded-iron-formation-hosted orogenic lode gold deposit, and structural controls on the deposit have been linked to intrusions along the margins of the NCGB (Stott and Biczok 2010). The most prominent of these intrusions is the North Caribou Batholith (NCB), which forms the southern and western boundaries of the west-central half of the NCGB. The contact of the NCB with the greenstone belt is marked by a crescent of low magnetic susceptibility relative to the centre of the NCB, which has been interpreted by Stott and Biczok (2010) as a “crescent pluton,” like those found elsewhere in the Superior Province. These crescent plutons intrude along the contact of greenstone belts and older gneissic terranes and impose a strain aureole on the less-competent greenstone belts, causing them to form arcuate shapes. Since the margin of the NCB conforms to the structural and geometric constraints of crescent plutons, this area has been dubbed the North Caribou Pluton (NCP). This interpretation prompted an investigation of the NCP to determine if this pluton is a discrete, younger intrusion. New U-Pb ages from zircon and titanite, along with whole rock and zircon geochemistry, and amphibole and plagioclase thermobarometry illuminate the evolution and relationship between the NCP and the rest of the NCB.

Rocks in the NCB range from tonalites to granites and have a wide variety of textures and compositions. Textures throughout the NCB include enclaves of isotropic, equigranular, weakly-deformed granitoids, strongly foliated and lineated gneisses, and migmatites. Some of the migmatites are partially-melted amphibolites, which occur near the northern margin of the intrusive complex, but there are also granitoids with schlieren and other textures suggesting either partial melting, melt segregation, or magma mixing. Late K-feldspar-rich pegmatites occur around the margins of the NCB, in both the NCP and the central batholith.

U-Pb geochronology on zircon and titanite was conducted using LA-ICP-MS methods at the University of New Brunswick. Single zircon ages range from 3132-2693 Ma, with a majority of rock ages falling between 2870 Ma and 2830 Ma. These ages are consistent with those reported by previous workers in the NCB and elsewhere in the NCT (e.g. Biczok et al., 2012). Ages from titanite are similar to the younger zircon populations. In the central NCB, titanite ages from 2798-2791 Ma are found in rocks with zircon ages of 2834-2833 Ma. This 30 m.y. difference could represent cooling through the different closure temperatures of titanite and zircon (500 and 900 °C, respectively). The titanite in the NCP, however, record ages between 2766 Ma and 2748 Ma, with a ~100 m.y. difference between the zircon and titanite ages. As the titanites from these rocks are roughly aligned with the foliation, and the ages match zircon ages in younger intrusions surrounding the NCGB, these ages likely reflect later tectonism.

To further assess the relationship between the rocks in the NCP and those in the central NCB, depth and temperature of emplacement was estimated using the plagioclase-amphibole thermobarometer and the Ti-in-zircon thermometer. Titanium concentrations in zircon were measured using LA-ICP-MS, and calculated temperatures range from 830-760 °C in the NCP and 790-750°C in the central NCB. Plagioclase-amphibole temperatures and pressures were calculated following Holland and Blundy (1994) and Anderson and Smith (1995). Only five samples from the NCB have the appropriate mineralogy for the thermobarometer, only one of which was in the NCP. The temperature/ pressure conditions for the NCP sample are 600 ± 20 °C and 6.3 ± 0.2 kbar (~22 km). Since this sample also contained isotopically disturbed titanite, it is possible that the plagioclase and amphibole compositions record this later event, rather than the emplacement conditions. The PT conditions in the central part of the batholith range from 640-620 °C and 7.5-6.7 kbar (~26-23 km).

These data provide some evidence supporting the crescent pluton model of the NCP. The shape of the NCGB, the magnetic signature of the NCP, and the structural data from previous workers are similar to the observations of crescent plutons in other greenstone belts. The model requires an intrusive contact between the crescent plutons and the supracrustal rocks, and the partially-melted amphibolites at the contact between the NCP and the NCGB clearly demonstrate that this contact is intrusive. Major, minor, and trace element geochemistry from the NCP is less variable than that from the rest of the NCB, despite a wide range of SiO₂ concentrations, and REE patterns in zircon in the NCP have distinct, shallower slopes than those in the NCB. This suggests that the rocks in the NCP are more similar to each other than those in the rest of the NCB. U-Pb ages from titanite in the NCP are also younger than those in the central NCB.

There are, however, new data that do not support a late crescent pluton. Zircon U-Pb ages in the NCP range from 2870-2858 Ma, which is slightly older than the ages from the centre of the NCB, which are 2852-2833 Ma. There is also no difference between the textures in the pluton and the batholith, as both contain gneisses and isotropic granitoids. Temperatures and pressures are also indistinguishable across the contact between the NCP and the central NCB.

The older zircon ages in the NCP suggest either that the NCP represents a chill-margin on the NCB or a discrete earlier intrusion. Since the NCB has a map area of ~2800 km² and does not exhibit cumulate textures, it is unlikely the entire complex was emplaced as a single melt batch. It is more likely that the primary conduit for the magma was near the centre of the NCB, and that several intrusions emanating from this area were emplaced at roughly the same depth over ~40 m.y.. This model predicts older granitoids on the margins of the intrusive complex, which have been shouldered aside radially by continued magmatism at the centre of the complex. This is consistent with the aeromagnetic data and textures observed in the NCB, as well as the geochronology, geochemistry and thermobarometry. Since this study did not investigate fabrics and structures related to the intrusions, we cannot comment on whether the kinematics of this model are consistent with these data. Further studies of the NCB, including fabric analysis, could constrain the dynamics of the intrusions and improve the proposed model.

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Paleomagnetic data in stratigraphic context from 1.1 Ga Osler Group basalt flows on Simpson Island, Ontario: Evidence for rapid plate motion of Laurentia in the late Mesoproterozoic

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The Osler Group represents the extrusive component of the early magmatic stage of the Midcontinent Rift in the northern Lake Superior region. The Osler Group overlies the epicontinental sediments of the Mesoproterozoic Sibley Group with angular unconformity. The lowest 100 m of stratigraphy of Osler Group contains rift-related sandstones and conglomerates (Hollings et al., 2007). In some locales, these basal sedimentary units are overlain by a quartz-feldspar porphyritic rhyolite for which a U-Pb zircon age of 1107.5 ± 2 Ma has been reported (Davis and Sutcliffe, 1985). This age was obtained from an outcrop of rhyolite porphyry on Black Bay Peninsula, about 40 km to the west of Simpson Island. This unit was tentatively interpreted as extrusive (Davis and Sutcliffe, 1985; Lightfoot et al., 1991; Hollings et al., 2007), and the age has been interpreted as constraining the time at which Osler Group volcanism commenced. However, observations made during this study of a quartz-feldspar porphyry unit on Simpson Island, mapped as equivalent to the unit from which the age was obtained (Giguere, 1975), provide additional evidence for Giguere's inference that this unit is actually intrusive. A thin veneer of basalt, ranging in thickness from several cm down to 1-2 mm, is variably present overlying the porphyry. The basalt veneer displays pahoehoe flowbanding, which is unlikely to have developed if the flow was originally this thin, implying that the felsic unit intruded into the basalt, cutting into an originally thicker flow. We also observed protrusions of porphyry surrounded by host basalt, providing further support for an intrusive relationship. This evidence suggests that the 1107.5 Ma age is a minimum age for the eruption of the first Osler basalt flows, rather than an absolute age for that point in the Osler Group stratigraphy. Above the felsic porphyry is a succession of relatively continuous tholeiitic basalt flows, with minor siltstone and conglomerate interbeds. The flows range in thickness from 5 cm to about 40 m thick; individual flows are recognized by a transition from massive basalt at the base of flows (occasionally with pipe vesicles in the basal 10-20 cm) to vesicular basalt towards the top, and by occasionally well-exposed pahoehoe flow tops. A rhyolite, interpreted as extrusive by Davis and Sutcliffe (1985), occurs near the top of the Osler Group basalt flows at Agate Point (stratigraphically higher than the highest flow on Simpson Island). Davis and Green (1997) obtained a U-Pb zircon age from the Agate Point Rhyolite of 1105 ± 2 Ma, which because of the extrusive nature of this rhyolite, is a robust age for that point in the Osler Group stratigraphy. It is worth noting that this age is statistically indistinguishable from the rhyolite porphyry discussed above.

Here we report the first paleomagnetic investigation of the lower portion of the Osler Group stratigraphy, which builds on the work of Halls (1974) in the Nipigon Strait region. Oriented paleomagnetic cores were collected from 45 basalt flows in 5 stratigraphic sections along the eastern and southern shores of Simpson Island, spanning about 2500 m of Osler stratigraphy. Alternating field demagnetization, thermal demagnetization and low-temperature cycling experiments show that the majority of the remanent magnetization in Osler flows is held by magnetite and records a thermal remanent magnetization acquired at the time of eruption.

Paleomagnetic data from the Osler Group suggest rapid plate motion during the early stages of the Midcontinent Rift. A preliminary paleomagnetic pole ($\lambda_p = 220.6$, $\phi_p = 44.2$, $A_{95} = 5.0$) was calculated for 8 measured flows towards the bottom of the Osler Group and another preliminary pole ($\lambda_p = 197.9$, $\phi_p = 35.2$, $A_{95} = 6.3$) was calculated for 9 flows towards the top of the reversely magnetized Osler flows. These two poles imply $\sim 20^\circ$ of latitudinal motion during the time the Osler Group was erupted. Significant latitudinal change during the lower reversed polarity zone of the Midcontinent Rift supports similar data from correlative stratigraphy at Mamainse Point, Ontario and represents the second place in the rift where such motion has been documented in

the lower reversed polarity zone (Swanson-Hysell et al., 2009). These data add to the database of paleomagnetic poles from Keweenawan volcanics that together imply rapid plate velocities (>20 cm/yr) for Laurentia during the development of the Midcontinent Rift.

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The Little Commonwealth exploration - An example of a SEDEX deposit

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The Little Commonwealth Exploration (LCE) is located in Florence Co., Wisconsin. The LCE represents a subaqueous synsedimentary exhalative deposit where silica, iron and manganese rich minerals are deposited on an elevated mound that formed a barrier separating sand (quartzite) to the west from mud (slate) to the east. The entire deposit outcrops in a small area encompassing less than 80 acres. The surface geology is primarily Michigamme slates with minor quartzites, conglomerates and isolated hydrothermal banded iron formation deposits. The quartzite can be characterized as a vitreous white ortho-quartzite except at the LCE where banded magnetite chert and Mn-chlorite, Mn-stilpnomelane, Mn-garnet chert breccias were deposited. The garnet, chlorite, stilpnomelane and ilmenite are all enriched in manganese characteristic of mineralization associated with SEDEX/VMS deposits. The rock with abundant spessartine garnet has been called coticule.

Beginning with the deposition of the quartzite unit within the Michigamme formation a restricted area was subjected to hydrothermal mineralization. Some minerals are replacement of existing sediments (i.e. Dunkel Exploration located one mile to the northwest) while others are subaqueous exhalites like the one found at the LCE. Hot fluids carried Fe, Si, Al, Mn, Mg, P, B and REE. Upon reaching the surface and experiencing a significant drop in the pressure and temperature some of the minerals immediately crystallized and were deposited directly on the slope of the mound. Specularite appears to be later as the crystal laths display a random orientation usually enclosing magnetite or ilmenite. Late addition of sulfur, Fe⁺⁺, copper and arsenic is evidenced by the presence of small quantities of sulfides. The major minerals present are magnetite, chert, specularite, Mn-chlorite, Mn-Stilpnomelane, Mn-garnet and apatite. Minor minerals include Mn-ilmenite, monazite, tourmaline, pyrite, chalcopyrite and arsenopyrite. The only carbonate identified was a few grains of kutnohorite and dolomite. The manganese oxide content in the garnet is quite variable (Table 1) while the manganese in the chlorite and stilpnomelane is about more constant at about 1.8%. Ilmenite exhibits MnO values of ~10%.

Table 1. Garnet Composition

Oxide	FC-103 @80'	FC-104 @ 250'	Breccia 2A E. Sft	Breccia 2B E. Sft
SiO ₂	35.00	35.09	35.37	36.12
Al ₂ O ₃	18.62	18.5	18.95	19.14
FeO	31.41	28.39	26.53	27.38
MnO	7.38	12.91	13.87	20.23
MgO	0.47	0	0	0.69
CaO	3.62	1.93	2.31	2.53

The rocks appear to have experienced low grade greenschist alteration as evidenced by replacement of the garnet by either Mn-chlorite or Mn-stilpnomelane. Some of the magnetite is believed to be the result of immediate crystallization on exit from the vent and has undergone some oxide overgrowth resulting in crystals that are +100 microns in size.

The rare earth elements reside in monazite which yields a high LREE pattern and a very low HREE suite in a chondrite normalized plot (Fig. 1). A slight negative Eu value would support the presence of hydrothermal fluids but with abundant sea water dilution.

The age of the LCE deposit is constrained between 1836 and 1833 Ma based on a tuff age in the basal Rove formation and the local intrusive of the Tobin Lake granite indicating the magma chamber that produced the iron oxide rich Hemlock volcanics and associated with the northward subduction zone was still viable near the end

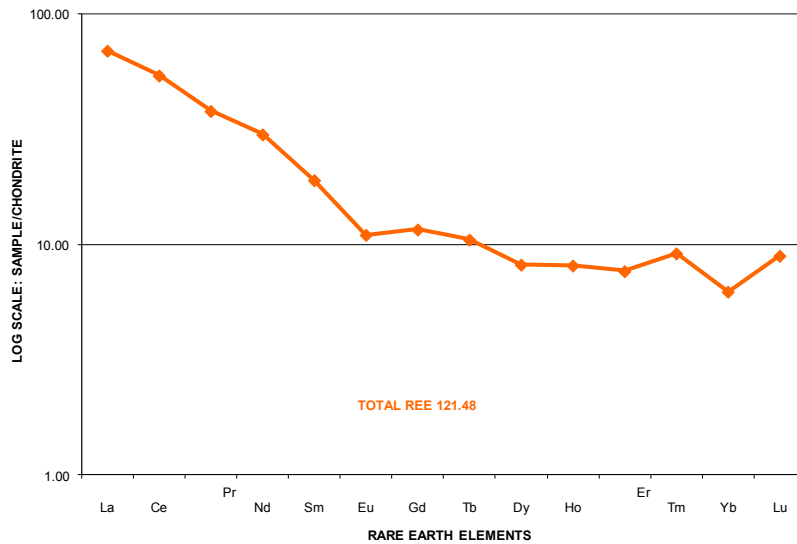


Figure 1. Chondrite normalized REE plot for Little Commonwealth martite

of the Penokean Orogeny.

When the Wisconsin Magmatic terrain moved northeast along a series of NW-SE major faults it resulted in three parallel allochthons that were tilted and rotated exposing repeat sections of Michigamme strata.

There are abundant indications within the three fault blocks to indicate the SEDEX mineralization is not an isolated occurrence. A number of iron oxide rich showings have been noted in the Michigamme formation particularly from the quartzite unit upward. Replacement of existing sediments is indicated in a few of the shows like the Dunkel located one mile northwest of the LCE.

The LCE is an excellent example of a synsedimentary exhalative deposit with both SEDEX and IOCG features situated adjacent to an active hydrothermal vent (not located) that produced iron oxides-chert-Mn silicates. A series of much larger and more active vents can easily be envisioned as a source for Lake Superior Type iron deposits found in the Animikie Basin.

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The curious meteorite harvest of the Lake Superior region I - Overview

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Introduction

The historic trove of discrete meteorite falls and finds in the region surrounding Lake Superior is 52 (the official total, on 10 April 2012, as recounted in the on-line database of the Meteoritical Bulletin, <http://www.lpi.usra.edu/meteor/metbull.php?>), plus five more in Manitoba awaiting official recognition. Current official tallies for large countries include: U.S.A. (1,633); Australia (646); Chile (206); India (136, plus 4 insufficiently documented); Argentina (74); and Canada (60, plus 13 “in progress” of certification). Our chosen region for this short survey includes the four Superior-bounding jurisdictions plus Manitoba (with 3 finds in and near Whiteshell Park, which is closer to Superior than the populous south of Ontario). For the three states the documented haul of meteorites corresponds to a cumulative mean density of 32 in 645,304 km², or 1 meteorite recovered per 20,166 km². For the two provinces the total is 25 in 1,724,192 km², or 1 meteorite recovered per 68,968 km² (in this instance, the cosmic odds appear 3.4 times better in the U.S.!). The two sub-regions have respective populations of 20.891 and 14.291 million, and mean population density of the three states is 3.9 times that of the two provinces (data from National Geographic Society, 2011).

The table breaks down the 57 meteorites into their most basic families (see Norton and Chitwood, 2008, for a readable taxonomy of meteorites; Grady, 2000, may be the last global meteorite catalogue in print). Irons and the rarer stony-irons (the two regional examples are both the olivine-metal mixtures known as pallasites) are quite distinct from Earth rocks. The stony meteorites, both the more primitive, undifferentiated chondrites and the rare, igneous achondrites, vary in their properties but can be much harder to identify, especially when weathered. There are 29 irons, two stony-irons and just 26 stones, including 25 ordinary chondrites (43.9% of the total). The latter (Met.Bull., 10 April 2012) are 87.4% of all authenticated meteorites, irons just 2.5% (but 51% of the regional meteorite haul), stony-irons just 0.6% (the other 9.5% are a legion of achondrites and rare chondrites). Note also the rarity of achondrite recoveries: none in the region, depending on the classification of Mount Morris (Wisconsin), nor in the whole of Canada; and of the reduced enstatite chondrites (just one in Ontario – Blithfield – which being near the Ottawa valley lies far from Superior).

Table 1. Meteorites of the Lake Superior region

State / province	Irons	Stony-irons	Achondrites	Chondrites	All meteorites	Impact structures
Ontario	8	1	0	7	16	5
Manitoba	4	1	0	4	9	2
Minnesota	4	0	0	4	8	0
Wisconsin	7	0	0	7	14	2
Michigan	6	0	0	4	10	1

The volume of research on the meteorites varies greatly, as will be seen: although all the meteorites are in Grady (2000) and/or the Met.Bull. database, no other specific records were found* for eight of the 32 U.S. meteorites, while 21 of these were described by 1 to 10 citations each, and just three by 20-plus articles. A tabular review of Canadian meteorites is available at <http://www.turnstone.ca/canamet4.pdf> (update of April 2012, cf. Wilson and McCausland, 2012).

* The more exact rendering of “found” is “accrued to the MINLIB database by 13 April 2012”: the above link further explains the methodology and serendipity involved. Note that the MINLIB coverage of Canadian meteorites will be more complete than for those recovered south of the border.

Ontario

The significant meteorite haul in Ontario (n=16; seven irons, one stony-iron, six ordinary chondrites and an enstatite chondrite, plus a 2.7-kg iron named in, and for, Toronto but probably found in Quebec) has been won largely along the populous corridor extending from Ottawa W.S.W. towards Detroit. There are 11 finds and five falls, most recently the Grimsby (2009) fall (Brown et al., 2011). The sole meteorite from northern Ontario is the Osseo iron, recovered in the Temiskaming region. The Manitouwabing iron and Southampton pallasite (Kissin et al., 2012) were recovered east of Georgian Bay and along the eastern shore of Lake Huron, respectively. The only meteoritic calling-cards west of Sudbury, in fact, seem to be the Slate Islands impact structure and the debris layer from the 1850 Ma Sudbury impact, preserved around Thunder Bay (e.g., Cannon and Addison, 2007).

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The curious meteorite harvest of the Lake Superior region II - Gems in the rough

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From Ontario, we continue a counterclockwise tour of the meteorites closest to Lake Superior ...

Manitoba

Three irons and two chondrites await certification, for an unofficial total of nine finds. The five “candidates” include an H4 chondrite plucked from a road by a grader operator and recognized for its unusual nature, and the informally-named Pinawa and Lone Island Lake irons. These last, plus Bernic Lake, were all retrieved from the southeast corner of the province by a single person, between 2002 and 2005.

Minnesota

Minnesota has two small (<10 g) meteorites of muddled provenance (like Toronto), an iron and a stone. To be a Minnesota meteorite is to be doomed to obscurity, except for three interesting irons. Redressing the balance of the tiny, misplaced finds is the 22.39-kg Turtle River IIIAB iron, largest find in the state. Best-studied is Arlington, one of the rare IIE irons that may strictly be non-magmatic, arising as melt pools on the surface of their parent body (Wasson and Wang, 1986). The Anoka iron has also been a test case in iron meteorite classification. Minnesota is home to one fall and seven finds.

Wisconsin

The Trenton iron, a 505-kg find collected in 1858 and subsequent years, remains the largest meteorite known in the five jurisdictions. At least 29 articles refer to it, 1961 onwards, making it, after Allegan, perhaps the best-researched meteorite in the Upper Great Lakes States. Five falls and nine finds are recorded. The Hammond iron (24 kg) was ploughed up in a cornfield in St. Croix County (a synonym) in 1884. George Kunz etched a piece and noted troilite (FeS) nodules and a Widmanstätten pattern (Fisher, 1887). There is an intriguing possibility of kinship between the Pine River iron with silicate inclusions, and Mount Morris (Wisconsin), two murkily-documented finds within 15 km of one another. The latter has been interpreted to be the remains of a large silicate inclusion in Pine River, and itself possesses the mineralogy of a winonaite, a rare achondrite (Bevan and Grady, 1988). The most recent meteorite fall in the Superior region was the Mifflin L5 chondrite on the evening of 14 April 2010.

Michigan

The closest known meteorite visitor to Lake Superior is Iron River, a IVA iron find in 1889, ~75 km south of the head of Keweenaw Bay. The best-researched meteorite in the Upper Great Lake States is probably Allegan (H5 chondrite fall of 1899) with 48 references on file, 1903 onwards (in 1903 just three meteorites were known in the state – the next 109 years have added but 7 more: six finds and four falls are known). Eight are described by Del Chamberlain (1968). The Rose City H5 chondrite is another interesting Michigan meteorite, a highly shocked, black chondrite (23 references known, third-most-studied local meteorite). As an impact melt breccia, with recrystallized olivines, melt veins and masses of metal (Rubin, 1995), it has been compared to the Portales Valley H6 stone (a 1998 fall in New Mexico), and has been exhibited at the Smithsonian and in the Arthur Ross Hall of Meteorites at the A.M.N.H. in New York City.

Conclusions

The modest meteorite trove of the region is easy to attribute to low population density, predominant lakes and forests, and large distances. Persons in the region are often transient or seasonal (e.g., hunters, loggers, cottagers) cf. farmers. The factors all limit the chances of tracking a fireball and making a recovery, thus finds are predominant (a regional total of 15 falls and 42 finds, cf. India, with at least 10 witnessed falls recovered in 2001-2008 alone: <http://www.turnstone.ca/indmet.htm>).

In general, the best prospects for recovery of a fall are a well-tracked fireball crossing populous areas to land on farmland. It is surely not a coincidence that 9 of the 10 recovered falls in the three states are in Wisconsin and Michigan. At least five of the 32 US meteorites were ploughed up, and a further three or more found in fields. A Wisconsin farmer is more apt to find a meteorite than a logger in Minnesota or the U.P. of Michigan! The best prospects for finds may be discoveries in a zone of glacial stillstand. The three recent iron finds in southeast Manitoba may lie in such a concentration (Hildebrand et al., 2006). The predominance of iron finds in the region may speak to their unique nature, since they are relatively easy for the general public to recognize as something out of the ordinary.

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