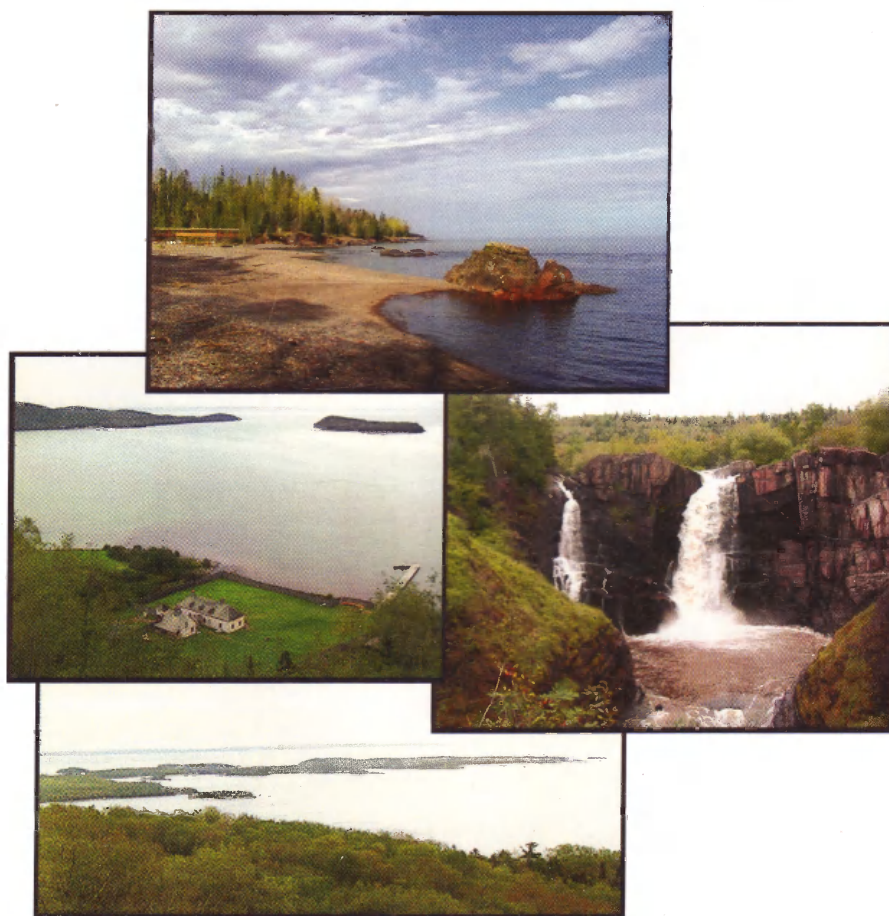


53RD ANNUAL MEETING



INSTITUTE ON LAKE SUPERIOR GEOLOGY

LUTSEN, MINNESOTA MAY 8 – 13, 2007



PROCEEDINGS VOLUME 53
PART 1 – PROGRAM AND ABSTRACTS



INSTITUTE ON LAKE SUPERIOR GEOLOGY

**53RD ANNUAL MEETING
MAY 8-13, 2007
LUTSEN, MINNESOTA**

HOSTED BY:

**LAUREL G. WOODRUFF AND JAMES D. MILLER, JR.
Co-Chairs
U.S. Geological Survey
Minnesota Geological Survey**

Volume 53 Part 1 – Proceedings and Abstracts

Edited by Laurel Woodruff, U.S. Geological Survey

Cover Photos: Top - Lake Superior shoreline at Lutsen Resort; Right - Grand Portage National Monument stockade and Hay Bay; Left - High Falls on Pigeon River; Bottom - Suzie Islands (photographs courtesy of Bill Cannon)

53RD INSTITUTE ON LAKE SUPERIOR GEOLOGY

VOLUME 53 CONSISTS OF:

PART 1: PROGRAM AND ABSTRACTS

PART 2: FIELD TRIP GUIDEBOOK

TRIP 1: IGNEOUS STRATIGRAPHY OF THE POPLAR LAKE INTRUSION
(FORMERLY NATHAN'S LAYERED SERIES)

TRIP 2: GEOLOGIC AND CULTURAL HISTORY OF GRAND PORTAGE NATIONAL
MONUMENT

TRIP 3: MIDCONTINENT RIFT-RELATED MAFIC INTRUSIONS NORTH OF THE
INTERNATIONAL BORDER

TRIP 4: GEOLOGY AND CU-NI-PGES MINERALIZATION – NICKEL LAKE
MACRODIKE, SOUTH KAWISHIWI INTRUSION

TRIP 5: GEOLOGY OF THE NORTH SHORE FROM LITTLE MARAIS TO GRAND
MARAIS

TRIP 6: GEOLOGY OF THE GUNFLINT TRAIL

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

Hart, T.R. and MacDonald, C.A., 2007, Emplacement of the Nipigon Sill Complex and mafic to ultramafic intrusions of the Nipigon Embayment [abstract]; Institute on Lake Superior Geology Proceedings, 53rd Annual Meeting, Lutsen, MN, v. 53, part 1, p. 36-37.

Published by the 53rd Institute on Lake Superior Geology and distributed by the ILSG
Secretary:

Peter Hollings
Department of Geology
Lakehead University
Thunder Bay, ON
P7B 5E1
CANADA
peter.hollings@lakeheadu.ca

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

ISSN 1042-9964

TABLE OF CONTENTS
PROCEEDINGS VOLUME 53
PART 1—PROGRAM AND ABSTRACTS

Institutes on Lake Superior Geology, 1955-2007	iv
Goldich Medal Committee.....	vi
Past Goldich Medalists	vi
Citation for 2007 Goldich Medal Recipient	vii
Sam Goldich and the Goldich Medal.....	viii
ILSG Student Research Fund	x
Student Paper Awards.....	xi
Eisenbrey Student Travel Awards	xii
Report of the Chair of the 52nd Annual Meeting	xiii
2007 Board of Directors	xv
2007 Session Chairs.....	xv
2007 Student Paper Awards Committee	xv
2007 Local Committees	xv
2007 Banquet Speaker	xvi
Program.....	xvii
Poster Presentations	xxiii
Abstracts	xxv

PREVIOUS INSTITUTES ON LAKE SUPERIOR GEOLOGY

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

30	1984	Wausau, Wisconsin	G.L. La Berge
31	1985	Kenora, Ontario	C.E. Blackburn
32	1986	Wisconsin Rapids, Wisconsin	J.K. Greenberg
33	1987	Wawa, Ontario	E.D. Frey and R.P. Sage
34	1988	Marquette, Michigan	J. S. Klasner
35	1989	Duluth, Minnesota	J.C. Green
36	1990	Thunder Bay, Ontario	M.M. Kehlenbeck
37	1991	Eau Claire, Wisconsin	P.E. Myers
38	1992	Hurley, Wisconsin	A.B. Dickas
39	1993	Eveleth, Minnesota	D.L. Southwick
40	1994	Houghton, Michigan	T.J. Bornhorst
41	1995	Marathon, Ontario	M.C. Smyk
42	1996	Cable, Wisconsin	L.G. Woodruff
43	1997	Sudbury, Ontario	R.P. Sage and W. Meyer
44	1998	Minneapolis, Minnesota	J.D. Miller, Jr. and M.A. Jirsa
45	1999	Marquette, Michigan	T.J. Bornhorst and R.S. Regis
46	2000	Thunder Bay, Ontario	S.A. Kissin and P. Fralick
47	2001	Madison, Wisconsin	M.G. Mudrey, Jr. and B.A. Brown
48	2002	Kenora, Ontario	P. Hinz and R.C. Beard
49	2003	Iron Mountain, Michigan	L.G. Woodruff and W.F. Cannon
50	2004	Duluth, Minnesota	S.A. Hauck and M. Severson
51	2005	Nipigon, Ontario	P. Hollings and M.C. Smyk
52	2006	Sault Ste. Marie, Ontario	R.P. Sage and A.C. Wilson
53	2007	Lutsen, Minnesota	L.G. Woodruff and J.D. Miller, Jr.

PAST GOLDICH MEDALISTS

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

2007 GOLDICH MEDAL RECIPIENT

Joseph Mancuso

Bowling Green State University
Bowling Green, Ohio

GOLDICH MEDAL COMMITTEE

Serving for the meeting year shown in parentheses

Tom Hart (2004-2007)

Doug Duskin (2005-2008)

Richard Ojakangas (2006-2009)

Government representative

Industry representative

Academic representative

CITATION FOR GOLDICH MEDAL RECIPIENT

Joseph Mancuso, 2007 Goldich Medal Recipient

Membership in the Institute of Lake Superior Geology is composed of government personnel who produce maps and other essential services; exploration geologists who walk the bush looking for ore deposits, and university professor who teach geology to future government personnel, exploration geologists, and professor. Membership also includes students who are learning the dimensions of the profession.

In addition to teaching, Joe was an active exploration geologist during the 40 years he taught at Bowling Green State University.

Joe has been an active member of ILSG for over 50 years. He attended the first meeting when he was an undergraduate student at Carleton College. During the past 50 years he has contributed more than 20 oral presentations and posters to ILSG meetings, plus 42 published papers and abstracts on the geology of the Lake Superior region. He also direct 39 MS theses on the geology of the Lake Superior region, as well as conducting annual field trips for his students to examine Precambrian geology in the field and in mines in Michigan, Wisconsin, and Ontario.

Joe has produced some outstanding students. One brought two gold mines into production; another induced Freeport to drill Grasberg Mountain (4100 meters elevation) in Irian Jaya, Indonesia. Grasberg is now the largest single gold producer in the world in terms of ounces and revenue per year. It is also a high profitable porphyry copper mine (225,000 tons per day milled) that has produced the cash to Freeport to purchase Phelps-Dodge.

Another student recognized the alteration associated with a blind VMS deposit in Manitoba and directed a successful drilling program. He was recognized for this achievement by being named "Prospector of the Year" by the Prospectors and Developers Association of Canada. Another student collected the grab samples on the J-M platinum/palladium layer in the Stillwater layered Igneous Complex in Montana. This layer now supports two mines: Stillwater and Boulder. Finally, two of his students did the grab and development sampling at the Jarrett Canyon gold mine prior to being brought into production.

Joe, you earned the Goldich award.

Submitted by Ron Seavoy

SAM GOLDICH AND THE GOLDICH MEDAL

Sam Goldich received an AB from the University of Minnesota in 1929, a M.A. from Syracuse University in 1930, and a Ph.D. from 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

ILSG STUDENT RESEARCH FUND

The 2005 Board of Directors established the ILSG Student Research Funds 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.
- The proposal application should be at least 500 words, and should have a statement of the research project, background information, a map of the research area, research steps necessary to complete the research, figures (if needed), references, and a list of research expenses. The proposal should also include a proposed end date for the research.
- The proposal will need to be signed by researcher's supervisor.

In 2006 the ILSG Board of Governors awarded the first three \$500 awards from the Student Research Fund. This year awards were made to:

Cole Edwards (University of Wisconsin - Oshkosh) - *Controls on the formation of the earliest marine phosphate deposits, Marquette Supergroup, Michigan*

Noah Planavsky (Rosenstiel School of Marine and Atmospheric Sciences
Marine Geology and Geophysics, Miami) - *Iron isotopes as oceanographic tracers in Animikie Basin Iron Formations*

Michael Taylor (University of Minnesota - Duluth) - *Pleistocene glaciation as a mechanism for emplacement of high-salinity groundwater at anomalously shallow depths in the Lake Superior basin*

STUDENT PAPER AWARDS

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

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

Student papers are noted on the Program.

In 2006 the ILSG Student Paper Committee presented four awards from the ILSG Student Paper Fund. The awards were made to:

Patrick Moran -- Lakehead University, Thunder Bay, ON (best oral presentation) -- \$250
Noah Planavsky -- Lawrence University, Appleton, WI (oral presentation, honorable mention) -- \$50
Amanda Gross -- Kent State University, Kent, OH (best poster) -- \$250
Ryan Bartingale -- University of Wisconsin - Eau Claire, Eau Claire, WI (poster, honorable mention) -- \$50

EISENBREY STUDENT TRAVEL AWARDS

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

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

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

In 2006 the ILSG awarded six travel awards from the ILSG Eisenbrey Student Travel Fund. The awards were made to:

Peggy Stonier -- Kent State University, Kent, Ohio
Amanda Gross -- Kent State University, Kent, Ohio
Jenny Murphy -- Lawrence University, Appleton WI
Noah Planavsky -- Lawrence University, Appleton WI
Clare Stielstra -- Lawrence University, Appleton WI
Davis Voights -- Lawrence University, Appleton WI

REPORT OF THE CHAIRS OF THE 52ND ANNUAL MEETING INSTITUTE ON LAKE SUPERIOR GEOLOGY SAULT STE MARIE, ONTARIO

The Ontario Geological Survey hosted the 52nd Annual Institute on Lake Superior Geology meeting on May 10-11 2006 in Sault Ste Marie, Ontario. The meeting consisted of two days of technical sessions with two pre-meeting and four post-meeting field trips. Pete Hollings and Mike Mudrey provided invaluable technical assistance with the web site and Anthony Pace provided on site assistance with the audio-visual component of the program. Gerry Bennett, Mike Easton, Mike Hailstone and Anthony Pace provided assistance with field trip preparation. Vivienne Côté and Roger Poulin (Ontario Prospectors Association) and Marc Gaudreau and Anthony Pace (Ontario Geological Survey) provided aid with the loan, retrieval, delivery and set-up of the poster boards for the poster session. Lisa Bagnall, Scheduling Office, was the on site co-ordinator with the Sault College of Applied Arts and Technology. Total registration for the meeting was 110 students and professionals.

Proceedings Volume 52 was published in six parts: Part 1 – Proceedings and Abstracts, edited by A. C. Wilson contained abstracts for 19 oral presentations and 21 posters; Part 2 – Glacial Lakes Algonquin and Nipissing Shoreline Bedrock Features: Mackinac Island, Michigan – Field Trip Guidebook; Part 3 – Unusual Diamond-bearing breccias of the Wawa Area – Field Trip Guidebook; Part 4 – The Huronian Supergroup between Sault Ste Marie and Elliot Lake – Field Trip Guidebook; Part 5 – Keweenawan Rocks of the Mamainse Point Area – Field Trip Guidebook and Part 6 – Geological Guidebook to the Paleoproterozoic East Bull Lake Intrusive Suite Plutons at East Bull Lake, Agnew Lake and River Valley, Ontario – Field Trip Guidebook. All guidebook volumes were edited by R. P. Sage.

Last held in Sault Ste Marie, Ontario in 1974, a return visit to the area allowed participants to take part in a smorgasbord of new field trips. On Monday, May 8, Gerry Bennett, assisted by Mike Hailstone, led a two-day field trip to examine the classic stratigraphy of the Huronian Supergroup in the Elliot Lake and Searchmont areas. The next day, Ann Wilson introduced a rain-soaked but enthusiastic crowd of participants to the unusual diamond-bearing breccias of the Wawa area. Following the conference four field trips were held: Ann Wilson reprised the Wawa field trip; Tom Hart and Anthony Pace's trip examined the Keweenawan rocks along the Lake Superior shoreline; Ron Sage led a small group of bicyclists to Mackinac Island to examine bedrock exposures there; and Mike Easton and Dick James (Laurentian University) took a group east of the Sault to investigate a suite of intrusive rocks along the boundary between the Archean Superior and the Proterozoic Southern provinces.

Eighty-five participants attended the Annual Banquet. Dr. Ed Walker gave the after dinner key note address providing his insight into the "*Emplacement and Geochemistry of Archean-aged diamondiferous rocks of the Wawa Area*". Jim Miller presented the 2006 Goldich Medal to Mike Mudrey for his 30 years of contributions to the understanding of the regional geology and for his service to the Institute.

The student paper committee consisted of Dan England, John Klasner and Norm Trowell all of whom conscientiously deliberated over the four oral presentations and four poster presentations. The winners were:

2006 Best Student Paper Awards

- 1) Patrick Moran – Lakehead University
(\$250, winner best oral presentation)
- 2) Amanda Gross – Kent State University
(\$250, winner best poster presentation)
- 3) Noah Planavsky – Lawrence University
(\$50, honourable mention oral presentation)
- 4) Ryan Bartingale – University of Wisconsin
(\$50, honourable mention poster presentation)

In addition, Eisenbrey travel awards were presented to:

- 1) Noah Planavsky – Lawrence University (\$150)
- 2) Jenny Murphy – Lawrence University (\$150)
- 3) Clare Stielstra – Lawrence University (\$150)
- 4) Davis Voights – Lawrence University (\$150)
- 5) Penny Stonier – Kent State University (\$200)
- 6) Amanda Gross – Kent State University (\$200)

The Institute's Board of Directors met on May 10, 2006 and a brief summary of the meeting follows.

1. Accepted the Report of the Chairs for the 51st ILSG from Mark Smyk and Pete Hollings, and the minutes of the last Board meeting, May 26, 2006 from Pete Hollings.
2. Received, discussed and accepted the 2005-06 ILSG Financial Summary from ILSG Treasurer, Mark Jirsa.
3. Approved Ann Wilson as the on-going board member.
4. Approved 2007 (53rd annual) meeting location as Lutsen, Minnesota with Laurel Woodruff as chair.
5. Replaced George Hudak, academic member, on the Goldich Committee with Dick Ojakangas.

The 52nd meeting was not without its challenges, including the last minute resolution of a strike at Ontario's Colleges. However, no challenges were insurmountable and the meeting and field trips went off without a hitch. We thank all individuals who contributed to the success of the meeting, including the staff of Sault College, the bus drivers from AJ Bus Lines Limited and Reid Bus Line, volunteer field trip leaders and drivers and the Ontario Geological Survey. The field trips were astonishingly well attended and we are grateful for the kind feedback that we received from the field trip participants.

Both of us were extremely satisfied with the 52nd meeting. We appreciated all of the positive feedback from the delegates who enjoyed a return visit to the Sault. As always, we wouldn't have succeeded without the continuing support of the ILSG members.

Respectfully submitted

Ron Sage and Ann Wilson
Co-Chairs, 52nd ILSG Meeting

2007 BOARD OF DIRECTORS

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

Laurel Woodruff and Jim Miller, Co-Chairs 53rd meeting (2010)

U.S. Geological Survey, St. Paul, MN

Minnesota Geological Survey, Duluth, MN

Ann Wilson (2009)

Ontario Geological Survey, South Porcupine, ON

Mark Smyk (2008)

Ministry of Northern Development and Mines, Thunder Bay, ON

Steve Hauck (2007)

Natural Resources Research Institute, University of Minnesota – Duluth, Duluth, MN

Peter Hollings – Secretary (2007)

Lakehead University, Thunder Bay, ON

Mark A. Jirsa – Treasurer (2009)

Minnesota Geological Survey, St. Paul, MN

2007 SESSION CHAIRS

Ted Bornhorst, Michigan Technological Survey, Houghton, MI

Mary Louise Hill, Lakehead University, Thunder Bay, ON

Gordon Medaris, Jr., University of Wisconsin, Madison, WI

Klaus Schulz, U.S. Geological Survey, Reston, VA

Thomas Waggoner, retired, Cliffs Mining Services Co., Ishpeming, MI

Ann Wilson, Ontario Geological Survey, South Porcupine, ON

2007 STUDENT PAPER COMMITTEE

Marcia Bjornerud (Chair), Lawrence University, Appleton, WI

Daniela Vallini, Woodside Energy, Ltd., Perth, Western Australia

Graham Wilson, Magma Metals, Campbellford, ON

2007 LOCAL COMMITTEES

General Co-Chairs

Laurel G. Woodruff – U.S. Geological Survey, St. Paul, MN

James D. Miller, Jr. – Minnesota Geological Survey, St. Paul, MN

Program and Abstracts Editor

Laurel G. Woodruff -- U.S. Geological Survey, St. Paul, MN

Field Trip Guidebook Editor

James D. Miller, Jr. – Minnesota Geological Survey, St. Paul, MN

Acting Local Committee, Lutsen, MN

Gretchen Klasner – Marquette, MI

2007 BANQUET SPEAKER

Don Hunter

PolyMet Mining, Inc.
Hoyt Lakes, MN

**PolyMet's NorthMet Project – the long road from
exploration to production**



PROGRAM

TUESDAY MAY 8, 2007

8:00 a.m. **FIELD TRIP 1: IGNEOUS STRATIGRAPHY OF THE POPLAR LAKE INTRUSION (FORMERLY NATHAN'S LAYERED SERIES)**

Jim Miller, *Minnesota Geological Survey*
Eric Jerde, *Morehead State University*

WEDNESDAY MAY 9, 2007

8:00 a.m. **FIELD TRIP 2: GEOLOGIC AND CULTURAL HISTORY OF GRAND PORTAGE NATIONAL MONUMENT**

Bill Cannon, *U.S. Geological Survey*
Brian Phillips, *Lakehead University*
David Cooper, *National Park Service*

8:00 a.m. **FIELD TRIP 3: MIDCONTINENT RIFT-RELATED INTRUSIONS NORTH OF THE INTERNATIONAL BORDER**

Mark Smyk, *Ministry of Northern Development and Mines*
Peter Hollings, *Lakehead University*

6:00 p.m. **Return of Trips 1, 2 and 3**

4:00 p.m. - 8:00 p.m. **Registration**

7:00 p.m. - 9:00 p.m. **Ice Breaker Social and Poster Setup**

THURSDAY MAY 10, 2007

Note: Asterisk * denotes a student eligible for Best Student Paper Award
Presenter underlined

8:00 a.m. - 9:00 a.m. **REGISTRATION**

8:25 a.m. **INTRODUCTORY REMARKS**

Laurel Woodruff and Jim Miller, Co-Chairs, 2007 ILSG

TECHNICAL SESSION I

Session Chair: Klaus Schulz, U.S. Geological Survey

8:30 a.m. **Addison, William D., Cannon, William F. and Brumpton, Gregory R.**

How to identify Sudbury impact ejecta in the Lake Superior Region

8:50 a.m. **Cannon, William F. and Addison, William D.**

The Sudbury impact layer in the Lake Superior iron ranges: A time-line from the heavens

9:10 a.m. **Burton, Justin and Fralick, Philip**

*Deposition and cementation of Paleoproterozoic Gunflint Formation carbonate:
Implications for early hydrosphere chemistry*

9:30 a.m. **Planavsky, Noah* and Murphy, Jennifer**
Rare earth element patterns in Steep Rock Carbonates

9:50 a.m. - 12:00 p.m. **COFFEE BREAK AND EXTENDED POSTER SESSION**

12:00 p.m. **Lunch Break – 2007 ILSG Board Meeting** (by invitation)

TECHNICAL SESSION II

Session Chairs: **Mary Louise Hill**, Lakehead University
Gordon Medaris, Jr., University of Wisconsin, Madison

1:30 p.m. **Green, John C. and Slade, Andrew**
A State Scientific and Natural Area and a North Shore non-profit association

1:50 p.m. **Boerboom, Terry J.**
Newly recognized thick interflow sandstones in the upper northeast limb of the North Shore Volcanic Group, Minnesota

2:10 p.m. **Mudrey, Michael G., Jr. and Wooden, Joseph L.**
A chemical and Sr isotopic study of the Pigeon Point Sill, Cook County, Minnesota

2:30 p.m. **Bjornerud, Marcia**
Evidence for paleoseismic events during closure of the Midcontinent Rift, Atkins Lake-Marenisco Fault, N. Wisconsin

2:50 p.m. **Hudak, George J., Hoffman, Adam T., Peterson, Dean M. and Heine, John**
Recent developments understanding the volcanic, magmatic, tectonic, and metallogenic evolution of the Ely Greenstone Formation, Vermilion District, NE Minnesota

3:10 p.m. **COFFEE BREAK AND POSTER SESSION**

3:30 p.m. **Puumala, Mark A.**
New insights into the metallogeny of the eastern portion of the Archean Uchi Domain, Superior Province, Ontario

3:50 p.m. **Alexander, Malcolm* and Mitchell, Roger H.**
Rare metal mineralization in pegmatites of the Coldwell Alkaline Complex

4:10 p.m. **Good, David and Walford, Phillip**
PGE-rich mineralization at the Marathon Deposit, Coldwell Alkaline complex, Ontario

4:30 p.m. **Brown, Alex C.**

Deposition of native copper lodes on the Keweenaw Peninsula, northern Michigan, from a gravity-driven evolved meteoric brine

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

7:00 p.m. **ANNUAL BANQUET AND AWARD PRESENTATION**

- **Announcement of 54th Annual Meeting Location**
- **2007 Goldich Award Presentation to Joseph Mancuso**
- **2007 Banquet Address**

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

FRIDAY MAY 11, 2007

8:25 a.m. **INTRODUCTORY REMARKS**

Laurel Woodruff and Jim Miller, Co-Chairs

TECHNICAL SESSION III

Session Chairs: Thomas Waggoner, retired, Cliffs Mining Services Co.
Ann Wilson, Ontario Geological Survey

8:30 p.m. **Student, James J., Wark, David A., Mutchler, Scott R. and Bodnar, Robert J.**

Thermal evolution of Proterozoic (>1Ga) rhyolite magma based on analysis of melt inclusions and trace elements in quartz from the Keweenaw Peninsula of Michigan

8:50 p.m. **Hart, Tom R. and MacDonald, Carol Anne**

Emplacement of the Nipigon Sill Complex and mafic to ultramafic intrusions of the Nipigon Embayment

9:10 p.m. **Hollings, Pete, Smyk, Mark C. and Hart, Tom**

Geochemistry of Midcontinent Rift-related mafic dykes and sills near Thunder Bay: new insights into geographic distribution and the geochemical affinities of Nipigon and Logan sills and Pigeon River and other dykes

9:30 p.m. **Forsha, Clint J.* and Zieg, Michael J.**

Textural stratigraphy of Nipigon diabase sills: A tool for correlation and petrologic interpretation

9:50 p.m. **Zieg, Michael J. and Forsha, Clint J.**

A comparison of textural profiles in diabase sills from the Midcontinent and Transantactic rift

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

- 10:30 p.m. **Cockerton, Sarah, Conly, Andrew G. and Lee, Peter**
An experimental water-rock interaction study into the origin of high-sulfate waters associated with the Steep Rock Mines, Atikokan, Ontario
- 10:50 p.m. **Stevens, Larissa B.* and Fralick, Philip**
Investigation of ferromanganese nodule precipitation and arsenic uptake in modern lacustrine biochemical sediments
- 11:10 a.m. **Rodengen, Tommy*, Theissen, Kevin and Sugita, Sugita**
Elemental and isotopic shallow lake proxies of landscape changes in the Prairie Pothole region of Minnesota
- 11:30 a.m. **Diedrich, Tamara* and Sharp, Thomas G.**
The effect of H₂O on olivine to ringwoodite transformation: Implications for subduction zone dynamics and the deep earth water cycle
- 11:50 a.m. **Thorliefson, Harvey**
Potential use of the Midcontinent Rift for CO₂ sequestration
- 12:10 p.m. **LUNCH BREAK**

TECHNICAL SESSION IV

Session Chair: Ted Bornhorst, Michigan Technological University

- 1:40 a.m. **McSwiggen, Peter L.**
Trace element analyses: Avoiding data distortion
- 2:00 p.m. **Waggoner, Tom D.**
Definition of the Proterozoic terrain under the Paleozoic – Central U.P., Michigan
- 2:00 p.m. **Oreskovich, Julie**
Documenting underground mine workings on the Mesabi Iron range in GIS format
- 2:40 p.m. **Metsaranta, Riku T., Fralick, Philip W. and Bowdidge, Colin**
Metamorphosed halite-dominated evaporates of the Lower Sibley Group
- 3:00 p.m. **Presentation of Student Paper Awards**
Marcia Bjornerud, Lawrence University: Student Paper Committee
- 3:10 a.m. **FINAL COFFEE BREAK AND POSTER SESSION – POSTERS TO BE REMOVED AFTER THE BREAK**

SATURDAY MAY 12, 2007

8:00 a.m. FIELD TRIP 4: GEOLOGY AND CU-NI-PGES MINERALIZATION – NICKEL LAKE MACRODIKE, SOUTH KAWISHIWI INTRUSION

Dean Peterson, *Natural Resources Research Institute*

Paul Albers, *Duluth Metals*

8:00 a.m. FIELD TRIP 5: GEOLOGY OF THE NORTH SHORE FROM LITTLE MARAIS TO GRAND MARAIS

Terry Boerboom, *Minnesota Geological Survey*

John Green, *University of Minnesota - Duluth*

Jim Miller, *Minnesota Geological Survey*

8:00 a.m. FIELD TRIP 6: GEOLOGY ALONG THE GUNFLINT TRAIL

Mark Jirsa, *Minnesota Geological Survey*

Paul Weiblen, *University of Minnesota – Twin Cities*

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

SUNDAY MAY 13, 2007

6:00 p.m. Return of Trip 4

POSTER PRESENTATIONS

Behling, Stuart J.

Mercury in fish: a geologist's perspective

Boerboom, Terry J., Green, John C., Albers, Paul and Miller, James D., Jr.

Bedrock geologic map of the Little Marais, Schroeder, and Tofte 7.5 minute quadrangles, North Shore of Lake Superior, Minnesota

Boisjoli, Troy* and Flood, Timothy P.

Petrographic differentiation of the five phases of the Lower Cretaceous Star Kimberlite, Saskatchewan, Canada

Buchholz, Thomas W., Falster, Alexander U. and Simmons, William B.

A novel locality for pseudobrookite – the Nine Mile-Pluton, Marathon County, Wisconsin

Costello, Daniel E.*, Flood, Timothy P. and Thole, Jeffrey T.

Origin of a mafic pegmatite within the Duluth Complex, Northern Minnesota

Dean, J. Frederick and Phillips, Brian A.M.

Distribution of certain ichthyofauna in relation to eastern outlets of Lake Agassiz, with emphasis on the Gunflint-Arrow Lakes corridor and the Keating Complex

Elsenheimer, Don, Frey, Barry A. and Hudak, Joe N.

Gold mineralization in the Virginia Horn Greenstone Terrain, St. Louis County, Minnesota: A prospect re-visited

Hogan, Amanda*, Jacobs, Travis* and Theissen, Kevin

Lacustrine sedimentary organic matter proxies of recent lake state changes and climatic conditions on Christina and Morrison Lakes of western Minnesota

Hudak, Joe N. and Frey, Barry A.

Evaluation of mineral exploration drill cuttings in the Rice River area, east central Minnesota

Jasinevicius, Renata R.* and Gordon, Elizabeth A.

Paleoenvironmental interpretation of a Lower Paleozoic stromatolite reef, northeastern Wisconsin

Jirsa, Mark A., Boerboom, Terry J., Chandler, Val W., Lively, Richard S., Miller, James D., Jr., Mossler, John H., Runkel, Anthony C., Setterholm, Dale R. and Wahl, Timothy E.

Proposed new bedrock geologic map of Minnesota

Medaris, L. Gordon, Jr., Fournelle, John H. and Guggenheim, Stephen J.

An occurrence of agrellite in the Wausau Alkaline Igneous Complex, Marathon County, Wisconsin

Nicholas, Sarah L.*, Wirth, Karl R., Engstrom, Jennifer and Lapakko, Kim A.

Investigations of sulfide minerals leached in the presence of alkaline solids

Quigley, Patrick O.*

Michigan kimberlites revisited: New mineral, chemical and petrographic analyses

Rymaszewski, Jody A.*, Friedrich, Jason L. and Czeck, Dyanna M.

Bedrock fractures in southeastern Wisconsin: Paleostress estimates and relationships to the Waukesha Fault

Saxton, Samantha* and Cordu, William

Precambrian geology of the Opelt Quarry, Neillsville, Wisconsin

Severson, Mark J. and Heine, John

Revised stratigraphy of the Biwabik Iron Formation, Mesabi Range, Minnesota – developing the “Rosetta Stone”

Stott, Greg, Corkery, Tim, LeClair, Alain, Boily, Michel and Percival, John

A revised terrane map for the Superior Province as interpreted from aeromagnetic data

Taylor, Michael L.* and Swenson, John B.

Pleistocene glaciation as a mechanism for emplacement of high-salinity groundwater at anomalously shallow depths in the Lake Superior basin

Theriault, Stephanie A.* and Hickson, Thomas A.

Possible influence of a buried fault on elevated indoor radon levels, south Washington County, Minnesota

Thorliefson, L. Harvey, Harris, Kenneth L., Hobbs, Howard C., Jennings, Carrie E.,

Knaeble, Alan R., Lively, Richard S., Lusardi, Barbara A. and Meyer, Gary N.

Till geochemical and indicator mineral reconnaissance of Minnesota



ABSTRACTS

HOW TO IDENTIFY SUDBURY IMPACT EJECTA IN THE LAKE SUPERIOR REGION

Addison, William D., R.R. 2, Kakabeka Falls, Ontario, POT 1W0, Canada

Cannon, William F., U.S. Geological Survey, MS 954, Reston VA 20192, USA

Brumpton, Gregory R., 211 Henry St., Thunder Bay, Ontario, P7E 4Y7, Canada

For at least 15 years geologists looked for ejecta from the 1850 Ma Sudbury impact in sedimentary rocks of the Lake Superior region. Addison and others (2005) first reported its occurrence but more recent work has shown that “volcaniclastic breccia” or “submarine slump deposits” described and mapped as early as the 1940’s are, in fact, ejecta deposits and other impact-related rocks (Cannon and Addison, 2007). To date, Sudbury ejecta deposits have been identified in six areas in the western Lake Superior region and provide a precise regional stratigraphic marker (Cannon and Addison, 2007). It seems nearly certain that other sites will be discovered. Toward that end we pass on some of our observations and experience in the commonly frustrating search for the impact layer in hopes that others will make additional discoveries of this important chrono-stratigraphic marker bed.

Ejecta, the material thrown upward and outward from the Sudbury impact, arrived in the Lake Superior region in two ways. First, was coarse to fine material, primarily melted and solid target rock, that followed a ballistic trajectory to about five times the final crater radius (5r), most recently estimated at 130 km (Spray and others, 2004). Thus, ballistic ejecta should not be expected beyond 650 km from the impact center. Five of the six known occurrences lie within the 5r distance. At those sites ballistic ejecta arrived with horizontal velocities as high as a few km/sec, and were capable of causing extreme disruption and erosion of surface sediments. The result was breccia deposits of ejecta and local country rock. Ejecta inside the 5r ballistic zone include devitrified glass in vesicular blobs (both streamlined and irregular shapes) and microtektites and spherules (frozen melt droplets), both singly and in clusters. Other features include accretionary lapilli, and angular grains of quartz, a small percentage of which contain relict planar deformation features, the only proof that the ejecta are of impact origin (French, 1998).

Second, a huge super-heated expanding cloud of vapor, sub-mm melt droplets, and sub-mm rock shards reached hundreds of km above Earth. Condensed and solidified melt droplets and tiny rock shards settled over a period of days to more than a year covering all of Earth. These ejecta do not substantially alter the surface on which they are deposited and do not form the breccias typical of ballistic ejecta. Microtektites and spherules and quartz and feldspar grains, some showing shock metamorphic features, from the cloud have been found at sites near Hibbing, Minnesota, beyond the range of ballistic ejecta.

Finally, most of the ballistic deposits and perhaps some of the earlier vapor cloud deposits have been reworked by impact-induced tsunamis resulting in polymict breccias of local rocks and ejecta (Cannon and Addison, 2007).

So, how and where should you look for a Sudbury ejecta deposit and how will you recognize it? Known sites are near the top of the principal iron-bearing units (Gunflint, Biwabik, Ironwood, etc.) in the region to about 300 m farther up section and new discoveries will most likely be within or not far from this interval.

Within the 5r zone, easily seen macroscopic features include breccia, especially black chert breccia, mm-cm size blobs of devitrified vesicular glass, and clusters or beds of accretionary lapilli. Smaller-scale features include 0.5-2 mm gray ovoid, round, or irregular microtektites and spherules that may also be replaced by green clay minerals. Similar sized rounded quartz and feldspar grains occur along with sub-mm angular quartz and feldspar grains, a few of which contain one or more sets of thin parallel lamellae, the diagnostic shock deformation features. Note that these lamellae are very rare and commonly require hours or days of careful petrographic examination under high magnification to find.

Beyond the 650 km ballistic zone, represented by only the sites near Hibbing, MN, there are no characteristic macroscopic features. Ejecta at the top of the Biwabik Iron-formation are within a siliceous, light gray coarsely recrystallized carbonate layer. Within the light carbonate there is a darker gray reticulated pattern giving a vague appearance of 2-4 mm circles. Thin sections from the reticulated zone reveal microtektites, spherules and vesicular glass. Rounded quartz grains are present as are angular quartz and feldspar. Shocked quartz and feldspar grains with the relict lamellae are exceedingly rare.

All known localities are in pristine to weakly metamorphosed rocks. Unfortunately, the considerable regions of higher grade metamorphism in the Lake Superior region may never yield any of the features described here, particularly the diagnostic shock lamellae in quartz, because of thorough recrystallization. Certainly this is true at Peter Mitchell Mine, Babbitt, MN. Searches in weakly metamorphosed sequences are most likely to succeed.

References:

- Addison, W. D., Brumpton, G.R., Vallini, D.A., McNaughton, N.J., Kissin, S.A., Fralick, P.W., and Hammond, A.L., 2005, Discovery of distal ejecta from the 1850 Ma Sudbury impact event: *Geology*, v. 33, p. 193-196.
- Cannon, W. F. and Addison, W.D., 2007, The Sudbury impact layer in the Lake Superior iron ranges: a time-line from the heavens: *Institute on Lake Superior Geology Proceedings*, Vol. 53, Part 1.
- French, B.M., 1998, Traces of catastrophe: *Lunar Planetary Inst. Contrib.* 954, 120 p.
- Spray, J. G., Butler, H. R., and Thompson, L. M., 2004, Tectonic influences on the morphometry of the Sudbury impact structure: Implications for terrestrial cratering and modeling: *Meteoritics & Planetary Sci.*, V. 39, p. 287-301.

Rare Metal Mineralization in Pegmatites of the Coldwell Alkaline Complex

Malcolm Alexander and Roger H. Mitchell

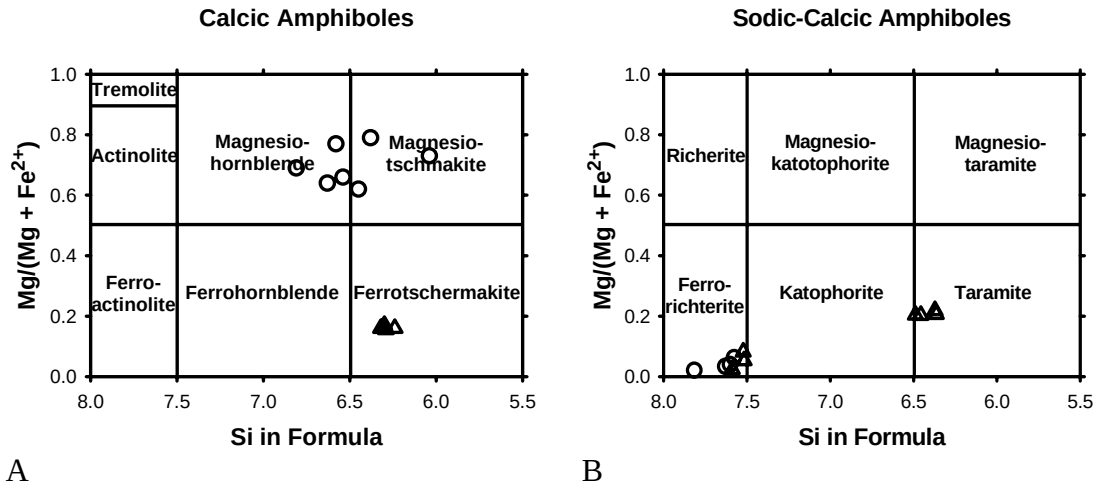
Department of Geology, Lakehead University, Thunder bay, Ontario

ABSTRACT

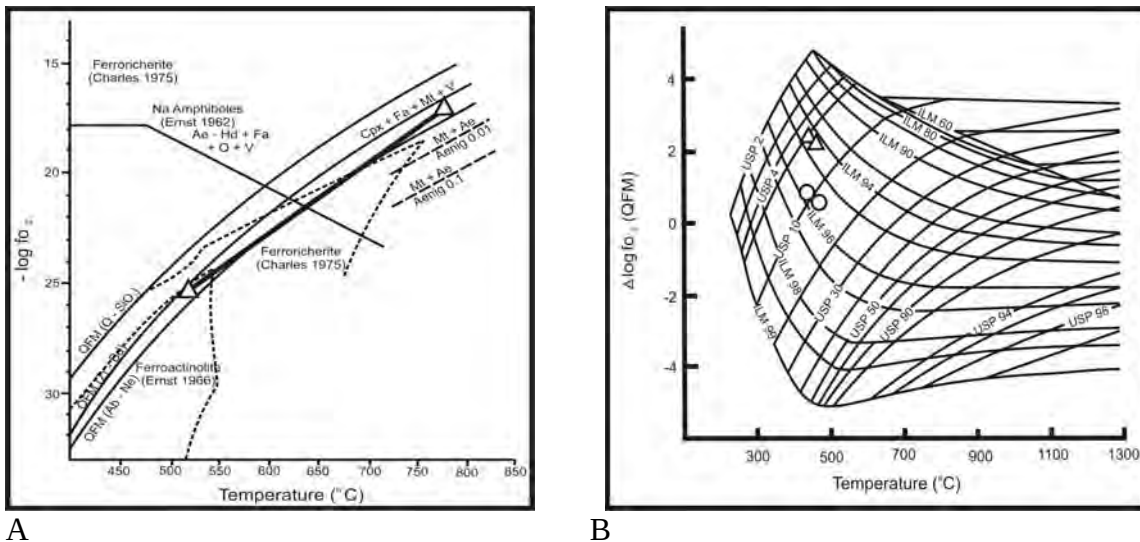
The Coldwell Complex (northwestern Ontario), is a multiphase alkaline intrusion that is host to rare earth element, actinide and other high field strength element mineralization. Preliminary studies have shown that these minerals are concentrated in pegmatites associated with Center 1 ferrichterite-ferroaugite syenites. These syenites exhibit the geochemical characteristics of A-type granitoid magmatism. The focus of this study is the distribution, nature and petrochemical controls of rare metal mineralization within these pegmatitic bodies.

Within the Center 1 formation there are two subunits; the border gabbro, a massive to layered intrusion ranging in composition from wehrlite to diorite and locally to anorthosite; and oversaturated massive to locally layered ferroaugite syenites. Both subunits host pegmatitic quartz bearing residua characterized by cumulus perthitic alkali feldspar, hedenbergite-aegirine pyroxenes, with interstitial quartz, calcite, and calcic-to-sodic-calcic-to-sodic amphiboles (Fig. 1). The pegmatitic residua are of the niobium-yttrium-fluorine (NYF) type, and characterized by the enrichment of Nb-Ti-Ta oxides, with niobium predominant over tantalum. Back-scattered electron petrography and quantitative X-ray spectrometry have been used to characterize the mineral paragenesis. Pegmatitic syenitic residua emplaced in, but not derived from, the border gabbro contain a wide range of rare element minerals which include: chevkinite; fergusonite; monazite; allanite; kainosite; xenotime; REE fluorocarbonates: bastnaesite, synchysite and parisite. Other rare element enriched minerals include fersmite, apatite, zirconolite, U-Th-Si-pyrochlore, Nb-rutile and Nb-bearing ilmenite. Early-formed rare element minerals such as chevkinite and pyrochlore are commonly replaced by complex aggregates of later-forming phases. REE-fluorocarbonates commonly exhibit syntaxial intergrowths. Other ferroactinolite-quartz bearing pegmatitic residua, occurring in the upper series of a differentiated aenigmatite-ferroaugite syenite unit, contain a more limited range of rare element minerals, including zircon, xenotime, monazite and the fluorocarbonates together with REE bearing apatite and pyrochlore. The differences in rare element mineralization between the two pegmatites examined to date suggest that they were derived from different batches of ferroaugite syenite magma.

Initial data indicate that different pegmatitic residua in the Center 1 subunits also evolved differently. Intensive parameters have been estimated using amphibole mineralogy and Fe-Ti-oxide compositions, as seen in Figure 2. These parameters indicate the pegmatites intruding the border gabbro and syenite residua had equilibration temperatures of 450 °C at oxygen fugacities of +0.5-1.0 and +2.0-2.2, relative to QFM, respectively.



A B
Figure 1: Stability fields of calcic (A) and sodic-calcic (B) amphiboles. Each point represents a mean value of 5 to 9 point analyses. Circles represent the residua injected into the border gabbro, while triangles represent residua injected into the saturated ferroaugite syenite.



A B
Figure 2: Oxygen fugacity diagrams, using the quartz-fayalite-magnetite (QFM) oxygen buffer. Diagram A contains two points, the right hand value is representative of the ferroaugite syenite and the left hand value is representative of the pegmatitic residua (Mitchell and Platt, 1977). Diagram B is a Fe – Ti oxide geothermometer and oxygen barometer. ILM is given in mol% ilmenite, USP is mol% ulvöspinel. Triangles are saturated ferroaugite syenite residua, circles are border gabbro residua. Adapted from Ghiorso and Sack (1991).

REFERENCES

- Ghiorso, M.S. and Sack, O.S. 1991, Fe – Ti oxide geothermometry: thermodynamic formulation and the estimation of intensive variables in silicic magmas: Contributions to Mineralogy and Petrology, v.108, p. 485.
Mitchell, R.H. and Platt, R.G. 1977, Mafic mineralogy of ferroaugite syenite from the Coldwell Alkaline Complex, Ontario, Canada: Journal of Petrology, v. 19, p. 627.

MERCURY IN FISH: A GEOLOGIST'S PERSPECTIVE

BEHLING, Stuart James, Retired, Superior National Forest Geologist
4712 Anderson Rd., Duluth, MN 55811 USA stu-ball@mchsi.com

Mercury contamination of fish has been a health concern in Northeastern Minnesota since testing began over 30 years ago. In spite of this concern, less than 15% of the lakes in this area have been tested. The data show that fish mercury contamination varies considerably between lakes but no pattern of distribution has been recognized. The data also show that fish mercury contamination varies between species and increases with length of fish. For example, walleyes are more contaminated than northern pike of the same size, from the same lake, and longer fish have more mercury than shorter ones. However, there is not enough data available from most lakes to plot these contamination trends. A model that could predict fish mercury contamination levels by species and length of fish would be a great asset in understanding the extent and distribution of fish mercury in this area.

In this study, Northeastern Minnesota was divided into groups of geologically related lakes termed lake provinces. Ten lake provinces were identified in two distinct geomorphic areas; seven are in an area of bedrock controlled terrain and three are in an area of glacial deposition. In the bedrock controlled terrain, the size shape and orientation of the lakes are directly related to structural or compositional weakness in the underlying bedrock. Weathering and glacial erosion exploited these weaknesses to produce distinct patterns of lakes that were used to identify the provinces. In the areas of glacial deposition, the lake provinces were associated with the deposits left by three distinct glacial advances. When fish mercury was plotted against length of fish by province, the correlation coefficients increased significantly. The R squared values for the provinces ranged from .58 to .81 as compared to an R squared value of .32 for all samples from the study area plotted collectively. A map showing the distribution of mercury contamination in walleyes and northern pike was produced using the results from this ongoing study.

EVIDENCE FOR PALEOSEISMIC EVENTS DURING CLOSURE OF THE MIDCONTINENT RIFT, ATKINS LAKE-MARENISCO FAULT, N. WISCONSIN

Bjornerud, Marcia, Geology Department, Lawrence University, 115 S. Drew St.

Appleton, Wisconsin 54911 USA. bjornerm@lawrence.edu

The closure, or inversion, of the Midcontinent Rift at ca. 1.0 Ga remains one of the least well understood chapters in the Precambrian tectonic history of the Lake Superior region. Rift-bounding normal faults were reactivated as major reverse faults, some with estimated net reverse displacements of several kilometers. One such structure is the north-dipping Atkins Lake-Marenisco fault in Bayfield, Ashland and Iron Counties of northern Wisconsin. According to the interpretation of Cannon et al. (1993), the Atkins Lake-Marenisco fault is a crustal-scale listric fault zone along which lower Proterozoic metasedimentary rocks and middle-Proterozoic rift-related volcanic rocks have been thrust southward over Archean gneisses (the Proterozoic sequences had originally occupied a structurally lower position in the axial graben of the rift).

The Atkins Lake-Marenisco Fault is well exposed near the falls of the Marengo River in eastern Bayfield County. There the fault zone is ca. 100 m wide and cuts through the Archean (ca. 2.7 Ga) Puritan Batholith, a granitic body with a weak gneissic fabric. In a downstream transect beginning just below the falls, the rocks record extreme strain gradients. Over a distance of < 20 m, pristine gneiss gives way first to cataclasite and then to dark, extremely fine-grained phyllonites, all heavily veined with K-feldspar, chlorite and zeolite. In thin section, cataclastic textures can be seen to overprint quasi-ductilely deformed feldspars, indicating that displacement along the fault zone may have begun at temperatures close to 450°C and continued as the rocks cooled.

Most of the cataclasites have a crudely fractal (log-linear) clast size distribution, with the average grain size decreasing progressively with strain intensity, as expected when cataclasis is the dominant deformation mechanism. Samples from one outcrop near the base of Marengo Falls, however, have textures suggestive of devitrified pseudotachylyte. Dark-colored veins and lenses, now chloritized, contain relatively large (mm-sized) clasts of feldspar, but finer-grained clasts are notably absent. Many of the

larger clasts, moreover, show unusual microstructural features. Some have embayments and concave edges – shapes not typical of ordinary cataclasites, in which grains are commonly equant and polygonal to rounded. Some of the clasts also display mosaicism, a texture that can form as a result of rapid volumetric changes. The bimodal grain size distribution and embayed and mosaicized grains could be explained by the presence of a seismically generated frictional melt, which could have preferentially assimilated the finest grains, partly resorbed larger ones, and created a short-lived pressure pulse as a result of expansion upon melting.

If this interpretation is correct, we should begin to consider the role seismicity may have played in facilitating transient fluid flow and consequent mineralization during the closure of the Midcontinent Rift.

Reference cited:

Cannon, W., Z. Peterman, and P.K. Sims, 1993. Crustal-scale thrusting and origin of the Montreal River monocline: A 35-km thick cross section of the Midcontinent Rift in Northern Michigan and Wisconsin. *Tectonics* v. 12, p. 728-744.

NEWLY RECOGNIZED THICK INTERFLOW SANDSTONES IN THE UPPER NORTHEAST LIMB OF THE NORTH SHORE VOLCANIC GROUP, MINNESOTA

BOERBOOM, Terrence J., Minnesota Geological Survey, *boerb001@umn.edu*

New mapping, funded in part by the USGS STATEMAP program, has identified several major units of interflow sandstone between lava flows in the upper Northeast Sequence of the North Shore Volcanic Group (NSVG), which are as much as 200-300 feet (60-90 meters) thick. The recognition of these sandstones approximately triples the total thickness of known interflow sandstones in that area. These sandstones were intersected in several water well cutting sets collected by McKeever Well Drilling of Schroeder, Minnesota. Although the wells intersect only partial sections of the sandstone units, these intersections project into prominent northeast-trending topographic lows which correspond with linear low aeromagnetic anomalies. These lie between and parallel to ridges held up by basalt that correspond to linear positive magnetic anomalies. The eastern extent of these sandstones has yet to be determined, but will be examined in the coming field season.

The sandstones identified in water well cuttings are pinkish-tan, medium-grained, and similar in composition and appearance to the well-known Cutface Creek sandstone (Fig. 1). In the northern-most sandstone, a well just south of the Monker Lake diabase (Fig. 1) intersected 80 feet (25 meters) of sandstone above the Devil's Track rhyolite. However, a well located 8 miles along strike to the southwest intersected only 10 feet of sandstone, below basalt and above the Devil's Track rhyolite, indicating either that it pinches out to the southwest or that the thickness varies due to deposition on an irregular surface. The middle sandstone unit shown on Fig. 1 was intersected in only one well, which penetrated 15 feet (5 meters) of sandstone beneath basalt. The color, composition, and grain size is consistent with it being the uppermost part of a thick interflow sediment, quite distinct from the typical thin interflow sediments that are found throughout lava flows in the NSVG. The southern-most of the three sandstone units is inferred entirely on the basis of topographic and aeromagnetic features that mimic those of the middle unit.

Sandstone of substantial thickness was also intersected in water wells near the top of Eagle Mountain at the Lutsen Ski Resort (Fig. 1), which penetrated 15–60 feet (4-20 meters) of tan, medium-grained sandstone. This sandstone lies below the Leveaux ferrodiorite and above the Eagle Mountain basalt, and likely acted as an anisotropic plane of weakness that controlled emplacement of the Leveaux ferrodiorite sill. Its irregular thickness may be the product of having been variably cut out by the intrusion.

Two thick interflow sandstone units – the Cut Face and Indian Camp Creek sandstones, had long been recognized in the upper NE limb of the NSVG from outcrops near Lake Superior. Both of these are soft and easily eroded relative to the surrounding volcanic rocks, hence are exposed only near the shore in actively eroding stream channels.

Based on inferences from paleocurrent measurements, the interflow sandstones in the NSVG were deposited in two separate depositional basins that correspond to the SW and NE limbs of the NSVG (Jirsa, 1984). Sedimentary rocks between the SW and NE limbs, in the area from Illgen City to Lutsen (Fig. 1), are composed mainly of conglomerate and fragmental volcanic rocks, in contrast to sandstone that dominates on either side. This area coincides with a negative gravity anomaly known as “White's Ridge” (White, 1966), that represents a block of uplifted crust (Boerboom, 1994). To the southwest of White's ridge (SW Limb NSVG), the stratigraphically lower lavas dip more steeply towards the center of the rift than higher lavas, implying greater subsidence towards the rift axis during volcanism. To the NE of White's ridge (NE Limb NSVG), the volcanic rocks throughout the stratigraphy show no appreciable change in dip, implying that subsidence during volcanism was uniform, and that tilting towards the rift axis occurred after volcanism. (Green, 1972).

The 250 foot (76 meter) thick Cut Face Creek sandstone, exposed at Terrace Point (Fig. 1), is dominantly a reddish-brown, medium-grained, well-sorted, lithic arkose, but nearly 30% of the section is composed of thinly bedded, graded layers of fine-grained sand, silt, and clay, with lithologic and

sedimentary features indicative of deposition into a fluvial-lacustrine environment, such as streams flowing into ponded water (Jirsa, 1984). The lacustrine aspect is speculated to be caused by blockage of flowing water against an obstruction, perhaps related to deformation and magmatism along White's ridge.

The recognition of several thick interflow sandstones indicates that clastic sedimentation in the NE limb of the NSVG played a more significant role than in the SW limb, but whether this is a result of a higher rate of clastic input, more efficient trapping of sediment against a topographic impediment such as White's ridge, a higher rate of subsidence, or longer periods of volcanic quiescence is not clear. The inferred fluvial-lacustrine depositional environment of the Cut Face Creek sandstone implies that ponding and sediment-trapping processes were more operative than in the SW limb, where dominantly fluvial sedimentary features indicate sediment flow-through, and deposition closer to the axis of the rift.

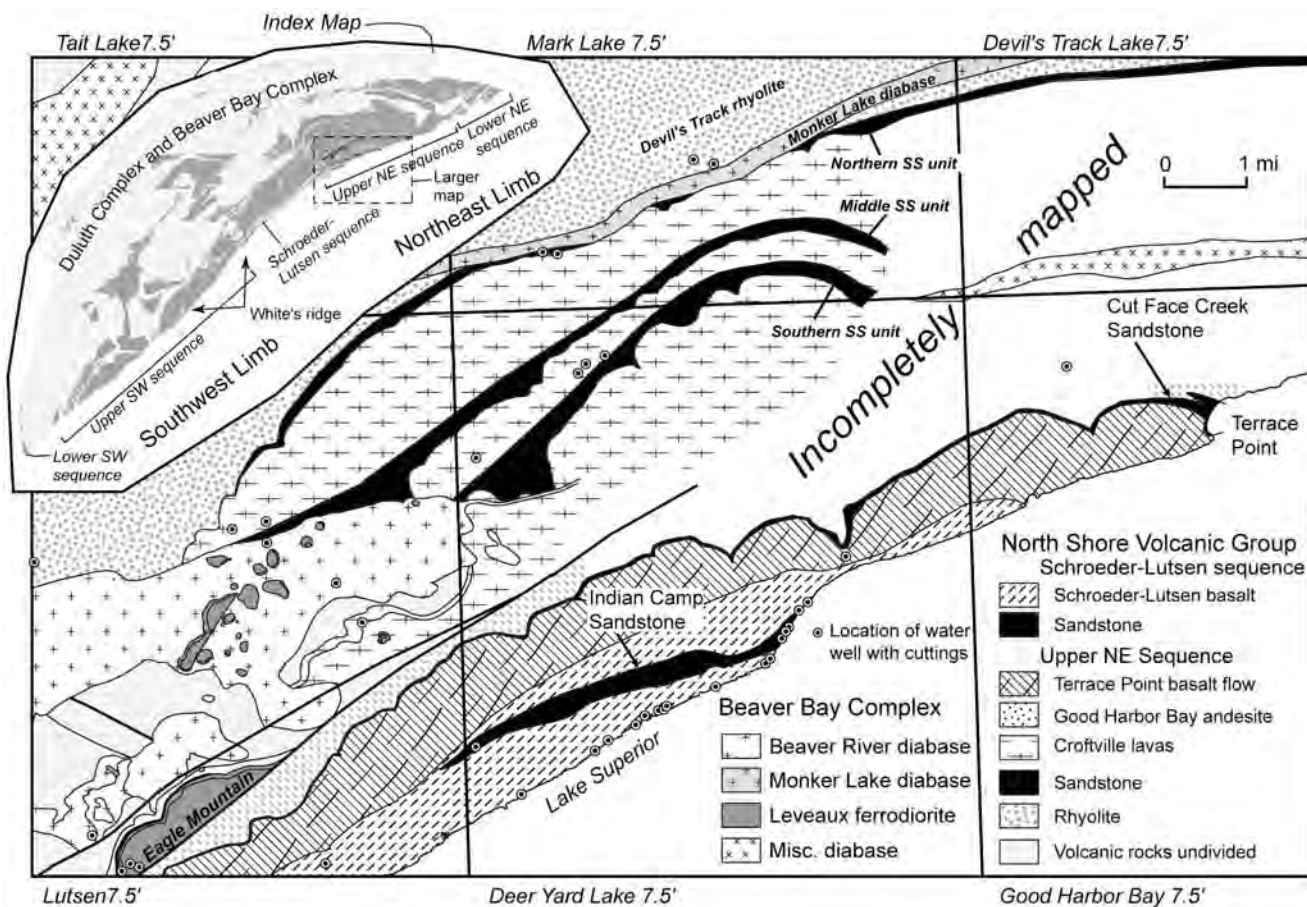
From a practical standpoint, these sandstones may be important aquifers, however, little is presently known about their water-yielding characteristics.

Boerboom, T. J., 1994, Archean crustal xenoliths in a Keweenaw hypabyssal sill, northeastern Minnesota. White was right!: Institute on Lake Superior Geology 40th Annual Meeting, Houghton, MI: Proceedings v. 40, pt. 1 - Abstracts, p. 5-6.

Green, J.C., 1972, North Shore Volcanic Group, in Sims, P.K., and Morey, G.B., eds., *Geology of Minnesota: A Centennial Volume*, p. 294-332

Jirsa, M.A., 1984, Interflow sedimentary rocks in the Keweenaw North Shore Volcanic Group, northeastern Minnesota: Minnesota Geological Survey Report of Investigations 30, 20 p.

White, W.S., 1966, Tectonics of the Keweenaw basin, western Lake Superior region: U.S. Geological Survey Professional Paper 524-E, 23 p.



BEDROCK GEOLOGIC MAP OF THE LITTLE MARAIS, SCHROEDER, AND TOFTE 7.5-MINUTE QUADRANGLES, NORTH SHORE OF LAKE SUPERIOR, MINNESOTA

BOERBOOM, Terrence J., Minnesota Geological Survey, *boerb001@umn.edu*

GREEN, John C., University of Minnesota-Duluth, *jgreen@d.umn.edu*

ALBERS, Paul, Duluth Metals, *palbers@duluthmetals.com*

MILLER, James D., Jr., Minnesota Geological Survey, *mille066@umn.edu*

The Minnesota Geological Survey is continuing to map the bedrock geology of 7.5' quadrangles near Lake Superior as part of the USGS STATEMAP program, resulting to date in ten published 1:24,000 scale maps from Duluth to Tofte, in addition to 10 quadrangles already published under the former USGS COGEO MAP program. The Lutsen quadrangle will be published in July 2007; the Deer Yard Lake and Good Harbor Bay quadrangles will be mapped in the 2007 and published in 2008 (Fig. 1A). All the maps in this series are available as printed maps, or as PDF and ArcView export files at the MGS website (<http://www.geo.umn.edu/mgs/>).

Field trip 5 of this meeting will begin in the Little Marais quadrangle at the southwest, and end in the Good Harbor Bay quadrangle at the northeast.

With the exception of a strip near the shore of Lake Superior (Green, 1992), parts of the Little Marais quadrangle that were mapped but not published, and thesis work by Albers (UMD M.S. 2007), much of the area covered by these maps had never been mapped.

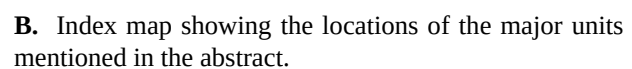
The combined area of these three maps straddles the transition across the uppermost Southwest to the uppermost Northeast sequences of the North Shore Volcanic Group (NSVG), as well as the Schroeder-Lutsen sequence, which unconformably overlies the Southwest and Northeast sequences (Fig. 1B). Together, these maps cover the stratigraphically highest portion of the NSVG in Minnesota. In addition, components of the Beaver Bay Complex, including multiple phases of the Beaver River diabase, the Blesner Lake diorite, and the Leveaux ferrodiorite are present in the area of these maps.

The new mapping has delineated a series of dominantly felsic to intermediate composition volcanic rocks (rhyolite, icelandite, and andesite) beneath the Schroeder-Lutsen basalts, informally termed the Onion River lavas, which include some tholeiitic basalt flows. The strike of these flows at a high angle to that of the overlying Schroeder-Lutsen basalts, which are nearly parallel to the Lake Superior shoreline (Fig. 1B). The basal contact of the Schroeder-Lutsen sequence is repeated by several shore-parallel reverse faults. Poorly exposed units of rhyolite, volcanic breccia, and conglomeratic to sandy sedimentary rocks, which are likely components of older volcanic and interflow sedimentary rocks such as the Onion River lavas, are exposed within the Schroeder-Lutsen sequence by normal and reverse faults.

The Carlton quarry lavas (Fig. 1B) form a northwest-dipping group of lavas composed of rhyolite at the base, andesite, and ophitic basalt at the top. The position of these lavas relative to the surrounding lavas is poorly constrained due to lack of outcrop, but they are assumed to be in fault contact, given the anomalous northwest dip. The rhyolite here has been dated at 1094.3 ± 2.0 , the youngest age obtained to date from the NSVG in Minnesota, but the surrounding volcanic rocks have not been dated.

Intrusive rocks of the Beaver Bay Complex are most abundant and diverse in the Little Marais quadrangle, where they are composed of multiple phases of the Beaver River diabase and the slightly older, multi-phase Blesner Lake diorite. Elsewhere, the Beaver River diabase is restricted to erosional remnants of a larger, generally southeast-dipping sheet that commonly contains large anorthosite inclusions, such as at Carlton Peak. The porphyritic Leveaux ferrodiorite occurs mainly in the Tofte quadrangle as a subvolcanic sill emplaced into volcanic rocks, and as inclusions in the Beaver River diabase.

Green, J.C., 1992, Geologic map of the North Shore of Lake Superior, Lake and Cook Counties, Minnesota: Part 1. Little Marais to Tofte: Minnesota Geological Survey Miscellaneous Map M-71, scale 1:24,000.



PETROGRAPHIC DIFFERENTIATION OF THE FIVE PHASES OF THE LOWER CRETACEOUS STAR KIMBERLITE, SASKATCHEWAN, CANADA

BOISJOLI, Troy and **FLOOD, Timothy P.**, Department of Geology, Saint Norbert College, DePere, WI 54115; troy.boisjoli@snc.edu

Geologic Setting

The Star Kimberlite in the Fort a la Corne region, east-central Saskatchewan, is a large lithologically complex structure that preserves both intra-crater and extra-crater kimberlite (Zonneveld et al. 2004). The Star Kimberlite occurs on the eastern rim of the North American Platform. The oldest rocks in the area are believed to be part of the Archean Sask craton, which are overlain by other Precambrian rocks similar to those exposed to the north in the Glennie Domain. These Precambrian rocks are successively overlain by 300-500m of mixed siliciclastic-carbonate sediments that range in age from Cambrian to Devonian; these sediments are overlain by approximately 150m of Lower Cretaceous sediments; which are overlain by 85 to 115m of glacial deposits. The Star Kimberlite itself is intermittent and interstratified with Lower Cretaceous rocks that include the Cantuar Formation inferred as coastal plain facies, the Pense Formation inferred as shoreface facies, and the Joli Fou and Viking Formations inferred to be proximal offshore to shoreface facies.

Geology of the Study Area

Five different phases of the Star Kimberlite have been recognized (Zonneveld et al. 2004). In stratigraphic order from oldest to youngest they are; Cantuar Kimberlite (CK), Pense Kimberlite (PK), Early Joli Fou Kimberlite (EJFK), Middle Joli Fou Kimberlite (MJFK) and Late Joli Fou Kimberlite (LJFK). The purpose of this study was to determine if petrography and geochemistry could be used as tools to differentiate these different phases of the Star Kimberlite.

The CK is the oldest kimberlite in the Star body. In drill core, kimberlite intersections in this unit range in thicknesses from 0.3 to 11.8m and are bedded at the 0.2 to 9.0m scale. The beds within the kimberlites have sharp contacts and are usually massive or fining upwards. The CK is interpreted as medial to distal primary pyroclastic airfall material, with some reworked sedimentary equivalents. The location of the feeder vent for this event has not been determined.

The PK overlies CK and drill core intersections range in thickness from approximately 2 to 20m. The individual beds are highly variable, with massive, normal graded and reverse graded beds. Sharp contacts are typical and in some beds the upper 0.1 to 1m show evidence of marine reworking. PK is interpreted as proximal to distal, primary volcanoclastic material.

The EJFK overlies the PK and is volumetrically the most important phase of the Star Kimberlite. The EJFK deposits are 1 to 25 m thick, with bedding ranging from 1 to 10 m. Individual beds have sharp to diffuse contacts and are typically massive or normally bedded. Reverse bedding is rare. The EJFK is interpreted as primary subaerial and distal marine fall material.

The MJFK overlies the EJFK and until recently was lumped with the upper portion of the EJFK (Kjarsgaard 2007).

The LJFK overlies the MJFK. The thickness of this unit is unknown but bedding within the unit occurs on a scale of 0.5 to 30m, with beds of 10 to 20m the most common. The LJFK is interpreted primarily as pyroclastic subaerial fall material to pyroclastic flow material (Zonneveld et al. 2004).

Analysis

Petrographic analysis was performed on 23 thin sections using an average of 600 points per thin section. For all units, altered olivine comprised from 40-60% of the sections. Juvenile clasts comprised from 5-30% of the sections and opaques ranged from 1-4%. Late alteration calcite and serpentine accounted for between 0.5-6% of the sections. Quantitative petrographic analysis was not useful for distinguishing the different phases of the Star Kimberlite.

An alternate petrographic method based on textural and mineralogical criteria of the juvenile clasts (Webb 2006) was performed. In this analysis, ten criteria are the basis for distinguishing various mechanisms of emplacement for kimberlites. These criteria include; sphericity, roundness, irregularity, internal structure, vesicularity, clast-host relationship, primary phenocrysts, groundmass crystallinity, mineralogy and size range/modal average. A preliminary compilation of these criteria suggest that some units are distinguishable from other units relative to emplacement mechanisms. For example, vesicularity in the CK is high relative to other phases and consistent with the original interpretation as distal primary pyroclastic airfall.

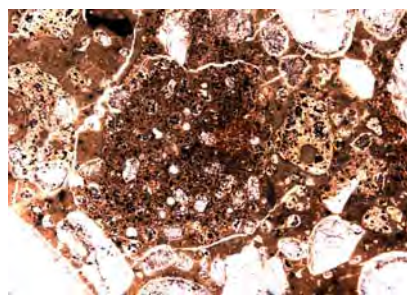
Geochemical analysis was performed on the primary olivine clasts using an SEM-EDS. The initial results of this analysis were inconclusive due to the highly altered nature of the grains but work is on going.

References:

Kjarsgaard, B.A., 2007, personal communication.

Webb, K.J., 2006, Juvenile clasts in kimberlites: Standardized comprehensive description towards unraveling emplacement mechanisms: in Kimberlite Emplacement Workshop, DeBeers Canada Inc, p. 1-5.

Zonneveld, J.P., Kjarsgaard, B.A., Harvey, S.E., Heaman, L.M., McNeil, D.H., and Marcia, K.Y., 2004, Sedimentologic and stratigraphic constraints on emplacement of the Star Kimberlite, east-central Saskatchewan: Lithos 76 115-138.



1: Juvenile clast with primary olivine and vesicles infilled with calcite. Field of view 10mm.

DEPOSITION OF NATIVE COPPER LODS ON THE KEWEENAW PENINSULA, NORTHERN MICHIGAN, FROM A GRAVITY-DRIVEN EVOLVED METEORIC BRINE

BROWN, Alex C., *Dept. of Civil, Geol. and Min. Eng., École Polytechnique de Montréal*
P.O. Box 6079, Sta. Centre-Ville, Montreal, QC, Canada H3C 3A7, acbrown@polymtl.ca

The Keweenaw Peninsula of northern Michigan is the site of famous native copper lodes hosted by flow-top breccias and amygdaloidal portions of flood basalts and interbedded conglomerates of the Portage Lake Volcanics (PLV). This mineralization is generally attributed to an up-dip flow of a cupriferous metamorphogenic fluid generated during deep burial metamorphism of the host strata in axial portions of the Midcontinent Rift (Stoiber & Davidson 1959; White 1968; Jolly 1974; Livnat et al. 1983).

In an alternative model proposed here, copper is leached from immature rift sediments and porous portions of the PLV by deeply circulating, gravity-driven meteoric water. The meteoric water is initially cool, fresh, slightly acid and oxygen-rich. At depth, it becomes warmer, highly saline by the assimilation of evaporites or evaporitic brine, near-neutral in pH by equilibration with silicates and carbonates, and oxygen-deficient by reddening of its aquifers (hematitization of ferrous iron in abundant labile mafic mineral constituents of the rift sediments and mafic constituents of the PLV basalts). At first, the Eh of the brine evolves progressively toward *moderately* oxidizing conditions at which it becomes capable of leaching and transporting trace amounts of copper from its aquifers. Metamorphogenic water and copper may have been incorporated during circulation at deep burial levels. Highland recharge eventually drives the hybrid cupriferous brine up-dip along PLV aquifers. With continued hematitization of its aquifers, the brine becomes highly reducing by oxygen depletion, and native copper is deposited (in the absence of sulfide). Coincidentally, the same highly reducing conditions favor the solution of hematite, a feature readily visible as locally bleached rock (hematitic pigment removed) where native copper mineralization occurs on the Keweenaw Peninsula.

This conceptual model provides 1) an explanation for the highly saline brine needed to mobilize copper, and 2) a means to drive dense brines up-dip from axial portions of the rift basin. It also explains the pervasive hematitic reddening of the PLV, and ties the timing of copper leaching to that diagenetic reddening event. The overall timing of native copper mineralization may be linked to the Grenvillian compressional event which tilted PLV strata to deep levels along the rift axis and probably raised highlands around the rift basin.

References:

- Brown, A.C. (2006) Genesis of native copper lodes in the Keweenaw district, northern Michigan: a hybrid evolved meteoric and metamorphogenic model: *Economic Geology*, v. 101, p. 1437-1444.
- Jolly, W.T. (1974) Behavior of Cu, Zn and Ni during prehnite-pumpellyite rank metamorphism of the Keweenaw basalts, northern Michigan: *Economic Geology*, v. 69, p. 1118-1125.
- Livnat, A., Kelly, W.C., Essene, E.J., and Rye, R.O. (1983) P-T-X conditions of sub-greenschist burial metamorphism and copper mineralization, Keweenaw Peninsula, northern Michigan: *Geological Society of America Abstracts*, v. 15, p. 629.
- Stoiber, R.E. and Davidson, E.S. (1959) Amygdale mineral zoning in the Portage Lake Lava Series, Michigan copper district; Part I, Part II: *Economic Geology*, v. 54, p. 1250-1460, 1444-1460.
- White, W.S. (1968) The native-copper deposits of northern Michigan, in Ridge, J.D., ed., *Ore Deposits of the United States, 1933-1967*: Amer. Inst. of Mining, Metallurgical and Petroleum Eng., Graton-Sales Volume, p. 303-326.

Fig. 1 Schematic illustration of the geologic setting of native copper lodes (from Brown 2006)

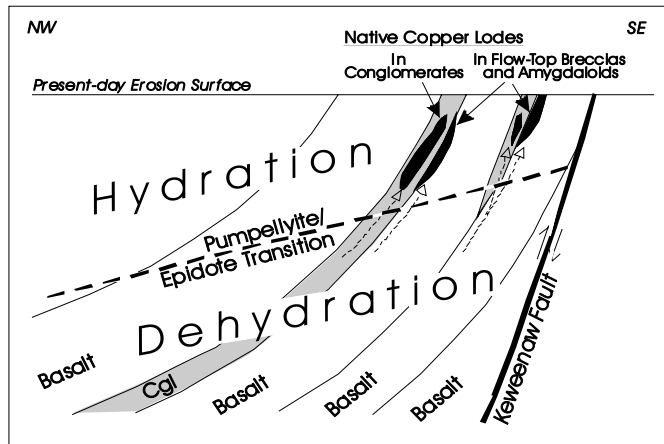


Fig. 2 Eh-pH stability diagrams (below) for A) the transport of copper, and B) the deposition of native copper (from Brown 2006)

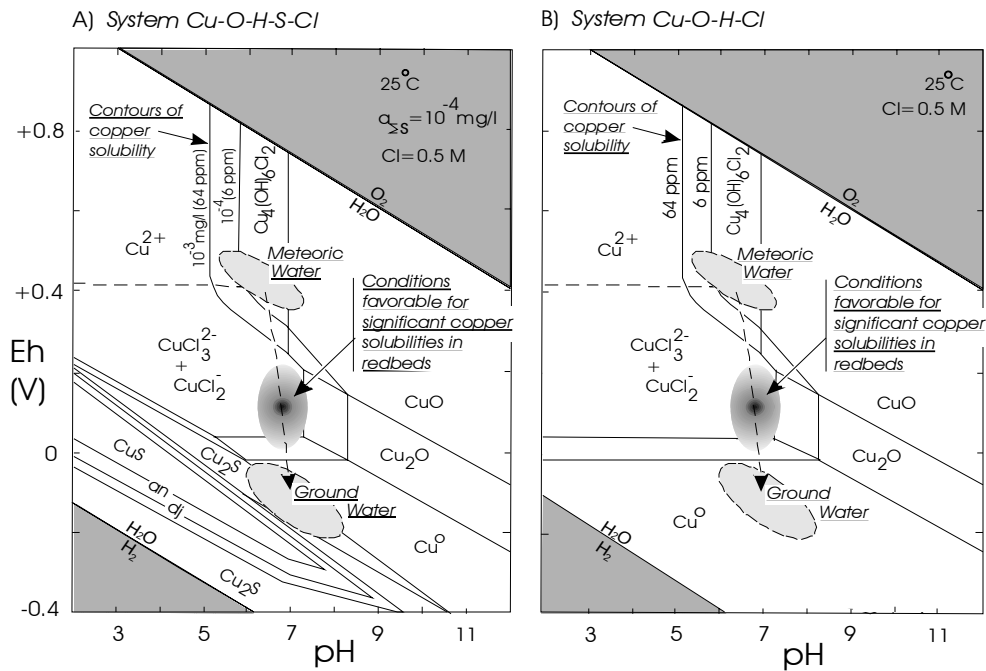
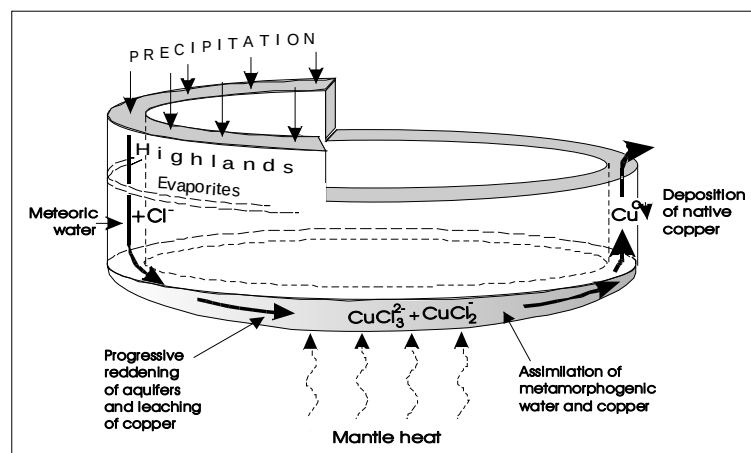


Fig. 3 Schematic illustration of the deep flow of meteoric and metamorphic waters, to form native copper lodes (from Brown 2006)



A NOVEL LOCALITY FOR PSEUDOBROOKITE - THE NINE MILE PLUTON, MARATHON COUNTY, WISCONSIN

T.W. Buchholz¹, **A.U. Falster**², **Wm. B. Simmons**². ¹1140 12th St. N., Wisconsin Rapids, WI 54494; ²Department of Earth and Environmental Sciences, University of New Orleans, New Orleans, LA 70148.

Pseudobrookite, $(\text{Fe}^{3+}, \text{Fe}^{2+})_2(\text{Ti}, \text{Fe}^{3+})\text{O}_5$, is a typical pneumatolytic mineral found in lithophysae in extrusive Ti-rich rocks such as andesite and rhyolites (Anthony et al., 1997). Recent work in the Ladick Trucking & Excavating weathered granite quarry has exposed a novel occurrence of pseudobrookite within the Proterozoic Nine Mile Pluton, the youngest and most silicic of four plutons comprising the Wausau Complex.

The Ladick quarry is located approximately ¼ mile east of STH 107 in the southwest portion of the Nine Mile Pluton. Black to dark grey elongated crystals of pseudobrookite up to approximately 1.5 mm in length and clustered in radiating sheaves and as single crystals were found in an alteration assemblage associated with a thin quartz-pyrite-fluorite vein. The material was recovered from a pile of shot rock derived from blasting large boulders removed from the grus in the northern portion of the operation. The vein was emplaced in a fracture cutting the granite, and it appears fluids circulating along the fracture preferentially removed quartz and perhaps other minerals from adjacent granite to a distance of up to about 12 cm from the fracture. Subsequently K-feldspar, biotite, minor quartz and a series of associated minerals described below were deposited.

EMP analysis of clean grains of pseudobrookite shows no significant components other than Ti and Fe and minor amounts of Mn and Nb, and XRD analysis yielded excellent structural agreement. Morphology is that of ideal, short-prismatic pseudobrookite. Associated minerals other than K-feldspar, biotite and quartz include ilmenite, rutile, anatase, sphalerite, chalcopyrite, pyrite, arsenopyrite or marcasite (now represented by goethite pseudomorphs), molybdenite, cassiterite, fluorapatite, fluorite, monazite, zircon and a LREE-carbonate mineral, probably bastnaesite-(Ce). Secondary minerals include small but attractive sprays of gypsum crystals; the Ca was probably derived from weathering fluorite, and the S from weathering sulfides. Interestingly, the cassiterite crystals often contain inclusions of fluorapatite and monazite; all monazite identified so far has been as inclusions in cassiterite. The monazite and fluorapatite inclusions may represent an earlier, otherwise transient paragenesis that was preserved by inclusion in cassiterite; the LREE released by breakdown of early-formed monazite may have contributed to the later formation of the LREE-carbonate mineral.

Although pseudobrookite typically is found in lithophysae in certain eruptive rocks and this would seem to be a very different environment, the Nine Mile pseudobrookite probably formed in an environment that was not inconsistent with its usual environment of formation. As indicated by the association with cassiterite, molybdenite (this is the first report of molybdenite for the Nine Mile granite), fluorite and other Ti-bearing oxides the conditions were probably high-temperature, volatile- and Ti-rich. Conditions were likely close to a pneumatolytic environment – consistent in these respects with typical

pseudobrookite occurrences. The principal variant may have been ambient pressure, although it is believed that the Nine Mile granite was intruded at a shallow, albeit as yet undefined level in the crust. Hence the environment of formation probably had at least some features in common with the usual volatile-rich, high temperature andesites and rhyolites that are the normal hosts for pseudobrookite.

Reference cited:

Anthony, J.W., Bideaux, R.A., Bladh, K.W. and Nichols, Monte C., 1997, Handbook of Mineralogy, V. III, p. 453.

Deposition and Cementation of Paleoproterozoic Gunflint Formation Carbonate: Implications for Early Hydrosphere Chemistry

Justin Burton and Philip Fralick, Department of Geology, Lakehead University, Thunder Bay, Ontario, Canada, philip.fralick@lakeheadu.ca

The Gunflint Formation extends 190 km towards the northeast from an intrusive contact with the Duluth Complex. Surface exposures form a narrow band of outcrops with basal siliciclastics and underlying Neoproterozoic rocks to the west and overlying black shales of the conformable Rove Formation to the east. Erosional remnants 98 km northeast of Thunder Bay at Schreiber, Ontario, suggest a pre-erosional continuation of the chemical sedimentary rocks to the east. Rock comprising the Gunflint Formation primarily consists of an assemblage of chemical sediments including chert, iron oxides and carbonates. Volcanogenic shales and similar debris within the chemical sediments is also present. In 1956 the Formation was divided by Goodwin into six major sedimentary facies representing two depositional cycles and four members: 1) Basal Conglomerate, 2) Lower Gunflint, 3) Upper Gunflint, and 4) Upper Limestone. These units were deposited on a wave and tide influenced broad shelf deepening to the south (Fralick and Barrett 1995, Pufahl and Fralick 2004). Storm events eroded the fine-grained chemical sediments abrading them into sand-sized fragments that accumulated as cross-stratified layers and lenses (Fralick 1988).

In this study we examine the limestone unit at the top of the Gunflint Formation and compare its petrology and geochemistry to ferruginous dolomitic (ankeritic) grainstones common in the shore-proximal exposures near Thunder Bay. The stratigraphy of the limestones is consistent in the outcrops studied, even though some are tens of kilometers apart. The unit is conformable with underlying silicified ankeritic grainstones. The boundary between the two units forms a replacement front in places, with microscopic examination clearly revealing replacement of calcite by ankerite. The limestone consists of a very coarse sand to granule grainstone layer overlain by cabbage sized and shaped stromatolites. Layers of both fine-grained and very coarse-grained calcareous sand are banked up against and overlie the stromatolites. This assemblage is less than one meter thick. It is sharply overlain by a pebble to boulder conglomerate with some tabular clasts up to four meters long. Fragments of the underlying ankerite and limestone layers form most of the clasts.

Ankerites from lower in the succession are composed of neomorphic spar with none of the original texture preserved. Geochemically they have high concentrations of Ca, Fe, Mg and Mn with relatively low abundances of most other elements. Their REE curves are LREE enriched with positive La and, to a lesser extent, Ce anomalies. Eu is flat to positively enriched. The limestones have clasts composed of Fe-rich chlorite, consistently with V contents of 1-2 percent. They are surrounded by blocky calcite cement that in places overgrows the grains. Samples from higher in the grainstone assemblage have more pronounced dissolution pathways along calcite crystal boundaries. These dissolution channels are filled with either calcite or quartz. The stromatolites have alternating layers of Fe-rich chlorite and blocky calcite cement similar in composition to the adjacent grainstones. The grains in some grainstones are pieces of stromatolite. The limestones are very geochemically different from the ankerites. The limestones have higher values of most elements, but especially U (5 to 10 times more abundant), REE's (10 to 100 times more abundant) and V (100 times more abundant). Their REE curves are LREE enriched and show distinct Ce and Eu depletion.

New U-Pb geochronological data (Don Davis, Pers. Comm) indicates that the pebble to boulder conglomerate is the tsunami deposit that resulted from the Sudbury impact. This reinforces previous interpretations that a significant nondepositional interval with subaerial exposure existed between deposition of the Gunflint and Rove Formations in the study area (Addison et al. 2005). The blocky calcite cements and Fe chlorites would have formed in the phreatic zone during this interval. The extreme V-U enrichments indicate oxidized fluids leaching V and U from the subaerial environment and precipitating these redox sensitive elements upon encountering the organic-rich sediments. The negative Ce anomalies of the REE curves for the calcite cements agree with this interpretation. The ankeritic sediments deposited in the marine environment have REE abundances typical of precipitation from oxygen deficient water with abundant dissolved Fe and Mn. This data points to an imbalance in oxygen levels at this time with a relatively oxic atmosphere and anoxic oceans. This agrees with findings from other geochemical investigations of the Gunflint and Rove Formations (Poulton et al. 2004).

Addison, W. et al., 2005. *Geology*, vol. 33, p. 193-196.

Fralick, P.F. 1988. *Memoir 13, Can. Soc. of Petroleum Geologists*, p. 24-29.

Fralick, P.W. and Barrett, T.J., 1995. *Spec. Publ. 22, Inter. Ass. of Sedimentologists*, p. 137-156.

Poulton, S.W., Fralick, P.W. and Canfield, D.E., 2005. *Nature*, vol. 431, p. 173-177.

Pufahl, P.K. and Fralick, P.W., 2004. *Sedimentology*, vol. 54, p. 791-808.

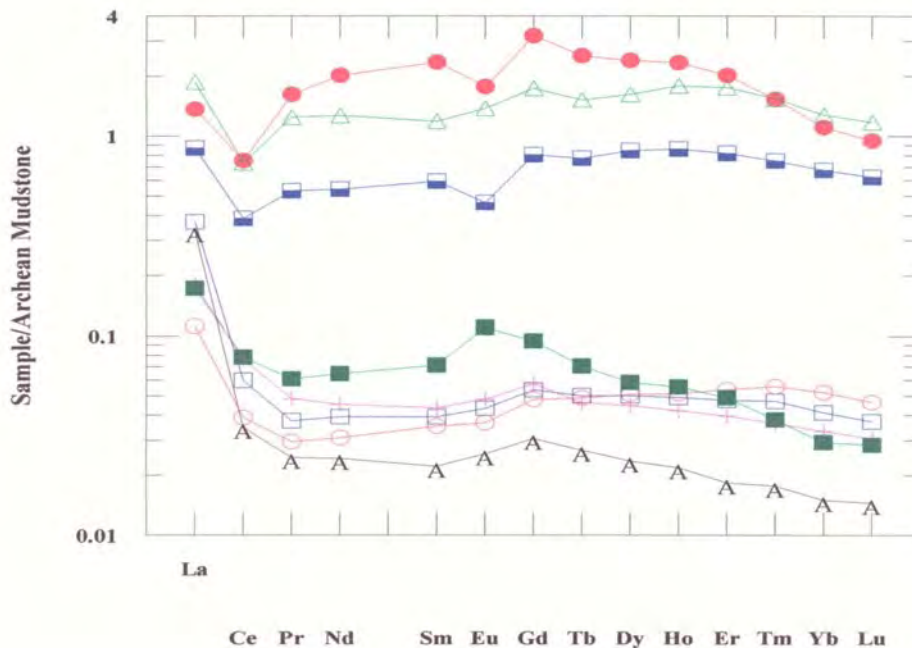


Figure 1. Archean mudstone normalized REE curves for ankeritic samples (lower 5 curves) and limestone samples (upper 3 curves).

THE SUDBURY IMPACT LAYER IN THE LAKE SUPERIOR IRON RANGES: A TIME-LINE FROM THE HEAVENS

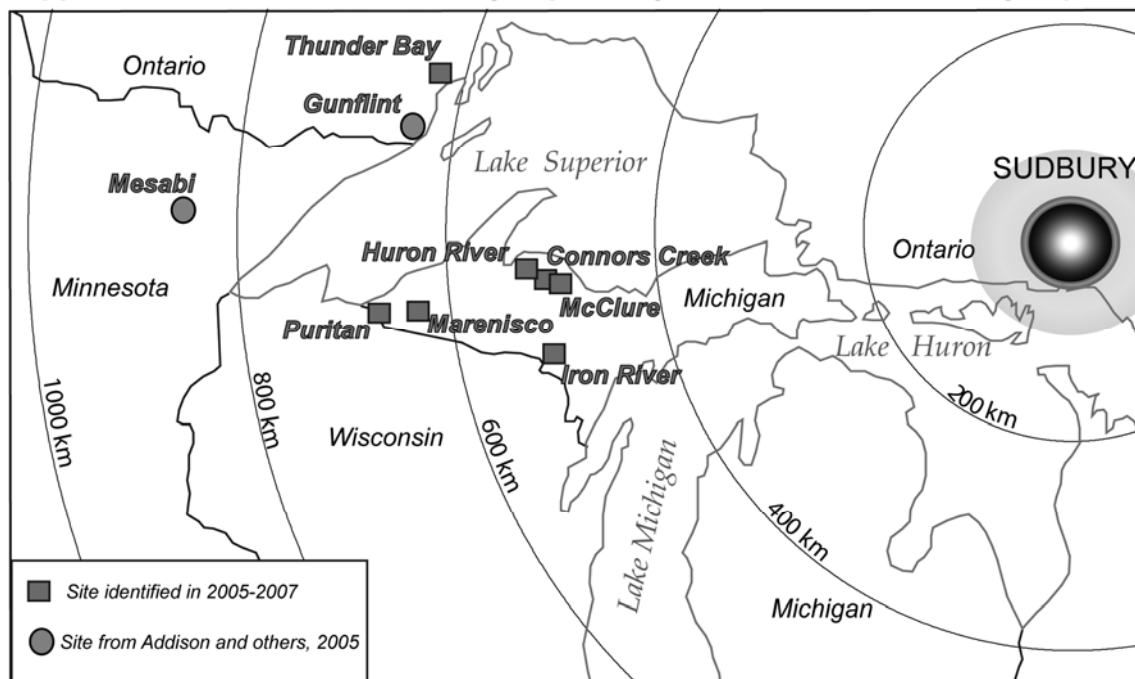
Cannon, William F., U.S. Geological Survey, MS 954, Reston VA 20192

Addison, William D., R.R. 2, Kakabeka Falls, Ontario, POT 1W0, Canada

A large meteorite impact near Sudbury, Ontario at 1,850 Ma produced a geologically instantaneous regional, and probably global, catastrophe leaving a unique imprint within the classic iron ranges of the Lake Superior region 500 to 900 kilometers from the impact site. We have now identified the impact layer in or near five of the iron ranges. The layer is a unique and ultra-precise time line, having formed over a time span of days or less across the region, and allows an unequivocal temporal correlation of the stratigraphic units with which it is interbedded.

The impact layer consists of various rock types and may have formed by processes including direct deposition of airborne ejecta either from a high energy ejecta curtain traveling at ballistic velocities, or from a turbulent cloud of finer ejecta. More commonly the layer consists of polymict marine breccias of reworked ejecta and local sediments possibly formed by 1) “ballistic erosion” and mixing of sediment caused by high energy ejecta deposition, 2) erosion and redeposition caused by mega-tsunamis generated by the impact, 3) resurge of ocean water toward the “hole in the bottom of the sea”, or possibly 4) submarine slumping triggered by impact generated earthquakes. Regardless of diverse lithology and depositional processes, occurrences of the impact layer are linked by the presence of quartz grains exhibiting relict shock metamorphic features, which form only under the extreme pressures produced by hypervelocity impacts.

Approximate locations of Sudbury Impact Layer Sites and the Sudbury Impact



The following are brief summaries of the characteristics each site:

Gunflint- At top of Gunflint Iron-formation; nearly pure ejecta deposits of devitrified vesicular glass, microtectites, and spherules; accretionary lapilli and shocked quartz; apparently not reworked by tsunamis.

Thunder Bay- Tsunami debrisite at top of Gunflint Iron-formation containing reworked, locally derived breccia fragments plus ejecta similar to the Gunflint ejecta; shocked quartz known from one locality.

Mesabi- Poorly known unit at top of Biwabik Iron-formation; contains devitrified spherules, microtectites, and vesicular glass; shock metamorphosed quartz.

Puritan- Known from a few thin sections of drill core from 1960's study. "Volcaniclastic breccia" in Tyler Formation about 100 m above Ironwood Iron-formation; rare shock metamorphosed quartz.

Marenisco- Possible tsunami deposit at base of Cops Formation lying on Archean granite. Shock metamorphic features not well documented at this time.

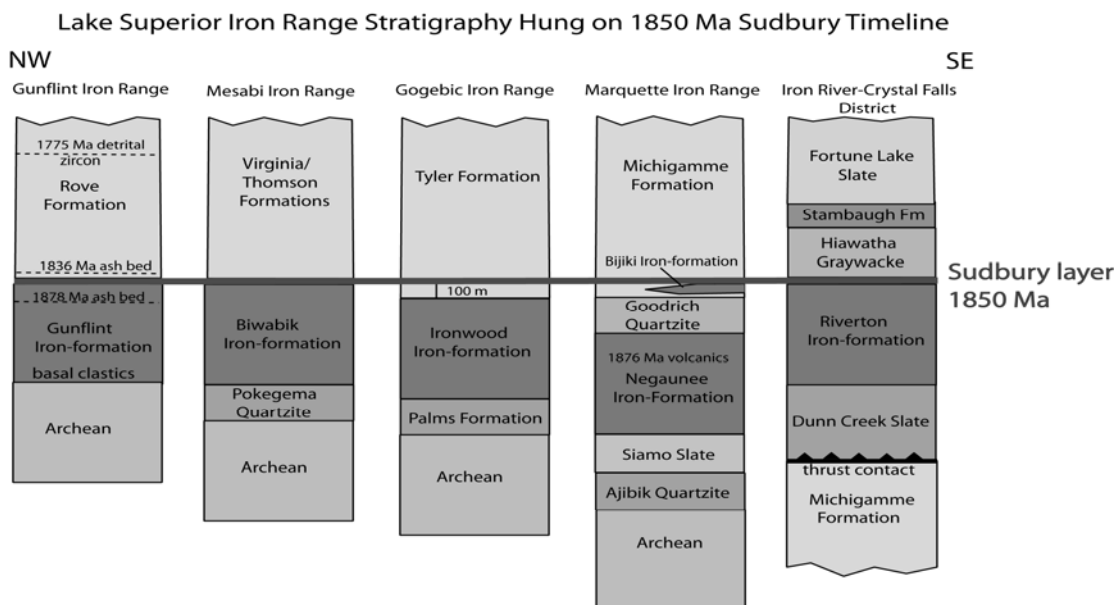
Huron River- Breccia and fine "volcaniclastic rocks"; near base of Michigamme Formation a few meters above contact with Archean granite. Abundant shock metamorphosed quartz grains.

Connors Creek- Breccia, greywacke, and accretionary lapilli beds; erosional contact on slightly ferruginous chert about 150 m above base of Michigamme Formation; shock metamorphosed quartz.

McClure- Breccia and greywacke about 300 m above base of Michigamme Formation; erosional contact on carbonate iron-formation; shock metamorphosed quartz; grades up to black slate.

Iron River- Breccia and greywacke forming lower part of Hiawatha Graywacke; shock metamorphosed quartz; known best from thin section collection from 1940's; erosional contact on Riverton Iron-formation.

The diagram below shows the precise temporal correlation of stratigraphic units in the five areas where we have identified the Sudbury impact layer.



AN EXPERIMENTAL WATER-ROCK INTERACTION STUDY INTO THE ORIGIN OF HIGH-SULFATE WATERS ASSOCIATED WITH THE STEEP ROCK IRON MINES, ATIKOKAN, ONTARIO.

COCKERTON, S., and CONLY, A.G., Department of Geology, Lakehead University,
Thunder Bay, ON, P7B 5E1 andrew.conly@lakeheadu.ca
LEE, P., Department of Biology, Lakehead University, Thunder Bay, ON, P7B 5E1

Continual flooding of the two primary open pits of the Steep Rock iron mines near Atikokan, Ontario, has led to the formation of Hogarth and Caland pit lakes, which are located in the former middle and eastern arms of Steep Rock Lake, respectively. At present both lakes are ~200 m deep and display distinct differences in water chemistry [1]. Hogarth pit lake is characterized by non-stratified to weakly stratified and oxygenated water column (4-12 mg/L O₂), near neutral pH (6.4-8.0), extraordinarily high SO₄²⁻ concentrations (1200-2000 mg/L), lower alkalinity (50-125 mg/L), increased hardness (1200-1800 mg CaCO₃/L) and is chronically toxic to aquatic fauna. On the other hand, Caland pit lake is well stratified with an upper oxygenated fresh water lens (~20 m in depth and 4-12 mg/L O₂) that is not toxic, which overlies an anoxic (<1 mg/L O₂) and moderately saline (200-500 mg/L SO₄²⁻) water column. The pH of Caland pit water is similar to that of Hogarth, but is more alkaline (100-200 mg/L) and has a lower hardness (400-1000 mgCaCO₃/L). The concentration of metals in both lakes is negligible. With the pits being filled at a rate of ~3 m/year [2] and ground water presumed to be the largest input of water, the differences in water chemistry between the two pit lakes likely reflect differences in the nature of water-rock interactions between ground water and bedrock. Previous stable sulfur isotope studies have concluded that the dissolved sulfate of the pit waters is derived from oxidation and leaching of pyrite-bearing units of the Joliffe ore zone by either ground water or due to pit water-wall rock interaction [1,3]. The geology of two pits is largely similar and includes [4,5]: 1) footwall rocks that consist of the Marmion Geniss Complex, Wagita Formation and Mosher Carbonate; 2) the Joliffe ore zone, which is comprised of the Manganiferous Paint, Goethite and Pyrite members; and, 3) hanging wall rocks that include the Dismal Ashrock Formation and the Witch Bay Formation.

In order to better determine the nature of ground water-rock interactions a series of batch-reaction column leaching experiments were performed. A series of four PVC columns (4 inches in diameter and 24 inches in length) were loaded with crushed (1-2 mm) pyrite and goethite-hematite waste rock, representing the Goethite and Pyrite members. Two of the columns also contained 2 inches of crushed Mosher Carbonate at the base. Columns were filled with Atikokan ground water ensuring that the crush rock was completely submerged. In addition, another three columns were loaded with crushed goethite-hematite tailings (jit reject), goethite-hematite waste rock and pyritic waste rock, and filled with rain water in order to assess the contribution provided from surface water. Approximately 30 mL of water was extracted and filtered at 3 hr, 24 hr, 3 days, 5 days, 7 days and then weekly for a total of 14 weeks. Cations and metals were determined by ICP-AES, anions (SO₄²⁻, Cl⁻) were determined by ion chromatography, and pH was measured using an Accumet AB15 pH meter.

Results from the column leaching experiments indicate that the high SO₄^{2-(aq)} concentration of the pit lakes could only be produced from ground water oxidation of pyritic portions of the Joliffe ore zone (Fig. 1a).

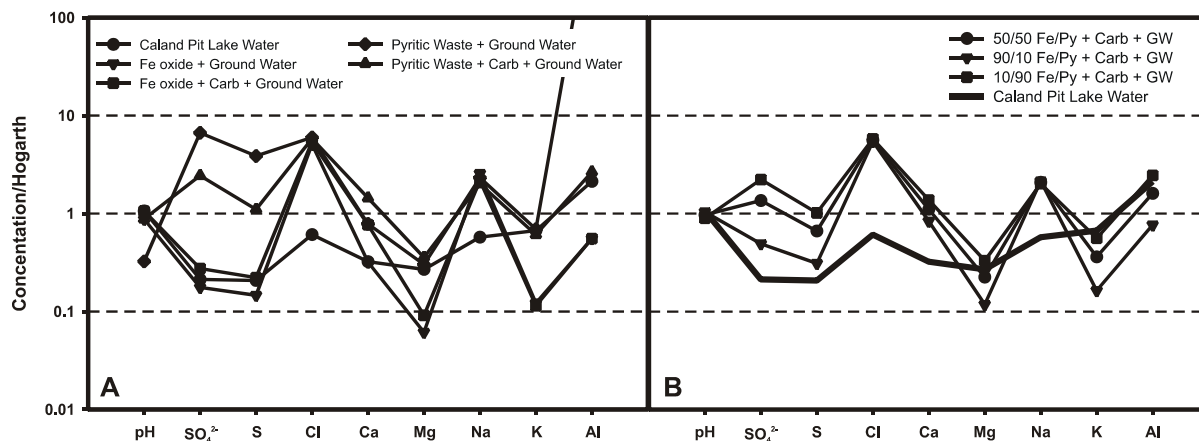


Figure 1. Normalized plots, to the average composition of Hogarth pit lake, showing the (A) relative concentration of pH, anions and cations from goethite-hematite and pyrite waste rock experiments, and (B) results of mixing between leachates derived from goethite-hematite and pyrite waste rock.

To generate the near neutral pH of either pit lake requires subsequent interaction with Mosher Carbonate (Fig. 1a). Figure 1b shows the results of mixing the leachates derived from goethite-hematite and pyrite waste rocks. Consequently, the pit waters are likely produced from the mixing of ground waters derived from both iron oxide and pyritic portions of the ore zone that were subsequently buffered by carbonate wall rock.. However, discrepancies between experimental waters and measured Hogarth pit lake water (e.g., Mg) likely reflect interaction of pit lake water with other wall rock lithologies and/or other ground water contributions. Experiments are currently underway to assess both the interaction of ground water with different lithologies and the effect of varying water-rock ratios. Initial results from these experiments will be presented at the meeting. Notwithstanding these discrepancies, the results from batch-reaction column experiments supports stable isotope evidence [1,3] that the sulfate in the two lakes is derived from ground water leaching of pyritic portions of the Joliffe ore zone. In addition, the differences in water chemistry between Hogarth and Caland pit lakes primarily reflects differences in the relative pyrite content of the Joliffe ore zone, with the ore zone beneath Hogarth pit lake containing a higher abundance of pyrite.

References:

- [1] Goold, A., Conly, A.G., and Lee, P., 2006. Integrated uses of water chemistry, stable isotope geochemistry and tie studies in identification of metal toxicity in pit lakes: A case study at the Steep Rock iron mine, Atikokan, Ontario: GAC-MAC Program with Abstracts, v. 31, p. 57-58.
- [2] McNaughton, K.A., 2001. The limnology of two proximal pit lakes after twenty years of intense flooding. M.Sc. Thesis, Lakehead University, Thunder Bay, Ontario, 85 p.
- [3] Conly, A.G. and MacDonald, J.C., 2005. An Investigation into Potential Sulphate Sources of the Hogarth Pit Lake, Steep Rock Iron Mine, Atikokan. ILSG 51st Annual Meeting, Proceedings Volume 51.
- [4] Joliffe, A.W. 1966. Stratigraphy of the Steeprock Group, Steep Rock Lake, Ontario. GAC Special Paper No. 3, p. 75-96.
- [5] Stone, D., Kamineni, D.C., and Jackson, M.C., 1992. Precambrian geology of the Atikokan area, northwestern Ontario. Geological Survey of Canada, v. 405, 106 p.

ORIGIN OF A MAFIC PEGMATITE WITHIN THE DULUTH COMPLEX, NORTHERN MINNESOTA

COSTELLO, Daniel E.¹, FLOOD, Timothy P.¹, and THOLE, Jeffrey T.²

¹ Department of Geology, Saint Norbert College, De Pere, WI 54115,
dan.costello@snc.edu,

² Department of Geology, Macalester College, St Paul, MN 55105

Geologic Setting

The Duluth Complex of Northern Minnesota is a layered igneous intrusion that formed due to rifting of continental North America approximately 1.1 billion years ago. The Complex is composed of numerous layered plutonic bodies, which formed through multiple intrusions of mafic to felsic tholeiitic magmas. These layered series are typically thick and exhibit foliation and layering that dips to the southeast, towards the axis of the Keweenaw Rift (Miller et. al. 2002). This study focuses on units within the South Kawishiwi intrusion (SKI). Near the base of this intrusion, two similar troctolitic units are separated by a pegmatitic unit. The petrogenetic relationship between the overlying and underlying troctolitic units is uncertain, as is the origin of the pegmatite. This project aims to determine the origin of and relationship between these three units using petrographic and geochemical data.

Igneous Stratigraphy

The pegmatitic unit, hereafter referred to as the PEG, was first noted by Foose and Weiblen (1984). This unit is used as a marker bed to differentiate the surrounding troctolites: The rock below the PEG is classified as the ultramafic three unit (U3), and the rock above the PEG is classified as part of the ultramafic two unit (U2). In drillholes where there is no PEG present, it is impossible to differentiate between these two troctolitic units.

The U3 is the lowermost ultramafic unit within the SKI. The thickness of this unit averages approximately 100 feet, and ranges from 3 to 410 feet. (Severson 1994). The U3 is characterized by massive oxide horizons as well as mineralization of sulfides and platinum group elements.

The PEG overlies the U3 unit and has an average thickness of approximately 95 feet. The pegmatite is used as a marker boundary between a sulfide-rich zone below and a sulfide-poor zone above (Foose and Weiblen 1986). The pegmatite is not always present in drill core.

The U2 overlies the PEG and is petrologically similar to the U3 unit, with the exception that the U2 lacks massive oxides and sulfide-rich horizons (Severson 1994). This unit averages about 90 feet in thickness.

Analysis

Petrographic study revealed visible variations among the three units. The U2 and U3 appear to be similar; however, multiple differences occur within the pegmatite. The presence of minerals such as amphibole and biotite in the PEG suggests that this unit formed at a later stage of crystallization and/or within higher P(H₂O) conditions than its surrounding units. The PEG also contains significant amounts of a plagioclase symplectite texture (Figure 1). This texture may indicate the presence of a late stage magmatic fluid which would promote the growth of a pegmatitic unit. This symplectitic texture is rare below the pegmatitic unit, but is present in small amounts in all units above the PEG (Severson 1994).

Geochemical studies focused on the changing concentrations of elements, notably the different behaviors of compatible and incompatible trace elements. From the U3 to the U2, not including the PEG, the concentrations of both Ni and Co decrease, suggesting olivine fractionation. In a similar fashion, the concentration of Ba increases from the U3 to the U2, suggesting plagioclase fractionation. This is consistent with a model of Ba as an incompatible element during early stages of crystallization.

Preliminary mineral chemistry was obtained on plagioclase and olivine grains from all units. The two troctolitic units contain olivine of Fo₆₃₋₆₅ and plagioclase of composition An₇₅₋₇₇. In comparison, the pegmatite contains olivine with Fo₄₇₋₆₀ and plagioclase with An₅₉₋₆₃. These results are consistent with a model of fractional crystallization between the U3 and the U2 and with elevated P(H₂O) conditions within the pegmatite.

Using the preliminary results outlined above, we infer that the three units are syngenetic and the U2 and U3 units formed through fractional crystallization. The pegmatite formed as a water rich phase concentrated within the magma chamber, with some water being derived from the footwall. As normal fractionation occurred from the U3 to the U2, a concentration of water resulted in the formation of a pegmatitic horizon between these two units.

References:

Foose, M.P. and Weiblen, P.W., 1986, The physical and chemical setting and textural and compositional characteristics of sulfide ores from the South Kawishiwi Intrusion, Duluth Complex, Minnesota, USA: in 27th Int. Geol. Congress (Moscow), Special Copper Symposium: Springer-Verlag, New York, p. 8-24.

Miller, J.D., Jr., Green, J.C., Severson, M.J., Chandler, V.W., Hauck, S.A., Peterson, D.M., and Wahl, T.E., 2002, Geology and mineral potential of the Duluth Complex and related rocks of northeastern Minnesota: Minnesota Geological Survey Report of Investigations 58, 207 p.

Severson, M.J., 1994, Igneous stratigraphy of the South Kawishiwi intrusion, Duluth Complex, northeastern Minnesota: Natural Resources Research Institute, University of Minnesota, Duluth, Technical Report NRRI/TR 93/34, 210 p.

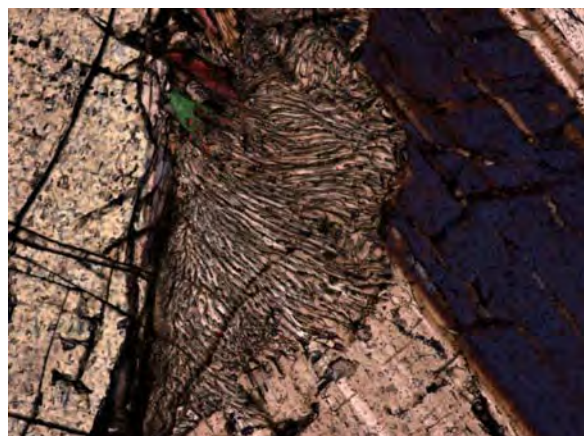


Figure 1: Plagioclase symplectite texture found in the pegmatitic unit. Field of view 1.5mm

Distribution of Certain Ichthyofauna in relation to Eastern Outlets of Lake Agassiz, with emphasis on the Gunflint-Arrow Lakes Corridor and the Keating Complex

J. Frederick Dean and Brian A. M. Phillips, Lakehead University, Thunder Bay, ON Canada.

Based on a retrodeformed elevation model (Phillips, 1997) of the Upper Herman stage of Lake Agassiz, Phillips and Hill (2004) proposed that the lake discharged via the Gunflint-Arrow Lakes Corridor into Lake Superior down the Arrow valley. Fisheries work in Minnesota and Ontario reveals a distribution of fish species that corroborates a flow of Agassiz water into the Arrow, Whitefish and lower Kaministiquia watersheds.

There are two sub-species of the temperate Johnny Darter (*Etheostoma nigrum eulepis* and *Etheostoma nigrum nigrum*), a small benthic fish unable to migrate up rapids or falls. The former, the earlier of the two, is found along the trend of the Herman shoreline and into the Gunflint-Arrow Lakes Corridor (Figure 1). The later sub-species relates to the Campbell shoreline, appearing in the Matawin and Shebandowan rivers. Intergrades developed where the two sub-species mixed (Underhill, 1963; Schmidt, 1993; Momot and Stephenson, 2007).

An Arctic marine glacial relict, Deepwater Sculpin also inhabits Gunflint-Arrow Corridor lakes. Dean (2006, pers. comm.) found *Pontoporeia affinis* (*Lindstrom*), another Arctic marine relict amphipod, in bottom waters of Arrow Lake. Both migrated along the northern, ice-bound margin of Lake Agassiz, as flow was funneled eastwards through the corridor.

The topographically rugged west-east trend of the borderlands, the “Keating Complex”, likely caused ice margin retreat to be intricate in detail (Figure 2). During and after the Steep Rock phase of Rainy Lobe retreat (circa 11,000 B.P.), Dean suggests successive spillways directed Agassiz waters towards Lake Superior. While Superior Lobe ice blocked the Arrow-Pigeon valley, water ran through the Stump and Swamp valleys and along the northern edge of coastal ice, first exiting via the Brule and Kimball valleys. Underscored is the potential for people to have migrated eastwards into the corridor at this time. Further ice retreat later deflected flow down the Whitefish-Kaministiquia valleys, before the Matawin exit opened.

- Momot, W.T. and Stephenson S.A., 2007, Atlas of the Distribution of Fishes within the Canadian Tributaries of Western Lake Superior: Lakehead University, Thunder Bay, 383p.
- Phillips, B.A.M., 1997, Retro-deformation of the D.E.M. of Northern Minnesota as a Tool for Reconstruction of Former Glacial Lakes, *in* Proceedings of the 9th Minnesota GIS/LIS Consortium Conference, St. Cloud, Mn.
- Phillips, B.A.M. and Hill C.L., 2004, Deglaciation History and Geomorphological Character of the Region Between the Agassiz and Superior Basins, Associated with the ‘Interlakes Composite’ of Minnesota and Ontario, *in* L.J. Jackson and A. Hinshelwood, Eds., The Late Palaeo-Indian Great Lakes - Geological and Archaeological Investigations of Late Pleistocene and early Holocene Environments, Mercury Series, Archaeology Paper 165, Canadian Museum of Civilization, Chapter 10, p. 275-301.
- Schmidt, K.P., 1993, Minnesota Parks Fish Species Lists: <http://www.nativefish.org>, 67p.
- Underhill, J.L., 1963, Distribution in Minnesota of the Sub-species of Percid Fish *Etheostoma nigrum*, and their Intergrades: *American Midland Naturalist*, v.70, p. 470-478.

Figure 1 – Distribution of Johnny Darters and Flow from Lake Agassiz to Lake Superior.

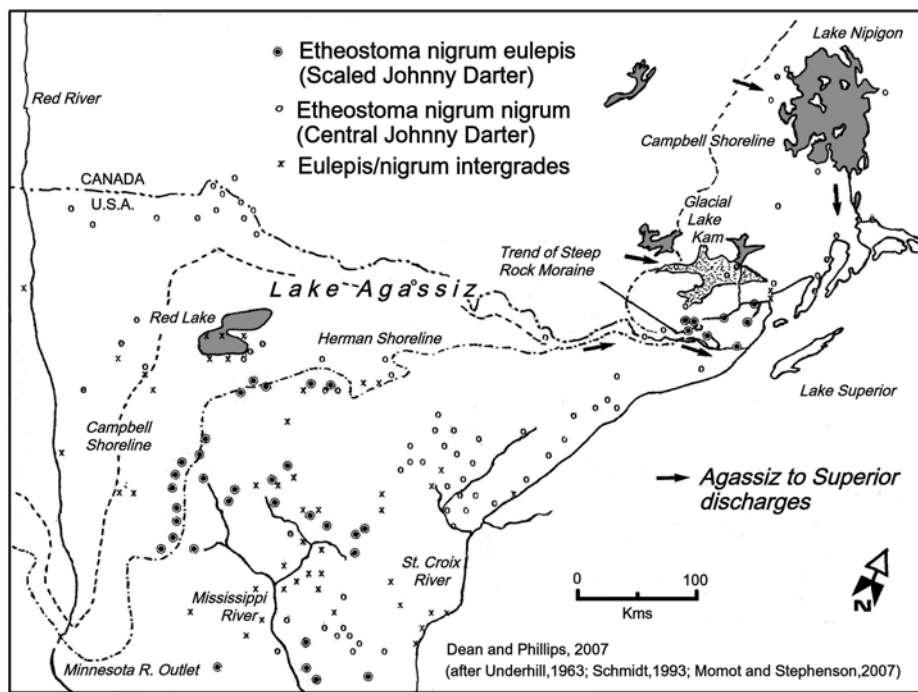
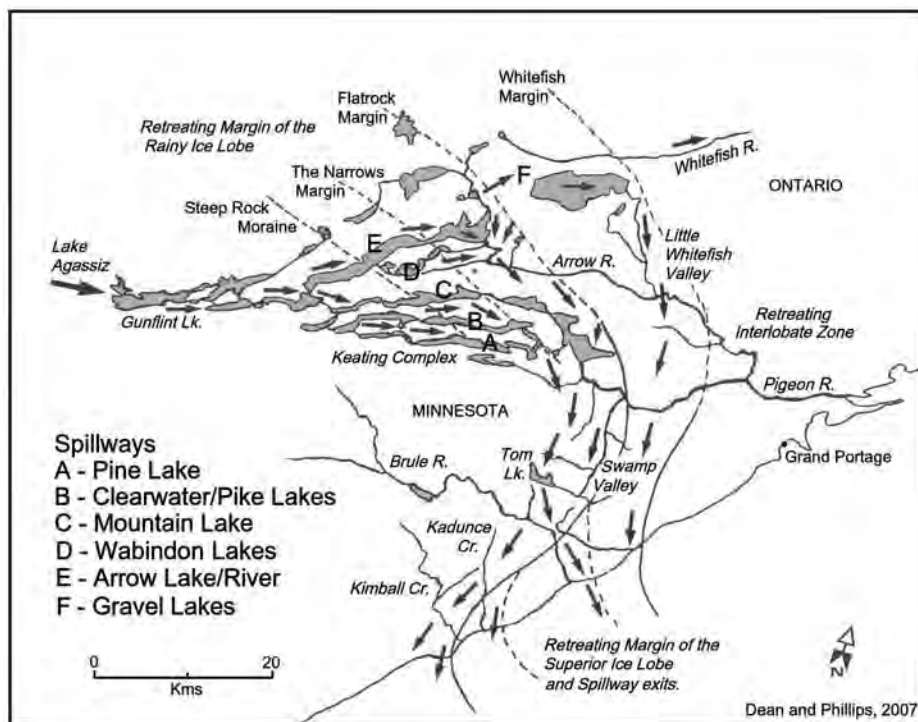


Figure 2 – Flow from Lake Agassiz to Lake Superior and the Keating Complex, MN-ON.



The effect of H₂O on olivine to ringwoodite transformation: Implications for subduction zone geodynamics and the deep earth water cycle

Tamara Diedrich^{*†}

Thomas G. Sharp

School of Earth and Space Exploration, Arizona State University, Tempe, Arizona 85287

As the most abundant minerals in the earth's upper mantle and transition zone, phase transformations between olivine and its high-pressure polymorphs, wadsleyite and ringwoodite, have major consequences for mantle geodynamics. Based on the thermal profile of subducting lithospheric slabs, it has been proposed that metastable olivine could persist into the mantle transition zone. Its presence would decrease negative buoyancy of the slab and slow subduction. In addition, the rapid transformation of metastable olivine has been identified as a potential initiating mechanism for deep-focus earthquakes. Several lines of evidence suggest that mantle olivine may contain significant H₂O in the form of hydroxyl point defects. While previous studies have shown that H₂O enhances olivine to wadsleyite transformation rates, under sufficiently cold conditions, olivine would transform directly to ringwoodite. Our research measures the effect of H₂O on olivine to ringwoodite transformation rates and shows that even modest hydration of olivine results in near equilibrium transformation of olivine under subduction zone conditions and no metastable wedge of olivine below 400 km.

For this study, a novel experimental approach was developed that consisted of two stages: hydration of mantle derived olivine in a piston-cylinder apparatus, and partial transformation of

^{*} Present address: Economic Geology Group, Natural Resources Research Institute, University of Minnesota, 5013 Miller Trunk Hwy, Duluth, MN 55811

[†] Corresponding author e-mail: tdiedric@nrri.umn.edu

these spheroids in a multi-anvil device. After hydration, the olivine contained 298 (± 29) ppm by weight H₂O. The multi-anvil experiments were conducted for varying run durations at 18 GPa and 700°C, 900°C, and 1100°C. The partially transformed samples were thin sectioned and the ringwoodite rim thicknesses were plotted as a function of run duration. Both growth rates and activation enthalpy for growth were determined.

Water appears to promote olivine to ringwoodite transformation by enhancing growth rates, decreasing activation enthalpy for growth, and facilitating the dissipation of transformation stress. Growth rates for the hydrated olivine are almost two orders of magnitude faster than for anhydrous olivine at 1100 °C and about four orders faster at 700°C. At 700°C, growth is fast enough to be observed on an experimental timescale; this is significant because kinetic parameters from previous studies suggest that, at 500°C, anhydrous olivine does not transform on a *geologic* timescale. The addition of water also enables ringwoodite growth rates to remain constant throughout transformation. The large volume decrease associated with olivine to ringwoodite transformation, if not accompanied by sufficient plastic deformation, causes transformation stress. As transformation progresses, this stress results in the build-up of strain energy, which slows growth by counteracting the driving force for transformation. Hydrolytic weakening of the olivine and/or ringwoodite facilitates the dissipation of transformation stress so that growth rates can remain constant throughout transformation. Using our kinetic parameters for hydrated olivine transformation, the addition of as little as 289 ppm by weight H₂O effectively eliminates metastable olivine from the transition zone. Alternatively, if the presence of metastable olivine is confirmed, it must contain significantly less than 298 ppm H₂O, placing a constraint on models of the deep earth water cycle.

GOLD MINERALIZATION IN THE VIRGINIA HORN GREENSTONE TERRAIN, ST. LOUIS COUNTY, MINNESOTA: A PROSPECT RE-VISITED

Elsenheimer, D.¹, **Frey, B.**², and **Hudak, J.**², ¹Minnesota Department of Natural Resources, 500 Lafayette Rd., St. Paul, MN 55155, ²Minnesota Department of Natural Resources, 1525 Third Ave. E, Hibbing, MN, 55746, donald.elsenheimer@dnr.state.mn.us

Petrologic, geochemical and fluid inclusion data from archived drill core have been combined with a digital compilation of historic exploration data and new maps to reassess the gold mineralization potential of the Virginia Horn Greenstone Terrain, a fifty square kilometer exposure of Wawa subprovince rocks located in St. Louis County, Minnesota.

The Virginia Horn Greenstone Terrain consists of a folded and faulted metamorphosed assemblage of Archean volcanic and sedimentary strata, intruded by a quartzofeldspathic porphyry (QFP) and overlain by a conglomerate sequence that was interpreted by Jirsa and Boerboom (2003) as a Timiskaming-type package correlative with parts of the Knife Lake and Shebandowan Groups (Figure 1). Metamorphic grade varies from prehnite-pumpellyite to middle greenschist facies.

Visible gold within QFP outcrops were first identified in the 1930's and associated with quartz veining, carbonate-sericite alteration and major shear zones. Historic mineral leasing and gold exploration activity involved the completion of more than fifty diamond drill core borings, mostly within or near the highly-altered and sheared QFP (Figure 2). Assay results within portions of drill core were significant, but too inconsistent to be considered economic. There has been no drilling within the Virginia Horn since 1991, and all mineral leases held on state-owned or managed lands (which cover more than 50% of the terrain) have been allowed to expire.

Completion of subsequent geologic mapping and analog modeling, combined with a resurgence of price-sensitive gold exploration activity prompted the Minnesota Department of Natural Resources (MnDNR) to reassess the potential for economic gold deposits within the Virginia Horn. A digital compilation was created of historic mineral lease records and subsequent petrologic and geochemical analyses on drill core housed in the MnDNR's drill core repository. This compilation includes the conversion of hard-copy sample location reports and laboratory reports into GIS-friendly maps, shape files and data tables. Drill core samples were reviewed to fill identified data gaps and better correlate drill core logs prepared by different companies, and new petrologic, geochemical and fluid inclusion samples were collected to better constrain the conditions and timing of gold mineralization.

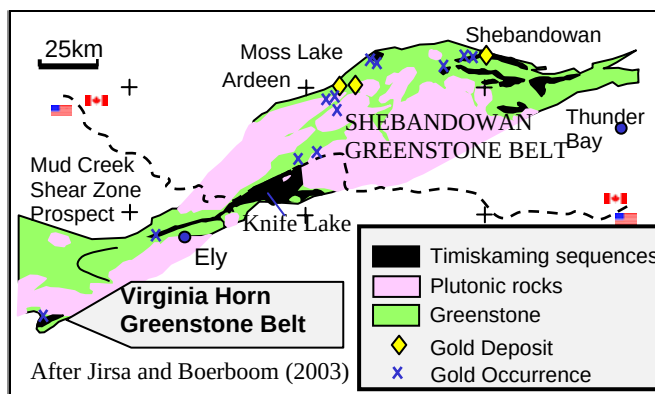
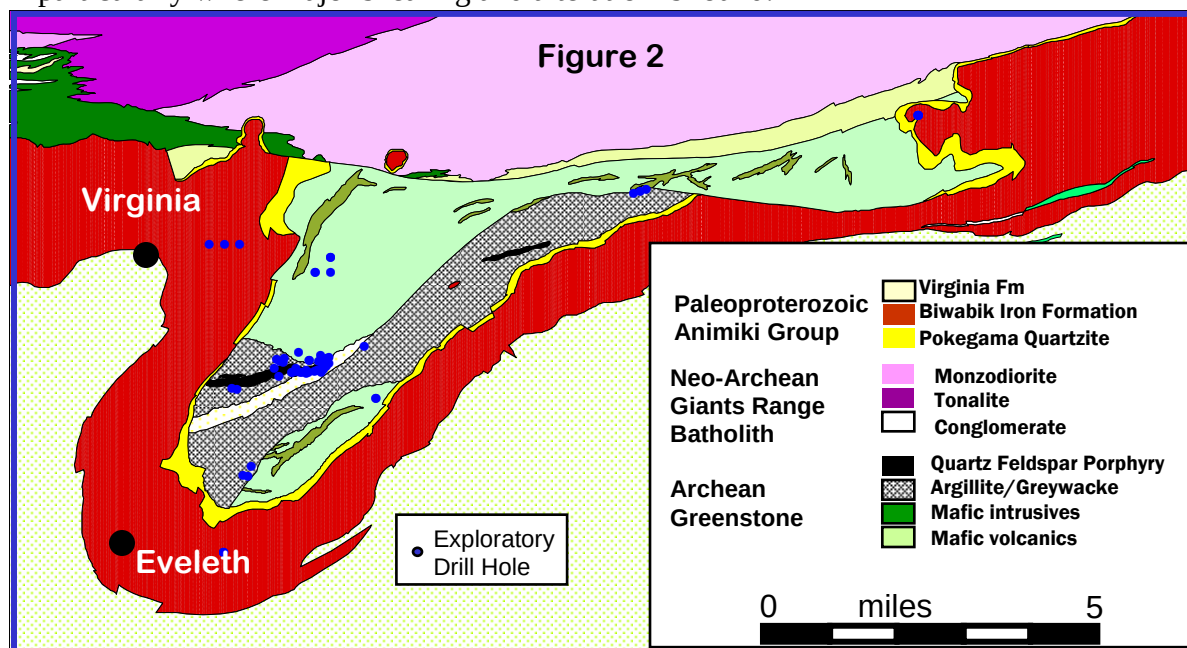
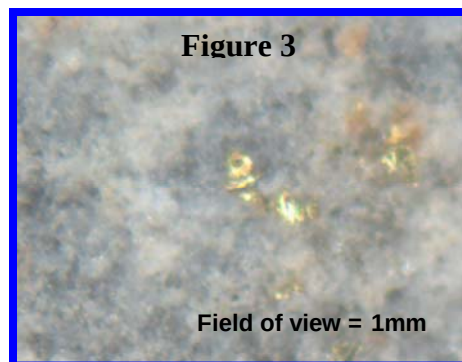


Figure 1

Historic exploration efforts focused on a lode gold mineralization model for the QFP. The depth and density of drill cores completed using this model were not sufficient to rule out the possibility of economic lode gold deposits within the QFP. That said, reinterpretation of the Virginia Horn as a Timiskiming-type greenstone terrain would support new exploration efforts beyond the QFP, and into both the overlying basal conglomerate and associated country rock, particularly where major shearing and alteration is found.



Support for new drilling within relatively unexplored portions of the Virginia Horn comes from a new visible gold occurrence (Figure 3), discovered during re-logging and examination of drill core DML-3. This bore hole intersected a major fault and was completed within a meta-argillite unit located approximately 8,000 feet from the QFP. The visible gold occurred in a quartz-calcite vein with local minor pyrite. The quartz vein, at 207.5 to 209 feet, had a broken ribbon texture parallel to the vein margins. The vein was oriented about 5 degrees to the core axis. Other quartz-calcite (and minor pyrite) veins were more numerous, but the internal texture was one of crackled quartz with infilling calcite. Prior orientation of the vein during this stage of deformation may have created the different styles.



Gold grain counts and pathfinder element concentrations in glacial till collected from locations down ice from both the QFP and this new visible gold occurrence will be used to further constrain competing gold mineralization models.

Textural Stratigraphy of Nipigon Diabase Sills: A Tool for Correlation and Petrologic Interpretations

FORSHA, Clinton J. and **ZIEG, Michael J.**, Department of Geography, Geology, and the Environment, Slippery Rock University, 1 Morrow Way, Slippery Rock, PA 16057, USA, cjf8856@sru.edu

The relationship between texture and position in an igneous intrusion can be used to interpret the injection dynamics of a sill. In addition, because texture is a strong function of cooling history, textures can be used to determine position in the sill, when the upper and lower contacts are not exposed. The primary purpose of this study is to examine the textures variations in sections through a diabase sill at multiple locations in the Nipigon area, in an attempt to correlate the profiles and construct a composite section.

Previous investigations of the Nipigon sills, 1.1-Ga olivine tholeiites, have demonstrated, on the basis of mineralogical variations (e.g., Sutcliffe, 1989), and textural anomalies (Zieg and Forsha, this volume), that the sills were filled via a series of injection pulses rather than in a single, instantaneous injection. This episodic filling history impacted the modal mineralogy and textural variations in the lower contact zone, and is clearly discernible using crystal size distribution (CSD) variations.

In order to test the use of textural variations for stratigraphic correlation in igneous intrusions, three sample profiles, from different heights within the sill, were investigated. The Kama Point section includes the lowermost 35 m of the sill, and exhibits strong internal discontinuities related to reinjection events. The Moseau section, which has a total thickness of ~45 m, but does not include an upper or lower contact, is significantly coarser-grained than the Kama Point section and contains no significant textural anomalies. The Palisades section, which has a thickness of ~40 m but does not include an upper or lower contact, does not follow same coarsening-upwards trend as the Kama Point and Moseau sections. The rocks in this section display a slight coarsening toward the center of the section, and appear to become slightly finer-grained in the upper part. With the coarse nature of the Palisades section and its gradual change from coarsening to fining, it is believed that this section is located in the center of the sill.

As an application of this method, we combine the different sections into a composite profile through the lower half of the sill. This technique is useful in areas such as Nipigon, where total relief is less than the thickness of individual sills. Used together with mineralogical and chemical constraints, textural stratigraphy is a powerful tool for comparing and interpreting the histories of igneous intrusions.

References

Sutcliffe, R.H. 1989. Mineral variation in Proterozoic diabase sills and dykes at Lake Nipigon, Ontario. *Canadian Mineralogist*, **27**: 67-79.

PGE-rich mineralization at the Marathon Deposit, Coldwell Alkaline Complex, Ontario

David Good and **Phillip Walford**, Marathon PGM Inc.

Mineralization at the Marathon deposit occurs within the Two Duck Lake gabbro, a late-stage gabbroic subunit of the Eastern Gabbro located along the eastern margin of the Coldwell alkaline complex. To date, 70 million tonnes of in-pit resource including 750,000 tonnes of PGE-rich ore have been outlined.

PGE-rich ore occurs within a mineralized envelope that is stratigraphically above relatively Cu-rich ore in the Malachite and Southern Resource areas and has been intersected in 64 drill holes over a strike length of 1 km. The highest grade intersection is 106 ppm Pt+Pd+Au and 0.02% Cu over 2m and the highest value intersection is 55 ppm Pt+Pd+Au and 0.59% Cu over 8m. The 64 drill hole intersections were subdivided into a subset of 28 intersections based on a cut-off value of 3ppm Pt+Pd and a minimum thickness of 4 m (2 samples). The average grade and thickness of this subset is 9.38 ppm Pt+Pd+Au and 0.21% Cu over 7.56m. The Pd/Pt ratio is 3.25+/-0.81.

The host Two Duck Lake gabbro consists of coarse grained to pegmatitic gabbro with subhedral plagioclase and olivine with ophitic-textured clinopyroxene and magnetite, and minor apatite and biotite. Xenoliths of fine-to medium-grained gabbro are common. Alteration or secondary minerals such as chlorite, sericite, serpentine and calcite occur locally and typically make up less than 5% of the rock.

Sulphide mineralization occurs as disseminated chalcopyrite and minor pyrrhotite within coarse grained to pegmatitic olivine gabbro. A detailed study of platinum-group minerals in samples from the Malachite zone determined that approximately 70% of the observed individual grains were closely associated with chalcopyrite or bornite and that less than 7% were associated with secondary minerals such as chlorite or serpentine (Liferovich, 2007).

Previous examination of metal-metal distribution diagrams for the Main zone showed strong inter-element correlations between Pd-Pt, Pd-Rh, Pd-Cu and Pd-Au (Good and Crocket, 1994). A comparison of PGE-rich ore to that of the Main zone shows two interesting relationships. First, the trend for Pd-Pt and Pd-Rh shown in the Main zone is continuous with that for the high grade ore. Second, there is no correlation between Pd and Cu in the high grade ore. The Au data are less decisive and somewhat scattered but seem to show behaviour similar to that for Pd.

A magmatic model for partitioning of PGE and Cu by sulphide segregation and variations in the R-factor as described for mineralization in the Partridge River Intrusion (Theriault et al, 2000) is somewhat consistent with the data. A simple calculation using a concentration factor of 1000 for the mineralized zones suggests a magma column that is at least 10,000 m thick is required to produce a 10 m intersection with 10 ppm Pd, but the host Two Duck Lake gabbro is only 200 to 400 m thick.

Thériault, R. D., Barnes, S.-J. and Severson, M. J., 2000, Origin of Cu-Ni-PGE Sulfide Mineralization in the Partridge River Intrusion, Duluth Complex, Minnesota: *Economic Geology*, v. 95, p. 929-943

Liferovich, R., 2007, Mineralogy of PGE, Gold and Silver in the Malachite ore zone, Two Duck Lake deposit, Marathon, NW Ontario, Internal Company report.

Good, D.J., and Crocket, J.H., 1994, Genesis of the Marathon Cu-platinum-group element deposit, Port Coldwell alkalic complex, Ontario: A mid-continent rift-related magmatic sulfide deposit: *Economic Geology*, v. 89, p.131 –149

Sugarloaf – A State Scientific and Natural Area and a North Shore Non-Profit Association

John C. Green

Department of Geological Sciences, University of Minnesota Duluth, Duluth, MN 55812

Andrew Slade

Sugarloaf: The North Shore Stewardship Association, 6008 London Road, Duluth, MN 55802

The 7-acre Sugarloaf Point Scientific and Natural Area (SNA) in southwesternmost Cook County, Minnesota, was designated in 1992 to preserve and protect the geological and ecological features of this bit of the North Shore, especially the basalt lava-flows and the dynamic beaches. Despite its history as a logging-era brownfield, it preserves excellent and accessible evidence for the character of both the 1.1 Ga Midcontinent Rift volcanism and Holocene postglacial processes, still active today.

The bedrock consists of olivine tholeiite flows, part of the Schroeder basalts, near the top of the North Shore Volcanic Group (Miller et al., 2001; Miller et al., 2006). Features such as ophitic and amygdaloidal textures, columnar jointing, pipe amygdules, segregation veins, ropy surfaces, vesicle cylinders, and clastic dikes are well exposed (Green, 1989). Surficial features include an abandoned strandline and the overall tombolo form, with modern beaches linking the rocky point to the mainland. Beach clasts imply derivation from Rainy Lobe as well as Superior Lobe glacial deposits, along with local bedrock.

The SNA, as well as 27 surrounding acres, is managed by a nonprofit group known as Sugarloaf, the North Shore Stewardship Association. The Association has built a log interpretive center, and has accomplished considerable environmental restoration on this heavily impacted site. Major restoration projects include excavation and replanting, with locally-grown native vegetation, of a rare coastal wetland between the berms of the tombolo.

Sugarloaf hosts many popular interpretive programs, including day-long workshops on various aspects of North Shore natural history. It works with landowners and public land managers throughout the North Shore on both landscape restoration and interpretation.

A major current initiative is the opening of the North Shore Interpretive Center at the University of Minnesota Duluth's historic "Limno Lab" building at the Lester River in northeastern Duluth. Exhibits there will introduce visitors to North Shore natural and settlement history and UMD based research on the North Shore and Lake Superior.

References Cited

- Green, J. C., 1989, Physical volcanology of mid-Proterozoic plateau lavas: The Keweenawan North Shore Volcanic Group, Minnesota: Geological Society of America Bulletin, v. 101, p. 486-500.
- Miller, J.D., Jr., Green, J.C., Severson, M.J., Chandler, V.W., and Peterson, D.M., 2001, Geologic map of the Duluth Complex and related rocks, northeastern Minnesota: Minnesota Geological Survey Miscellaneous Map Series Map M-119, scale 1:200,000.
- Miller, J.D., Jr., Green, J.C., and Jerde, E.A., 2006, Bedrock geologic map of the Little Marais quadrangle, Lake and Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map Series Map M-172, scale 1:24,000.

Emplacement of the Nipigon Sill Complex and Mafic to Ultramafic Intrusions of the Nipigon Embayment

T.R. Hart and C.A. MacDonald

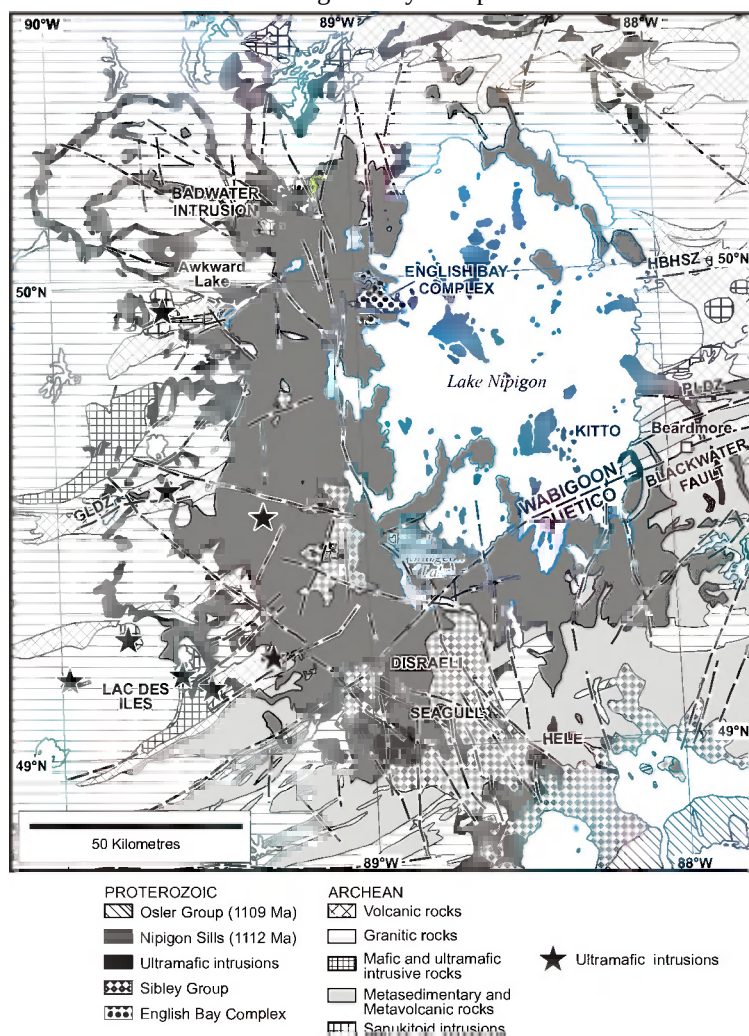
Precambrian Geoscience Section, Ontario Geological Survey (tom.hart@ontario.ca) (caroleanne.macdonald@ontario.ca)

The Nipigon Embayment consists of Proterozoic sedimentary and intrusive rocks underlain by Archean rocks of the English River, Wabigoon, and Quetico subprovinces. Recent geological mapping suggests that the Nipigon Embayment is underlain by a series of north-, northwest- and northeast-trending faults (e.g. Hart 2005; MacDonald et al. 2005). The north-trending faults can be traced for over 150 km, and commonly have apparent sinuous traces resulting from an intersection with north- and northwest-trending faults. A number of the northwest-trending faults control the roughly circular-shape of diabase sills as in the Kopka River (Sutcliffe 1986). The east- to northeast-trending faults include deformation zones exposed in surrounding greenstone belts, as well as greenstone belt and subprovince boundaries.

Some faults, and particularly the intersections of a number of faults, appear to have been the locus for magmatic events active at a number of geological periods. A number of 2697-2686 Ma late- to post-tectonic mafic to ultramafic intrusions (Heaman and Easton 2006) occur across the central Wabigoon Subprovince from Lac des Iles north to Awkward Lake in the Obonga Lake greenstone belt near major east- to northeast-trending structures. The ~1540 Ma English Bay Complex and ~1595 Ma Badwater Intrusion (Heaman and Easton 2006)

are located near the junction of the east-trending Obonga Lake mylonite zone / Humboldt Bay high-strain zone and a number of north-trending faults traceable south to Black Sturgeon Lake. These intrusions may represent magmatism related to formation of the Nipigon Embayment. In the same area, the 1159±33 Ma Inspiration diabase sill and 1112 Ma ultramafic Jackfish sill (Heaman and Easton 2006) may represent early stages of the MRS. To the south, the 1109 Ma Disraeli, 1113 Ma Seagull, and 1107 Ma Hele ultramafic intrusions are located near the intersection of north- and northwest-trending faults with the Quetico-Wabigoon subprovince boundary (QWSB), also represent early MRS magmatic events. The 1117 Ma mafic to ultramafic Kitto Intrusion (Heaman and Easton 2006) is located near the intersection of the QWSB, and the north-trending Nipigon River fault. Many of the diabase sills have morphologies controlled in part by these three faults directions, particularly the roughly circular sills exposed in the Kopka and Garden Lake areas.

Franklin et al. (1980) suggested that the Embayment represented a failed arm of the Midcontinent Rift System



(MRS). Alternatively, the Embayment could represent a structurally controlled basin formed by subsidence following an anorogenic thermal upwelling event represented by the ~1540 Ma English Bay Complex (Hollings et al. 2004). Studies completed by Rogala et al. (2005) indicate that deposition of the lower portions of the Sibley Group sedimentary rocks (>1339 Ma; Franklin 1978) pre-dated the formation of the ~1100 Ma MRS by ~200 Ma. The presence of sills rather than dykes and apparent lack of a dyke swarm common in many failed rift arms (Ernst et al. 2006) suggest that the Embayment was not extensional during the MRS event. A uniform lithogeochemistry for the diabase sills suggests a single magma source (e.g. Hollings et al. in press). Limited anisotropy of magnetic susceptibility data (Middleton et al. 2004) indicates westerly flow directions in the western Embayment suggesting a source, or sources, near the north-trending faults in the Black Sturgeon Lake area. Manson and Halls (1997) proposed that the geometry of the MRS could be the result of the interaction between the MRS and a series of faults within the bounding Archean rocks. The faults in Nipigon Embayment could be part of this series of faults and partially explain the lack of a classic failed arm. Some of these faults could have been deep structures providing pathways for the emplacement of a variety of magmas at different periods. The timing and magnitude of displacement along these faults is difficult to determine, but a high degree of fracturing and hematite alteration in diamond drill core from the 1112 Ma Seagull Intrusion (Heaman and Easton 2006) suggests multiple periods of fault activity. Late stage activity may be related to a 1090 $\pm$ 20 Ma uranium mineralization (Ruzicka and LeCheminant 1984) located along a north-trending structure east of Black Sturgeon Lake. This younger age is closer to many of the events in the late Keweenawan, including the 1091 $\pm$ 4.5 Ma Blake Gabbro (Heaman and Easton 2006), and suggests fault activity in the Nipigon Embayment for a period of up to 20 Ma.

REFERENCES

- Ernst, R.E., Buchan, K.L., Heaman, L.M., Hart, T.R., and Morgan, J. 2006. Multidisciplinary study of N to NNE trending dykes in the region west of the Nipigon Embayment: Lake Nipigon Region Geoscience Initiative; Ont. Geol. Sur., Misc. Release Data, MRD 194.
- Franklin, J.M. 1978. The Sibley Group, Ontario; in Rubidium-strontium isochron age studies, report 2; ed. R.K. Wanless and W.D. Loveridge; Geol. Sur. Canada, Paper 77-14: 31-34.
- Franklin, J.M., McIlwaine, W.H., Poulsen, K.H. and Wanless, R.K. 1980. Stratigraphy and depositional setting of the Sibley Group, Thunder Bay District, Ontario, Canada; Can. J. Earth Sci., 17: 633-651.
- Hart, T.R. 2005. Precambrian geology of the southern Black Sturgeon River and Seagull Lake area, Nipigon Embayment, northwestern Ontario; Ont. Geol. Sur., Open File Report 6165, 63p.
- Heaman, L.M. and Easton, R.M. 2006. Preliminary U/Pb Geochronology Results: Lake Nipigon Region Geoscience Initiative; Ont. Geol. Sur., Misc. Release—Data, MRD191
- Hollings, P., Hart, T.R., Richardson, A., and MacDonald, C.A. in press. Geochemistry of the Mesoproterozoic Intrusive Rocks of the Nipigon Embayment, Northwestern Ontario: Evaluating the earliest phases of rift development; Can. J. Earth Sci.
- Hollings, P., Fralick, P. and Kissin, S. 2004. Geochemistry and geodynamic implications of the Mesoproterozoic English Bay granite-rhyolite complex, northwestern Ontario; Can. J. Earth Sci., 41: 1329-1338.
- MacDonald, C.A., Tremblay, E. and Easton, R.M. 2005. Precambrian geology of the west-central map area, Nipigon Embayment, northwestern Ontario: L.N.R.G.I.; Ont. Geol. Sur., Open File Report 6164, 49p.
- Manson, M.L. and Halls, H.C. 1997. Proterozoic reactivation of the southern Superior Province and its role in the evolution of the Midcontinent Rift. Can. J. of Earth Sci., 34: 562-575.
- Middleton, R. S., G. J. Borradaile, D. Baker, and K. Lucas, 2004. Proterozoic diabase sills of northern Ontario: Magnetic properties and history; J. of Geop. Res., 109, B02103, doi:10.1029/2003JB002581.
- Rogala, B., Fralick, P.W. and Metsaranta, R. 2005. Stratigraphy and Sedimentology of the Mesoproterozoic Sibley Group and Related Igneous Intrusions, Northwestern Ontario: Lake Nipigon Region Geoscience Initiative; Ont. Geol. Sur., Open File Report 6174, 87p.
- Ruzicka, V. and LeCheminant, G.M., 1984. Uranium deposit research, 1983; in Current Research, Part A, Geol. Sur. Canada, Paper 84-1a: 39-51.
- Sutcliffe, R.H. 1986. Proterozoic rift related igneous rocks at Lake Nipigon, Ontario; unpublished PhD thesis, University of Western Ontario, London, Ontario, 325p.

Lacustrine Sedimentary Organic Matter Proxies of Recent Lake State Changes and Climatic Conditions in Christina and Morrison Lakes of Western Minnesota

Amanda Hogan, Travis Jacobs, and Kevin Theissen

Department of Geology, University of St. Thomas, 2115 Summit Ave., St. Paul, MN 55105

Organic matter in shallow lake sediments reveal past states of the lake, indicating dryer or wetter periods as well as periods which were dominated by algal or vascular plants. We have analyzed lake sediment cores dating approximately back to the year 1400 and have correlated stable isotopic and elemental data to support recent lake transitions.

In the summer of 2006, we collected sediment cores from Lake Christina and Morrison Lake, shallow lakes (< 4 m max depth) in western Minnesota's Prairie Pothole Region. We took samples from the cores at 1 cm intervals and prepared them to be sent to the Stanford University Stable Isotope laboratory where they were analyzed for stable isotopic ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) and elemental (C/N, TOC, TN) values. Finally, over the last two months, the data have been analyzed and correlated to a sedimentation-rate based time scale to determine changes in ecological status of the lakes as well as past changes of precipitation in the areas surrounding them. Here we report preliminary results for Lake Christina.

C/N ratios (8 to 10) and $\delta^{13}\text{C}$ values (-24 to -19 per mil) show a history where the lake has been dominated by lacustrine algae (Figure 1). The range of these values is small, and while they fluctuate, the levels never reach those of a lake dominated by vascular plants (1). These small changes indicate slight changes in organic matter production and sourcing. Based on our preliminary age estimates for Lake Christina, the values for $\delta^{15}\text{N}$ show a steady increase from the year 1680 to 1900 where they begin to decline sharply over the next 100 years (Figure 2). The low values in the years 1400-1700 might indicate a wetter climatic period where the lake level was higher and algal productivity in the lake was greater (1). Precipitation slightly decreased over the next 300 years causing upward shifts in the value of $\delta^{15}\text{N}$ as well as a decrease in %CaCO₃. This drier period was possibly windier, causing more sediment particles to be blown into the lake leading to more turbulent waters with large amounts of mixing (3). It is likely that land use changes had an impact on the overall carbon isotopic values of the sediments. Values of $\delta^{13}\text{C}$ show a sharp decline around 1900, which corresponds to a time when most of this area was farmland rather than grassland. This might signal a change to a more algal dominated lake at this time. However, around the year 1940, $\delta^{15}\text{N}$ values begin to decline again indicating a wetter period. In the years since 1938, more wet years are on record than in the years prior. The decline in $\delta^{15}\text{N}$ could be attributed to the wetter climatic conditions in the area over the last 60 years (1).

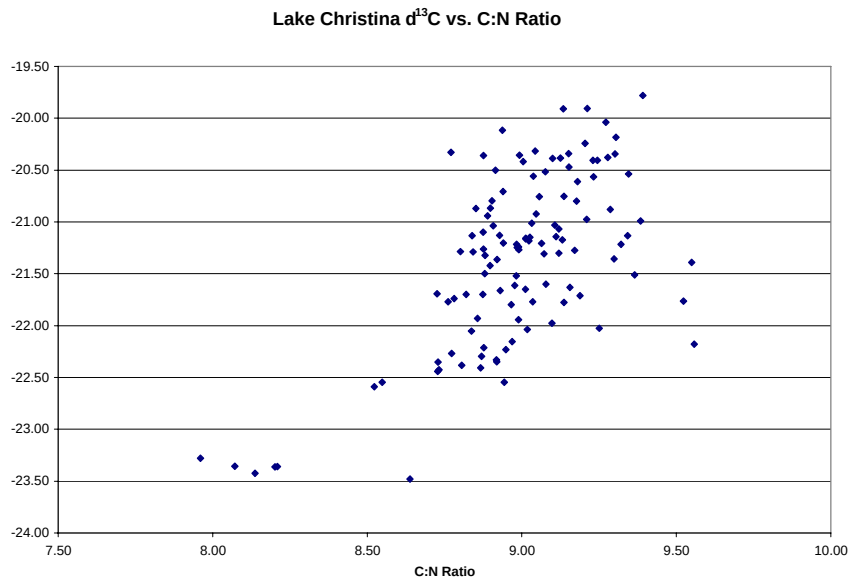


Figure 1.

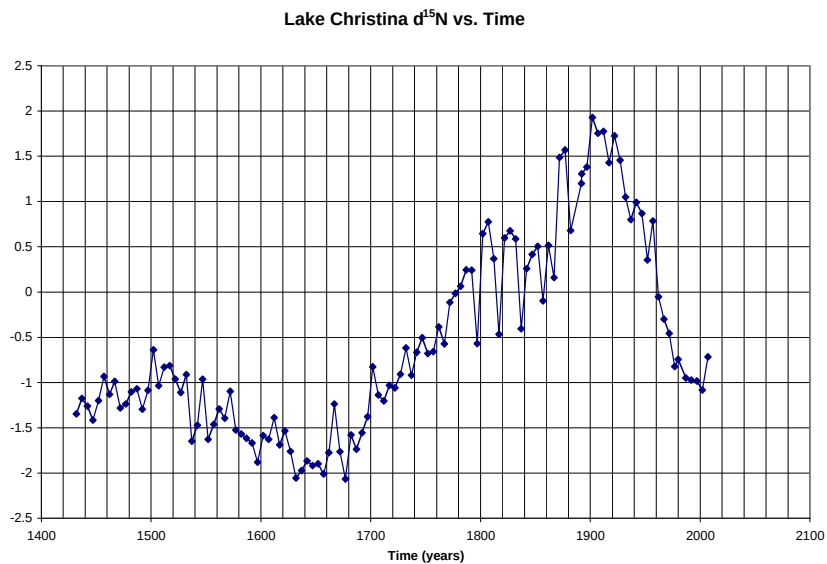


Figure 2.

References:

- (1) Meyers, P.A., and Lallier-Verges, E., 1999, Lacustrine sedimentary organic matter records of Late Quaternary Paleoclimates. *Journal of Paleolimnology*, 21, 345-372.
- (2) Pratt, L.M., Comer, J.B., and Brassell, S.C., 1992, *Geochemistry of Organic Matter in Sediments and Sedimentary Rocks*, 29-72.
- (3) Xu, H., Ai, L., Tan, L., An, Z., 2006, Stable isotopes in bulk carbonates and organic matter in recent sediments of Lake Qinghai and their climatic implications. *Chemical Geology*, 235, 262-275.

Geochemistry of Midcontinent Rift-related mafic dykes and sills near Thunder Bay: New insights into geographic distribution and the geochemical affinities of Nipigon and Logan sills and Pigeon River and other dykes

HOLLINGS, Pete, Department of Geology, Lakehead University, 955 Oliver Road, Thunder Bay, ON, P7B 5E1, Canada, **SMYK, Mark C.**, Ontario Geological Survey, Ministry of Northern Development and Mines, Suite B002, 435 James St. South, Thunder Bay, ON P7E 6S7 Canada, **HART, Thomas**, Precambrian Geoscience Section, Ontario Geological Survey, 933 Ramsey Lake Road, Sudbury, ON, P3E 6B5, Canada

Recent geochronological studies (Heaman et al., 2007) have shown that the diabase sills and mafic/ultramafic intrusions in the vicinity of Lake Nipigon are among the oldest expression of igneous activity associated with the Midcontinent Rift (~1106 to 1115 Ma). Diabase sills, extending from the vicinity of Thunder Bay to east of Lake Nipigon, represent the northern expression of the Midcontinent Rift (MCR), and have previously been collectively referred to as the Logan sills (Stockwell et al. 1972). However recent work suggests a geochemical difference between the sills to the north and south of Thunder Bay (Hart 2003; Hart et al. 2005). It has been proposed that the term Logan Igneous Suite, which would fall within the Midcontinent Rift Intrusive Supersuite (Miller et al. 2002), should be applied to all the diabase sills in the area north of Lake Superior, with subdivision into more informal categories (i.e. Nipigon sills for the sills north of Thunder Bay, and Logan sills for those to the south) (Hollings et al., 2007). In 2006 a sampling traverse was undertaken through Thunder Bay in order to help determine the boundary between these two suites. The large geochemical data set for the Nipigon sills obtained as part of the Lake Nipigon Region Geoscience Initiative (Hollings et al., 2007) and a number of recently analyzed, east-northeast- to northeast-trending dykes south of Thunder Bay provide a means of comparing the sills near Thunder Bay.

The sills and dykes sampled for this study are all characterized by LREE and enrichment and negative Nb anomalies typical of the majority of the local intrusive rocks associated with the MCR (Hollings et al., 2007). The majority of these sills fall are geochemically similar to the Nipigon sills. However, two ultramafic sills are geochemically similar to the Logan sill suite (i.e. with higher TiO_2 and Gd/Yb_n ; Fig. 1). This suggests that the boundary between the Nipigon and Logan sills lies southwest of Thunder Bay.

Data from other dykes south of Thunder Bay (L. Hulbert and R. Ernst, Geological Survey of Canada, pers. comm., 2006) show that the geochemistry of the Pigeon River dykes (Arrow River and Rita Bolduc occurrences) is similar to the range of data from other dykes of the Pigeon River swarm sampled on Lake Superior (Cloud Bay and Jarvis Point; Fig. 1). The Pigeon River dyke swarm geochemistry more closely resembles that of the sills of the Nipigon suite (Hollings et al., 2007) than that of the ultramafic intrusions or the Logan sills (Fig. 1). In contrast, the Mt. Mollie dyke appears to be transitional between Nipigon sills and Inspiration sills.

Geochemical trends in individual dykes suggest fractionation or assimilation/contamination but data is currently limited. A sample taken from a Pigeon River dyke near its chilled contact with Rove Formation on Jarvis Point (JP-3) shows elevated Th and LREE compared to the dyke interior (JP-1, -2, -4; Fig. 2). A granophyric phase of the Mt. Mollie dyke on the southern end of Victoria Island (VI-9) displays similar, but elevated, REE compared to the main gabbroic part of the dyke. The granophyre also shows a marked depletion in Al and also in Ti and V, perhaps due to the relative lack of oxides in this late-stage differentiate. Additional isotopic and

geochronological studies will be required in order to further investigate the relationships between these MCR-related intrusions.

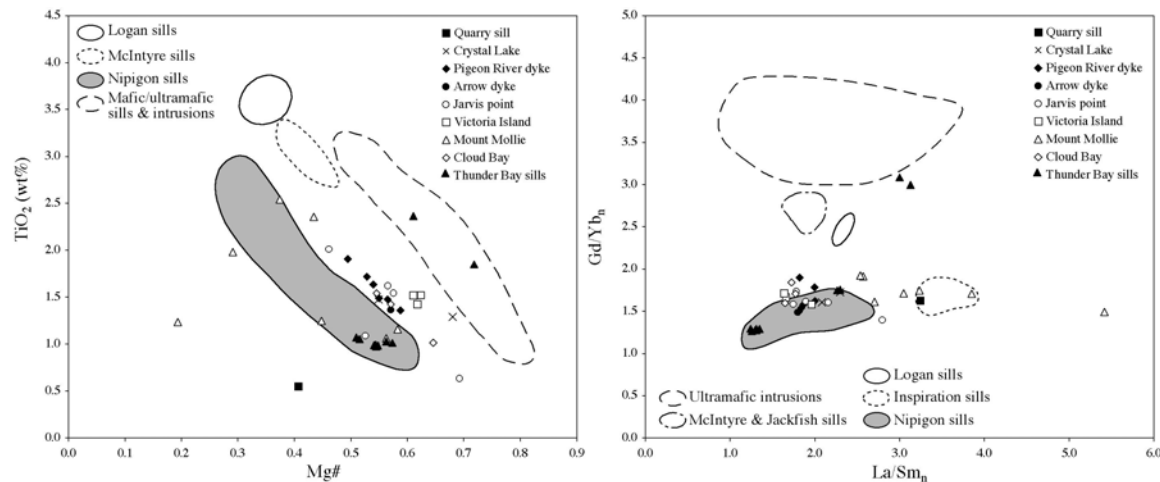


Figure 1: Major and trace element variation diagrams illustrating the geochemical affinities of the dykes and sills in around Thunder Bay. Data from Logan sills are from Hart (2002), Nipigon data are from Hollings et al. (2007). Data for dykes south of Thunder Bay are from L. Hulbert and R. Ernst (Geological Survey of Canada, pers. comm., 2006) from samples collected by M. Smyk and J. Scott (Ontario Geological Survey).

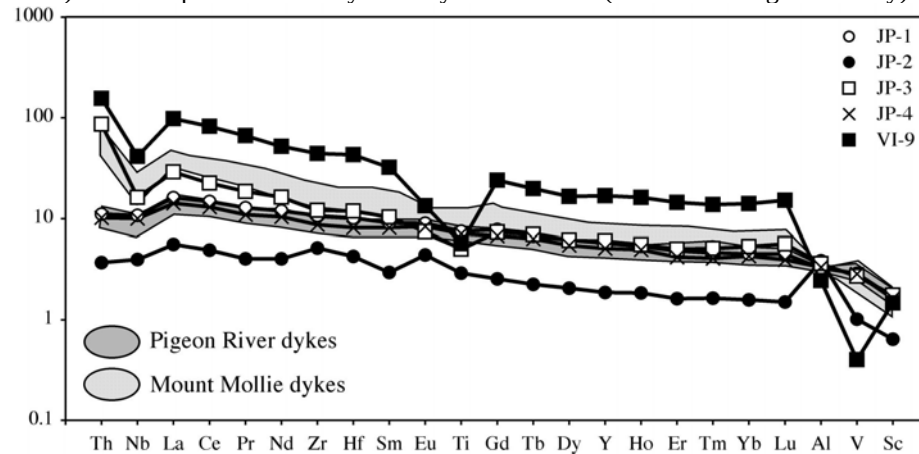


Figure 2: Primitive mantle normalised diagram comparing geochemistry of dykes south of Thunder Bay.

References

- Heaman, L.M., Easton, R.M., and Hart, T.R., 2006. Further Refinement to the Timing of Mesoproterozoic Magmatism, Lake Nipigon Region, Ontario. *Canadian Journal of Earth Sciences*, in press.
- Hart, T.R. 2003. Keweenawan mafic and ultramafic intrusive rocks of the Lake Nipigon and Crystal Lake areas, northwestern Ontario; ILSG, Proceedings Volume 49, Part 1-Programs and Abstracts: 21-22.
- Hart, T.R. 2005. South Black Sturgeon River–Seagull Lake Area, Nipigon Embayment, Northwest Ontario: Lithochemical, Assay and Compilation Data. Ontario Geological Survey, Miscellaneous Release of Data 147.
- Hollings, P., Hart, T., Richardson, A. and MacDonald, C.A., 2007. Geochemistry of the Mesoproterozoic Intrusive Rocks of the Nipigon Embayment, Northwestern Ontario: Evaluating the Earliest Phases of Rift Development. *Canadian Journal of Earth Sciences*, in press.
- Miller, J.D., Jr., Green, J.C., Severson, M.J., Chandler, V.W., Hauck, S.A., Peterson, D.M., and Wahl, T.E. 2002. Geology and mineral potential of the Duluth Complex and related rocks of northeastern Minnesota: Minnesota Geological Survey Report of Investigations 58.
- Stockwell, C.H., McGlynn, J.C., Emslie, R.F., Sanford, B.V., Norris, A.W., Donaldson, J.A., Fahrig, W.F., and Currie, K.L. 1972. Geology of the Canadian Shield. In *Geology and economic minerals of Canada*. Edited by R. Douglas. Geological Survey of Canada Economic Geology Report 1: 838.

RECENT DEVELOPMENTS UNDERSTANDING THE VOLCANIC, MAGMATIC, TECTONIC AND METALLOGENIC EVOLUTION OF THE ELY GREENSTONE FORMATION, VERMILION DISTRICT, NE MINNESOTA

HUDAK, G. J., Department of Geology, University of Wisconsin Oshkosh, Oshkosh, WI 54901, hudak@uwosh.edu

HOFFMAN, A. T., Department of Geology, University of Minnesota – Duluth, Duluth, MN 55812

PETERSON, D.M., HEINE, J., Natural Resources Research Institute, University of Minnesota – Duluth, Duluth, MN 55811

The Ely Greenstone Formation comprises a steeply north- to southwest-dipping sequence of Neoarchean supracrustal and associated intrusive rocks associated with the Tower-Soudan anticline in the Vermilion District of northeastern Minnesota. Three distinctive units comprise this formation. The Lower Member of the Ely Greenstone (LMEG) is composed of calc-alkalic and tholeiitic basalt and basalt- andesite lava flows and tuffs with subordinate felsic lava flows, tuffs, epiclastic rocks and iron formations (Schulz, 1980; Southwick et al., 1998; Hudak et al., 2002, Hoffman, in press). The LMEG has been subdivided into the older Fivemile Lake Sequence (FLS) and the younger Central Basalt Sequence (CBS; Peterson and Patelke, 2003). The Soudan Iron Formation Member (SMEG) comprises Algoma-type interlayered cherty iron formation, basalt lava flows, epiclastic rocks and felsic tuffs (Peterson and Patelke, 2003; Hoffman, in press). The Upper Member of the Ely Greenstone Formation (UMEG) is composed of a monotonous sequence of poorly vesiculated tholeiitic basalt lava flows and localized Algoma-type iron formation lenses (Schulz, 1980; Southwick et al., 1998). The UMEG is commonly interstratified with the Lake Vermilion Formation (LVF; Schulz, 1980; Southwick et al., 1998), which is composed of greywacke, slate, conglomerate, and dacite tuff, as well as subaerial to submarine dacite to trachyandesite lava flows, tuffs, and associated intrusions (the informally named Gafvert Lake Sequence (GLS)); locally, however, LVF unconformably overlies LMEG and SMEG strata (Southwick et al., 1998; Peterson and Patelke, 2003). Schulz (1980) interpreted volcanological and sedimentary textures to indicate a change from a subaerial / shallow subaqueous setting to a deeper subaqueous environment during the temporal genesis of the Ely Greenstone Formation. Southwick et al. indicate a sharp transition from arc-associated volcanism (LMEG) to MORB-like volcanism (UMEG) occurs abruptly at the top of the SMEG.

Recent volcanological reconstructions between the Soudan Mine and Armstrong Lake provide further evidence for the interpretations of Schulz (1980). The initial deepening of the submarine volcanic setting occurred during the development of the LMEG (Peterson et al., 2005; Hoffman, in press). Abundant primary mafic and felsic volcanoclastic strata, highly vesicular basalt to basalt-andesite pillow lavas and sheet flows, multiple selvege pillows, and epithermal-like zinc stringer mineralization that characterize the FLS indicate a depositional setting in a shallow subaqueous environment (Hudak et al., 2002; Hoffman, in press). The overlying CBS comprises exceptionally well-preserved, single-selvege pillow lavas and associated sheet flows with sparse (generally <5%) vesicularity which are interstratified with subordinate banded iron formation and mafic tuff (resedimented basalt hyaloclastite) interpreted to have formed in a deep subaqueous setting (Peterson and Patelke, 2003; Peterson et al., 2005). The SMEG contains

finely laminated chemical sediments and resedimented tuffs, as well as sparsely vesicular mafic lava flows suggestive of deposition within a deep subaqueous setting (Peterson and Patelke, 2003; Hoffman, in press). This deeper water setting appears to have persisted through the development of the UMEG, and at least locally during the development of the LVF.

New major- and trace element data indicate the lithogeochemistry of volcanic rocks in the LMEG is more complicated than previously recognized. Arc-related basalts and basaltic andesites and FI- and FII-type rhyodacites and rhyolites characterize the FLS. In the CBS, arc-associated basalts and basaltic andesites transition up-section into E-MORB, OIB and back-arc basin-like basalts which are associated with FIII-type felsic volcanic rocks (Hudak et al., in prep. Hoffman, in press). The UMEG is characterized by MORB compositions that may also be the product of back-arc spreading (Southwick et al., 1998). A model encompassing initial arc development followed by back-arc development and rifting during the CBS, with subsequent development of the SMEG, appears to be most consistent with the observed volcanological and lithogeochemical characteristics in this part of the Vermilion District. Iron formations within the SMEG occur immediately up-section from the arc – back-arc transition, a stratigraphic position shown in many studies to have high prospectivity for hosting volcanogenic massive sulfide orebodies.

References

- Hoffman, A. T., in press, Lithostratigraphy, Hydrothermal Alteration, and Lithogeochemistry of Neoproterozoic Rocks in the Lower and Soudan Members of the Ely Greenstone Formation, Vermilion District, NE Minnesota: Implications for Volcanogenic Massive Sulfide Deposits: Unpublished M. S. thesis, University of Minnesota – Duluth.
- Hudak, G. J., Heine, J., Newkirk, T., Odette, J., and Hauck, S., 2002, Comparative geology, stratigraphy, and lithogeochemistry of the Five Mile Lake, Quartz Hill, and Skeleton Lake VMS occurrences, Vermilion District, NE Minnesota: A report to the Minerals Coordinating Committee, DNR, Minerals Division, State of Minnesota: Natural Resources Research Institute Technical Report NRRI/TR-2002/03, 390 pages.
- Hudak, G. J., Heine, J., Newkirk, T. T., Hocker, S. M., and Hauck, S., in prep., Comparative Geology, Stratigraphy, and Lithogeochemistry of the Needleboy Lake – Six Mile Lake Area, Vermilion District, NE Minnesota: Natural Resources Research Institute Geological Report of Investigation.
- Peterson, D. M., Jirsa, M. A., and Hudak, G. J., 2005, Architecture of an Archean greenstone belt: stratigraphy, structure, and mineralization; in Robinson, L, ed., 2005, Field trip guidebook for selected geology in Minnesota and Wisconsin: Minnesota Geological Survey Guidebook 21, p. 154-180.
- Peterson, D. M., and Patelke, R. L., 2003, National Underground Science and Engineering Laboratory (NUSEL). Geological site investigation for the Soudan Mine, NE Minnesota: Natural Resources Research Institute Technical Report NRRI/TR-2003, 88p.
- Schulz, K. J., 1980, The magmatic evolution of the Vermilion Greenstone Belt, NE Minnesota: Precambrian Research, v. 11, p. 215-245.
- Southwick, D. L., Boerboom, T. J., and Jirsa, M. A., 1998, Geological setting and descriptive geochemistry of Archean supracrustal rocks and hypabyssal rocks, Soudan-Bigfork area, northern Minnesota: implications for metallic mineral exploration: Minnesota Geological Survey Report of Investigations 51, 69 p.

EVALUATION OF MINERAL EXPLORATION DRILL CUTTINGS IN THE RICE RIVER AREA, EAST CENTRAL MINNESOTA

Hudak, J. N. and Frey, B. A., Minnesota Department of Natural Resources, Lands and Minerals Division, 1525 3rd Ave. East, Hibbing, MN 55746

The Rice River area is located at the east end of the Cuyuna South Range, near the town of Aitkin. From 1949 to 1952, M.A. Hanna drilled 334 reverse circulation drill holes along approximately 12 km strike length of an iron formation related magnetic anomaly, to search for naturally enriched iron ore.

Current DNR work in the Rice River area involves relogging of core and cuttings, the analysis of 325 samples for indications of base and precious metals, and the recovery of more accurate drill hole locations. The mid-Proterozoic basement rock does not crop out in the area, and drill cuttings and core are currently the only available bedrock samples.

Recent replotting of geochemical lake sediment survey data revealed clustered metal anomalies in the Cuyuna South Range area. The Rice River area drill holes have been predominantly analyzed for iron and manganese and not fully evaluated for mineral potential. The main goal of the current evaluation is to see if there is any evidence of those anomalies in the Rice River area. Plausible ore deposit models for the area include SEDEX and iron-oxide-copper-gold.

The magnetic iron anomaly is linear except for the large s-shaped fold, which is spatially associated with stratified sulfide occurrences and large quartz veins. Pyrite is often remobilized within shear zones of the graphitic argillite associated with this area. Veinlets with small amounts of bornite also occur scattered within the Rice River area.

Currently, 60 of the 325 samples collected have been analyzed yielding anomalous levels of copper (2200 ppm) and antimony (6.75 ppm). A report of the work and findings are scheduled for release on June 30, 2007.

PALEOENVIRONMENTAL INTERPRETATION OF A LOWER PALEOZOIC STROMATOLITE REEF, NORTHEASTERN WISCONSIN

JASINEVICIUS, Renata R., GORDON, Elizabeth A., St. Norbert College Geology Department, De Pere, WI 54115, elizabeth.gordon@snc.edu

INTRODUCTION

Strata recently exposed in Schaal Quarry near Gillett, Wisconsin, provide an exceptional opportunity to examine the facies architecture of a lower Paleozoic stromatolite reef. The three-dimensional nature of the reef, and its stratigraphy, are the focus of this study. The dolomitic rocks yield conodonts of early Ordovician age (Miller, 2006) and these strata are therefore assigned to the Oneota Formation. The Oneota dolomite overlies an unconformity, considered by many to be of regional extent. At this quarry, sandstones of uncertain Cambrian(?) age lie beneath the unconformity. Bedrock exposures in northeastern Wisconsin are extremely rare, due to widespread glacial deposits. This site therefore provides an important new opportunity to study Cambro-Ordovician boundary strata along the eastern margin of the Wisconsin Arch.

RESULTS

The Oneota Formation contains diverse stromatolite morphologies. At this locality, four stromatolite types occur in regular stratigraphic order: laterally linked hemispheroids, cabbage-shapes, isolated small domes, and larger elliptical compound domes. In cross section, the larger stromatolites appear to form a mound- or ridge-shaped structure. The following paragraphs offer a summary and interpretation of the major sedimentary features associated with these stromatolites.

The base of the Oneota in Schaal Quarry is dominated by an intraclastic conglomerate of variable thickness which overlies an unconformity. Desiccation cracks on the base of the conglomerate record subaerial exposure of the underlying units. Clast types include red shale, dolostone, sandy to silty dolomite pebbles and cobble to boulder-sized silcrete. The matrix is a dolomitic sandstone, and the unit grades upwards to sandy and silty dolomites. The silty dolomites contain discontinuous layers with microbial-like structures and laminated mats. These layers are interbedded with cross- and planar laminated, flaser- to wavy-bedded grainstones, and rare desiccation cracks. Grain types are primarily coated quartz sand and minor dolomite intraclasts.

Upsection, discontinuous horizons of laterally linked hemispheroids (LLHS; Logan, 1964) mark the first visibly distinctive stromatolites, which predominate several horizons. In places they are vertically stacked, forming beds up to 20 cm thick. Individual hemispheres are round to elliptical with variable dimensions. LLHS are buried by ripple cross- and planar-laminated grainstones, grading to wackestones. Clay and glauconite locally contribute a greenish color to these rocks.

Farther upsection, a fine-grained silty dolomite contains chert-lined vugs interpreted to be molds of anhydrite. These structures suggest hypersaline conditions. The overlying grainstones contain abundant crescent-shaped fossils of unknown origin, similar to “chitons” reported by Raasch (1952). Gastropod molds are present but rare. Conodonts include “*Teridontus* sp., *Acanthodus uncinatus*, *Aloxoconus* sp., *Cordylodus lindstromi*, and are assigned to the interval from the uppermost *Cordylodus lindstromi* Zone, the *Iapetognathus* Zone, and into the lower part of the *Cordylodus angulatus* Zone” (Miller, 2006), indicating an early (but not earliest) Ordovician age.

Continuing upsection, there is a general upwards increase in bed thickness, accompanied by a decrease in coated quartz sand grains, and an increase in peloids and sparry cored ooids. Local grapestone intraclasts are also present. Within this interval cabbage-shaped stromatolites (CS) form discontinuous patches along one horizon. They are widely associated with chert. One wall reveals a curious relationship: adjacent stromatolite heads successively increase in size, suggesting a mound-like geometry of this cluster. CS are overlain by cross-bedded, oolitic peloidal grainstones, indicating burial by subaqueous dunes.

Near the top of the quarry, thicker cross-bedded grainstones enclose nearly circular, isolated stromatolite domes. The domes appear to be concentrated in a mound or ridge. Higher still, the top surface of the quarry exposes large elliptical domes. A visible change in stromatolite synoptic relief indicates increasing water depth with time (Gerdes and Krumbein, 1994). The elliptical domes are clustered locally with subparallel long axes. The axes are aligned with paleocurrent azimuths measured from adjacent crossbeds and parting lineations. This association suggests stromatolite morphology was controlled in part by subaqueous currents. The predominant paleocurrent direction is approximately perpendicular to the inferred paleoshoreline. This implies subaqueous currents were tidal in origin and that stromatolite domes developed in subtidal channels.

Collectively, these sedimentary features record evolution of a reef during marine transgressions. Interpreted paleoenvironments reflect tidal flat to subtidal environments under extreme conditions.

REFERENCES

- Gerdes, G. and Krumbein, W., 1994, Peritidal stromatolites; in Phanerozoic Stromatolites II, ed. Bertrand-Sarfati, J. and Monty, C.: 114-17.
- Logan, B.W., Rezak, R., and Ginsburg, R.N.; 1964, Classification & environmental significance of stromatolites; *Journal of Geology* 72: 68-83.
- Miller, James F., 2006, Southwest Missouri State University; personal communication.
- Raasch, G. O., 1952, Oneota Formation, Stoddard Quadrangle, Wisconsin; *Illinois Academy of Science Transactions*, V. 15 p. 85-95.

PROPOSED NEW BEDROCK GEOLOGIC MAP OF MINNESOTA

JIRSA, Mark A. (jirsa001@umn.edu), **BOERBOOM, T.J.**, **CHANDLER, V.W.**, **LIVELY, R.S.**, **MILLER, J.D., Jr.**, **MOSSLER, J.H.**, **RUNKEL, A.C.**, **SETTERHOLM, D.R.**, and **WAHL, T.E.**,
Minnesota Geological Survey (www.geo.umn.edu/mgs)

Having conducted detailed geologic mapping in many areas of the state, and reprocessed state-wide geophysical data, the Minnesota Geological Survey (MGS) is well positioned to produce a new interpretation of bedrock geology. We are preparing to construct a state-wide bedrock geologic map—one that will be comprehensive, up to date, digital, and multi-layered. In the process, we also intend to upgrade digital bedrock topography and depth to bedrock maps and make them consistent with the new geologic framework (for preliminary imagery, see MGS website, Open-File 06-02). Together, these maps will provide the context necessary for various minerals and water-related applications in progress and under consideration. They will also establish the understanding of bedrock geology and crustal structure needed to address a number of impending, high-profile regional and national science initiatives, including EARTHSCOPE (www.earthscope.org). At this writing, the work of compiling hundreds of archival maps is underway.

The existing state-wide bedrock map (MGS map S-20), completed in 2000, was reasonably detailed and accurate for its time; however, more than 50 new bedrock geologic maps have been created in the intervening 7 years since its production. Furthermore, the earlier map was compiled at a generalized 1:1,000,000 scale. As such, it portrays contacts that locally are inconsistent with high-resolution geophysical imagery, and it is 2-dimensional—in the sense that it depicts only the uppermost bedrock units. By contrast, the new map will be compiled at more detailed scales overall (compilation scale 1:100,000; publication scales 1:500,000 and 1:1,000,000), and geologic contacts will be reconciled with reprocessed geophysical data. It will also contain thematic layers, including trajectories of diabasic dikes, generalized metamorphic grades, and themes depicting Mesozoic, Paleozoic, Mesoproterozoic, Paleoproterozoic, and Archean geology. The Quaternary layer will be represented at this stage by revised depth to bedrock imagery. This layering will give users the opportunity to consider the third dimension by permitting removal of geologically younger layers to reveal older ones, to the extent that this can be done with some certainty. Perhaps more important than the printed maps and printable pdfs of archived maps, is the aim of producing a digital platform that will allow web-based user navigation from compilations to the most recent, accurate, and detailed mapping. Associated digital files will be searchable on attributes of lithology, age, and other themes. Mapping will be integrated with broader digital efforts using compilation formats consistent with those developed nationally (e.g., USGS) and globally (e.g., OneGeology.org).

The project requires compilation of the best available maps—both digital and analog—together with new work designed to fill voids, augment existing map imagery, and evaluate the nature of buried geologic terranes. In addition, a small program of high-precision geochronology will acquire ages for a hand-full of critical samples. The results will be a seamless state-wide geologic interpretation, a web-based project that links this image to original mapping, and a digital cache of associated files. The poster presented here for general discussion depicts an initial effort to bring together the various digital map coverages.

TRACE ELEMENT ANALYSES: AVOIDING DATA DISTORTION

McSWIGGEN, Peter L., McSwiggen and Associates, P.A., 2855 Anthony Lane South, Suite B1, St. Anthony, MN (PMcS@McSwiggen.com)

Electron microprobes have been used for trace element analyses for decades. This is because they can analyze minerals *in situ*, the size of the analytical area is very small, and the cost per analysis is very low. None-the-less, there is an ongoing push to measure trace elements in ever-lower concentrations. Over the years, improvements in both the electronics and the spectrometers of microprobes have made this possible. However, how the data is collected and how it is subsequently processed can mean the difference between meaningless numbers and real insights into the geologic question being investigated.

Typically, people collecting trace element data want to know the minimum detection limit (MDL) of the method being used. Secondly, they want to know what should they do with the data that fall below the MDL. Should those values be set to zero? Should those values be set to the MDL? Should all of the data that fall below the MDL be discarded? If the set of data is going to be used to determine an average concentration for a rock body or a mineral type, all three options are wrong. In most cases involving trace element analyses, the calculated minimum detection limit for a single analysis should be ignored.

Often, analysts will attempt to adjust their analytical conditions to get the lowest calculated minimum detection limit. However this can result in erroneous data. The MDL can be lowered using a number of strategies – for example, by counting for a longer period of time or by using a higher beam current to produce a higher count rate, both will lower the MDL. However both of these strategies can work against the overall objective. A higher beam current can damage the mineral being analyzed and therefore completely throw-off the results. Similarly, extremely long counting times can mask electronic instability in the instrument, thereby producing erroneous results. A far better strategy would be to collect a series of analyses, using more reasonable counting times and beam currents, and determine an average value from that set of data. This would minimize the effect of beam damage and would both monitor and correct for any electronic drift in the instrument; thus yielding a true detection limit that is much lower than that from the individual analyses.

If one is using a set of analyses to determine an average composition, the calculated MDL becomes a meaningless value. Figure 1 shows a set of analyses run on a glass standard with a reported Ni content of 0.046 wt% using only a two second counting time per analysis. The average for this set of data was 0.053 wt%, a difference of only 0.007 wt% from the reported value. However, the calculated MDL for a single analysis was 0.25 wt%. Therefore, if all of the data that fell below the MDL was discarded, most of the data would have been thrown out, and those remaining values would have produced a completely erroneous composition of 0.275 wt% (Fig. 1).

Not only should the data that fall below the MDL not be discarded, results that are below zero should also NOT be discarded. These negative values are just as important in determining the true average, as are the positive values. Each analysis has a certain error component associated with it. That error may be positive or negative. For trace element analyses, a negative error added to the real value, may result in a measured value less than zero. To get the true value, you need to average all of the data. By discarding only values on the negative side of the histogram, the data set becomes biased to a higher average value (Fig. 2). This is a big problem, because most commercial analytical instruments handle their data in this manner.

Figure 1. Histogram showing multiple analyses of the NIST standard SRM-610. Two second counting times were used, resulting in a calculated MDL of 0.25 wt%, for a single analysis. The calculated average composition is 0.053 wt%, which agrees closely with the reported composition of 0.046 wt%.

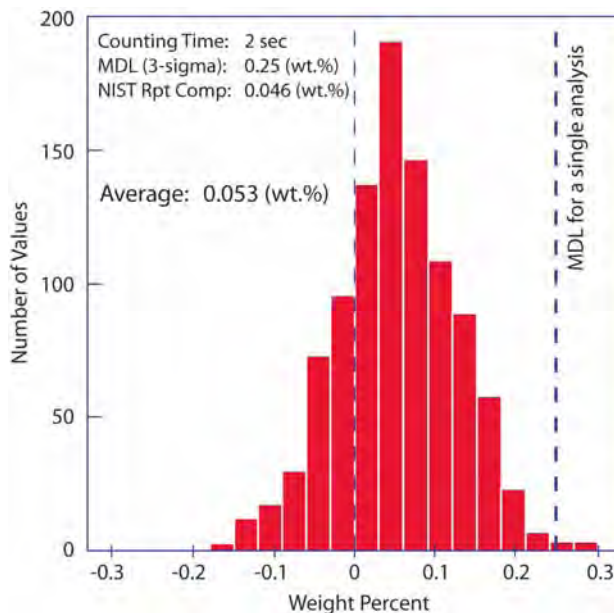
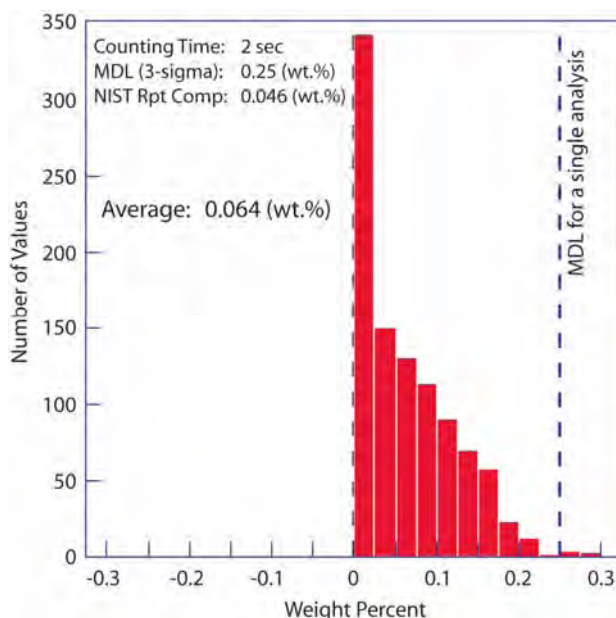


Figure 2. Shown is the same data set used in Figure 1, however all of the analyses that reported a negative concentration were set to zero. This is the typical procedure used by commercial analytical equipment. However, this method produces a distortion of the results. The average has been shifted from 0.053 wt% to 0.064 wt%, and this will distort any other statistics generated from the data.



AN OCCURRENCE OF AGRELLITE IN THE WAUSAU ALKALINE IGNEOUS COMPLEX, MARATHON COUNTY, WISCONSIN

MEDARIS, L. G. Jr and **FOURNELLE, J. H.**, Dept. of Geology and Geophysics, Univ. of Wisconsin-Madison, Madison, WI 53706, medaris@geology.wisc.edu, johnf@geology.wisc.edu; **GUGGENHEIM, S.**, Dept. of Earth and Environmental Sciences, Univ. of Illinois at Chicago, Chicago, IL 60607, xtal@uic.edu

Agrellite is a rare, triclinic sodium-calcium fluorosilicate that occurs in alkaline (agpaitic) igneous complexes. Agrellite was first described from metamorphosed nepheline syenite in the Kipawa Complex, Quebec (Gittins et al., 1976), and its crystal structure was determined by Ghose and Wan (1979). To date, the only other reported occurrence is in the Khibina alkaline complex, Russia (Khomyakov, 1995). During construction of Interstate Highway 39 in north-central Wisconsin, an agrellite-bearing dike was exposed in a roadcut, which was subsequently covered. The agrellite-bearing dike is located in the northern margin of Center 1 in the Wausau Complex (Fig. 1), where it cuts syenite and monzodiorite. White to light gray, tabular crystals of agrellite, ranging up to 15 mm in length, are concentrated along the center of the dike, where they are associated with quartz, perthitic alkali feldspar, plagioclase, aegirine-augite, miserite, apatite, fluorite, and locally eudialyte (Fig. 2).

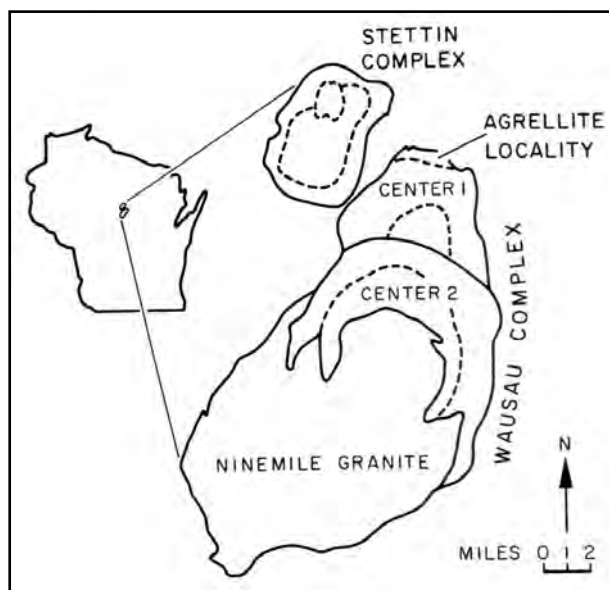


Fig. 1 Simplified map of igneous complexes near Wausau and the agrellite locality (modified from LaBerge and Myers, 1983)

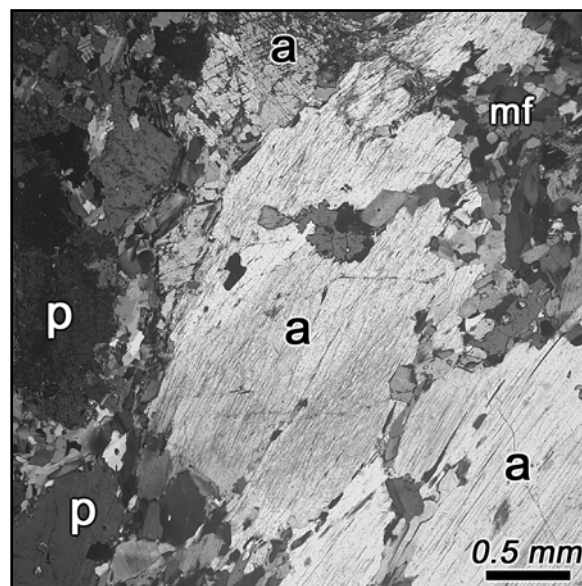


Fig. 2 Photomicrograph under crossed polarizers; a, agrellite; p, pyroxene (aegirine-augite); mf, fine-grained miserite and feldspar

Agrellite is biaxial, with $2V_X = 55^\circ$, $n_X = 1.570(1)$, $n_Y = 1.581(1)$, $n_Z = 1.584(1)$, and $n_Z - n_X = 0.014$. Cleavage is excellent on $\{110\}$ and $\{1\bar{1}0\}$ and poor on $\{010\}$. The optic directions, Z and Y, are nearly parallel to the crystallographic axes, c and b, respectively, and the angle between the $\{110\}$ and $\{1\bar{1}0\}$ cleavages is 40° (Fig. 3).

Agrellite is triclinic, space group $P\bar{1}$, and has the following cell parameters: $a = 7.757(7)$ Å, $b = 18.90(3)$ Å, $c = 6.975(6)$ Å, $\alpha = 90.00(8)^\circ$, $\beta = 116.81(6)^\circ$, $\gamma = 94.4(1)^\circ$, $V = 909.5(1)$ Å³, and $Z = 4$.

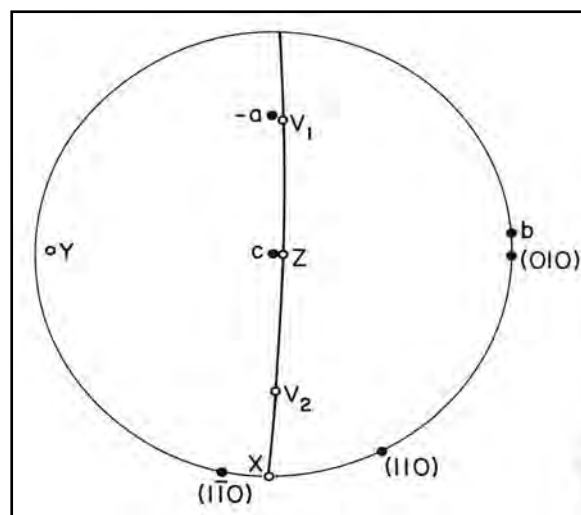


Fig. 3 Stereographic projection of optical and crystallographic elements of agrellite

The theoretical end-member formula for agrellite is $\text{NaCa}_2\text{Si}_4\text{O}_{10}\text{F}$. Naturally occurring agrellite lies close to this composition, with the main deviations arising from the substitution of minor amounts of REE, Mn, and Sr for Ca (Table 1). Agrellite from the Wausau Complex is similar compositionally to that from the Kipawa Complex, except for having lower contents of REE and higher contents of MnO and SrO.

The phase equilibrium conditions for agrellite are presently unknown, but the crystallization of agrellite, rather than wollastonite, in alkaline igneous complexes is likely promoted by high alkaline contents, *i.e.*, $(\text{Na} + \text{K}) / \text{Al} > 1$, and high fluorine activity. The coexistence of agrellite with quartz in the Wausau Complex and with nepheline in the Kipawa Complex demonstrates that agrellite is stable in both silica-saturated and silica-undersaturated environments.

Table 1
Composition of Agrellite

	<u>1</u>	<u>2</u>	<u>3</u>
SiO ₂	59.7	58.8	60.9
ZrO ₂	na	0.18	
REE*	1.18	3.84	
MnO	0.79	0.25	
CaO	24.8	25.7	28.4
SrO	2.91	0.16	
BaO	0.15	0.06	
Na ₂ O	7.39	7.90	7.86
K ₂ O	0.07	0.22	
F	<u>4.55</u>	<u>4.45</u>	<u>4.82</u>
	101.5	101.6	102.03
-O=F	<u>1.9</u>	<u>1.9</u>	<u>2.03</u>
Total	99.6	99.7	100.00

na, not analyzed

1 Wausau Complex, EMP analysis, UW-Madison

2 Kipawa Complex, Gittins *et al.*, 1976

3 Theoretical end-member composition

* Total of REE oxides

References

- Ghose, S.G. and Wan, C (1979) *Amer. Mineral.* 64, 563-572.
Gittins, J. *et al.* (1976) *Canadian Mineral.* 14, 120-126.
Khomyakov, A.P. (1995) *Mineralogy of Hyperagpaitic Alkaline Rocks*: Oxford, 223 pp.
LaBerge, G.L. and Myers, P.E. (1983) *Wisc. Geol. Nat. Hist. Survey, Inf. Circ.* 45, 88 pp.

Metamorphosed, halite-dominated evaporites of the Lower Sibley Group

Metsaranta, R.T.¹, Fralick, P.W.² and Bowdidge, C.¹

¹*RPT Uranium Corp. 537 Hilldale Rd., Thunder Bay, Ontario, P7B5N1, Canada*

²*Department of Geology, Lakehead University, 955 Oliver Rd., Thunder Bay, Ontario, P7B 5E1, Canada.*

This paper describes newly discovered sedimentary halite deposits of Mesoproterozoic age from the Lower Sibley Group. The deposits were intersected in two closely spaced diamond drill holes, BSW-06-1a and BSW-06-4, drilled by RPT Uranium Corporation during the summer of 2006. The drill holes are located in the central portion of the preserved Sibley Basin, immediately west of the Black Sturgeon Fault, a major structure controlling the outcrop pattern of the Sibley Group. In the area, the Sibley Group is intruded by two thick Nipigon diabase sills that have produced significant contact metamorphic effects. The evaporites occur in an approximately 50m thick section of Sibley Group rocks preserved between the lower diabase sill and Archean basement rocks.

The basic stratigraphy beneath the lower diabase sill consists of from, bottom to top: a lower, well-cemented, sandstone dominated unit 14m thick, an interbedded halite-mudstone unit 5m thick, an upper almost totally unconsolidated, partially halite cemented sandstone unit approximately 10-15m thick and an upper unit of interbedded calcareous mudstones and siltstones 20m thick. Lithostratigraphically, the lower sandstone unit can be correlated with the Pass Lake Formation while calcareous mudstones and siltstones in the upper portion of the section likely correlate with the lower Rossport Formation.

Halite occurs in several forms within the section. First, it occurs as relatively large angular nodules within sandstones in the top few metres of the lower sandstone dominated interval (Fig. 1a). Second, it occurs as massive relatively pure beds 1-25cm in thickness within the interbedded halite-mudstone interval (Fig. 1b and c). Third, it occurs in irregular mixtures with clastic material, where clastic material is found as inclusions within halite and/or halite occurs in nodular form within the clastic sediment (Fig. 1d). Finally, it occurs as cement and isolated nodular material in clastic sediments of the upper unit (Fig. 1e and f).

Mineralogically, the composition of the evaporites is dominated by halite. Based on x-ray diffraction and reflectance spectroscopy gypsum is entirely absent from salt samples analyzed but there may be trace sylvite in some cases. Interbedded clastic materials commonly consist of mineral assemblages containing tremolite-actinolite, calcite, phlogopite, and serpentine group minerals consistent with contact metamorphism of carbonate-rich lithologies. Some samples contain clay minerals vermiculite, saponite and allophane which likely resulted from post metamorphic alteration of the contact metamorphic mineral assemblage.

Sedimentologic and geochemical analysis of these unique deposits is currently underway.

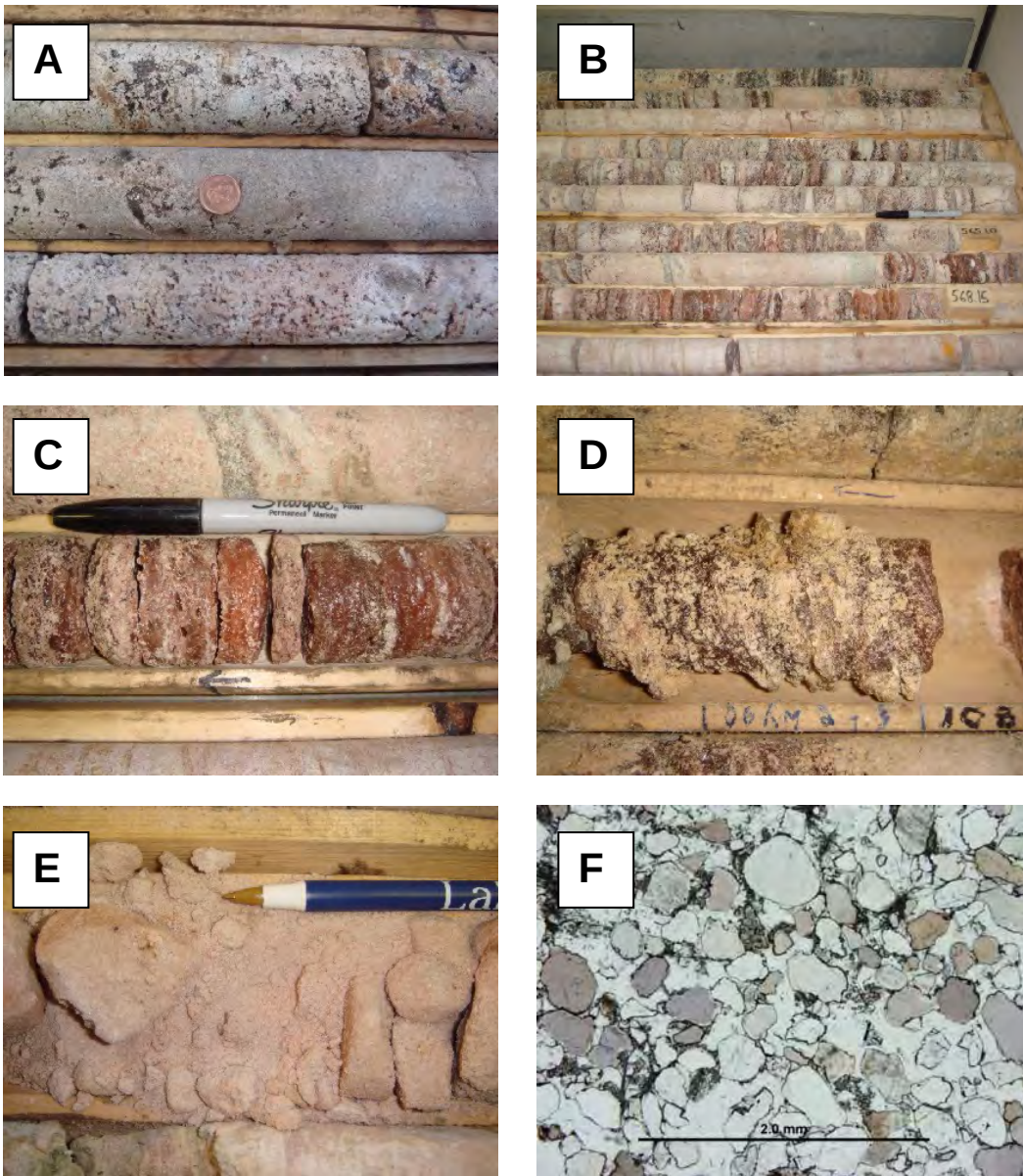


Figure 1. Various halite facies in the BSW-06-01a and BSW-06-4. A) Angular halite nodules within quartz-rich sandstone. B) Interbedded halite and mudstone, showing cyclically interbedded nature of halite beds (dark) with mudstone (light). C) Detail of a relatively pure, massive halite bed. D) Irregularly interbedded clastic material and halite. E) Very poorly consolidated halite-cemented sandstone. F) Photomicrograph of a halite cemented quartz sandstone.

A CHEMICAL AND SR ISOTOPIC STUDY OF THE PIGEON POINT SILL, COOK COUNTY MINNESOTA

M.G. Mudrey, Jr., 106 Ravine Road, Mount Horeb, WI 53572, mgmudrey@mhtc.net
Isotopic and trace element by J.L. Wooden, then of LOCKHEED, NASA-Johnson Space Center, Houston, TX)

In 1980, Wooden and Mudrey presented some isotopic and trace element data for the Keweenawan troctolite sill on Pigeon Point, Minnesota, the type locality of the mineral pigeonite. Wooden's data were collected at the Johnson Space Center, Houston Texas, under exceedingly controlled laboratory conditions, comparable to lunar specimens at that time. The data have never been published, and interpretation has been limited because of other obligations of Mudrey and Wooden. Major elements were analyzed by a combination of colormetric, gravimetric and other classical techniques by S.S. Goldich and colleagues at Northern Illinois University and Pennsylvania State University.

The Pigeon Point sill is an approximately 120 meter thick, differentiated troctolite to olivine gabbro intrusion of Keweenawan age situated on the Pigeon River between Minnesota and Ontario. The sill is of petrologic interest because of the association of three rock types - troctonite/olivine gabbro, a ferro granodiorite, and a granophyre, whose genetic relationships have been debated for many years. Processes that have been invoked to explain the basaltic magma composition and significant abundance of granophyre (30 percent of sill thickness) on Pigeon Point include: **Crystal Fractionation** (Grout, 1928); **Magma Mixing Assimilation** (Daly, 1917); **Partial Melting** (Bayley, 1893); **Hydrothermal Alteration** (Bastin, 1938); and **Assimilation-Differentiation** (Mudrey, 1973).

The basal, chilled troctolite (PP-219-3) is a high alumina olivine tholeiite with a light enriched REE pattern (normalized La=19, Yb=6.8) having a positive Eu anomaly ($Eu^*/Eu=1.22$), and for many years was viewed as a possibility as a parental magma for some parts of the Keweenawan. While this sample may approximate a parental liquid composition, an origin involving plagioclase and olivine accumulation is also possible.

Rb-Sr isotopic data for 5 olivine gabbro and ferrogranodiorite samples form an approximate 1.429 Ga (initial $87Sr/86Sr = 0.70417$) isochron. This "age" is similar to Rb-Sr ages determined for the Rove Formation that the Pigeon Point sill intrudes. Compositional data for the sill suggests that selective contamination by alkalis and radiogenic Sr from the Rove Formation has occurred. The Sr isotopic data of the granophyre does not follow the pattern of the other samples, and its Rb/Sr ratio of 1.64 allow model ages of 1.11 to 1.15 Ga (probably representative of the crystallization age) to be calculated when the other sill samples are used for initial ratio control ($I=0.7076 - 0.7046$). (Best model age 1.132 Ga, $87Sr/86Sr = 0.70549$).

Petrologic, and trace element data argue for magma ascent from the upper mantle through Archean basement with low degrees of partial melting of potassic/alkaline constituents adjacent to the conduit followed by differentiation at an intermediate reservoir with ascent and emplacement at Pigeon Point at shallow depths (volcanic cavities, 1000 m). Local partial melting

of overlying Rove Formation and stoping of quartzite within the Rove Formation account for the significant volume of granophyric rock.

Bastin, E.S., 1938, Hydrothermal alteration in rocks of Pigeon Point, Minnesota, *Journal of Geology*, v. 46, p. 1058-1072.

Bayley, W.S. 1893, The eruptive and sedimentary rocks on Pigeon Point, Minnesota and their contact phenomena: U.S. Geological Survey Bulletin 109, 121 p.

Daly, R.A., 1917, The geology of Pigeon Point, Minnesota: *American Journal of Science*, Series 4, v. 43, p. 423-448.

Grout, F.F., 1928, Anorthosites and granite as differentials of a diabase sill on Pigeon Point, Minnesota, *Geological Society of America Bulletin* v. 39, p. 555-577.

Mudrey, M.G., Jr., 1973, Structure and petrology of the sill on Pigeon Point, Cook County, Minnesota: University of Minnesota PhD dissertation, 310 p.

Wooden, J.L., and Mudrey, M.G., 1980, A Chemical and Sr Isotopic Study of the Pigeon Point Sill, Cook County Minnesota (abs): *EOS (Transactions AGU)* v. 61, no 48 p. 1193.

	PP-219-3	PP-477-B	PP-698-F	PP-219-4	PP-466-B	PP-799-1	PP-845
SiO ₂	47.4			52.7	50	51.4	67.8
TiO ₂	1.01			1.9	1.63	1.74	0.56
Al ₂ O ₃	18.2			14.1	19.2	17.2	12.7
Fe ₂ O ₃	0.83			2.12	2.05	3.29	3.73
FeO	10.32			10.69	7.96	6.76	3
FeO(total)	11.07			12.6	9.8	9.72	6.36
MnO	0.16			0.205	0.16	0.152	0.09
MgO	8.46			4.6	3.27	2.76	0.05
CaO	9.44			8.46	9.82	7.45	1.25
Na ₂ O	2.57	2.92	2.93	2.28	2.92	3.57	3.62
K ₂ O	0.33	0.51	0.73	0.93	0.93	3.16	4.53
P ₂ O ₅	0.065			0.185	0.165	0.21	0.066
H ₂ O+	0.46			1.49	1.14	1.6	0.96
H ₂ O-	0.09			0.53	0.29	0.44	0.1
CO ₂	0.01			0.04	0.03	0.01	0.37
Cu	88	155		250	155	92	6
Zn	100	90		116	90	107	130
La	6.31	10.9	12.4	20	13.7	20.9	52.7
Ba	125		335				
Ce	15.7						
Nd	3.9	6.6	8.6				
Sm	2.33						
Eu	0.98						
Y	13	25	27				
Tb	0.45						
Yb	1.35	2.43	2.75	3.36	2.53	3.34	8.18
Lu	0.22						
Zr	57	113	130	164	128	198	609
K	2739	3985	5894				
Rb	9.3	14.8	20.5	37.1	36	115.1	150.4
Sr	258.3	294.4	332.5	220.3	318	527.5	91.7
⁸⁷ Sr/ ⁸⁶ Sr	0.7059	0.7070	0.7077	0.7162	0.7111	0.7156	0.7827
⁸⁷ Rb/ ⁸⁶ Sr	0.1042	0.1455	0.1785	0.4879	0.3278	0.6321	4.7824

INVESTIGATIONS OF SULFIDE MINERALS LEACHED IN THE PRESENCE OF ALKALINE SOLIDS

Nicholas, S.L. and Wirth, K.R., Geology Dept., Macalester College, St. Paul, MN 55105

Engstrom, J. and Lapakko, K.A., MN-DNR, Div. of Lands and Minerals, St. Paul, MN 55155

The oxidation of sulfide minerals present in mine waste exposed to the atmosphere can lead to the generation of acidic drainage. We used scanning electron microscopy and energy dispersive spectrometry (SEM-EDS) to examine unreacted rock and eight remnant solids. The solids were leached for periods of 117 to 899 weeks in laboratory experiments conducted by the Minnesota Department of Natural Resources (MN-DNR) on finely-ground (<0.149 mm) Duluth Complex rock (75 g) (Lapakko et al. 1997; 2000). This rock, which contains approximately four percent pyrrhotite (Fe_{1-x}S) and lesser amounts of chalcopyrite-cubanite, pyrite, and pentlandite, was mixed with different amounts of rotary kiln (RK) fines or limestone.

The rock samples were rinsed weekly with 200 mL of distilled deionized water, and the resultant drainage was analyzed regularly to assess acid-producing and acid-neutralizing reactions of each mixture and the controls. The effects of chemical reactions on water quality were documented and evaluated in detail, but little was known about the effects on the solid-phase sulfide minerals. A working hypothesis was that oxidation of sulfide minerals occurred from the outside of the grain inward, leaving a sulfur-depleted rind around the grain. This oxidation rind might retard diffusion of sulfur from the center of the grain into solution.

We identified the presence or absence of residual alkaline solids using a binocular microscope. SEM was used to describe the degree of sulfide oxidation, using the relative proportions of sulfur and oxygen determined by EDS. The extent of oxidation was described as the fraction of total analyzed sulfide area that was oxidized to a specific degree.

Limestone grains persist in the limestone-loaded reactors, whereas no alkaline grains were detected in the reactors loaded with RK fines. Oxidation of sulfide grains begins along the edges, cracks, and partings of grains, eventually forming irregular rinds of sulfur-bearing iron oxide (Figures 1 and 2). Less of the pyrrhotite area was oxidized in samples with an alkaline addition than in the control (Figure 3), and reactors with limestone additions had smaller extents of oxidized areas than did the reactors loaded with RK fines. Comparison of the extent of pyrrhotite oxidation in two reactors with the same loading that were leached for different lengths of time (Figure 3, reactors loaded with 4.7g RK fines) indicates that the rate of pyrrhotite oxidation is greater under acidic conditions, a result that is consistent with leachate water chemistry. The four treated reactors that generated no acidic drainage were among the five least oxidized.

References

- Lapakko, K.A., D.A. Antonson, and J. Wagner 1997. Mixing of limestone with finely-crushed acid-producing rock. Proc. 4th Int. Conf. on Acid Rock Drainage, Vol. 3, Vancouver, B.C., p. 1345-1360.
- Lapakko, K.A., D.A. Antonson, and J. Wagner 2000. Mixing of rotary-kiln fines with fine-grained acid-producing rock. Proc. 5th Int. Conf. on Acid Rock Drainage. SME, Littleton, CO. p. 901-910.

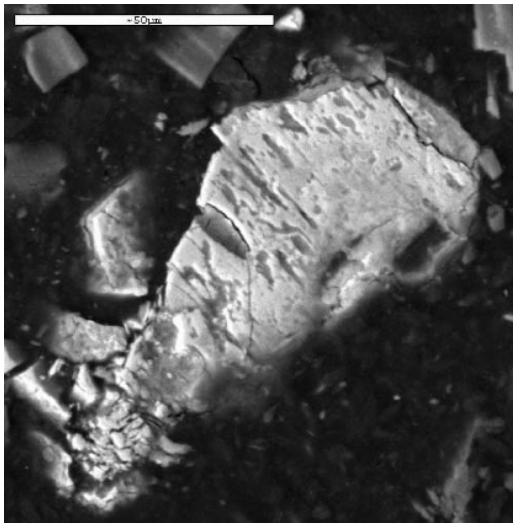


Figure 1: Backscattered electron (BSE) image of pyrrhotite from reactor (0.8 g RK fines addition) showing complex oxidation (darker regions) along grain edge and fractures (scale = 50 μ m).

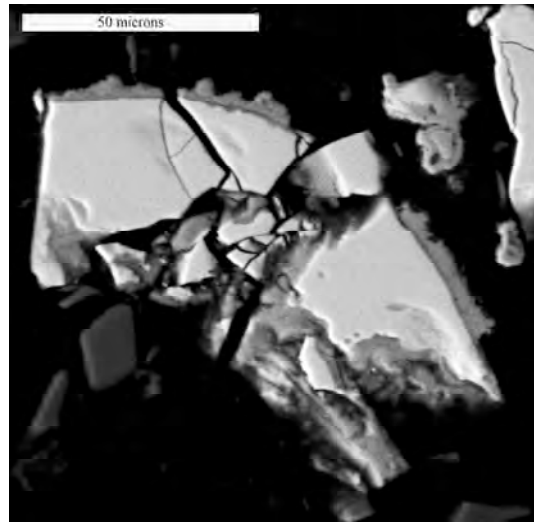


Figure 2: BSE image of pyrrhotite with a rind of sulfur-bearing iron oxide from reactor with 7.9 g limestone addition. Shattering of grain occurred during sample preparation (scale = 50 μ m).

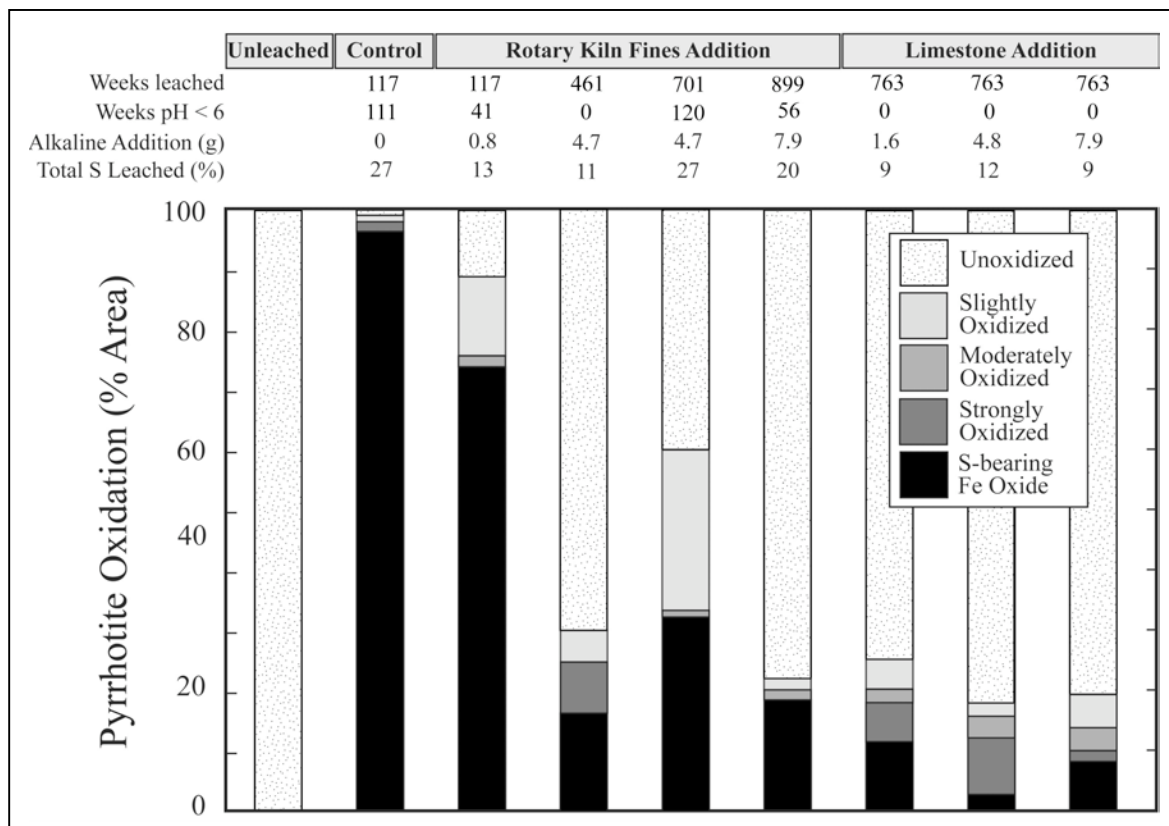


Figure 3: Extent of pyrrhotite oxidation as a function of reactor conditions and water quality data. The degree of oxidation increases from unoxidized pyrrhotite (unleached original) to sulfur-bearing iron oxide (>95% of control reactor). Weeks pH<6 is the number of weeks of leaching under acidic (pH<6) conditions. Alkaline Addition (g) is the total amount of Rotary Kiln Fines or limestone added to a reactor. Total S Leached (%) is the total sulfur measured in the reactor leachate expressed as a percentage of the initial sulfur present in the solid sample prior to leaching.

DOCUMENTING UNDERGROUND MINE WORKINGS ON THE MESABI IRON RANGE IN GIS FORMAT

ORESKOVICH, JULIE A., Natural Resources Research Institute, Duluth, MN 55811
(joreskov@nrri.umn.edu)

Seventy years of mining natural iron ore by underground methods on the Mesabi Iron Range of northeastern Minnesota has resulted in an extensive network of subsurface voids along much of the Range. Subsidence resulting from these voids is manifested today as sinkhole depressions, pools, ponds, lakes and, most notably, road and structure damage. These voids impact the area hydrology and pose unknown risks to existing and potential surface developments, as well as to present-day mining operations.

Because towns grew up adjacent to the early mines, today's Range cities are often located, at least in part, on top of the Biwabik Iron Formation (BIF). Underground workings faded from the collective memory as generations passed and open pit mining became the norm, with an occasional jolt to the public consciousness caused by a dropped highway lane, a shifted building, or a newly opened hole in the ground. However, with prospects for several major developments on the Range, along with an expected population increase, planning groups such as the Central Iron Range Initiative (CIRI) have recognized the need to factor the underground mine workings into planning and design work in the region.

The Central Iron Range Sanitary Sewer District (CIRSSD) has secured funding for the Minnesota Department of Natural Resources (MN DNR) to research the underground mines of the central Mesabi Range. CIRSSD's study area extends from the Itasca county line on the west (T 57 N, R 21 W) to midway between the cities of Buhl and Mountain Iron on the east (T 58 N, R 19 W), following the trend of the Biwabik Iron Formation. Nearly 150 natural ore mines (underground, open pit, or both) operated in this area.

Mining of natural iron ore on the Mesabi Range began with underground workings in the early 1890's. The last of the underground mines, the Godfrey Mine, closed in 1963. The history of each mine in the study area can be traced through mining directories dating back to 1922. Data, including land parcels, operators, dates of operation, type of operations, fee interests, and lessees, is captured and entered into an Access database.

Mine maps are collected from numerous sources, including mining companies, fee representatives, the MN Department of Revenue, the MN DNR map collection, and the archives of the Iron Range Resource Center (IRRC) located at Ironworld in Chisholm, MN. These maps are digitally scanned, and then rectified and digitized in ArcGIS. A unique USX aperture card collection housed at the IRRC contains annual level maps for Oliver Iron Mining Company operations dating back to 1903, enabling 3-D renderings of these mines. The end product of this research will be a GIS database that will be made accessible to counties, local communities, development organizations and mines for planning purposes.

Rare Earth Element Patterns in Steep Rock Carbonates

Noah Planavsky: Rosenstiel School of Marine and Atmospheric Sciences, 4600 Rickenbacker Causeway Miami FL 33149. nplanavsky@rsmas.miami.edu.

Jennifer Murphy: Eastern Mineral Resources, USGS. Reston, VA 20194. jmurphy@usgs.gov

One of the most dramatic changes in Earth's history is the shift from a reducing to an oxidizing atmosphere. Multiple lines of evidence suggest the atmosphere first became oxygenated around 2.4 billion years ago. The evolution of oxygenic photosynthesis is ultimately responsible for the Earth's oxygenation. The timing of the emergence of the earliest oxygenic photosynthetic organisms, likely cyanobacteria, is typically thought to predate the rise the atmospheric oxygen. Thus there exists the possibility for redox disequilibrium between ocean atmospheric systems; local areas of high photosynthetic productivity could induce local oxidizing conditions under an overall reducing atmosphere.

Rare earth element (REE) trends can be used to explore paleoredox conditions. Modern oxygenated oceans display a strong negative cerium anomaly when normalized to shale composites, representative of bulk crustal values, (Byrne and Sholkovitz, 1996) while anoxic or microaerophilic conditions display a positive or no cerium anomaly (shale normalized). The negative cerium anomaly is largely due to the oxidation of Ce^{3+} to Ce^{4+} and its preferential removal from the water column onto Mn-Fe oxide particles or as precipitate. In suboxic and anoxic waters Ce anomalies are smaller due to reductive dissolution and redox cycling of settling Mn- and Fe-rich particles within the suboxic and anoxic zones, respectively. Microbial induced carbonate precipitates and carbonate cements have been shown to faithfully record seawater REE values in modern reefs and can be used as a paleoredox proxy (Kamber and Webb, 2001). REE provide a unique tool at basin scale redox cycling in ancient environments.

The approximately 2.9 Ga Steep Rock Group is one of the oldest extensive carbonate successions with a low metamorphic grade and a high state of preservation. The Steep Rock Group, therefore, is an ideal place to explore the redox state of mid-Archean marine environments. Stromatolites and abiogenic carbonate cements from various depositional settings do not contain negative cerium anomalies. The trace element systematics, traditional stable isotopes, and carbonate textures indicate exceptional preservation and rule out the possibility of a diagenetic overprint. Since Ce is preferentially released during anoxic diagenesis (Byrne and Sholkovitz, 1996), the cerium anomalies observed in the siliceous stromatolites could not have formed during early anoxic diagenesis. Thus despite apparently high biological productivity, noted by the abundance of stromatolites and organic matter, the Steep basin was anoxic or suboxic. The lack of negative cerium anomalies in previously investigated early Archean stromatolites has been used to argue for absence of cyanobacteria (e.g., Tice and Lowe, 2005). Basic modeling of reductant and oxidant fluxes at the basin scale, rather than the more commonly modeled global

scale, provides atmospheric scenarios in which oxygenic photosynthesizing communities could exist in reducing conditions.

References:

- Byrne R. H. and Sholkovitz E. R. 1996. Marine chemistry and geochemistry of the lanthanides. In Handbook on the Physics and Chemistry of Rare Earths (eds. K. A. Gschneidner, Jr. and L. Eyring), Vol. 23, pp. 497–593. Elsevier, Amsterdam.
- Kamber, B.S. and Webb, G.E. 2001. The geochemistry of late Archaean microbial carbonate: Implications for ocean chemistry and continental erosion history. *Geochimica et Cosmochimica Acta*. 65: 2509-2525.
- Tice, M.M. and Lowe, D.R. 2006. Hydrogen-based carbon fixation in the earliest known photosynthetic organisms: *Geology*, 34: 37-40.

New Insights into the Metallogeny of the Eastern Portion of the Archean Uchi Domain, Superior Province, Ontario

PUUMALA, Mark A., Ontario Geological Survey, Ministry of Northern Development and Mines, Suite B002, 435 James Street South, Thunder Bay, ON P7E 6S7 Canada

In 2005, the Ontario Geological Survey began the Far North Geological Mapping Initiative (FNGMI). The goal of this program is to obtain a better understanding of the geological history and mineral resource potential of the portions of Ontario that are located north of 51°N latitude. The Far North is a remote area that has a much smaller historical geological database than the southern portions of Ontario. Nevertheless, this region does have a long history of mineral exploration that has resulted in the collection of much valuable information about the nature of economic mineralization. These data are currently being compiled to evaluate metallogenic patterns that can in turn be used to better understand the regional tectonic framework and economic mineral distribution.

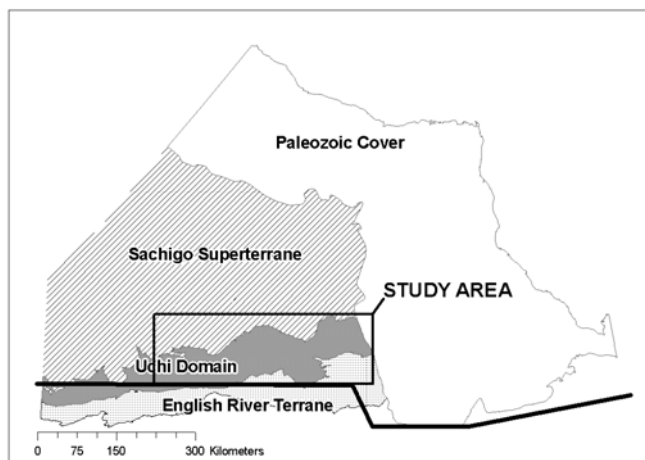


Figure 1. Map illustrating Far North Mineral Deposit Compilation study area.

To date, geological data have been compiled for mineral occurrences located within the eastern portions of the Archean Uchi Domain of the Sachigo Superterrane (Stott and Rainsford, 2006), of the Superior Province (Figure 1). The majority of the mineral deposits in this area are located within or immediately adjacent to supracrustal rocks of the Miminiska-Fort Hope, Pickle Lake, Lake St. Joseph, Meen-Dempster and Lang Lake greenstone belts of Stott and Corfu (1991). A wide variety of mineral deposit types have been identified in the study area, including: vein and replacement gold; polymetallic vein; mafic to ultramafic intrusion-hosted copper-nickel-platinum group elements (PGE); rare-element-bearing pegmatite; volcanogenic massive sulphide (VMS) copper-zinc; intrusive porphyry-related copper-molybdenum-gold; and Algoma-type banded iron formation.

Although the individual greenstone belts listed above are useful geographic subdivisions, it is perhaps more useful to ascribe styles of mineralization to individual assemblages that were deposited during a discrete interval of time in a common depositional or tectonic setting (Stott

and Rainsford 2006). The relationships between mineral occurrences and the individual tectonic assemblages have been used to obtain information regarding the possible locations and timing of significant metallogenic events in the study area. Preliminary observations suggest the following sequence of metallogenic events:

1. Mafic to ultramafic intrusion-hosted Cu-Ni-PGE mineralization in rocks of the >2860 Ma Pickle Crow assemblage in the Pickle Lake and Miminiska-Fort Hope belts;
2. VMS-type mineralization associated with rocks of the 2825-2842 Ma Kaminiskag (former Woman) Assemblage in the Pickle Lake and Meen-Dempster belts;
3. Later VMS-type mineralization associated with rocks of the <2744 Ma Confederation Assemblage in the Lang Lake, Meen-Dempster, and Pickle Lake greenstone belts, and with rocks of the <2723 Ma St. Joseph Assemblage in the Miminiska-Fort Hope Greenstone Belt;
4. Copper-nickel-PGE mineralization associated with late-tectonic mafic (commonly anorthositic) intrusions located near the southern boundary of the Miminiska-Fort Hope Greenstone Belt, and in the Lang Lake Greenstone Belt near the Bear Head Fault Zone; and
5. Structurally controlled gold mineralization that was likely to have been associated with the 2.72-2.70 Ma collision between the Uchi Domain and the Winnipeg River Terrane (Percival et al. 2006). In the Pickle Lake Greenstone Belt, this event post-dates Confederation Assemblage volcanism (>2739 Ma) and pre-dates the emplacement of the post-tectonic 2697-2716 Ma Hooker-Burkoski stock (Young et al. 2006).

The metallogeny of other deposit types in the study area is currently more difficult to interpret due to the small number of known occurrences and/or a lack of geological data. However, as additional information is collected through FNGMI mapping projects, it is anticipated that the tectonic events associated with porphyry copper mineralization observed in the Lang Lake Belt and polymetallic veins found in the North Bamaji Lake area, for example, can be determined.

References

- Percival, J.A., Sanborn-Barrie, M., Skulski, T., Stott, G.M., Helmstaedt, H., and White, D.J. 2006. Tectonic evolution of the western Superior Province from NATMAP and Lithoprobe Studies; *Canadian Journal of Earth Sciences*, Vol. 43, p. 1085-1117.
- Stott, G.M. and Corfu, F. 1991. Uchi Subprovince; *in* *Geology of Ontario*, Ontario Geological Survey, Special Volume 4, Part 1, p. 145-236.
- Stott, G.M. and Rainsford, D.R.B. 2006. The Precambrian geology underlying the James Bay and Hudson Bay lowlands as interpreted from aeromagnetic data and a revised terrane map for Northwestern Ontario; *in* *Summary of Field Work and Other Activities 2006*, Ontario Geological Survey, open File Report 6192, p. 13-1 to 13-10.
- Young, M.D., McNicoll, V., Helmstaedt, H., Skulski, T., and Percival, J.A. 2006. Pickle Lake revisited: New structural, geochronological and geochemical constraints on greenstone belt assembly, western Superior Province, Canada; *Canadian Journal of Earth Sciences*, Vol. 43, p. 821-857.

MICHIGAN KIMBERLITES REVISITED: NEW MINERAL, CHEMICAL AND PETROGRAPHIC ANALYSES

Quigley, P. O., Department of Geology and Geophysics, University of Minnesota, Minneapolis, MN 55414, quig0026@umn.edu

Over twenty kimberlite pipes have been reported in the Western Upper Peninsula of Michigan (Jarvis, 1993). Most of the known activity in assessing these pipes took place during the 1980's, and therefore did not include classification according to currently available mineral chemical and petrographic methods. Drill core samples held by the Michigan DNR from several pipes across the Michigan kimberlite field therefore are presently being analyzed in order to provide a further assessment of diamond grade prospects based on mineral chemistry, as well as an updated petrographic classification. Data collection consisting of electron microprobe analyses of garnet, ilmenite, and pyroxene from heavy mineral concentrates have been completed for three of the kimberlites, and have shown a high degree of variability. Two of the intrusions appear to have sampled a portion of the mantle within the diamond stability field, due to the presence of harzburgitic garnets, and other favorable compositions, according to the Grütter et al. (2004) classification scheme. Overall diamond grade is, however, inferred to likely be economically insignificant as the proportion of diamond indicator garnets to overall garnets is moderate to low. Analyses currently in progress will further examine degree of variability in mineral chemical analyses among these kimberlite intrusions, as well as examination of polished thin sections to permit use of textural features to categorize the intrusions as crater, diatreme, or hypabyssal facies kimberlite.

REFERENCES

- Grütter, S. H., Gurney, J.J., Menzies, H.A., and Winter, F., 2004. *An updated classification scheme for mantle-derived garnet, for use by diamond explorers*. J. Barry Hawthorne Volume Proc. 8th Int. Kimb. Conf., pp 841-857.
- Jarvis, William, 1993. *Michigan Kimberlites: An Update*. Abstract at Prospectors and Developers Association of Canada 61st Annual Meeting (Paper M-10).

Elemental and Isotopic Shallow Lake Proxies of Landscape Changes in the Prairie Pothole Region of Minnesota

Tommy Rodengen¹, Kevin Theissen¹, and Shinya Sugita²

¹Department of Geology, University of St. Thomas, 2115 Summit Ave, St. Paul, MN 55105

²Department of Ecology, Evolution, and Behavior, University of Minnesota, 1987 Upper Buford Circle, St. Paul, MN 55108

Investigations of the manipulation of the landscape around lakes have shown to have profound impact on their sedimentary records (1). We have explored lake sediment cores with records spanning the last two centuries and correlated changes in proxy data to large shifts in landscapes around lakes in Western Minnesota.

In February 2006 we collected sediment cores from Lee, Bore, 8-Mile and Sweet lakes in the Prairie Pothole region of Minnesota. Cores were sampled for organic matter (SOM) at 1 cm intervals, dried, ground, weighed and treated with sulfurous acid (2). These samples were sent to the Stanford University Stable Isotope laboratory and analyzed for elemental (TOC, TN, C/N) and stable isotopic ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) values. Lastly, pollen was extracted from sediments using standard palynological methods (3). Over the past 6 months I have analyzed a set of aerial photographs spanning 1938-present for the region of interest.

$\delta^{13}\text{C}$ (-29 to -22 per mil) and C/N (5-17) values reflect a dominant algal source in the sediments but also show times of mixing and terrestrial sourcing across the lake core record (4). These values suggest changes in productivity and/or changes in sourcing organic matter. We used sharp increases in the abundance of ragweed (ambrosia) as a marker of the cultural horizon (~1850 A.D.) (5). We believe the sharp changes in N isotopes indicate land use change by humans and the addition of fertilizers. This is illustrated by a large $\delta^{15}\text{N}$ spike between 39cm and 21cm depth (Figure 1), which if you assume a linear rate of sedimentation (.224 cm/yr) is between ~1832 A.D. and ~1912 A.D. According to our earliest records of aerial photography these years were a time of extreme drought and farming of fertile lake soil was common, directly introducing high levels of nitrogen to the sedimentological record.

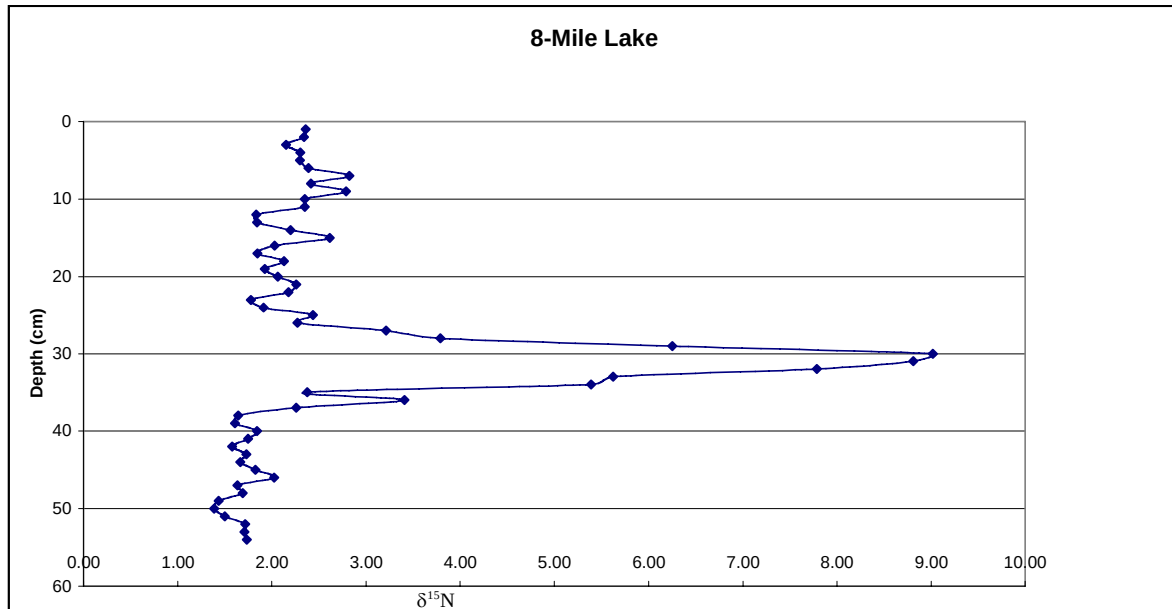
The importance of human manipulation of the landscape, specifically synthetic fertilizer, appears to have a clear effect on the sedimentological record found in these lakes.

References:

- (1) Lamb, H.F., Damblon, R.W., Maxted, R.W., 1991, Human Impact on the Vegetation of the Middle Atlas, Morocco, During the Last 5000 Years. *J. Biogeography*, 18, 1-14.
- (2) Verardo, D.J., Froelich, P.N., McIntyre, A., 1990, Determination of organic carbon and nitrogen in marine sediments using Carlo-Erba NA1500. *Deep-Sea Res.*, 37, 157-165.
- (3) Faegri, K. Iversen, J., 1989. *Textbook of Pollen Analysis*. 4th ed. J. Wiley & Sons, Chichester. 328pp.

- (4) Meyers, P.A., and Lallier-Verges, E., 1999, Lacustrine sedimentary or Late Quaternary paleoclimates. *J. Paleolimnology*, 21, 345-372.
- (5) Jacobson, G.L. and Grimm, E.C., 1986. A numerical analysis of Holocene forest and prairie vegetation in central Minnesota. *Ecology*, 67, 958-966.

Figure 1: 8-Mile lake $\delta^{15}\text{N}$ values



BEDROCK FRACTURES IN SOUTHEASTERN WISCONSIN: PALEOSTRESS ESTIMATES AND RELATIONSHIPS TO THE WAUKESHA FAULT

RYMASZEWSKI, Jody A., FRIEDRICH, Jason L., and CZECK, Dyanna M.

Department of Geosciences, University of Wisconsin – Milwaukee, P.O. Box 413,
Milwaukee, WI 53201 jody@uwm.edu

INTRODUCTION

The Waukesha Fault is an enigmatic structure cutting through Silurian dolomite in southeastern Wisconsin. It is a normal fault, oriented ~N40E, 60SE with an apparent offset of 10 m (Mikulic and Mikulic, 1977; Sverdrup et al., 1997). It is only known to outcrop at the Waukesha Lime and Stone Co. quarry in Waukesha, Wisconsin. Detailed gravity surveys in the region reveal the lateral and vertical extent of the fault (Sverdrup et al., 1997; Skalbeck et al., 2006). The fault trace extends NE to the town of Port Washington, Wisconsin on the shore of Lake Michigan (Sverdrup et al., 1997) and can be traced to depths greater than 600m (Skalbeck et al., 2006), showing that it is a major feature of an otherwise undeformed region.

The goals of our study are to 1) estimate the paleostress orientations that formed the Waukesha Fault, 2) measure the orientations of nearby small-scale fractures, 3) estimate the paleostress orientations that formed the small-scale fractures, and 4) compare the paleostress orientations for all the structures.

METHODOLOGY

The one known exposure of the Waukesha Fault is currently not available for active study. Therefore, we conducted paleostress orientation estimates on the Waukesha Fault, assuming its geometry matched that predicted by Sverdrup et al., 1997. We measured the orientations of 158 fractures in Silurian bedrock at the Lannon Stone Products quarry (located in Lannon, Wisconsin: ~11km NE of the known Waukesha Fault outcrop and ~3 km NW of the Waukesha Fault trace) during field seasons from 2004-2006. We also measured the orientations of 38 fractures in Devonian bedrock at the Harrington Beach State Park abandoned quarry and beach outcrops (located ~ 10km NE of Port Washington, and ~2.5 km NW of the Waukesha Fault trace). We used standard stereonet procedures to calculate the orientations of the paleostresses likely to have formed the Waukesha fault and the fractures at each of the field locations.

RESULTS

Based on the assumed geometry of the Waukesha Fault, σ_1 , the maximum principal stress was oriented vertically, σ_2 , the intermediate principal stress, was oriented (plunge/trend) 0°/040° σ_3 , the minimum principal stress, was oriented 0°/130°.

The Lannon quarry contains fractures with no discernable offset, and faults with small-scale (maximum ~4 cm, mostly normal sense) offsets. Some rare fractures have preserved ridge and groove lineations or plumose features, allowing classification as shear fractures or extensional fractures, respectively. The fractures at the top of the quarry have a random distribution. The small faults found at the low-mid levels of the quarry exhibit an approximate N32E/56SE

orientation. Most of the fractures with no apparent offset at mid and lower levels have the approximate orientation N30E/65S; a second group has approximate orientation of N45W/ steep-subvertical. Cross-cutting relationships between the two sets are inconclusive.

Two prominent fracture sets formed at Harrington Beach State Park. The approximate orientations of these two sets are 1) N74E/subvertical and 2) N25W/ subvertical. Unfortunately, the textures of most fracture surfaces are too weathered to determine whether the fractures are extensional or shear fractures. Thus, the paleostress estimates must be partly based on the relative geometries.

The small faults at the Lannon quarry have estimated paleostress orientations: σ_1 = vertical; σ_2 = 0°/040, σ_3 = 0°/130. Most of the fractures at the Lannon quarry have a similar orientation (but often with slightly steeper dips) to the small faults. Therefore, we interpret that most of these fractures are small extensional or shear fractures with the same paleostress orientations as the small faults. The second group of fractures at the Lannon quarry could either be extensional or shear fractures, but lack of any offset supports the likelihood that they are extensional fractures. If so, the paleostress orientations are σ_1 = vertical; σ_2 = 0°/315, σ_3 = 0°/225.

The fractures at Harrington Beach could either be two distinct sets of extensional fractures or a conjugate set of shear fractures. If they are extensional fractures, the paleostress orientations are 1) σ_1 = vertical; σ_2 = 0°/074, σ_3 = 0°/164 and 2) σ_1 = vertical; σ_2 = 0°/335, σ_3 = 0°/245. If they are shear fractures, the paleostress orientations are σ_1 = 0°/114 σ_2 = vertical, σ_3 = 0°/024.

CONCLUSIONS

While the paleostresses on all fractures could not be conclusively determined, the paleostress orientations inferred from most of the geometries of the small-scale features in the Silurian bedrock at Lannon are consistent with those estimated for the Waukesha Fault. However, the paleostress orientations of the Devonian rocks at Harrington Beach are inconsistent with those estimated for the Waukesha Fault. Therefore, it seems likely that 1) the timing of the Waukesha Fault may be bracketed by the deposition of the Silurian rocks at Lannon and the Devonian rocks at Harrington Beach, or 2) the deformation associated with the Waukesha Fault encompassed a broader region in the south. Further study of fractures in the region is required to test these hypotheses.

REFERENCES

- Mikulic, D.G., Mikulic, J.L., 1977. History of geologic work in the Silurian and Devonian of southeastern Wisconsin: Guidebook 41st annual tri-state field conference, A19-A27.
- Skalbeck, J.D., Couch, J.N., Helgesen, R.S., Swosinski, D.S., 2006. Coupled modeling of gravity and aeromagnetic data to estimate subsurface basement topography in southeastern Wisconsin. *Geoscience Wisconsin* 17, 53-64.
- Sverdrup, K.A., Kean, W.F., Herb, S., Brukardt, S.A., Friedel, R.J., 1997. Gravity signature of the Waukesha Fault, southeastern Wisconsin. *Geoscience Wisconsin* 16, 47-54.

Precambrian Geology of the Opelt Quarry, Neillsville, Wisconsin

SAXTON, Samantha and **CORDUA, William**, Department of Plant and Earth Science,
University of Wisconsin- River Falls, River Falls, WI 54022, samantha.saxton@uwrf.edu,
william.s.cordua@uwrf.edu

Near Neillsville, Clark County, Wisconsin, a quarry owned and operated by Opelt Sand and Gravel exposes a complex group of rocks dominated by amphibolites but including biotite gneisses, granitic to dioritic plutons, intrusive breccias and chlorite-rich shear zones. Given the quarry's location south of the Eau Plaine shear zone, it gives an important fresh exposure of the rocks of the Marshfield Terrain in central Wisconsin. We did field reconnaissance at the quarry combined with thin section, geochemical and structural analyses to study the metamorphic history. Published research for the surrounding area suggests the Opelt rocks are associated with an accreting micro-continent, which formed the foundation for later deformation during the Penokean orogeny (1880 - 1830 mya) and perhaps younger metamorphic events (Holm and Schneider, 2007). Previous work performed by Maass (1983) on rocks within 10 miles of the quarry using U-Pb zircon dating gives ages in a range of 1875 to 1820 million years old. A study by Sims and Peterman (1980) using a Rb-Sr whole-rock technique places them at roughly 1885 +/- 65 million years, correlating with the Penokean Orogeny.

Thin section analysis showed the common mineral assemblage in the gneisses and amphibolites to be a combination of plagioclase, biotite, hornblende, and clinozoisite, with several minor minerals such as calcite, chlorite, and epidote among others. Within the granitic samples, quartz, plagioclase, and clinozoisite become the dominant minerals, with the same

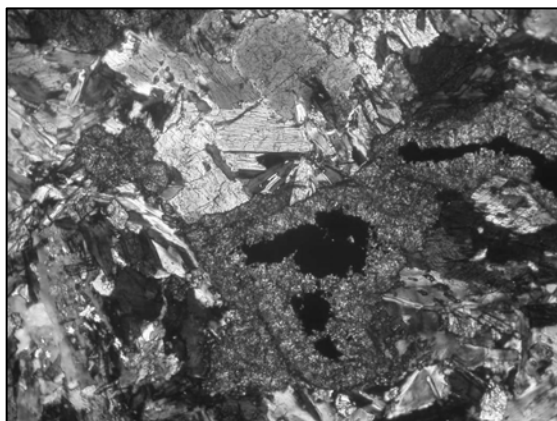


Figure 1: Amphibolite showing titanite replacing the opaque mineral, ilmenite, seen in the middle of the rings.

range of minor minerals. Veins of quartz and calcite are found cross-cutting the granites. Replacement textures were evident from the thin sections. Amphibolite samples display replacement rims or coronas of titanite surrounding the opaque ilmenite (Figure 1). We also see replacement relationships between several sets of minerals: primarily clinozoisite, muscovite, epidote and/or calcite replacing plagioclase feldspar, and chlorite replacing biotite. These two suites of minerals most likely represent a retrograde metamorphic event.

Geochemical analysis using discrimination diagrams derived from Pearce et al. (1982) and Gomez-Pugnaire et al. (2003) proved to be helpful in defining the protolith of the assorted rocks. A discrimination diagram for granitic rocks, based on the ratio of Rb versus Y + Nb, allocates samples to three origins- anorogenic, oceanic ridge, and island arc. Our data points, two granites and a diorite, indicate within a reasonable margin of error, a calc-alkaline island arc origin for the plutonic rocks found in the quarry. In addition,

several diagrams from Pearce (1982) show the igneous rocks that were protoliths for the amphibolites to be tholeiitic volcanic or island arc basalts.

Maass (1983) describes several folding events within in nearby rocks: F-1- isoclinal folds, to F-3 - very open to tight folds, as well as a mineral lineation associated with the F-3 folding. He also proposes that the plutonic activity of the area seems to have started at the latter part of the F-1 folding and continued past the end of the F-3 event. (Maass, 1983) Many of these same features can be seen in the Opelt Quarry.

Field, thin section, and geochemical data suggest the following sequence of events in the Opelt rocks:

1. Amphibolite protolith = tholeiitic island arc basalts
2. Penokean Orogeny
 - ~ Metamorphic Event #1 - Amphibolite Facies (Hb, plag)
Occurrences
 - F-1 Foliation
 - F-2 Veins and Granitic Intrusions
 - ~ Metamorphic Event #2 - Greenschist Facies (Chl, epi)
Occurrences
 - F-3 Foliation
 - ~ Formation of Shear Zones
 - ~ Veins- quartz, calcite, epidote
 - ~ Multiple series of faulting
3. Deposition of Younger Sediments/ Later Glacial Sediments

The later folding and retrograde metamorphism events could be late stage Penokean orogeny, or could be related to the Yavapai (1800-1750 mya) and Mazatzal (1650 mya) events that took place post-Penokean Orogeny (Holm and Schneider, 2007). Many structures and features originally attributed to the Penokean Orogeny now may actually be an overprint from later Yavapai and Mazatzal events (Cannon and Schulz, 2007). Radiometric work and further geochemical analysis will help resolve these questions.

- Cannon, W. and Schulz, K., 2007, *The Penokean Orogeny in the Lake Superior Region (abst.)*: The Geological Society of America Abstracts with Programs, 41st Annual Meeting, Lawrence, KS, v. 39, p. 76.
- Gomez-Pugnaire, M.T., Azor, A., Fernandez-Soler, J.M. and V. Lopez Sanchez- Vizcaino, 2003, *The amphibolites from the Ossa-Morena/Central Iberian Variscan suture (Southwestern Iberian Massif): geochemistry and tectonic interpretation*: Lithos, v. 68, p. 23-42.
- Holm, D. and Schneider, D., 2007, *Metamorphic Record of the Yavapai and Mazatzal accretion in the upper Great Lakes region, U.S. and Canada (abst.)*: The Geological Society of America Abstracts with Programs, 41st Annual Meeting, Lawrence, KS, v. 39, p. 76-77.
- Maass, R.S., 1983, *Early Proterozoic tectonic style in central Wisconsin*: Geological Society of America Memoir, v. 160, p. 85-95.
- Pearce, J.A., 1982, *Trace element characteristics of lavas from destructive plate boundaries*, In: Thorpe, R.S. (ed.) Andesite, p. 525-548.
- Sims, P.K. and Peterman, Z.E., 1983, *Evolution of Penokean foldbelt, Lake Superior region, and its tectonic environment*: Geological Society of America Memoir, v. 160, p. 3-14.

Revised Stratigraphy of the Biwabik Iron Formation, Mesabi Range, Minnesota – Developing the “Rosetta Stone”

SEVERSON, Mark, J. and HEINE, John, J., Natural Resources Research Institute, 5013 Miller Trunk Highway, Duluth, MN 55811

The NRRI is currently evaluating the possibility of using specific waste rock products from taconite mining as aggregate materials. Paramount to defining specific horizons with good aggregate potential, a better understanding of the stratigraphy of the iron-formation has been accomplished through detailed logging of drill holes and detailed in-pit mapping (where core are unavailable). To date, 130 holes have been logged from seven areas that include: Cliffs-Erie site (old Erie/LTV mine), Biwabik area (Mittal Steel’s planned “east reserve”), Laurentian Mine, United Taconite, Minntac, Hibtac, and the oxidized taconite of the Coleraine area. In each of these areas, the stratigraphy, as determined by bedding types in each of the holes, is compared to the stratigraphy as defined by each of the mining companies. Through this approach, a new picture of the iron-formation layering is evolving and for the first time it has become possible to correlate the mining units of one mine to those in adjacent mines - even though each of the mines uses a different stratigraphic terminology. In essence, this work has set forth the beginnings of a “Rosetta Stone” whereby ore and waste horizons can be better understood. Hopefully, the “Rosetta Stone” can eventually be used to aid in determining the depositional environments of internal units within the iron-formation.

All descriptions of the Proterozoic iron-formations consistently attribute thin-bedded iron-formations as reflecting deposition in a deep water environment, and granular, variably-bedded iron-formations as reflecting deposition in shallower water. Overall, the iron-formation has been divided into four members consisting of Lower and Upper Cherty members (regressive sequences), and Lower and Upper Slaty members (transgressive sequences). Using these simple concepts, coupled with other bedding types as seen in drill core, several unique relationships have been defined along the length of the Mesabi Range that include:

- The Lower Cherty is the most consistent member of the iron-formation and consists of a single shallowing-upward parasequence consisting of thin-bedded iron-formation at the base grading upwards through sequences of regular-bedded, wavy-bedded, irregular-bedded, and thick-bedded granular iron-formation units.
- The top of the Lower Cherty consists of an iron-poor, variably-bedded, granular chert that is currently being used as road aggregate, e.g., the “Mesabi Select” material from United Taconite’s Thunderbird North mine. This unit is inferred to have been deposited in shallow water near the edge of the shelf.
- The base of the Lower Slaty is the most persistent marker bed in the iron-formation and at most locales consists of carbonaceous mudstone referred to as the “Intermediate Slate.” Tuffaceous units are reported to be present at the base of the Lower Slaty but have yet to be encountered in the drill holes looked at in this study.
- For the most part, the Lower Slaty consists of a thick sequence of thin-bedded, iron-carbonate and iron-silicate iron-formation that was deposited in deep water. However, in the “east reserve” area, lenses of granular iron-formation (deposited in shallow water and similar to the “Mesabi Select” unit of the Lower Cherty) are commonly interbedded with the thin-bedded rocks of the Lower Slaty. Internal structures within these lenses

suggest that they formed from slumpage of shelf material into the basin; possibly related to large storm events or earthquakes during periods of tectonic instability.

- The top of the Lower Slaty member is perhaps the most poorly defined as it is transitional into the overlying Upper Cherty member. This is most evident in the Virginia Horn area where both slaty and cherty iron-formation types are common and alternate at all scales. This has led to stratigraphic inconsistencies wherein the actual division between the Upper Cherty and Lower Slaty members varies drastically from mine to mine. Recent stratigraphic correlations suggest that the upper portion of the Lower Slaty contains several laterally-restricted tongues/channels of Upper Cherty-type beds that have locally been referred to as “interbedded cherts” or IBCs. These IBCs appear to be related to several regressive/transgressive events and represent several small parasequences at the top of the Lower Slaty.
- The Upper Cherty member is profoundly different from the Lower Cherty in that it does not display a consistent stratigraphy nor is a shallowing-upward sequence evident. Furthermore, the Upper Cherty is commonly “oolitic.” These relationships suggest that the Upper and Lower Cherty members were deposited in distinctly different depositional environments.

While development of the “Rosetta Stone” adequately displays the various differences of the Biwabik Iron Formation along the entire length of the Mesabi Range, only continued logging of holes will aid in exhibiting the 3D nature of the iron-formation. When that point is reached, a more complete analysis of the actual depositional environments can be ascertained.

Investigation of Ferromanganese Nodule Precipitation and Arsenic Uptake in Modern Lacustrine Biochemical Sediments

Stevens, Larissa B. and Fralick, Philip, Department of Geology, Lakehead University, Thunder Bay, Ontario, Canada, (larissa.stevens@lakeheadu.ca)

This study was conducted to evaluate the environmental setting, geochemistry and formational processes involved in the precipitation of lacustrine ferromanganese nodules, and to investigate the mechanisms involved in arsenic uptake in these deposits. The research was conducted on precipitates in Lake Charlotte, Nova Scotia. However, the findings are applicable to the Lake Superior region as ferromanganese deposits have been found in a number of temperate North American lakes and may be present in many more.

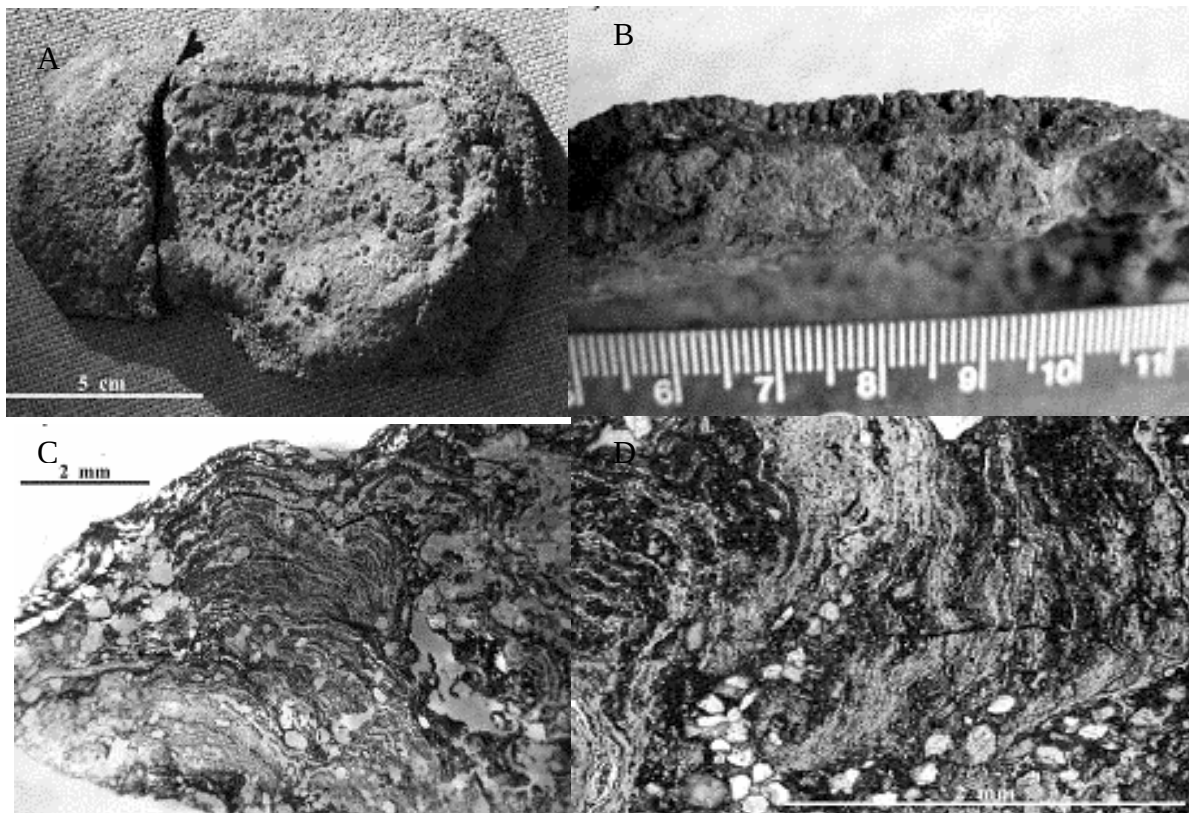
Ferromanganese deposits in the form of nodules, coated sand and layers in the sediment are present in all the Great Lakes (Sly and Thomas, 1974; Callender, 1970). Mothersill and Shegelski (1973) studied iron- and manganese-rich layers in Lake Superior near Thunder Bay. Ferromanganese concretions have also been found in inland lakes of the Lake Superior Region including: Lake Schebandowan, Ontario (Carpenter et al., 1972), Trout Lake, Wisconsin (Twenhofel et al., 1945) and the Minnesota Lakes (Zumberge, 1952).

The layering styles of ferromanganese nodules can be used to infer the approximate position of the redox boundary where precipitation is occurring. The concretions found in Lake Charlotte, NS, developed on the bottom in a shallow lacustrine setting. These deposits consist of 1 cm thick crusts divisible into 1) a lower zone of iron precipitates cementing siliciclastic sands; 2) thin laterally continuous laminae of manganiferous and ferric precipitates; 3) micro-stromatolites composed of manganiferous and ferric precipitates and 4) grumulous and clotted textured manganiferous and aluminous precipitates. These deposits formed by the interaction of oxygenated lake water with diffuse reduced groundwater seeps on the sandy bottom. The development of microbial mats and presence of stromatolites and clotted precipitates indicates biochemical processes played a role in the formation of the crusts.

The ferromanganese nodules are accumulating arsenic, with concentrations ranging from ~ 670 to 1400 ppm. Elevated arsenic concentrations were also found in groundwater samples suggesting that the arsenic is entering the lake from the groundwater seeps. Microbiological experiments investigating bacterial involvement in arsenic coprecipitation have found that no arsenic oxidizers were present. However, iron oxidizers are. This suggests a possible mechanism whereby: the iron oxyhydroxide precipitates were formed, at least in part, by the iron oxidizers in the microbial mats on the bottom. As the iron oxyhydroxide precipitated from the diffuse groundwater flow entering the oxygenated lake it scavenged the arsenic that was also being transported in solution.

References

- Sly, P.G. and Thomas, R.L., 1974. Review of geological research as it relates to an understanding of Great Lakes limnology. *J. Fish. Res. Bd Can.*, 31: 795-825.
- Callender E., 1970. The economic potential of ferromanganese nodules in the Great Lakes. *Proc. 6th Forum Geol. Ind. Miner. Michigan Geol. Surv. Misc.*, 1: 55-65.
- Mothersill, J.S. and Shegelski, R.J., 1973. The formation of iron and manganese rich layers in the Holocene sediments of Thunder Bay, Lake Superior. *Can. J. Earth Sci.*, 10: 571-576.
- Carpenter, R., Johnson, H.P. and Twiss, E.S., 1972. Thermomagnetic behavior of manganese nodules. *J. Geophys. Res.*, 77: 7163-7174.
- Twenhofel, W.H., McKelvey, V.E., and Feray, D.E., 1945. Sediments of Trout Lake, Wisconsin. *Bull. Geol. Soc. Am.*, 56: 1099-1142.
- Zumberg, J.H., 1952, The lakes of Minnesota, their origin and classification. *Bull. Minn. Geol. Surv.*, 35: 1-90.



A) Picture of a typical ferromanganese nodule overgrowing a cobble. The small domes are stromatolites; B) Cross section of a nodule with a stromatolitic zone at the top; C) Reflected light photomicrograph of stromatolitic layering in a nodule. The round white areas are sand grains; D) Reflected light photomicrograph of the internal layering of a nodule.

A REVISED TERRANE MAP FOR THE SUPERIOR PROVINCE AS INTERPRETED FROM AEROMAGNETIC DATA

STOTT, Greg, Ontario Geological Survey, Sudbury, ON, P3E 6B5, greg.stott@ontario.ca

CORKERY, Tim, Manitoba Geological Survey, Winnipeg, MB

LECLAIR, Alain, Géologie Québec, Québec, QC

BOILY, Michel, GÉON, Montréal, QC

PERCIVAL, John, Geological Survey of Canada, Ottawa, ON

The Superior Province has in the past been subdivided into “Subprovinces” characterized largely by contrasting lithology (e.g., Card and Ciesielski 1986). With an increasingly refined understanding of the tectonic assembly of the Superior Province through a progression of orogenies (Stott and Corfu 1988; Percival et al. 2006), supported by geochronological and Sm-Nd isotopic data (e.g., Tomlinson et al. 2004; Rayner and Stott 2005), we can identify individual terranes and associated domains. Recent aeromagnetic interpretation of the Precambrian crust underlying the James Bay and Hudson Bay lowlands (Stott and Rainsford 2006), permits more confident terrane correlations across James Bay. Figure 1 illustrates a new map of the Superior Province in Canada with its principal tectonic subdivisions as currently used in Manitoba, Ontario and Quebec. Archean *terrane*s are crustal blocks with geological histories substantially different from adjacent blocks, although parts of the late (Neoarchean) history of adjacent terranes typically overlap. They include one or more tectonic assemblages and plutonic suites, and at least parts of the terrane boundaries are clearly marked by major faults. Those regions with more complex Meso- to Neoarchean orogenic histories are superterrane thought to comprise at least two terranes. *Domains* are marginal parts of terranes or superterrane that are thought to have been added autochthonously or for which sparse evidence exists (e.g., Marmion domain) to treat them as separate terranes.

Card, K.D. and Ciesielski, A. 1986. DNAG #1. Subdivisions of the Superior Province of the Canadian Shield; Geoscience Canada, 13, 5-13.

Percival, J.A., Sanborn-Barrie, M., Skulski, T., Stott, G.M., Helmstaedt, H. and White, D.J. 2006. Tectonic evolution of the western Superior Province from NATMAP and Lithoprobe studies; Can. J. Earth Sci., 43, 1085-1117.

Rayner, N. and Stott, G.M. 2005. Discrimination of Archean domains in the Sachigo Subprovince: a progress report on the geochronology; Ontario Geological Survey, Open File Report 6172, 10-1 to 10-21.

Stott, G.M. and Corfu, F. 1988. Whither the Kenoran Orogeny?; Geological Association of Canada/Mineralogical Association of Canada Annual Meeting, Program with Abstracts, 13, A120.

Stott, G.M. and Rainsford, D.R.B. 2006. The Precambrian geology underlying the James Bay and Hudson Bay lowlands as interpreted from aeromagnetic data and a revised terrane map for northwestern Ontario; Ontario Geological Survey, Open File Report 6192, 13-1 to 13-10.

Tomlinson, K.Y., Stott, G.M., Percival, J.A. and Stone, D. 2004. Basement terrane correlations and crustal recycling in the western Superior Province: Nd isotopic character of granitoid and felsic volcanic rocks in the Wabigoon subprovince, N. Ontario, Canada; Precambrian Research, 132, 245-274.

Figure 1 (next page). This map displays a composite of an aeromagnetic base and bedrock geology of the northern portion of the Archean Superior Province across Manitoba, Ontario and Quebec with terrane and domain boundaries. Names of superterrane, terranes and domains are as currently used in each of the provinces.

Some features to note:

- The older, Mesoarchean North Caribou terrane forms a core flanked to the north and south by outward additions of Meso- to Neoarchean crust across Uchi and Island Lake domains, which merge eastward where the North Caribou terrane pinches out. Uchi domain and Oxford-Stull domain merge under the James Bay Lowland;
- A large indentor-like feature underlies the James Bay Lowland, flanked by faults;
- English River and Quetico metasedimentary domains are separated east of the Wabigoon Subprovince by a ridge of felsic plutonic rocks, with high magnetic field intensity, extending westward from the Opatica gneisses of Québec. The Opatica terrane might extend to the Winnipeg River terrane where the latter is interpreted to underlie the northern part of the eastern Wabigoon Subprovince;
- The Trans-Hudson Orogen underlies the northern half of the Hudson Bay Lowland;
- Apparent reworked Archean Northern Superior superterrane crust under Hudson Bay Lowland within the Trans-Hudson Orogen;
- Broad areas of pronounced aeromagnetic field intensity characterize large parts of the Northern Superior superterrane under the Hudson Bay Lowland in Ontario and correspondingly resemble the Pikwitonei gneisses, including the Assean and Split Lake blocks on strike in Manitoba.
- Potential correlation of Northern Superior superterrane with the 3.8 Ga Nuvvuagittuq greenstone belt (David et al. 2002) in Tikkerutuk domain and the >3.5 Ga Assean gneisses (Böhm et al. 2000).
- Areas interpreted to be part of the Paleoproterozoic Sutton Inlier are outlined where exposed. The Sutton “Inlier”, of shallow water platform sedimentary units and overlying gabbro sill, does not appear to be one large area but a set of inliers and should in future be referred to as the Sutton Inliers. The eastern Sutton Inliers with subsurface extensions are shallowly dipping, northward concave and crescent-shaped, based on aeromagnetic patterns, which correspond closely with the distribution of outcrops observed by Bostock (1970). They resemble “klippe” that might have been transported a short distance southwards. Folded strata related to the Sutton Inliers are shown aeromagnetically to extend discontinuously northwards towards the Hudson Bay coast upon apparently reworked Archean crust within the Trans-Hudson Orogen. The Trans-Hudson Orogen, including areas of reworked Archean crust, appears to underlie the northern half of the Hudson Bay Lowland, based on interpretation of aeromagnetic images.



THERMAL EVOLUTION OF PROTEROZOIC (>1Ga) RHYOLITE MAGMA BASED ON ANALYSIS OF MELT INCLUSIONS AND TRACE ELEMENTS IN QUARTZ FROM THE KEWEENAW PENINSULA OF MICHIGAN

STUDENT, James J., Central Michigan University, 314 Brooks Hall, Mount Pleasant, MI 48859, stude1jj@cmich.edu, **WARK, D.A.**, Department of Earth and Environmental Sciences, Rensselaer Polytechnic Institute, Troy, NY 12180, **MUTCHLER, S.R.**, Department of Geological Sciences, Virginia Tech, Blacksburg, VA 24061, and **Bodnar, R.J.**, Department of Geological Sciences, Virginia Tech, Blacksburg, VA 24061.

Melt inclusions (MI) form when small droplets (less than a few hundred microns in diameter) of magma become trapped inside growing crystals in magma. MI provide the best source of information concerning the chemical and physical evolution of a magma chamber. Glass-bearing MI are common in quartz and zircon from porphyritic rhyolite occurrences in the Midcontinent Rift System, including rhyolite flows in the North Shore Volcanic Group, the Porcupine Volcanics, and the Portage Lake Volcanics on the Keweenaw Peninsula of Michigan. Porphyritic rhyolite cobbles are abundant in the Allouez conglomerate within the Portage Lake Volcanics, and the characteristics and geochemistry of MI and quartz phenocrysts contained in this conglomerate are described below. The MI have been categorized based on their phase assemblages and preservation style. Type 1 MI contain clear glass and a shrinkage bubble, Type 2 contain clear glass, a shrinkage bubble and 1 or more, coarser grained ($> 3 \mu\text{m}$) crystals, and Type 3 MI are totally devitrified or otherwise breached. The MI range in size from 1 to over 200 μm in diameter, and they typically have a negative hexagonal bi-pyramidal morphology.

Cathodoluminescence (CL) observations of the quartz phenocrysts ($n=42$) reveal several periods of new quartz growth and dissolution on what we tentatively interpret to be non-magmatic cores (Fig. 1A). In eight quartz phenocrysts from four texturally different porphyritic rhyolite cobbles, Ti (measured by EPMA) increases from about 50 to 220 ppm towards the rim in the magmatic growth zones, corresponding to a temperature increase from 675 to 850 $^{\circ}\text{C}$, estimated using the TitaniQ method of Wark and Watson (2006) with a fixed TiO_2 activity equal to 1. Zircon microphenocrysts and MI are distributed throughout the magmatic portions of the quartz phenocrysts. Type 1 and Type 2 MI were analyzed by EPMA and LA-ICPMS for major elements and 13 trace elements, including Zr. Zircon saturation temperatures calculated using the model described by Watson and Harrison (1983) based on Zr and major oxide concentrations in MI ($n=11$) from one cobble range from 670 to 866 $^{\circ}\text{C}$ and agree well with the Ti in quartz geothermometry from the same cobble (Fig. 1B).

Petrographic observations and chemical analyses indicate that many (if not most) of the type 1 and 2 MI have remained chemically closed systems for over 1 Ga. Zoned calcite (imaged by CL) associated with native copper that is related to later non-magmatic mineralization has selectively replaced some of the feldspar in rhyolite cobbles from the Allouez conglomerate, and random fractures that are partially filled with calcite and secondary planes of fluid inclusions cut across the quartz phenocrysts and some Type 3 MI. The well-preserved growth zoning recorded by CL imaging of quartz is consistent with the preservation of other

chemical characteristics in the MI. Based on both textural and chemical evidence, zircon and quartz remained saturated in the magma while temperatures increased by more than 175 °C sometime prior to eruption. Blundy et al., (2006) and Wark et al., (2007) recently presented evidence that the magma temperature increased during eruption at Mount Saint Helens WA and prior to the eruption of the Bishop Tuff at Long Valley CA. Quartz-bearing porphyritic rhyolite from the Keweenaw shows a similar thermal trend. The thermal and chemical evolution of the Midcontinent Rift System rhyolite magmas may be better constrained utilizing the chemical record preserved in MI, quartz, and zircon.

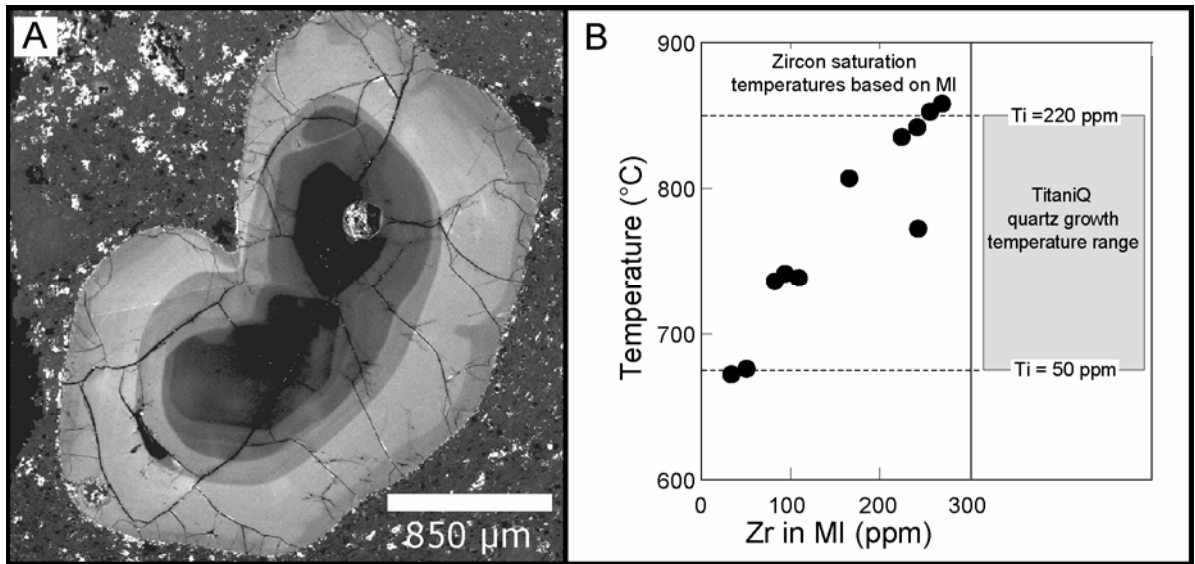


Figure 1. A) CL image of a typical quartz phenocryst from porphyritic rhyolite cobbles of the Allouez conglomerate. Light and dark regions in the quartz correspond to high and low Ti concentrations, respectively. The dark region in the core has very low Ti concentrations (15 ppm) and may be “non-magmatic” based on TitaniQ temperature estimates (567 °C). B) Calculated zircon saturation temperatures from MI (left) and TitaniQ temperature estimates for quartz growth (right) for one Allouez conglomerate rhyolite cobble.

References

- Blundy, J., Cashman, K., and Humphreys, M. (2006): Magma heating by decompression-driven crystallization beneath andesite volcanoes. *Nature*, 442, 76-80.
- Wark, D.A., and Watson, E.B. (2006): TitaniQ: A Titanium-in-Quartz geothermometer. *Contributions to Mineralogy and Petrology*, 152, 743-754.
- Wark, D.A., Hildreth, W., Spear, F.S., Cherniak, D.J., And Watson, E.B. (2007): Pre-eruption recharge of the Bishop magma system. *Geology*, 34, 235-238.
- Watson, E.B., and Harrison, T.M., (1983): Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types. *Earth Planet. Sci. Lett.*, 64, 295-304.

Pleistocene glaciation as a mechanism for emplacement of high-salinity groundwater at anomalously shallow depths in the Lake Superior basin

MICHAEL L. TAYLOR and JOHN B. SWENSON

Department of Geological Sciences, University of Minnesota Duluth, Duluth, Minnesota

Along the shores of Lake Superior, in northeast Minnesota and northern Wisconsin, highly saline groundwater exists at anomalously shallow depths of 30 meters or less, contaminating domestic wells and community water supplies. These saline waters, which produce significant hydrogeologic problems for determining locations for domestic water sources, appear geochemically similar to high salinity groundwater (Na-Ca-Cl brines) commonly found at depths greater than one kilometer on the Canadian Shield (Frape and Fritz, 1982). Currently there is little research that attempts to explain this phenomenon of anomalously shallow, highly saline groundwater from a hydrodynamic perspective. Most work completed thus far has been from a geochemical perspective. One recent hydrodynamic model suggests that glaciation acted as a mechanism for flushing deep brines closer to the surface: During the Pleistocene, the Superior Lobe of the Laurentide ice sheet repeatedly occupied the Lake Superior basin. The temperate (wet-based) lobe created a strong hydraulic-head gradient across the sedimentary and volcanic rock package beneath the ice. High hydraulic head existed down the axis of the lobe and decreased towards the margins. In response to this head gradient, meltwater at the base of the glacier may have been driven deep into the underlying rock package beneath the lobe axis, where it could mix with and flush brines to the basin margins. As the Superior Lobe retreated, the head gradient was removed and the high-salinity groundwater displaced to the lobe margins began to migrate (back-flush) to its original position deep within the basin. This study develops further this model and attempts to test it via a combination of mathematical modeling and geochemical fingerprinting. Mathematical modeling comprises the development of a relatively simple model of groundwater flow and solute transport to test basic physical plausibility of the 'flushing' model. The flushing model predicts that samples of groundwater should represent a combination of parent brine formed deep within the rock package underlying the Lake Superior basin, isotopically light, subglacial Pleistocene recharge, and modern meteoric recharge. Geochemically fingerprinting saline groundwater samples will test the model predictions which involved: (1) field work to sample wells in the Lake Superior basin, with emphasis on the south shore, where data are sparse, (2) stable isotope and major element analyses of the fluids, and (3) stable isotope and major-element analyses of the sedimentary rocks that comprise the Mid-continent Rift System.

Reference:

Frape, S.K. and Fritz, P., 1982. The Chemistry and Isotopic Composition of Saline Groundwaters from the Sudbury Basin, Ontario. *Canadian Journal of Earth Sciences*, v. 19, p. 645-661.

Possible influence of a buried fault on elevated indoor radon levels, south Washington County, Minnesota

Stephanie A. Theriault and Dr. Thomas A. Hickson

Geology Department, University of St. Thomas, St. Paul, Minnesota 55105

Correlation between high indoor radon levels and a local fault in south Washington County were found in a 2004-2005 study done by the Geology Department at the University of St. Thomas and the Washington County Public Health and Environment Department. The location of the fault was important to this study because radon characteristically can travel farther along leaky faults, which could explain the unusually high levels of radon in this specific area. However, the Minnesota Geological Survey revised their mapping shortly after the 2004-2005 study and did not include the specific fault on their new map. This research focuses on determining if there is evidence for the proposed fault. Stratigraphic offset, as seen in well logs, aid in determining the possible presence of the fault. Three cross sections were created across the proposed fault from well log data. Offset was found both in the Prairie du Chien and Jordan units across the proposed fault. Structure contour maps of the top of the Prairie du Chien and Jordan units also support the presence of this fault. In conclusion, evidence provided by the well logs from the study area suggests the possible presence of a fault and that it could be related to the unusually high indoor radon levels encountered in this area.

POTENTIAL USE OF THE MIDCONTINENT RIFT FOR CO₂ SEQUESTRATION

Thorleifson, L. H., Minnesota Geological Survey, 2642 University Ave West
Saint Paul, Minnesota 55114-1057

Increasing concern about climate change and reliance on fossil fuels necessitate the exploration of carbon capture and geologic CO₂ sequestration as a technology to reduce CO₂ emissions. Characterization of the Midcontinent Rift, a southwestward extension of the Lake Superior basin that presents the best sequestration opportunity in the immediate region, is needed to permit a full feasibility assessment of this technology in the region. Unlike better known rocks in oil or coal producing regions, we have little information on the Rift, yet geologic factors suggest that it may be a potential target. A recent meeting therefore was held to develop a shared understanding of current knowledge on the potential opportunities and tradeoffs for deep geologic sequestration of CO₂ in Minnesota, Iowa, and western Wisconsin, and to facilitate collaboration between stakeholders. At the meeting, held on March 21, 2007, over forty representatives from upper Midwest governmental, community, academic, and industry groups met to discuss prospects for geologic CO₂ sequestration in the region.

At the meeting, Brad Crabtree, of the Great Plains Institute (GPI), described work done by the Coal Gasification Workgroup to build consensus on a long-term vision for low-carbon utilization of coal. In May 2007, GPI will release a 50-year regional energy roadmap including a chapter on the role of advanced coal technologies with geologic carbon capture and sequestration (CCS). Bill Grant of the Izaak Walton League outlined a bill currently before the Minnesota Legislature (H.F. 1666) that would provide funding for assessment of both geologic and terrestrial carbon sequestration in Minnesota. If enacted, this bill would provide funds to the Minnesota Geologic Survey and other agencies to begin geologic assessment of the Midcontinent Rift along with steps toward analysis of required policy and technology.

Elizabeth Wilson of the University of Minnesota Hubert Humphrey Institute provided an overview of policy considerations for a carbon-managed energy system. Carbon Capture and Sequestration (CCS) is currently in commercial operation at several sites around the world, and is the focus of a major research effort by the U.S. Department of Energy (DOE). Technology alone, however, will not be enough, as deployment will need to be embedded in a wider societal dialogue. States will play a key role in property rights and liability issues, as well as in managing potential risks to public safety, health and the environment. Wilson drew the attention of meeting participants to the Intergovernmental Panel on Climate Change report on Carbon dioxide Capture and Storage as an important reference.

Ed Steadman of the Energy & Environmental Research Center (EERC) at the University of North Dakota described the work of the Plains CO₂ Reduction Partnership (PCOR), one of seven regional partnerships under the U.S. Department of Energy's Regional Carbon Sequestration Partnership Program. PCORP has completed Phase I and Phase II research, including assessment and ranking of sequestration opportunities, outreach materials, and a PCOR Partnership Regional Atlas. PCOR is now preparing to conduct a number of CCS pilot projects

in the Williston Basin under Phase III. Ed discussed the Midcontinent rift as part of his broad presentation, both in terms of its potential and the lack of available information on the topic.

Ray Anderson of the Iowa Geologic Survey gave a presentation on the geology of the Midcontinent Rift. He described how the billion-year-old rift can be clearly seen across the region as a gravity and magnetic anomaly, while rocks of the rift are only exposed in the Lake Superior Area. The limited additional information available about rift formations comes from deep test borings done for petroleum exploration in Iowa and Wisconsin in the mid 1980s, along with a few shallower drillholes in Minnesota. He indicated that available data indicate that the rift is composed of a central volcanic block, flanked by sedimentary basins up to 5 miles in thickness. Smaller sedimentary basins sit atop the volcanic block in several areas. Geologic sequestration requires porous rock formations at a depth of at least 2,500 feet or roughly a km, overlain by impermeable rock formations to trap the carbon dioxide. Preliminary indications are that the Midcontinent Rift formations may have the necessary characteristics, but much more geologic assessment is required.

A breakout on policy and technology recommended that we pursue coordinated policy and regulatory development among neighboring states to pursue early development of a carbon management infrastructure, linking jurisdictions, power plants, coal resources, enhanced oil recovery (EOR) options, along with other sequestration options. This is presently emerging among Illinois Basin states, but could be expanded to other neighbors and even beyond the Illinois Basin. Once initial geological results are available, we will need to conduct comprehensive analysis of different energy futures. This analysis will examine the policy, economic and environmental implications of a) importing electricity from out of state, b) producing electricity in-state but exporting produced CO₂ through pipelines, and c) producing electricity and sequestering CO₂ within the state. Such an analysis will allow for the advantages and tradeoffs of different energy futures to be considered.

The geology breakout recommended that geologic assessment be conducted in phases. Phase One, at a cost of about \$0.1M, would assemble existing information, and could include new modeling based on existing seismic data, in order to lay the groundwork for a more rigorous geologic assessment of the CCS potential in the Midcontinent Rift. Bill H.F. 1666, currently before the Minnesota Legislature, could potentially fund Phase One. An important purpose of a Phase I study would be to inform a decision on whether it is warranted to move on to a phase II study. A Phase Two would be a geologic assessment based on new geophysical surveys and about 3 to 6 boreholes, at a cost of perhaps \$5M to \$10M, perhaps through public funding or a public-private partnership. The objective of Phase Two would be to determine whether Geologic Sequestration potential exists in the Midcontinent Rift. If the results of Phase Two are positive, Phase Three would expand the geological assessment to estimate the geologic storage capacity of the Rift, and begin characterizing the most promising sites.

References:

- http://www.geo.umn.edu/mgs/co2_seq.htm
- http://arch.rivm.nl/env/int/ipcc/pages_media/SRCCS-final/IPCCSpecialReportonCarbondioxideCaptureandStorage.htm

TILL GEOCHEMICAL AND INDICATOR MINERAL RECONNAISSANCE OF MINNESOTA

Thorleifson, L. H., K. L. Harris, H. C. Hobbs, C. E. Jennings, A. R. Knaeble, R. S. Lively, B. A. Lusardi, G. N. Meyer, Minnesota Geological Survey, 2642 University Ave West Saint Paul, Minnesota 55114-1057

As a cooperative project of the Minnesota Geological Survey and industry, the entire State of Minnesota and adjacent regions was sampled for till geochemistry and indicator minerals at a 30-km spacing during summer 2004. Within target cells, each a quarter-degree latitude by a half-degree longitude, till from between about 1 and 2 m depth was sampled by filling a 15 liter plastic pail. At a few sites, vertical profiles were collected. In addition, three transects to the north were sampled, to help identify sediments derived by long-distance glacial transport, to obtain reference samples from the Thompson nickel belt, and also to extend sampling to the limit of Hudson Bay-derived carbonate-bearing sediments, to permit comparison to Minnesota carbonate-bearing sediments. Three control samples anomalous in kimberlite indicator minerals from Kirkland Lake, Ontario, were also obtained. The resulting batch consisted of 250 samples covering Minnesota and adjacent areas, 20 samples from Canada, and the three standards. Upon completion of the sampling, the samples were randomized, given numeric laboratory identifications, and shipped to a processing lab, where four quarter-liter splits, two for fine fraction geochemistry, one for texture, and one for an archive were removed. The remaining 14 liters were disaggregated, screened at 2 mm, and the gravel was retained for lithological analysis. The <2 mm fraction was then processed for gold grains, a ferromagnetic heavy mineral concentrate, and a nonferromagnetic heavy mineral concentrate that supported subsequent analysis for precious metal, base metal, and gemstone indicator mineral counts, indicator mineral chemistry, bulk mineralogy counts, and heavy mineral geochemistry. The resulting data are now a significant new information resource with respect to environmental geochemistry topics such as understanding the distribution of deleterious elements in food and water, while providing insights into transport history and composition of the sediments that make up our soil parent materials. Many variables provide insights into regional geology, and reflect known mineral deposits. Some of the data seem to provide faint insights into what may be mineralization that was not previously recognized, such as various base-metal and precious-metal-related elements that show patterns of varying clarity over portions of the state. None of these patterns, however, are obvious discoveries of something that was previously unknown, at the current stage of interpretation. With respect to kimberlite indicator minerals, however, there are two noteworthy patterns, including a few Cr-pyrope garnets in an area from the Twin Cities to southwestern Minnesota (Figure 1), as well as Mg-ilmenites and high-chrome Cr-diopsides in the far north-central part of the State. Sample spacing in the thin sediments of northeastern Minnesota was not adequate to fully test for the presence of sources such as potential single kimberlite pipes, although samples at a closer spacing are presently being processed by Natural Resources Research Institute to address this point. The current results are, however, faint but clear indications of kimberlite indicator minerals sources that are not unlike several of the patterns that have been found, for example, in Canada, where some of such patterns have eventually resulted in kimberlite discoveries. In the case of the Minnesota results, the data may indicate sources

within the state, or quite possibly could be manifestations of long distance glacial sediment transport, possibly from known or unknown sources in neighboring states or in Canada. In summary, the results are a highly significant step forward in mapping our geochemical landscape, in clarifying mineral potential, in provision of reference data useful to environmental protection, public health, and exploration, and in supporting follow-up with respect to potential mineralization.

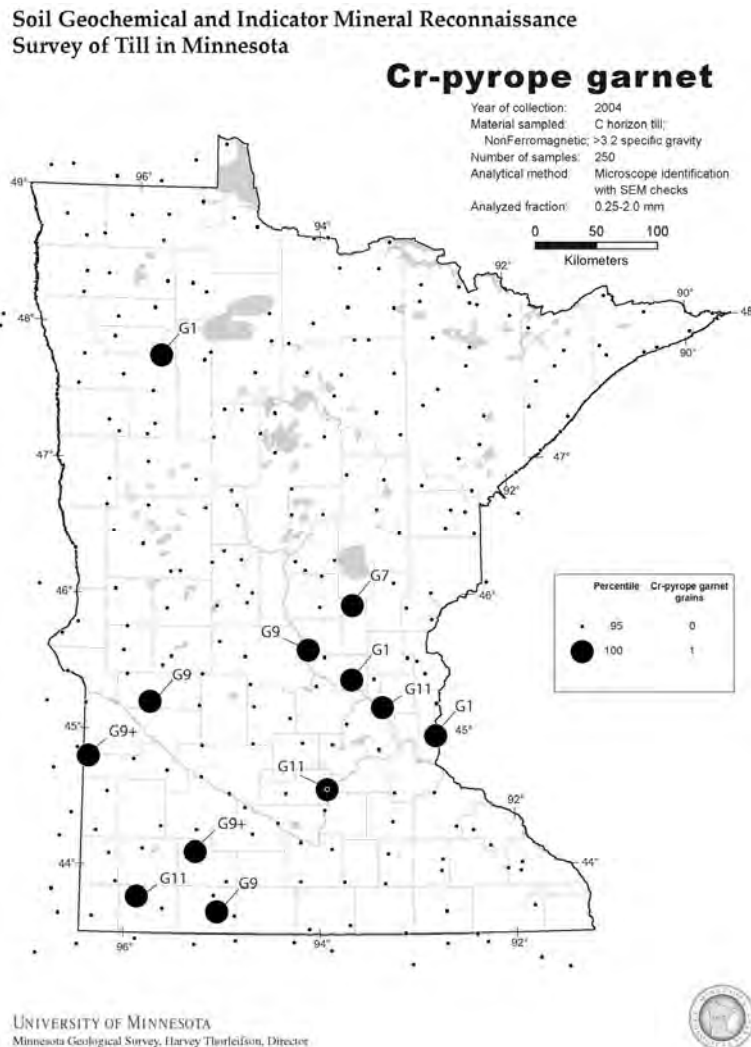


Figure 1: Example of results from the statewide survey

Reference:

Thorleifson, L. H., K. L. Harris, H. C. Hobbs, C. E. Jennings, A. R. Knaeble, R. S. Lively, B. A. Lusardi, G. N. Meyer, 2007, Till geochemical and indicator mineral reconnaissance of Minnesota. Minnesota Geological Survey Open File Report OFR-07-01, 512 p., 15 pdf digital files, 5 digital images

DEFINITION OF THE PROTEROZOIC TERRAIN UNDER THE PALEOZOIC-CENTRAL U.P., MICHIGAN

T.D. WAGGONER

141 CHIPPEWA, NEGAUNEE, MI 49866

E-mail: thomaswaggonergeo@hotmail.com

As soon as it was recognized in the 1880's that the eastern Menominee range was covered by Paleozoic sediments east of Waucedah, exploration has sought to identify iron mineralization under cover in the central Upper Peninsula. For over 100 years work has progressed to identify the sources of the magnetic anomalies that are found west of the NW-SE rift hinge line and the western limit of the Paleozoic cover.

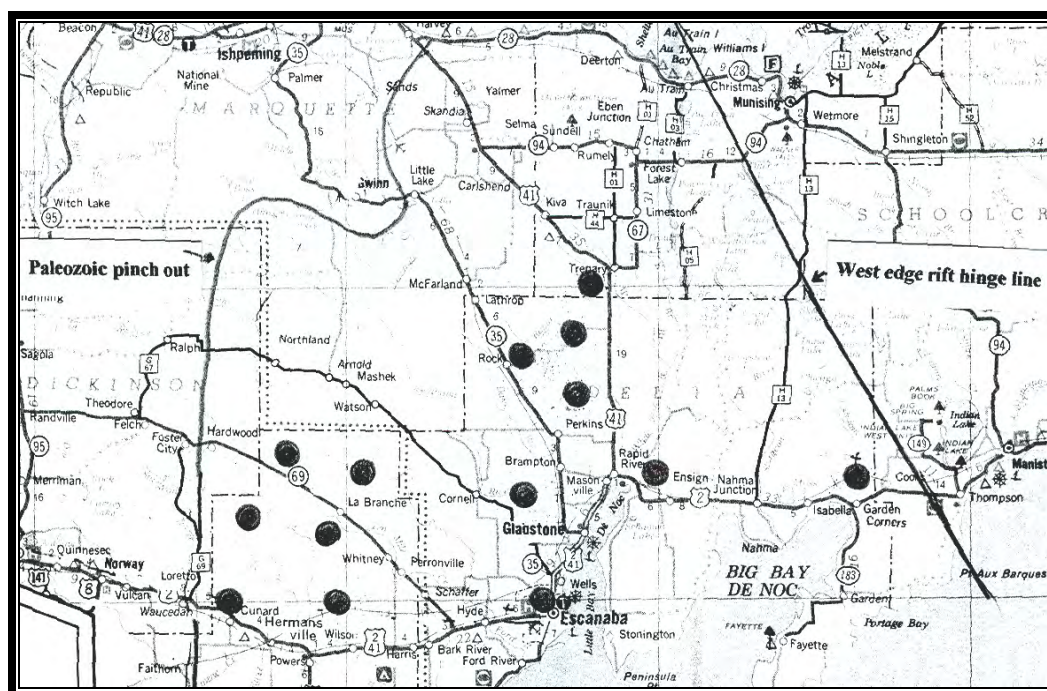


Fig. 1 Magnetic highs under the Paleozoic cover of the central U.P.

The amplitude of the airborne total intensity magnetic anomalies range from 3,000 to 23,000 gammas. The intensity is generally dependent on both the amount of magnetite and depth of burial. Airborne and ground magnetics along with ground gravity defined target areas that have since been drilled in the search for iron ore through the 1970's.

Most of the major anomalies are caused by steeply dipping banded iron formations (bifs) similar to the Proterozoic equivalents that outcrop west of the covered area. The primary iron oxide minerals are magnetite, specularite. These are accompanied by iron carbonate silicates, carbonate and chert. Supergene oxidation and enrichment is present in about half of these deposits. Paleozoic

cover ranges from inches to at least 1800 feet. Associated rocks include slates, quartzites and schists and in one case gneiss. Some of these rocks have been intruded by diabase and granite dikes. The east-west structural attitude of the anomalies and bifs are consistent with outcrop areas to the west.

Metamorphic rank from chlorite through garnet is present as noted by the gangue mineralogy associated with the bifs.

There have been geophysical data bases generated for diamond exploration that would be useful in further defining the buried Proterozoic terrain.

Although economic deposits of bif are probably not present, there is a distinct possibility that IOCG type deposits, feeders for the water deposited bifs are present. Further geophysical surveys like airborne gravity could help provide better definition.

Detrital Zircon Provenance and Structural Geology of the Hamilton Mounds Inlier, Central Wisconsin

Jakob Wartman, John P. Craddock, Karl R. Wirth, Geology Department, Macalester College, St. Paul, MN 55105; e-mail: craddock@macalester.edu
Gordon Medaris, Jr., Dept. of Geol. & Geophysics, UW-Madison, Madison, WI 53706
Jeff D. Vervoort, Dept. of Geology, Washington State Univ., Pullman, WA 99164
Cam Davidson, Geology Department, Carleton College, Northfield, MN 55057

Hamilton Mounds is one of a series of small inliers in Adams County, WI that are composed of Proterozoic quartzites (Oslander, 1931). Exposures in the Seven Sisters quarry at Hamilton Mounds reveal the presence of a lower, folded metasedimentary sequence, the Hamilton Mounds meta-arkose (HMM), that is intruded by granite (1762 ± 7 Ma [2 σ], TIMS-zircons; Medaris et al., 2007). The overlying Seven Sisters orthoquartzite (SSQ) is also folded and contains detrital zircon and monazite that suggest correlation with Baraboo-equivalent quartzites (see Table 1). Finite strains in the Seven Sisters quartzite are also consistent with the regional, NW-SE shortening Mazatzal orogen strain pattern (Craddock and McKiernan, 2007). Both sedimentary units at Hamilton Mounds are crosscut by breccia zones associated with Wolf River batholith intrusion at 1470 Ma. The HMM and SSQ are overlain unconformably by Cambrian sandstones (see Brown and Greenberg, 1986).

Detrital zircons are abundant in the Hamilton Mounds meta-arkose. We analyzed 120 grains of which 68 yielded nearly concordant (<10% discordant) results (Figure 1). The youngest zircon age we observed is 1750 ± 16 Ma (2 σ), the approximate age of the cross-cutting granite dike. The zircon population includes large numbers of post-Penokean (1775 Ma) to Penokean (1800-1875 Ma) grains, and lesser amounts of Archean (2500-3500 Ma) grains. These data suggest that the Hamilton Mound sediments were sourced

Table 1: Summary of Geochronology for Proterozoic Quartzites

<u>Quartzite</u>	<u>n</u>	<u>Method</u>	<u>Youngest Age</u>	<u>Range</u>	<u>Reference</u>
Barron	6*	SHRIMP	1751 Ma	1751-1180 Ma	Holm et al., 1998
Sioux	9*	SHRIMP	1730	1730-1850	Holm et al., 1998
Flambeau	9*	SHRIMP	1714	1714-1880	Holm et al., 1998
McCaslin	2	TIMS	1773	1773-1775	Van Wyck, 1995
Hamilton Mounds					
HMQ1 (SSQ)	69	LA-ICPMS	1772	1772-3566	Van Wyck & Norman
HM-SSQ (m)	11*	Electron Probe	1750	1750-2165	Medaris et al., 2007
HM-Basal (m)	10*	Electron Probe	1720	1720-2120	Medaris et al., 2007
HM-Basal (z)	68	LA-ICPMS	1783	1783-3456	This Study
Baraboo					
Basal	7	TIMS	1691	1691-1865	Medaris et al., 2003
1250 m up	7	TIMS	1844	1844-2588	Van Wyck, 1995
BARQ2	47	LA-ICPMS	1716	1716-3200	Van Wyck & Norman
BARQ1	100	LA-ICPMS	1724	1724-3100	Van Wyck & Norman

[Key: All ages are $^{207}\text{Pb}/^{206}\text{Pb}$. HM is Hamilton Mound, with upper Seven Sisters Quartzite (SSQ) and older, basal arkose (HM-Basal). Detrital monazite (m) and zircons (z) are indicated. Monazite ages (*) are from multiple analyses: Barron (6 grains, 28 spots); Sioux (9/19); Flambeau (9/16); HM-SSQ (11/83) and HM-Basal (10/154)]. Younger HMM monazite ages (<1760 Ma) are from non-detrital grains.

from the north, including the Penokee Mountains, Archean granite-greenstone terranes, and the Marshfield (or Watersmeet) Archean gneiss terranes. This is broadly consistent with detrital zircon results for other contemporaneous units (e.g., Virginia, Rove and Michigamme Fms.; see Wirth et al., 2006) along the Penokean margin. The Hamilton Mound arkose was deformed in the Yavapai orogeny, then eroded and buried by quartz arenites of the Baraboo interval (1750-1630 Ma).

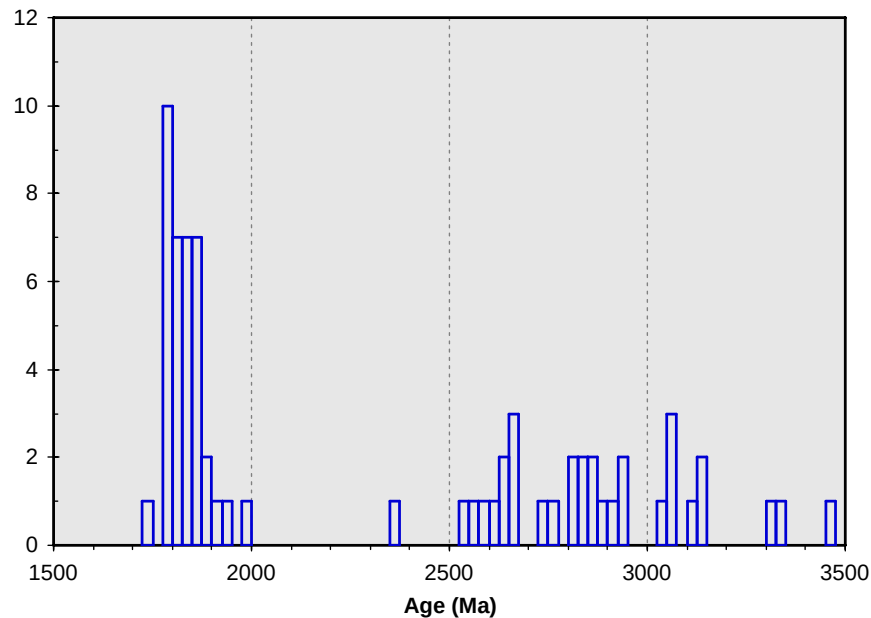


Figure 1. Histogram of detrital zircon ages from basal Hamilton Mound arkosic quartzite.

References Cited

- Brown, B.A. and Greenberg, J.K., 1987, Proterozoic quartzite at Hamilton Mound, central Wisconsin: Geological Society America Centennial Field Guide—North Central Section (DNAG), p. 195-98.
- Craddock, J. P. and McKiernan, A.W., 2007, Finite strain gradient in Baraboo-interval quartzites, Wisconsin and Minnesota, USA: *Prec. Res. Sp. Vol.*
- Holm, D., Schneider, D., and Coath, C.D., 1998, Age and deformation of Early Proterozoic quartzites in the southern Lake Superior region: Implications for extent of foreland deformation during final assembly of Laurentia. *Geology*, v. 26, p. 907-910.
- Medaris, L.G., Singer, B.S., Dott, R.H., Naymark, A., Johnson, C.M., Schott, R.C., 2003. Late Paleoproterozoic climate and tectonics in the southern Lake Superior region and Proto-North America: Evidence from Baraboo interval quartzites: *J. Geol.*, v. 111, p. 243-257.
- Medaris, L.G., Van Schmus, W.R., Loofboro, J., Stonier, P.J., Zhang, X., Holm, D.K., Singer, B.S., Dott, R.J., Jr., in press, Two Paleoproterozoic (Statherian) siliciclastic metasedimentary sequences in central Wisconsin: the end of the Penokean orogeny and cratonic stabilization of the southern Lake Superior region: *Precambrian Research*.
- Ostrander, A.R., 1931, Geology and structure of Hamilton Mounds, Adams County, Wisconsin: unpublished M.S. thesis, Univ. of Wisconsin, Madison, 27 p.
- Van Wyck, N., 1995, Major and trace element, common Pb, Sm-Nd, and zircon geochronology constraints on petrogenesis and tectonic setting of pre- and early Proterozoic rocks in Wisconsin. unpublished Ph.D. thesis, Univ. of Wisconsin, Madison, 47-280.
- Van Wyck, N. and Norman, M., 2004, Detrital zircon ages from early Proterozoic quartzites, Wisconsin, support rapid weathering and deposition of mature quartz arenites: *J. Geol.* 112, p. 305-315.
- Wirth, K.R., Vervoort, J., Craddock, J.P., Davidson, C., Finley-Blasi, L., Kerber, L., Lundquist, R., Vorhies, S., and Walker, E., 2006, Source rock ages and patterns of sedimentation in the Lake Superior region: results of preliminary U-Pb detrital zircon studies: *52nd Institute on Lake Superior Geology*, p. 69-71.

A Comparison of Textural Profiles in Diabase Sills from the Midcontinent and Transantarctic Rifts

ZIEG, Michael J. and FORSHA, Clinton J., Department of Geography, Geology, and the Environment, Slippery Rock University, 1 Morrow Way, Slippery Rock, PA 16057, USA, michael.zieg@sru.edu

The 176-Ma Ferrar Dolerite of the Transantarctic Rift (TAR) and the 1.1-Ga Nipigon Diabase of the Midcontinent Rift (MCR) represent magmatic activity during the early stages of continental rifting. Both of these systems include large sills intruded at or near the unconformity between basement rock and overlying sedimentary sequences (the Beacon Group and Sibley Group). Understanding the emplacement history of these sill complexes is critical to understanding the thermal and mechanical properties of the developing rifts. As in the Nipigon area, there are very few feeder dikes exposed in the Ferrar system. Thus, it has been suggested that a significant proportion of the magma transport in the TAR occurred within the sills themselves. Hart and Macdonald (2005) and Sutcliffe (1987, 1989) have suggested, and this work provides additional evidence, that the Nipigon sills experienced multiple injections of magma, which may be an indication that the sills acted as conduits for the distribution of magma through the system. Focused magma flow results in a very different thermal environment than episodic, discrete injection events, and therefore it is very important to understand the nature of the injection history when evaluating the tectonic development of a magmatically active region.

In this study, we focus on the application of textural stratigraphy within mafic sills to the understanding of sill emplacement history. In particular, textural profiles from Nipigon sills are compared to profiles from Ferrar sills. These comparisons illustrate the textural signatures of singular, pulsed, and flow-differentiated injections. While the Nipigon sill from Kama Point exhibits a strong reinjection signature, the reinjection signatures in the Antarctic sills are less clear.

The significance of different injection histories is that, while a network of sills and dikes emplaced via single injection events can efficiently distribute heat through a large crustal volume, reinjection and/or extended flow through a sill or dike can produce higher temperatures, though in a more localized volume.

References

- Hart, T.R., and McDonald, C.A. 2005. Mesoproterozoic diabase sills of the Nipigon Embayment, northwest Ontario. *In* Institute on Lake Superior Geology Proceedings, 51st Annual Meeting, Nipigon, Ontario, Vol. 51, Part 1, pp. 22-23.
- Sutcliffe, R.H. 1987. Petrology of middle Proterozoic diabases and picrites from Lake Nipigon, Canada. *Contributions to Mineralogy and Petrology*, **96**: 201-211.
- Sutcliffe, R.H. 1989. Mineral variation in Proterozoic diabase sills and dykes at Lake Nipigon, Ontario. *Canadian Mineralogist*, **27**: 67-79.