



INSTITUTE ON LAKE SUPERIOR GEOLOGY

**54TH ANNUAL MEETING
MAY 6-10, 2008
MARQUETTE, MICHIGAN**

HOSTED BY:
Michigan Technological University

**THEODORE J. BORNHORST AND JOHN S. KLASNER
Co-Chairs**

Proceedings Volume 54 Part 1 – Program and Abstracts

EDITED BY THEODORE J. BORNHORST AND GEORGE W. ROBINSON

A. E. SEAMAN MINERAL MUSEUM, MICHIGAN TECHNOLOGICAL UNIVERSITY

**Cover Photos: Lake Superior region minerals in the collection
of the A.E. Seaman Mineral Museum**

Top Left Clockwise: amethyst – Thunder Bay, Ontario; gold – Balmertown, Ontario; silver – Silver Islet, Ontario; copper – Phoenix, MI; goethite – Ishpeming, MI; gypsum – Crystal Falls, MI; chalcocite – Ladysmith, WI; rhodochrosite – Montreal, WI
(photographs by George Robinson and John Jaszczak)

54TH INSTITUTE ON LAKE SUPERIOR GEOLOGY

PROCEEDINGS VOLUME 54 CONSISTS OF:

PART 1: PROGRAM AND ABSTRACTS

PART 2: FIELD TRIP GUIDEBOOK

TRIP 1: BANDED IRON FORMATION OF THE MARQUETTE DISTRICT

TRIP 2: ARCHEAN-PALEOPROTEROZOIC UNCONFORMITY AT SILVER LAKE—SEISMITES
FROM THE SUDBURY IMPACT?

TRIP 3: GEOLOGY OF THE BACK FORTY PROJECT

TRIPS 4 AND 8: GEOLOGY OF THE EAGLE PROJECT.

TRIP 5: THE SUDBURY IMPACT LAYER AT THE MCCLURE LOCALITY

TRIP 6: SUSTAINABLE RECOVERY OF IRON FROM THE MARQUETTE DISTRICT

TRIP 7: GEOLOGY OF THE KEWEENAWAN BIC INTRUSION

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

Cannon, W.F. and Schulz, K.J., 2008, Unusual features along the Archean/Paleoproterozoic unconformity at Silver Lake, Michigan—seismites from the Sudbury impact [abstract]: Institute on Lake Superior Geology Proceedings, 54th Annual Meeting, Marquette, MI, v. 54, part 1, p. 10-11.

Published by the 54th 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 54

PART 1— PROGRAM AND ABSTRACTS

Institutes on Lake Superior Geology, 1955-2008.....	iv
Sam Goldich and the Goldich Medal.....	vi
Goldich Medal - Past Medalists and Committee	viii
Citation for 2008 Goldich Medal Recipient.....	ix
ILSG Student Research Fund.....	xi
Student Paper Awards.....	xii
Eisenbrey Student Travel Awards	xiii
Report of the Chair of the 53rd Annual Meeting.....	xiv
2008 Board of Directors.....	xvii
2008 Session Chairs.....	xvii
2008 Student Paper Awards Committee.....	xvii
2008 Local Committees	xvii
Special Recognition	xviii
2008 Banquet Speaker	xix
Program.....	xxi
Abstracts	xxix

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.
54	2008	Marquette, Michigan	T.J. Bornhorst and J.S. Klasner

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

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

The initial Goldich Award was presented to Sam by G.B. Morey in 1979 and consisted of a large paper proclamation. For the actual medal, G.B. Morey consulted with the foundry on production details, while Dick Ojakangas and Jorma Kalliokoski worked on the design of the award, suggesting that it be given for "outstanding contributions to the geology of the Lake Superior region." Simultaneously, a committee of J.O. Kalliokosi, W.F. Cannon, M.M. Kehlenbeck, G.B. Morey, and G. Mursky developed the Award Guidelines that were approved by the ILSG Board. By 1981 all the elements of the Goldich Award had come together, and the

second recipient, Carl E. Dutton, Jr., received the Goldich Medal for 50 years of significant contributions to the understanding of the geology of the Lake Superior region. Since the beginning, the Awards Committee has consisted of individuals representing industry, government and academia, with each member of the Committee serving for three years. The medal is now awarded every year at the annual ILSG meeting.

Reference:

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

Prepared by various Goldich Medal Awardees, 2007



INSTITUTE ON LAKE SUPERIOR GEOLOGY GOLDICH MEDAL

PAST GOLDICH MEDALISTS

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

2008 GOLDICH MEDAL RECIPIENT

Theodore J. Bornhorst

Michigan Technological University
Houghton, Michigan

GOLDICH MEDAL COMMITTEE

Serving for the meeting year shown in parentheses

Doug Duskin (2005-2008)

Richard Ojakangas (2006-2009)

Terry Boerboom (2007-2010)

Industry representative

Academic representative

Government representative

CITATION FOR GOLDICH MEDAL RECIPIENT

Theodore J. Bornhorst, 2008 Goldich Medal Recipient

It is my great pleasure to introduce Professor Ted Bornhorst as the recipient of the 2008 Goldich Medal. Ted is being honored with this award for his many contributions to the understanding of Lake Superior geology through his research and teaching and, most significantly, for his unparalleled service to the Institute over the past 25 years.

Ted began (and will likely finish) his geological career at Michigan Technological University. He received his B.S. from Michigan Tech in 1974 and actually presented his first ILSG talk at that year's meeting in Sault St. Marie on the topic of his senior research project - the geology and geochemistry of the Fish Cove rhyolite in Keweenaw County. Ted headed to the University of New Mexico to complete his M.S. (1976) and Ph.D. (1980) degrees in economic geology only to return to Michigan Tech as an assistant professor in 1981. Ted received a full professor appointment in 1993 and was appointed director of the world class A.E. Seaman Mineral Museum at Michigan Tech in 2003.

During his tenure at Michigan Tech, Ted has taught classes, advised students, and conducted research on a variety of topics and in a range of locations (e.g., gold in Finland, rhyolites in New Mexico, quaternary volcanic ashes off the coast of Guatemala). But by far, the main emphasis of his academic pursuits has been the Precambrian geology and mineral deposits of Upper Michigan. A true indication of his passion for Lake Superior geology is the fact that Ted has directed a five-week intensive Precambrian field course in the western UP almost every summer since arriving at Michigan Tech in 1981. This course has been taken by over 500 students. I would be willing to bet that the approximately 7000 students who have taken the introductory geology course from Professor Bornhorst since 1989 have probably received a hefty dose of Lake Superior geology, as well.

Ted has advised (to completion) 4 Ph.D. dissertations, 24 M.S. theses, and 29 senior research projects, almost all dealing with Lake Superior geology. In addition to being the advisor and mentor for scores of Michigan Tech geology students, many of whom still do research and mineral exploration work in the Lake Superior region, Ted also serves the general public and the geological community by being a member of the State of Michigan's Mineral Well Advisory Committee, representing the western Upper Peninsula. And because of his knowledge of UP geology and mineral deposits, Ted has been appointed to many state committees and boards looking into rules and regulations for non-ferrous mineral exploration and mining in the state.

Ted's research interests in the Lake Superior region have focused on three general areas: the Cu deposits of the Keweenaw Peninsula, the geology and mineral potential of the Ishpeming greenstone belt, and the petrology of granitoids in the Archean Northern Complex. Ted has been first or second author on over 50 journal publications. Of these, 19 were on topics dealing with Lake Superior geology. He has authored 16 field trip guides and 15 maps and technical reports on the geology and ore deposits of Upper Michigan.

Beyond this impressive resume of academic contributions to the geology of the Lake Superior region, perhaps the main reason that Ted is so deserving of the Goldich award is his unwavering commitment and very real service to the ILSG. Ted's impressive list of contributions to the institute include:

- Presenting 10 abstracts and coauthoring many more of his student's presentations.
- Organizing, writing guidebooks for, and leading 6 field trips; most impressive of these has been the Field Guide to the Geology of the Keweenaw Peninsula, by Bornhorst, Rose, and Paces. This now classic guidebook, which was originally published in 1983 and re-published in 1994, has sold over 5,000 copies to geologists and non-geologists alike.
- Serving as chairman or co-chairman of 4 annual meetings: 1983 (Houghton), 1994 (Houghton), 1999 (Marquette), and now 2008 (Marquette).
- Serving as the Institute's first webmaster beginning in 1995 and maintaining the ILSG webpage until 2004, when the position passed over to the Secretary-Treasurer.

It is the exceptional contributions and service given by individuals like Ted Bornhorst that has sustained the ILSG over these past 54 years. As token of the Institute's appreciation, it is altogether fitting and appropriate that Ted join the ranks of other prominent Lake Superior geologists who have been honored with this prestigious award. I know I speak for all the institute members when I say "thank you, Ted, for all you have given the Institute."

Jim Miller
University of Minnesota Duluth

ILSG STUDENT RESEARCH FUND

The 2005 Board of Directors established the ILSG Student Research Fund with \$10,000 US from the Institute's general fund to encourage student research on the geology of the Lake Superior region. A minimum of two awards of \$500 US each for research expenses (but not travel expenses) will be made each year. Students are expected to present their research orally or during a poster session at an ILSG meeting. The award winners will also be automatically eligible for the Eisenbrey Travel Awards. To allow the fund to grow, the Fund will receive one-half of any additional proceeds from each annual meeting, after all other commitments and expenses are covered.

- The ILSG Board of Directors will be responsible for selecting a minimum of two awards each year. The ILSG Treasurer will issue the awards.
- The ILSG Student Research Fund is available for undergraduate or graduate students working on geology in the Lake Superior region.
- The applications are due to the ILSG Secretary by August 31st of each year. Awards will be made by October 1st of each year.
- Names of the award recipients will be announced at the next annual meeting and posted on the ILSG website.
- 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 and 2007 the ILSG Board of Governors awarded three \$500 awards from the Student Research Fund.

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 2007 the ILSG Student Paper Committee presented four awards from the ILSG Student Paper Fund. Two first place Best Student Paper awards: (\$200 each) were given to:

Sarah Nicholas (Macalester College) for her poster titled: *Investigations of sulfide minerals leached in the presence of alkaline solids*

Noah Planavsky (Rosentiel School of Marine and Atmospheric Science) for his talk titled: *Rare earth element patterns in Steep Rock Carbonates.*

Two Honorable Mention Best Student Paper awards (\$100 each) were given to:

Troy Boisjoli (St. Norbert College)

Larissa Stevens (Lakehead University)

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 2007 the ILSG awarded 15 travel awards from the ILSG Eisenbrey Student Travel Fund. The awards were made to:

Malcolm Alexander – Lakehead University
Troy Boisjoli – St. Norbert College
Dan Costello – St. Norbert College
Clinton Forsha – Slippery Rock University
Amanda Hogan – St. Thomas University
Carissa Isaac – Lakehead University
Travis Jacob – St. Thomas University
Renata Jasinevicius – St. Norbert College
Noah Planavsky – Rosentiel School of Marine and Atmospheric Science
Patrick Quigley – University of Minnesota, Duluth
Tommy Rodengen – St. Thomas University and
Jody Rymaszewski – University of Wisconsin-Milwaukee
Larissa Stevens – Lakehead University
Michael Taylor – University of Minnesota, Duluth
Stephanie Theriault – St. Thomas University

**REPORT OF THE CHAIRS OF THE 53RD ANNUAL MEETING
INSTITUTE ON LAKE SUPERIOR GEOLOGY
LUTSEN, MINNESOTA**

The U.S. Geological Survey with assistance from the Minnesota Geological Survey hosted the 53rd Annual Institute on Lake Superior Geology on May 8 – 13, 2007 at Lutsen Resort in Lutsen, Minnesota. The meeting consisted of two days of technical sessions with pre- and post-technical session field trips. Bill Cannon and Klaus Schulz helped with pre-meeting logistics. Gretchen Klasner provided valuable logistical assistance on-site at Lutsen Resort during the technical sessions. Connie Dicken and Bill Addison were media czars for the technical sessions, keeping all presentations on track with fewer glitches than normal. Pre-meeting registration was 114 students and professionals with an additional 69 on-site registrations, for a total of 183 registrants, an excellent turn-out.

Proceedings Volume 53 was published in two parts. Part I – Program and Abstracts, edited by Laurel Woodruff, contains 49 published abstracts for 28 oral and 21 poster presentations; Part 2 – Field Trip Guidebook, edited by Jim Miller, contains descriptions of six field trips, three pre-meeting and three post-meeting.

The 53rd ILSG marked the first time in its long history that an ILSG meeting was held in this part of Minnesota. Field trips visited areas new to the ILSG, which resulted in an excellent subscription for all the trips. On Tuesday, May 8, Jim Miller and Eric Jerde led an intrepid group of 8 participants on a two-day field trip into the Boundary Waters Canoe Area Wilderness to examine the mafic igneous rocks of the Poplar Lake Intrusion. Based out of the Rockwood Lodge off the Gunflint Trail, the trip required canoeing across Poplar Lake and several lakes farther into the BWCAW, only two weeks after ice-out! Thanks to warm weather, the couple of “soggy mishaps” served only as fodder for the Homer Award (way to go Steve!). On Wednesday David Cooper, from the National Park Service, Bill Cannon, and Brian Phillips guided 18 participants on a trip through the Grand Portage National Monument, looking at both the geological and cultural history of the area. Another trip on Wednesday into southern Ontario to look at Midcontinent Rift-related intrusions north of the international border involved 31 participants and was lead by Mark Smyk and Pete Hollings. A misstep on the outcrop on that trip resulted in an injury to former Goldich Medal recipient and long-time ILSG stalwart Dick Ojakangas, who unfortunately had to miss the rest of the meeting as he returned to Duluth for treatment.

Throughout the meeting, the 60 people who had signed up for Mark Jirsa’s and Paul Weiblen’s Gunflint field trip were closely tracking the Ham Lake fire as it burned across the northern end of the Gunflint Trail. (The Poplar Lake Trip was far enough south of the fire to proceed, though the smoke plume was clearly visible). A final decision by the Forest Service closed the upper part of the Gunflint Trail on Friday and put the kibosh on any hope of running even a modified Gunflint Trail trip. Instead, Mark and Paul, with generous assistance from Bill Addison and Phil Fralick, quickly reconfigured the trip for a visit to the Thunder Bay area to see similar rocks as well as spectacular outcrops of Sudbury impact-related rocks. All of us involved appreciate the forbearance of seasoned and new ILSG attendees who were remarkably sanguine about the travails of the Gunflint Trail trip. Most of the people originally signed up for the Gunflint Trip

stayed on for the substitute Thunder Bay trip, and we heard of no one being disappointed. One consolation from the cancellation is the Gunflint's future potential as a field trip area for ILSG and enhanced exposure of rocks in burned areas, including newly discovered Sudbury ejecta layers found by Mark Jirsa while sneaking past the DO NOT CROSS signs on the Trail.

Also on Saturday, Terry Boerboom, John Green and Jim Miller led 16 participants on a field trip along the spectacular shoreline geology of the North Shore from Little Marais to Grand Marais to highlight some recent detailed mapping. A very timely and popular two-day trip lead by Dean Peterson and Paul Albers (of Duluth Metals) set off for Ely on Saturday with a group of 20 participants. The trip looked at the geology and Cu-Ni-PGE mineralization of the Nickel Lake macrodiike and South Kawishiwi Intrusion of the Duluth Complex.

One hundred and fifty participants attended the banquet on Thursday night, even without the prospect of dessert. This year's banquet speaker was Don Hunter, who is a Project Manager for the PolyMet Mining Corporation's NorthMet copper-nickel project near Babbitt, MN. Mr. Hunter drew on his long international career in the mining industry for his talk on the ins-and-outs of mineral exploration around the globe. The Powerpoint presentation of the informal 'Homer' award suffered from severe homerism itself due to an uncooperative projector, but eventually Steve Kissin was honored for his canoeing acumen. As always, a highlight of the banquet was the presentation of the 2007 Goldich medal to Joe Mancuso, retired professor from Bowling Green University in Bowling Green, OH. The medal was presented to Joe by Ron Seavoy, who ended his citation with "Joe, you deserve this," a sentiment echoed by all who know Joe and his long-term contributions to the geology of the Lake Superior region.

The student paper committee had its usual difficult job this year of selecting among 16 student oral and poster presentations. This year's committee was Marcia Bjornerud from Lawrence University, Daniela Vallini of Woodside Energy, Ltd., and Graham Wilson from Magma Metals. In the end, two first place Best Student Paper awards (\$200 each) were given to Sarah Nicholas (Macalester College) for her poster titled: *Investigations of sulfide minerals leached in the presence of alkaline solids*, and Noah Planavsky (Rosentiel School of Marine and Atmospheric Science) for his talk titled: *Rare earth element patterns in Steep Rock Carbonates*. In recognition of the excellent student presentations, two additional students were chosen for Honorable Mention (\$100 each) – Troy Boisjoli (St. Norbert College) and Larissa Stevens (Lakehead University). Eisenbrey Student Travel Grants were given to 15 students: Patrick Quigley and Michael Taylor – University of Minnesota, Duluth; Malcolm Alexander, Carissa Isaac, and Larissa Stevens – Lakehead University; Troy Boisjoli, Dan Costello and Renata Jasinevicius, – St. Norbert College; Clinton Forsha – Slippery Rock University; Amanda Hogan, Travis Jacob, Tommy Rodengen, and Stephanie Theriault – St. Thomas University; Jody Rymaszewski – University of Wisconsin-Milwaukee; and Noah Planavsky – Rosentiel School of Marine and Atmospheric Science. All awards were presented at the conclusion of the technical sessions. Two of the presentations at the meeting were made by recipients of the 2006 ILSG Student Research Fund, Michael Taylor and Noah Planavsky.

The Institute's Board of Directors met on May 8, 2007 and a brief overview of the meeting is provided below:

1. Accepted the Report of the Chair for the 52nd ILSG from Ron Sage and minutes of last Board meeting from ILSG secretary, Pete Hollings.
2. Accepted the 2006-2007 ILSG Financial Summary from ILSG treasurer, Mark Jirsa.
3. Approved one co-chair from the 53rd meeting, Jim Miller, as on-going board member.
4. Nominated Terry Boerboom of the Minnesota Geological Survey to replace Tom Hart on the Goldich Committee, a position that Terry later graciously accepted.
5. Approved Marquette, Michigan as the location for the 2008 (54th annual) ILSG and co-chairs Ted Bornhorst and John Klasner.
6. Discussed the continued scanning of the ILSG publications and posting of those electronic publications on the ILSG website

The 53rd ILSG meeting was a great success and we wish to thank all the people who contributed to that success. The staff of Lutsen Resort was professional and responsive to the needs of a large group. The setting on the shore of Lake Superior was stunning, and the weather was perfect (fire-weather, apparently). The field trips this year had a large number of participants, and thanks are due to field trip leaders, van and bus drivers, and everyone else who stepped up when needed to drive, sort lunches, lay out core, or keep the crowds moving. As always, everyone who attended the 53rd ILSG was willing to help as necessary or adapt to any situation that developed. The meeting this year was well attended and we are heartened by the excellent student participation and attendance, a trend we hope continues.

Jim and I were very pleased with the outcomes of the 53rd ILSG and hope that others agree that the meeting was a big success. Chairing a meeting requires a lot of organization and planning with a significant time commitment, and we thank our respective organizations for their recognition of the importance of the ILSG. We also thank the ILSG community and members who make the experiences of the co-chairs almost fun, especially once the meeting is over and we encourage others to take on the task.

Laurel Woodruff and Jim Miller
Co-Chairs, 53rd Institute on Lake Superior Geology

2008 BOARD OF DIRECTORS

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

Theodore J. Bornhorst and John S. Klasner, Co-Chairs 54th meeting (2011)

Michigan Technological University, MI and retired Western Illinois University, IL

Jim Miller (2010)

University of Minnesota Duluth, MN

Ann Wilson (2009)

Ontario Geological Survey, South Porcupine, ON

Mark Smyk (2008)

Ministry of Northern Development and Mines, Thunder Bay, ON

Peter Hollings – Secretary (2008)

Lakehead University, Thunder Bay, ON

Mark A. Jirsa – Treasurer (2009)

Minnesota Geological Survey, St. Paul, MN

2008 SESSION CHAIRS

Marcia Bjornerud, Lawrence University, Appleton, WI

Milt Gere, Michigan DNR, Lansing, MI

Elizabeth A. Gordon, St. Norbert College, De Pere, WI

Joe Maki, Michigan DEQ, Office of Geological Survey, Gwinn, MI

Penny Morton, University Minnesota, Duluth, MN

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

Glenn Scott, Cliffs Mining Service Company

George J. Hudak, University of Wisconsin, Oshkosh, WI

2008 STUDENT PAPER COMMITTEE

Allan Blaske (Chair), STS, Lansing, MI

Melanie Humphrey, Michigan DEQ, Office of Geological Survey, Gwinn, MI

Laurel Woodruff, U.S. Geological Survey, Mounds View, MN

2008 COMMITTEES

General Co-Chairs

Theodore J. Bornhorst – Michigan Technological University, Houghton, MI

John S. Klasner – Retired Western Illinois University, Macomb, Illinois

Program and Abstracts Editors

Theodore J. Bornhorst and George W. Robinson

Michigan Technological University

Field Trip Guidebook Editors

John S. Klasner – Retired Western Illinois University

Theodore J. Bornhorst – Michigan Technological University

Local Registration

Gretchen Klasner – Marquette, MI

Registration

Darlene M. Comfort – Michigan Technological University

SPECIAL RECOGNITION

The Co-Chairs of the 54th Annual Institute on Lake Superior Geology wish to give special recognition to several corporations for their generous financial support.

Kennecott Minerals Company

A Member of the Rio Tinto Group
Eagle Project
1004 Harbor Hills Dr
Marquette, MI 49855

Cliffs Mining Services Company

Subsidiary of Cleveland-Cliffs Inc.
550 E. Division St.
Ishpeming, MI 49849

Aquila Resources Inc.

U.S. Office:
Suite 310 - 314 W.
Superior Street
Duluth, MN 55802

STS

401 S. Washington Square, Suite 103
Lansing, MI 48933
1-800-959-4261

www.sts.aecom.com

Other STS offices in the Great Lakes region:

Marquette, Michigan; Green Bay, Wisconsin; Minneapolis, Minnesota

2008 BANQUET SPEAKER

Jon Cherry

General Manager
Kennecott Minerals - Eagle Project
Marquette, MI

The Kennecott Eagle Project



PROGRAM

TUESDAY MAY 6, 2008

8:00 a.m. **FIELD TRIP 1: BANDED IRON FORMATION OF THE MARQUETTE DISTRICT**
Tom Waggoner, retired, Cliffs Mining Services Company

WEDNESDAY MAY 7, 2008

8:00 a.m. **FIELD TRIP 1 CONTINUED: BANDED IRON FORMATION OF THE MARQUETTE DISTRICT**
Tom Waggoner, retired, Cliffs Mining Services Company

8:00 a.m. **FIELD TRIP 2: ARCHEAN-PALEOPROTEROZOIC UNCONFORMITY AT SILVER LAKE—SEISMITES FROM THE SUDBURY IMPACT?**
Bill Cannon, *U.S. Geological Survey*

8:00 a.m. **FIELD TRIP 3: GEOLOGY OF THE BACK FORTY PROJECT**
Tom Quigley and Bob Mahin, *Aquila Resources Inc.*

8:00 a.m. **FIELD TRIP 4: GEOLOGY OF THE EAGLE PROJECT**
Andrew Ware and Jon Cherry, *Kennecott Minerals Inc.*
Xin Ding, *Indiana University*

6:00 p.m. **Return of Trips 1, 2 3, and 4**

4:00 p.m. - 10:00 p.m. **Registration at Ramada Inn**

7:00 p.m. - 10:00 p.m. **Ice Breaker Social and Poster Session**

THURSDAY MAY 8, 2008

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

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

8:30 a.m. **INTRODUCTORY REMARKS**
Theodore J. Bornhorst and John S. Klasner, Co-Chairs, 2008 ILSG

TECHNICAL SESSION I

Session Chairs: **Milt Gere**, Michigan DNR, Lansing, MI
Penny Morton, University Minnesota, Duluth, MN

8:40 a.m. **Peter Hollings and Mark Smyk**

Whatever Happened to the Logan Sills? Ongoing Research into the Geochemistry of Midcontinent Rift-related Mafic Intrusive Rocks South of Thunder Bay

9:00 a.m. **Curtis D. Williams*, Edward M. Ripley, and Chusi Li**

The Effect of Magmatic Volatile Phase Separation Linked to Intrusion of the Duluth Complex: Solution to Anomalous Os Isotopic Compositions of the Virginia Formation?

9:20 a.m. **Duncan J. Bain***

The Shakespeare Cu-Ni-PGE Deposit: Evidence for a Two-Stage Emplacement Mechanism

9:40 a.m. **Xin Ding*, Edward M. Ripely and Li C**

Geochemical and Stable Isotope Studies of Hydrothermal Alteration Associated with the Eagle Deposit, Northern Michigan

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

10:20 a.m. **Natalie J. Pietrzak*, Norm Duke, Glenn Scott and Helen Lukey**

A Study of the Paragenetic Stages of Mineral Growth in Complex Iron Ores at the Tilden Mine and Development of a Mine Scale Model for Application to Ore Treatment Methods

10:40 a.m. **Muatala H. Muvi-Tjikalepo, Theodore J. Bornhorst, George W. Robinson and W.C. Williams**

Multi-element Geochemical Signature of Copper Mineralization at the White Pine Mine, Midcontinent Rift System, Western Upper Peninsula, Michigan

11:00 a.m. **Natalie King***

Using Mineralization to Evaluate Small-Scale Controls on Shale Permeability in the Nonesuch Formation

11:20 a.m. **Mary Louise Hill and Andrew Cheatle**

Iron-formation-hosted gold in the Superior Province of Northwestern Ontario

11:40 a.m. **Lunch Break – 2008 ILSG Board Meeting** (by invitation)

TECHNICAL SESSION II

Session Chairs: **Klaus Schulz**, U.S. Geological Survey
Glenn Scott, Cliffs Mining Service Company

- 1:00 p.m. **T.W. Buchholz, A.U. Falster and Wm. B. Simmons**
Observations on Lanthanide Fractionation in the Wausau Complex, Marathon County, Wisconsin
- 1:20 p.m. **G.J. Baldwin*, P.C. Thurston, B.S. Kamber, and M.G. Houle**
The Deloro-Tisdale SIZ of the Abitibi Greenstone Belt: An Example from McArthur Township, Ontario
- 1:40 p.m. **Patrick Moran*, Philip Fralick, Mary Louise Hill, and Peter Hollings**
Geochemistry of Sedimentary Rocks associated with the Musselwhite Gold Deposit, Northwestern Ontario
- 2:00 p.m. **Carrissa Isaac* and Pete Hollings**
Stable Isotope Geochemistry of the Musselwhite Au Mine, N. Ontario: Implications for Mineralization
- 2:20 p.m. **COFFEE BREAK AND POSTER SESSION**
- 2:20 p.m. **Norman Duke**
Evidence for Reactivating Archean Structural Breaks During Paleoproterozoic Rift Sedimentation and Subsequent Accretionary History "Once a Fault Always a Fault"
- 3:00 p.m. **Susan M. Karberg***
Structural and Kinematic Analysis of the Mud Creek Shear Zone, Northeastern Minnesota; Implications for Archean (2.7 Ga) Tectonics
- 3:20 p.m. **Emerald J. Erickson* and Vicki Hansen**
Structural and Kinematic Analysis of the Archean Shagawa Lake Shear Zone, Superior Province, Northeastern Minnesota
- 3:40 p.m. **Sally Goodman***
Structural and Kinematic Analysis of the Kawishiwi Shear Zone, Superior Province: Insight on Granite-Greenstone Terrain Tectonics and Archean Crustal Evolution

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

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

- **Announcement of 55th Annual Meeting Location**
 - **2008 Goldich Award Presentation to Ted Bornhorst**
 - **2008 Banquet Address by Jon Cherry, Kennecott Minerals Company**
- All registered participants are welcome to the banquet address
-
-

FRIDAY MAY 9, 2008

8:50 a.m. **INTRODUCTORY REMARKS**

Theodore J. Bornhorst and John S. Klasner, Co-Chairs, 2008 ILSG

TECHNICAL SESSION III

Session Chairs: Elizabeth A. Gordon, St. Norbert College, De Pere, WI

George J. Hudak, University of Wisconsin, Oshkosh, WI

9:00 a.m. **M.G. Mudrey Jr., Peter Hollings, Lura E. Joseph, Mark Jirsa and Jo Kalliokoski**

On-line Electronic Access to Institute on Lake Superior Geology Publications

9:20 a.m. **A.E. Hanson and B.A. Frey**

MN DNR Drill Core Evaluation Project—The Application of an XRF to Elucidate Gold Mineralization in the Vermilion Greenstone

9:40 a.m. **E.M. Fein*, E.C. Ferré and D.K. Holm**

Flow Fabric Determination of Two Mesoproterozoic Midcontinent Rift Dike Swarms, Northeastern Minnesota

10:00 a.m. **Val W. Chandler and Richard S. Lively**

Upgrade of Aeromagnetic Data at the Minnesota Geological Survey

10:20 a.m. **COFFEE BREAK AND LAST POSTER SESSION**

10:40 a.m. **Lauri J. Pesonen**

Keweenawan Apparent Polar Wander Path: New Observations , New Ideas

11:00 a.m. **James D. Miller, Dean M. Peterson, and George J. Hudak**

The Inaugural Season of the Precambrian Field Camp at the University of Minnesota Duluth

11:20 a.m. **Rodney Johnson, Robert Seasor, and Tom Suszek**

An Archean-aged PGE-bearing Intrusion, Baraga County, Michigan

11:40 a.m. **R.M. Easton and L.M. Heaman**

Detrital Zircon Geochronology of Huronian Supergroup Sandstones located within the Vernon Structure, North of Espanola, Ontario

12:00 p.m. **Presentation of Student Awards**

Student Travel Awards

Best Student Paper Awards

12:00 p.m. **LUNCH BREAK**

TECHNICAL SESSION IV

Session Chairs: Marcia Bjornerud, Lawrence University, Appleton, WI

Joe Maki, Michigan DEQ, Office of Geological Survey, Gwinn, MI

1:00 p.m. **L.G. Medaris Jr. and R.H. Dott Jr.**

The Seeley Slate and Baraboo Interval Sedimentation

1:20 p.m. **Jared D. Lubben**

Strategies for Drilling Unconsolidated Material and Historic Underground Mine Workings: Examples from Hibbing Taconite Company's 2007 Diamond Drilling Campaign

1:40 p.m. **W.F. Cannon and K.J. Schulz**

Unusual Features Along the Archean/Paleoproterozoic Unconformity at Silver Lake, Michigan—Seismites from the Sudbury Impact

2:00 p.m. **K.J. Schulz and W.F. Cannon**

Geochemistry of the Sudbury Impact Layer, Northern Michigan: Implications for the Nature of the Source Materials

2:40 p.m. **Mark A. Jirsa, Paul W. Weiblen, Tatiana Vislova and Peter L. McSwiggen**

Sudbury Impactite Layer Near Gunflint Lake, NE Minnesota

3:00 p.m. **FIELD TRIP 5: THE SUDBURY IMPACT LAYER AT THE MCCLURE LOCALITY**

Bill Cannon, U.S. Geological Survey

6:00 p.m. **Return of Trip 5**

SATURDAY MAY 10, 2008

8:00 a.m. **FIELD TRIP 6: SUSTAINABLE RECOVERY OF IRON FROM THE MARQUETTE DISTRICT**

Glenn Scott, Helene Lukey, Al Strandlie, and CCI/CCMO staff
Cleveland Cliffs Inc.

8:00 a.m. **FIELD TRIP 7: GEOLOGY OF THE KEWEENAWAN BIC INTRUSION**

Dean Rossell, *Kennecott Minerals Inc.*

8:00 a.m. **FIELD TRIP 8: GEOLOGY OF THE EAGLE PROJECT**

Andrew Ware and Jon Cherry, *Kennecott Minerals Inc.*
Xin Ding, *Indiana University*

6:00 p.m. **Return of Trips 6, 7, & 8**

54TH ANNUAL INSTITUTE ON LAKE SUPERIOR GEOLOGY ENDS

POSTER PRESENTATIONS

Terra N. Anderson* and Dyanna M. Czeck

Quartz Fabrics and Quantified Strains During Transpressional Deformation in the Seine Metaconglomerates

Terrence J. Boerboom, John C. Green and Paul Albers

Bedrock Geologic Map of the Lutsen Quadrangle, North Shore of Lake Superior, Minnesota

Elizabeth Drommerhausen* and Steven Losh

Properties of Fluid Involved in Formation of Natural Ore in the Mesabi Iron Range, Minnesota

R.M. Easton, M.G. Houlié, D. Rowell and N.F. Trowell

Toward a Common Map Legend for Ontario

Shelby J. Frost*, Natalie A. Juda, and Jim Miller

Student Capstone Map from the UMD Precambrian Research Center's Field Camp: Bedrock Geology Map of Homer Lake and Adjacent Areas, Cook County, Minnesota

Lynn Galston*, Karen G. Havholm and Stephen T. Hasiotis

Reinterpretation of the Trace Fossil-Bearing Devils Island Sandstone, Keweenawan Rift, Northern Wisconsin

Mark A. Jirsa, Edward Starns, Daniel E. Costello, Benedek Gal, Steven A. Hoaglund and Amanda J. Putz

"Capstone" Geologic Mapping Near Gabimichigami Lake, Boundary Waters Canoe Area Wilderness, By Students of the Precambrian Research Center's 2007 Field Camp

J.N. Koester*, J.W. Goodge, and V.L. Hansen

Structural and Metamorphic History of the Burntside Lake Shear Zone with Possible Implications for Archean Granite-Greenstone Formation

Helene M. Lukey

Mineral Zonation and Stratigraphy of the Tilden Hematite Deposit

S. Moosavi*, T.K. Johnson, C. Wendland, A. Anderson, and G.J. Hudak

Bedrock Geology of the Footwall to the Soudan Iron Formation South of Twin Lakes, St. Louis County, Northeastern Minnesota

Northern Michigan Geologic Repository Association

Richard Patelke

PolyMet Mining: NorthMet Cu-Ni-Co-PGE Project, Hoyt Lakes, Minnesota

Dean Peterson

*Geological Map of the Northern South Kawishiwi Intrusion and Surrounding Areas,
Duluth Complex: St. Louis and Lake Counties, Northeastern Minnesota*

A.K. Sartorelli*, A. Anderson and G.J. Hudak

*Pillow Morphological Studies Southwest of Fivemile Lake, Vermillion District, NE
Minnesota*

K.J. Schulz, S.W. Nicholson and W.R. Van Schmus

Penokean Massive Sulfide Deposits: Age, Geochemistry, and Paleotectonic Setting

Tharalson, E., Sweet, G., Boisjoli, T., Lentz, B., Fellows, T., Peterson, D.

*Geological Map of the Nickel Lake Macrodiike and Northern Bald Eagle Intrusion:
Lake County, Northeastern Minnesota*



ABSTRACTS

Quartz fabrics and quantified strains during transpressional deformation in the Seine Metaconglomerates

Anderson, Terra N., and Czeck, Dyanna M. Department of Geosciences, University of Wisconsin-Milwaukee, P.O. Box 413, Milwaukee, WI 53201; tna@uwm.edu.

INTRODUCTION

Previous studies have documented quartz fabrics in the field (e.g. Bestmann et al., 2004; Lisle, 1985; Stipp et al., 2002) and the lab (e.g. Heilbronner and Tullis, 2002; Hirth and Tullis, 1992; Mainprice and Paterson, 1984). However, these previous studies have not been conducted in areas with deformation under natural conditions where strain can be quantified and deformation mechanisms have been determined. In our study, we link quartz shape and crystallographic fabrics within a deformed metaconglomerate across a strain gradient. Fissler (2006) conducted strain analysis on the Seine Metaconglomerates from the Rainy Lake region in northwestern Ontario. She determined strain independently for various lithological groupings of clasts and determined various degrees of strain types and magnitudes throughout the region. Using her strain results as a framework for our fabric analysis, we use petrographic and Electron Backscattered Diffraction (EBSD) techniques to document the quartz grain fabrics throughout the region.

METHODOLOGY

Fissler (2006) classified twenty-six outcrops of the Seine Metaconglomerates as low, medium, or high strain. Oriented quartzite clasts and quartz veins were collected from several locations with different strain magnitudes. The quartzite clasts experienced the complete deformation history of the conglomerate whereas the quartz veins, having been intruded during the deformation, only exhibit evidence of later deformation stages. The quartzite clasts and quartz veins have a simple mineralogy that is readily compared to numerous results from deformation experiments.

Thin sections were made from quartzite and quartz vein samples with the x-direction parallel to lineation and the y-direction perpendicular to foliation. Using a SEM-EBSD system and CHANNEL5 software produced by HKL Technology, an automatic map of the thin section was used to determine the crystallographic orientations of quartz grains. The map was constructed to maximize the area analyzed on the thin section with one measurement taken from each grain. The step size was determined by the average grain size and ranged from 150 to 200 microns. The data were entered into PFch5, a pole figure-plotting program developed by Mainprice (2005).

Microstructures in the Seine have been studied in detail by Czeck (2001) and Fissler (2006). Both found evidence for very similar deformation mechanisms at all strain magnitudes in a range of clast types. Rocks were primarily deformed by diffusive mass transfer processes with some dislocation and micro-fracturing processes in certain phases. Using a petrographic microscope, we conducted additional microstructural analyses to infer deformation mechanisms within the quartz samples because the previous studies did not focus on quartz.

PRELIMINARY RESULTS

Petrographic analyses indicate the following microstructures. In low-moderate strained quartzite clasts, grain size is bimodal with larger grains 20 to 40 μm and smaller grains around 5 μm in diameter. Grain boundaries are irregular and show slight preferred orientation parallel to lineation, forming a shape preferred orientation (SPO). Within the grains, undulose extinction is common and some subgrains exist. Some recrystallized grains, primarily as “necklaces” around the larger quartz grains, can be observed at the edges of larger quartz grains. We interpret that the quartz underwent deformation primarily by dislocation creep with subgrain

formation and recrystallization recovery mechanisms. Late stage fractures occurred which cut the main fabric and allowed fluid movement resulting in veins filled with calcite and some minor amounts of mica.

In highly strained quartzite clasts, grain size is uniform ranging from 5 to 10 μm . The round, equant grains have regular smooth boundaries that often intersect at triple junctions. Internally, the grains often have undulose extinction throughout, and some subgrains are observed. Calcite fills in fractures that are oblique to lineation. The grain size near these zones is smaller, less than 5 μm in diameter. We interpret that the quartz grains are deforming primarily by dislocation creep, and that the reduced grain size is due to extensive recrystallization. The number and size of late stage fractures increased from the low strained examples. The fractures cut the main fabric and filled with calcite and more mica relative to the low strain clasts.

In low-moderate strained quartz veins, grain sizes vary greatly from 20 to 500 μm . Grain boundaries are irregular and show a slight SPO subparallel to lineation. Some ~ 5 μm recrystallized grains are observed at the edges of the larger quartz grains. These are seen primarily as “necklaces” around the larger quartz grain edges.

In moderate-highly strained quartz veins, grain size is fairly uniform ranging from 20-40 μm in diameter. Some larger grains that are 500 μm in diameter exist, often with “necklace” recrystallization of quartz and calcite around them. Boundaries are irregular and larger grains have undulose extinction. Calcite fills in fractures that are oblique to lineation.

Preliminary results of the EBSD analyses show increase cluster of crystallographic preferred orientation (CPO) in the c-axis of quartz within quartzite clasts with increasing strain magnitudes. Similarly, in most cases there was an increase in CPO of quartz c-axes within quartz veins when strain magnitudes increased. These observations are consistent with deformation by dislocation creep with recovery primarily by recrystallization. One interesting feature that stands out when comparing the microstructural and EBSD studies is that the SPO of quartz grains decreases with increasing strain, and the CPO of quartz grains increases with increasing strain. The increasing CPO without a corresponding increase in SPO is consistent with deformation by dislocation creep with recrystallization. We interpret the different microstructural observations between clasts of low to high strain to be consistent with dislocation creep that operated to a variety of strain magnitudes.

REFERENCES

- Bestmann, M., Prior, D.J., Veltkamp, K.T.A., 2004. Development of single-crystal σ -shape quartz porphyroclasts by dissolution-precipitation creep in a calcite marble shear zone. *Journal of Structural Geology*, 26: 869-883.
- Czeck, D.M., 2001. Strain analysis, rheological constraints, and tectonic model for an Archean polymictic conglomerate : Superior Province, Ontario, Canada. Thesis, University of Minnesota.
- Fissler, D.A., 2006. A Quantitative Analysis of Strain in the Seine River Metaconglomerates, Rainy Lake Region, Northwestern Ontario, Canada. M.S. Thesis, University of Wisconsin-Milwaukee.
- Heilbronner, R., Tullis, J., 2002. The effect of static annealing on microstructures and crystallographic preferred orientations of quartzites experimentally deformed in axial compression and shear. *Deformation Mechanisms, Rheology and Tectonics: Current Status and Future Perspectives*; Geological Society of London, Special Publications, 200: 191-218.
- Hirth, G., Tullis, J., 1992. Dislocation creep regimes in quartz aggregates. *Journal of Structural Geology*, 14: 145-159.
- Lisle, R.J., 1985. The effect of composition and strain on quartz-fabric intensity in pebbles from a deformed conglomerate. *Geologische Rundschau*, 74: 657-663.
- Mainprice, D. “PFch5” Petrophysical Software, Unicef Careware, 2005.
<<http://www.gm.univ-montp2.fr/PERSO/mainprice/index.html>>
- Mainprice, D.H., Paterson, M.S., 1984. Experimental studies of the role of water in the plasticity of quartzites. *Journal of Geophysical Research*, 89: 4257-4269.
- Stipp, M., Stunitz, H., Heilbronner, R., Schmid, S.M., 2002. The eastern Tonale fault zone: a ‘natural laboratory’ for crystal plastic deformation of quartz over a temperature range from 250 to 700°C. *Journal of Structural Geology*, 24: 1861-1884.

THE SHAKESPEARE CU-NI-PGE DEPOSIT: EVIDENCE FOR A TWO-STAGE EMPLACEMENT MECHANISM

Duncan J. Bain, B.Sc., P.Geo., Department of Earth Sciences, University of Western Ontario, London, ON, N6A 5B7, dbain3@uwo.ca

The Shakespeare Cu-Ni-PGE Project occurs in Shakespeare and Baldwin townships, located 70 km west-southwest of Sudbury, Ontario, Canada and is held by Ursa Major Minerals Incorporated. The property contains probable reserves of 7.3 million tonnes of 0.37% Ni, 0.39% Cu, 0.024% Co, 0.37 g/tonne Pt, 0.40 g/tonne Pd and 0.20 g/tonne Au and an indicated resource of 12.0 million tonnes of 0.35% Ni, 0.36% Cu, 0.02% Co, 0.34 g/tonne Pt, 0.38 g/tonne Pd and 0.19 g/tonne Au. It varies in width from 24 to 61 m and has an exposed strike length of 600 m but is open along strike and at depth. This mineralized zone occurs at the stratigraphic top of a Nipissing gabbro sill injected along the contact between metamorphosed hangingwall Mississagi Formation quartz arenites and footwall Pecors Formation wackes, both of the Paleoproterozoic age Hough Lake Group of the lower Huronian Supergroup. These units form the bulk of the Southern Structural Province. The deposit strikes ENE and dips steeply to the north. It consists of blebs, stringers and disseminated grains of pyrrhotite, chalcopyrite, pyrite, cobaltite and pentlandite within a melanogabbro to quartz diorite sill.

Several mafic magmatic events overlap with deposition of the Huronian sediments. The 2490 Ma East Bull Lake Layered Intrusive Suite underlies the Huronian Supergroup and is cut by the 2473 Ma Matachewan and 2446 Ma Hearst dyke swarms. Bimodal mafic to felsic volcanism (Elsie Mountain, Stobie, Copper Cliff and Salmay Lake formations) and granite intrusions (Creighton and Murray) occurred between 2450 Ma and 2380 Ma. The Nipissing gabbro sills intruded Huronian sediments between 2220 and 2210 Ma. These magmatic events indicate a continental margin or intracratonic rifting environment, probably initiated by a mantle plume head. This re-activated the long-lived Great Lakes Tectonic Zone of Neoarchean age. The ~ 1870 to 1850 Ma Penokean Orogeny collisional event overprints the Southern Province, and late thermal nodes relate to 1750 to 1730 Ma intrusions such as the Cutler Granite. In the Shakespeare area the thermal effects imposed upper greenschist to lower amphibolite facies metamorphism. Post-Penokean mylonitic shearing re-activated regional scale northeast-trending Penokean structures such as the Murray and Hunter Lake faults.

The East Bull Agnew Lake Intrusion occurs directly west of the Shakespeare deposit. Previous mapping by the Ontario Geological Survey shows the Nipissing gabbro at Shakespeare as a feeder system cutting up through both Archean basement rocks and Agnew Lake Intrusion. The 2003/2004 field seasons were spent detailed mapping and sampling the Shakespeare and Nipissing gabbro sills and Huronian sedimentary rocks. Examination of the deposit area and property grids to the ENE revealed “windows” of melanogabbro along a 10 km strike length under a thick cap of Mississagi Formation quartz arenites. This suggests the Shakespeare sill overlies much of the Nipissing sill throughout the immediate area. Locally the main Nipissing sill is a saucer shaped body dipping ~ 20° NNW but in the area of the deposit it and the overlying Shakespeare units dip 40° to 60° NNW. Cumulate layering of sulphides at the base of the Shakespeare melanogabbro indicates post-mineralization tilting. Lidar imagery shows numerous property scale structures with a NNE to NE trend associated with the Hunter Lake Fault system; at least two are mylonite shears, Stumpy Bay and Spanish River. The thin 24 to 61 m Shakespeare sill overlies the thick 350 to 600 m Nipissing sill and is differentiated from basal melanogabbro through to upper quartz diorite, and melanogabbro is the main host for Shakespeare mineralization.

Hand samples show color and texture differences between the melanogabbro at the base of the Shakespeare sill and the gabbro of the underlying Nipissing sill. Thin and polished section petrography of 45 samples of core and surface rock were studied to establish the degree of metamorphic overprinting. Most of the primary minerals, essentially plagioclase and augite, have been moderately to very strongly altered to chlorite, epidote, actinolitic hornblende and biotite, confirming the medium-grade regional metamorphism reported by others. Primary igneous textures are recognizable, a confirmation of essentially only thermal metamorphic effects. Apatite is a common trace mineral in thin section and accounts for the elevated P_2O_5 content. Polished sections showed fine blebs of pyrrhotite-chalcopyrite, with rare pentlandite. Minor amounts of ilmenite rim magnetite, accounting for a low TiO_2 to FeO^* ratio. However, both FeO^* and TiO_2 as well as V are higher in Shakespeare melanogabbro than in Nipissing gabbro, which indicates a Shakespeare melt more evolved than the main Nipissing magma.

Major, minor, trace and REE geochemical studies were carried out to compare Shakespeare melanogabbro to the main Nipissing gabbro. Melanogabbro ranged down to 47.01% SiO_2 whereas Nipissing gabbro is no lower than 50.23% and averages 52% SiO_2 . Al_2O_3 and CaO are also lower in melanogabbro, consistent with its lower plagioclase content. A lower Mg# indicates that melanogabbro is more differentiated than Nipissing gabbro. Rb/Sr ratios, Y and Zr are elevated in Shakespeare compared to average Nipissing gabbro values, reflecting contamination by continental crust. Chondrite-normalized REEs from Shakespeare melanogabbro and Nipissing gabbro show similar patterns but with higher abundances in Shakespeare, again indicating the Shakespeare melt is more evolved. No Eu anomaly is present in any of these rocks and Shakespeare and Nipissing are probably separate melt batches from the same chamber with Shakespeare more evolved than Nipissing. Ni-Cu-Co are erratically anomalous in both sill types. Agnew Lake mineralization has much lower Cu:Ni and Au/Pt+Pd ratios than the Shakespeare/Nipissing mineralization. These markedly differing metal signatures show the Shakespeare deposit cannot be derived by any direct re-mobilization process from Agnew mineralization that may have been encountered in the feeder system.

The Shakespeare sill originated from the evolved melt capping the Nipissing magma chamber. The initial heave of this melt was intruded along the contact between hangingwall Mississagi quartz arenites and footwall Pecors wackes. Continental contamination, including sulphur from Pecors and silica mixing from Mississagi, lowered the temperature of sulphur saturation within a sulphur-enriched Shakespeare melt, causing the rapid precipitation of Ni-Cu-Co sulphides and PGEs to the chamber floor. The large main heave of Nipissing melt was injected soon after, underplating the Shakespeare sill. Post-deposition extensional faulting caused the mineralized Shakespeare and Nipissing sills to be tilted along an ENE hinge line to produce the present day form of the deposit.

The Deloro-Tisdale SIZ of the Abitibi greenstone belt: an example from McArthur Township, Ontario

G.J. Baldwin¹, P.C. Thurston¹, B.S. Kamber¹, M.G. Houle²

1 Dept. of Earth Sciences, Laurentian University, Sudbury, ON P3E 2C6

2 Ontario Geological Survey, Sudbury, ON P3E 6B5

The NeoArchean Abitibi Greenstone Belt encompasses 6 geochronologically resolvable tectonostratigraphic assemblages consisting of volcanic and minor sedimentary rocks. The assemblages were autochthonously deposited between 2750 Ma and 2696 Ma. Evidence for autochthonous emplacement is, for example, evident from zircon xenocrysts inherited from the 2730-2724 Ma Deloro assemblage in the 2710-2704 Tisdale assemblage, which are in direct, stratigraphic contact. In the field, there is no evidence for an erosional unconformity between these units, but instead a series of sedimentary interface zones (SIZ's) consisting primarily of Banded Iron Formation (BIF) and other related sedimentary rocks. South of Timmins, ON, in the Bartlett Dome area (McArthur, Bartlett, and English Townships) three of these SIZ's can be observed in the Deloro assemblage. The uppermost SIZ follows the contact between the Deloro and Tisdale assemblages; however the best exposed and geochronologically constrained is the middle SIZ, particularly in McArthur Township.

A nearly complete section of the ~50 m thick middle SIZ reveals 6 distinct lithologies from base to top; a substrate of felsic volcanic rocks; basal sulphide facies BIF; silicate facies- BIF; oxide facies BIF; debris flow bearing BIF; and oxide-sulphide facies BIF, with some of these lithologies recurring higher in stratigraphy. Stratigraphy and primary structures represent features characteristic of submarine unconformities (Shanmugam, 1988), such as heterolithic debris flows, syn-sedimentary deformation features and cherty hardgrounds. Tabular chert breccia units were observed in stratigraphic association with debris flows, and chert-wacke units indicating syn-sedimentary production of the breccia units and early silicification prior to the debris flow event. Petrographic observations strongly suggest that many of the cherts within the BIF may in fact be silicified ash, an assertion that is being tested using REE+Y geochemistry. These geochemical studies will also aid in distinguishing between hydrothermal vs. seawater origin of Si in the formation of the BIF in the SIZ.

U-Pb zircon dating of rhyolites immediately above and below the SIZ are used to help to constrain the deposition period. The underlying rhyolite yielded an age of 2728.1 +/- 1.6 Ma while the overlying rhyolite returned a slightly less precise age of 2724.5 +/- 2.1 Ma. The deposition of this particular SIZ could thus have lasted for a period of 1-6 million years. Taken at face value, the dates indicate a depositional period of 3.6 Ma and hence extremely slow sedimentation rates, or prolonged periods of water-rock interaction during the period of deposition. Despite the potential overlap in these dates, the overlying U-Pb age is similar to ages for felsic rocks overlying iron formation, further north in Deloro Twp (2724 +/- 3.7 Ma), as well as in the correlative Swayze greenstone belt (2724 +/- 2 Ma) (van Breeman et al, 2006), indicating a regional pattern. Further study is required at other localities along this and other SIZ's in the Bartlett Dome area to confirm the interpretation that these SIZ's represent a major gap in volcanism, possibly across the Abitibi greenstone belt.

Shanmugan, G. 1988, Origin, recognition, and importance of erosional unconformities in sedimentary basins *in* Kleispehn, K.L. and Paola C., eds., *New Perspectives in Basin Analysis* (Frontiers in Sedimentary Geology): New York, Springer-Verlag, p. 84-108.

van Breeman, O., Heather, K.B., and Ayer, J.A. 2006, U-Pb geochronology of the NeoArchean Swayze sector of the southern Abitibi greenstone belt. *Geological Survey of Canada, Current Research 2006-F1*, p 1-32.

BEDROCK GEOLOGIC MAP OF THE LUTSEN QUADRANGLE, 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

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 eleven published 1:24,000 scale maps from Duluth to Lutsen, in addition to 10 quadrangles already published under the former USGS COGEOMAP program. The Deer Yard Lake and Good Harbor Bay quadrangles will be published in July 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/>).

With the exception of local thesis mapping by Albers (2006) and a regional-scale compilation map (Map M-119; Miller and others, 2001), the Lutsen quadrangle had not been published, and had been incompletely mapped. Approximately 30 sets of water well cutting samples, collected by McKeever Well Drilling of Little Marais, Minnesota, were examined as part of the mapping effort.

The area of this map lies in the uppermost portion of the Northeast sequence of the North Shore Volcanic Group (NSVG), and also the unconformably overlying Schroeder-Lutsen sequence (Fig. 1B). In addition, components of the Beaver Bay Complex, including the Leveaux ferrodiorite, the Lake Clara and Monker Lake diabases, and multiple phases of the Beaver River diabase are present in the map area.

The new mapping has refined the volcanic stratigraphy of the NSVG in this area and has identified several previously unrecognized units and stratigraphic relationships. In particular it has been demonstrated that the Terrace Point basalt flow, which was formerly considered to be the lowermost unit of the Schroeder-Lutsen sequence, is instead part of the underlying, slightly older lava flows. In addition, three thick sandstone units were identified. One of these, the Eagle Mountain sandstone, is intersected in several water wells, and ranges from 6 to 18 meters in thickness; however much of the original stratigraphic thickness may have been removed by intrusion of the overlying Leveaux ferrodiorite sill, which apparently utilized the sandstone as a plane of weakness during emplacement. The other sandstone units are largely extrapolated from the north and east, where they have been identified in outcrops or water well cuttings as units up to 100 meters thick; they are extrapolated into this map area on the basis of linear topographic depressions and coincident linear negative aeromagnetic anomalies.

Intrusive rocks of the Beaver Bay Complex are composed mainly of the Beaver River diabase, the porphyritic Leveaux ferrodiorite, and a newly-recognized 'Silver-Bay' type intrusion composed of a lower cumulate ferrogabbro and upper pyroxene-quartz ferromonzonite. The Leveaux ferrodiorite is a subvolcanic sill emplaced into volcanic rocks, and is intruded by the Beaver River diabase. The Monker Lake diabase dike (250 – 300 meters thick) is poorly exposed in the Lutsen quadrangle, but is easily demarcated by a sharp, linear positive aeromagnetic anomaly. The Lake Clara diabase, in the northwest corner of the map, is poorly constrained due to relatively poor outcrop and an indistinct aeromagnetic signature. This diabase locally forms a shallow-dipping sill capped by a thin quartz ferromonzodiorite which contains mafic enclaves interpreted as the product of melting of, and contamination by, the overlying rhyolite.

References

- Albers, P.B., 2006, The geology and petrology of the Leveaux porphyritic dioritic intrusion: Investigating possible magmatic relationships to the anorthositic series of the Duluth Complex, Cook County, Minnesota: Duluth, Minn., University of Minnesota Duluth M.S. thesis, 206 p.
- 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 Map Series Miscellaneous Map M-119, sheet 1 of 2, scale 1:200,000.

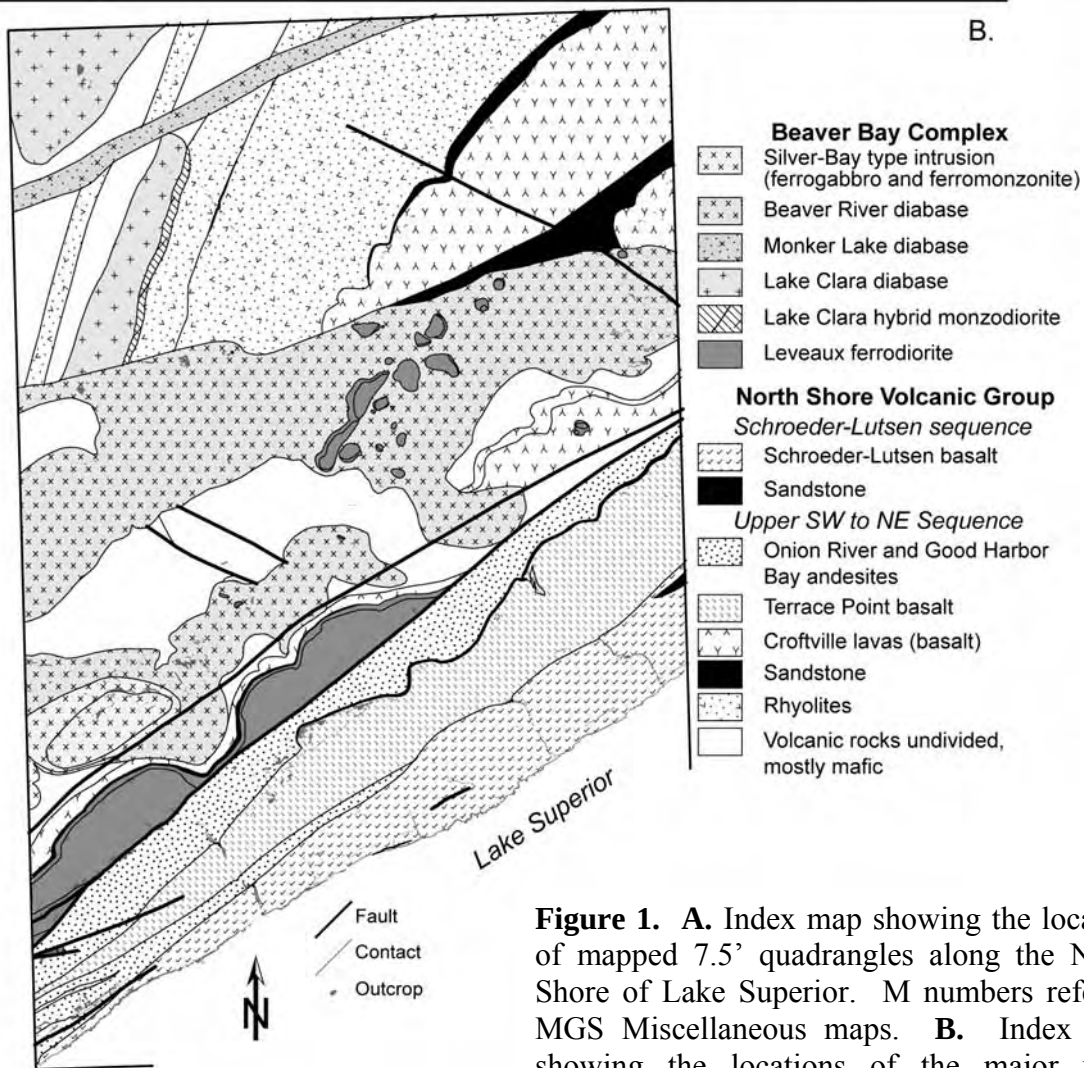
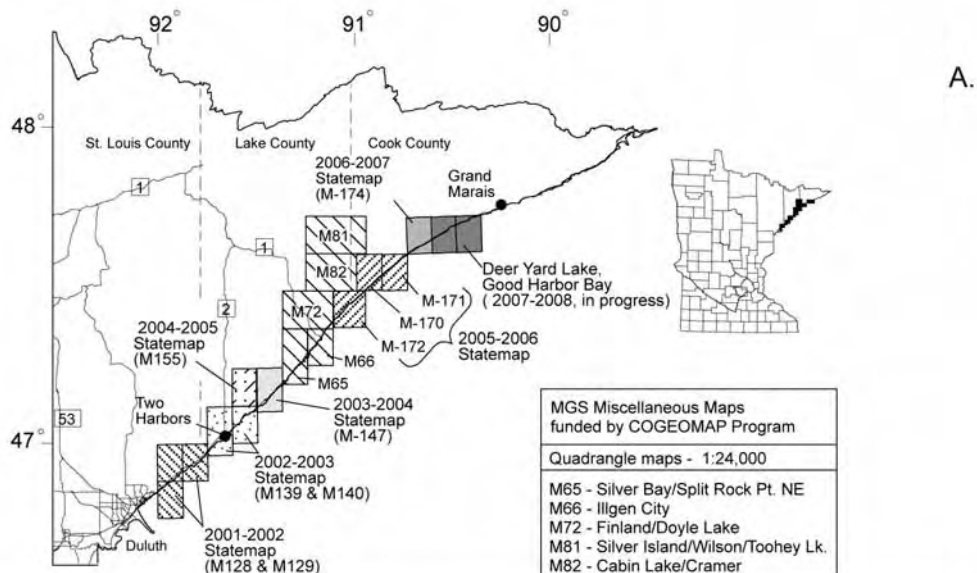


Figure 1. A. Index map showing the location of mapped 7.5' quadrangles along the North Shore of Lake Superior. M numbers refer to MGS Miscellaneous maps. **B.** Index map showing the locations of the major units mentioned in the abstract.

OBSERVATIONS ON LANTHANIDE FRACTIONATION IN THE WAUSAU COMPLEX, MARATHON COUNTY, WI.

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.

The Wausau Complex is composed of a series of four anorogenic intrusions ranging in age from 1565 Ma $\pm$ 3-5 for the alkalic Stettin pluton (Van Wyck, 1994) to 1505.9 $\pm$ 2.7 Ma for the Nine Mile Granite (Dewane & Van Schmus, 2007). The complex is usually considered to be a precursor to the younger Wolf River Batholith.

Recent work on various sites in the Stettin and Nine Mile plutons has revealed interesting trends in lanthanide fractionation. While most REE bearing minerals are not overly unusual in their compositions, exceptions exist and may be clues to processes involved in the formation of these plutons.

Minerals bearing the lanthanide elements, more commonly referred to as the Rare Earth Elements (REE), are relatively common in the Stettin and Nine Mile intrusions of the Wausau Complex (Falster et al, 2000). In general, minerals bearing REE elements will tend to accumulate either the light rare earth elements (LREE) or the heavy rare earth elements (HREE), and not both. LREE rich minerals are usually Ce-dominant, and HREE minerals are usually Y-dominant. Significant enrichments in other LREE elements are unusual, and in HREE elements even less common.

LREE fluocarbonates, usually bastnaesite or related species, are usually A-site Ce-dominant with lesser levels of La, Nd and other LREE. However, it is not particularly uncommon to observe A-site Nd-dominance, and less commonly La-dominance in bastnaesite-group minerals from the Wausau Complex. This has particularly been noted in a small pegmatite designated the Ravine Pegmatite on the west side of the old Dehnel quarry in the Stettin intrusion, in a pneumatolytic-like assemblage in the Ladick quarry, Nine Mile pluton, and in a late-stage miarolitic phase in the County Materials quarry, Nine Mile pluton.

LREE phosphates (typically monazite-(Ce)) are also usually A-site Ce-dominant. However, monazite-(Nd) has been noted in a small pegmatite exposed in a utility excavation on Evergreen Rd, and in mine dump material from the Summit Lake thorium prospect, both in the Stettin pluton. Additionally, minute crystals of rhabdophane-(Ce), rhabdophane-(Nd) and rhabdophane-(La) have been noted as late-formed minerals in a small miarolitic body briefly exposed in Wimmer Pit #3 in the Nine Mile pluton. Rhabdophane is a hydrated LREE phosphate typically formed as a late-stage mineral in pegmatites, and may also form under weathering conditions.

LREE-bearing members of the pyrochlore group associated with bastnaesite species in the Ravine Pegmatite in the Dehnel pit show LREE enrichment tendencies similar to trends in the associated bastnaesite-group minerals, as does closely associated fersmite (first report of this mineral for Wisconsin).

It is less common to observe enrichment of specific HREE relative to Y, and no instances have yet been noted in the Wausau Complex of HREE minerals which are not Y-dominant. However, strong enrichment in Dy and Yb was observed in xenotime-(Y) intergrown with monazite-(Nd) in a small pegmatite exposed by utility work on Evergreen Drive in the Stettin pluton. Concentrations of Dy_2O_3 are consistently near 12 wt %, a level that has only been reported previously from the Annie #3 claim, Manitoba. Lesser degrees of Dy and Yb enrichment have also been noted in xenotime-(Y) from border phases of the Dehnel ravine pegmatite, Stettin Pluton, in xenotime-(Y) from a greisen assemblage in the Maguire Pit associated with cassiterite, ferberite/huebnerite and topaz in the Nine Mile pluton, and in xenotime-(Y) from a pegmatite exposed in the Red Rock North pit off of Spring Brook Rd, also in the Nine Mile pluton. Euxenite-(Y) associated with xenotime from the Red Rock North pegmatite shows a similar HREE enrichment pattern, and is also enriched in Ta and somewhat in Ti as well, approaching though not reaching the compositional field of tanteuxenite.

Possible causes of fluctuations in relative abundances of LREE and HREE vary. Variations in LREE dominance in an oxidizing environment may result from oxidation of Ce^{3+} to Ce^{4+} , facilitating retention of Ce^{4+} in solution and/or removal of Ce^{4+} from the system. Causes of variations in enrichment of various HREE elements is less certain; some authorities have suggested high levels of F may facilitate enrichment in even-numbered HREE (Dy, Er, Yb) relative to Y. Since F in the form of fluorite and F-rich micas is generally abundant in the Wausau Complex, why is such enrichment uncommon?

References:

Dewane, T. J., Van Schmus, W. R. (2007): U-Pb geochronology of the Wolf River batholith, north-central Wisconsin: Evidence for successive magmatism between 1484 Ma and 1468 Ma. *Precambrian Research*, V. 157, pp. 215-234.

Falster, Alexander U., Simmons, Wm. B., Webber, Karen L., Buchholz, Tom (2000): Pegmatites and Pegmatite minerals of the Wausau Complex, Marathon County, Wisconsin. *Memorie della Società Italiana di Scienze Naturali e del Museo Civico di Storia Naturale di Milano*, V. XXX, pp. 13-28.

Van Wyck, N. (1994): The Wolf River A-type Magmatic Event in Wisconsin: U/Pb and Sm/Nd Constraints on Timing and Petrogenesis. *Institute on Lake Superior Geology, 40th Annual Meeting, Part 1, Program and Abstracts*, p. 81-82

Unusual features along the Archean/Paleoproterozoic unconformity at Silver Lake, Michigan—seismites from the Sudbury impact

W.F. Cannon and K.J. Schulz, U.S. Geological Survey, Reston VA

At Silver Lake, 50 km northwest of Marquette, Michigan, rocks along the unconformity between Archean crystalline rocks and the basal beds of Paleoproterozoic sedimentary rocks show an unusual type of deformation. About a meter of the Paleoproterozoic sediments, part of the Michigamme Formation, are preserved. They consist mostly of laminated mudstones and fine sandstone, with thin lenses of basal conglomerate and breccia. The Archean rocks are mostly granite with lesser metavolcanic rocks. Deformation in Archean rocks was brittle, varying from intense brecciation to small offsets between meter-scale joint blocks; in Paleoproterozoic sediments relict soft-sediment deformation indicates liquefaction and flow as well as injection as sediment dikes into Archean rocks and breccia zones. Fracturing and brecciation of the Archean rocks and consequent injection of dikes of the overlying Michigamme sediments occurs to some extent in all exposures. In places Archean granitic rocks are thoroughly broken into angular fragments ranging down to centimeter-scale or smaller (Figure 1). These fragments are now suspended in a matrix of clastic material derived from the overlying sedimentary beds. Brecciation and dike injection extends for at least 3-4 meters below the unconformity (Figure 2). Dikes with diverse orientations range from nearly a meter to only a few millimeters thick. In some exposures joint blocks of Archean basement rocks, some up to tens of meters long, show meter-scale displacements relative to each other. These displacements resulted in reshaping of the original nearly flat unconformity surface and molded the overlying sediments to this new shape to form an unusual array of small folds with very diverse orientations (Figure 3).

We suggest that these unusual features are near-surface manifestations of an earthquake of about M10.5 on the Richter scale that was generated by the Sudbury impact, centered about 500 kilometers to the east, and record the passage of unprecedentedly intense seismic waves. The Sudbury ejecta layer is well documented in the lower part of the Michigamme Formation about 3 km from Silver Lake. We have tentatively identified ejecta particles within some of the sediment dikes indicating that the rocks at Silver Lake were very near the earth's surface at the time of impact. Part of the energy released by giant impacts such as Sudbury is transmitted as seismic waves more intense than any generated by terrestrial events. The energy arrives first as a compressional wave which imparts energy to the rocks and is followed by the complementary rarefaction wave. During this rarefaction, rocks near the earth's surface may respond by shattering and upward displacement creating open spaces into which overlying sediments can be injected. We interpret the breccia zones and abundant sediment dikes within the Archean rocks at Silver Lake to record this explosive rarefaction and dilation. The diversely oriented dikes occur in an abundance that requires substantial dilation and volume increase of the upper parts of the basement rocks to create the space now occupied by the dikes. Seismogenic disruption may be an important process in the formation of the Sudbury ejecta horizon and may be the cause of autochthonous breccias at the base of the ejecta-bearing layer at many other recently discovered localities.

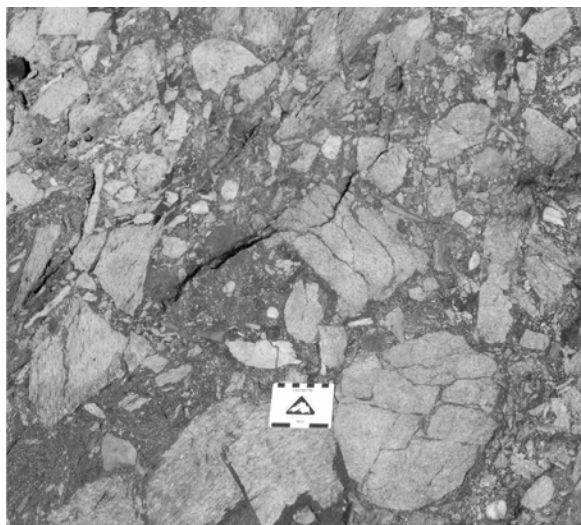


Figure 1. Breccia of granite fragments (light colored) in matrix of clastic sedimentary grains. Note “exploded boulders”, such as lower right, a feature typical of some seismogenic breccias.

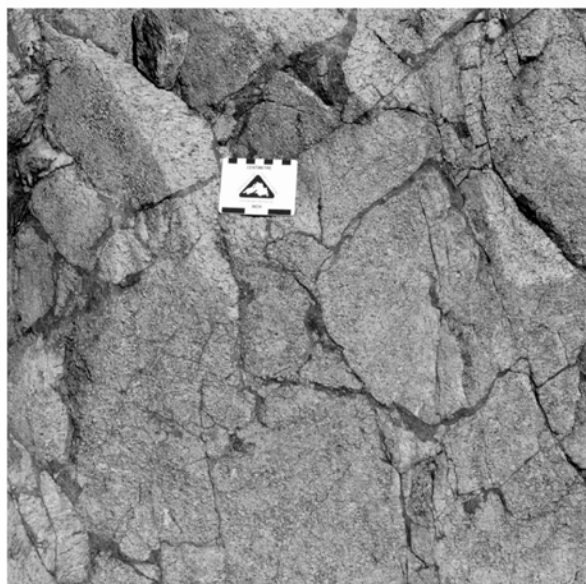


Figure 2. Archean granite about 3 m below the unconformity showing multiple dikelets of sediments (dark). Dikelet width ranges down to mm-scale and suggests forceful injection of sediments during a period of dilation.

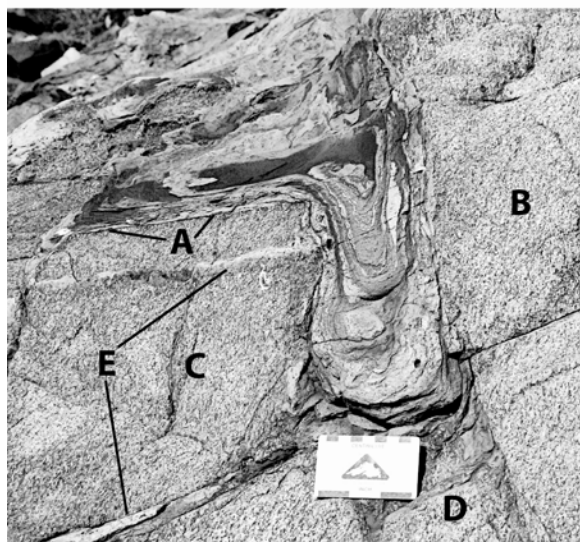


Figure 3. Paleoproterozoic sediments folded into declivity between joint blocks of Archean granite. The undisturbed unconformity is preserved at A. The sedimentary layers slumped into open space created when granite blocks underwent differential vertical movement. Block C appears to have moved down relative to block B, and block D moved down relative to block C. Joints in the granite are filled with sediment dikes (E).

UPGRADE OF AEROMAGNETIC DATA AT THE MINNESOTA GEOLOGICAL SURVEY

CHANDLER, Val W., and LIVELY, Richard S., Minnesota Geological Survey, 2642 University Ave., St. Paul, MN 55114, chand004@umn.edu

Between 2005 and 2007 the Minnesota Geological Survey (MGS) conducted an upgrade of the existing aeromagnetic data for Minnesota. These aeromagnetic data were acquired between 1979 and 1991 as part of a statewide survey, and data processing was limited by the computer capabilities of the time. Since then, significant technological improvements allow efficient handling of massive databases and post-processing tasks, such as line leveling and gridding, to be accomplished with small desktop computer systems. This project to upgrade the MGS aeromagnetic database was designed to reprocess and regrid the data using up-to-date software and hardware. As an added benefit access to the data was improved by making all the upgrades available via the internet.

Considerable effort was directed towards recovering line data that were missing from the primary digital archive, a CD produced in 1992 by the National Geophysical Data Center of the National Oceanic and Atmospheric Administration. Approximately 2,700 line kilometers of missing data were fully recovered from digital media that were archived at the MGS and U.S. Geological Survey. Residual magnetic anomaly values for an additional 1,038 line kilometers were approximately recovered by digitizing the position of photo-spotted points and interpolating 100-meter-spaced magnetic profiles from the original state aeromagnetic grid (213.36 meter interval).

Efforts were also made to mitigate line-leveling errors in the data, which locally caused striping artifacts, especially in derivative-enhanced grids. Selective leveling, using either statistical iteration or manual-editing, was applied to a total of 229 flight-lines and 101 tie lines, equating to approximately 21,000 line kilometers of adjusted data. In addition, approximately 522,933 line kilometers of data, nearly all of the available line data, were subsequently adjusted by micro-leveling.

The revised line data were used to generate new aeromagnetic grids for Minnesota with a grid interval of 100 meters. To provide a regional context and minimize boundary discontinuities, gridded aeromagnetic data from areas adjoining Minnesota were also incorporated. To enhance the utility of the data for geologic mapping, filtered grids were produced, including aeromagnetic data reduced to vertical polarization (reduced to pole or RTP), the first vertical derivative of the RTP data (Fig. 1), and the second vertical derivative of the RTP data.

The revised line data and the new statewide grids are downloadable from the MGS website at <http://www.geo.umn.edu/mgs/magnetics.htm>. Additional information available from this site includes copies of flight logs from the original surveys, and grid-based estimates of depth to magnetic basement derived using Euler's equation. These products represent a major step forward in providing complete and up-to-date aeromagnetic coverage for Minnesota, and should serve the needs of the exploration and scientific communities in the region for many years to come.

Acknowledgements: This study was supported by the Minnesota Minerals Coordinating Committee. Acquisition of most of the aeromagnetic data was supported by the Legislative Commission on Minnesota Resources. Additional data were contributed by the U.S. Geological Survey, U.S. Steel Corporation and the Geological Survey of Canada. David Dahl of the Minnesota Department of Natural Resources converted original line data to the NAD83 datum, and edited these data for repeats and other spurious features prior to this project. Robert Kuchs and Patricia Hill of the U.S. Geological Survey were instrumental in retrieving data originally acquired by their agency. Processing of the aeromagnetic data in this project was conducted using the OASIS/MONTAJ software system of Geosoft.

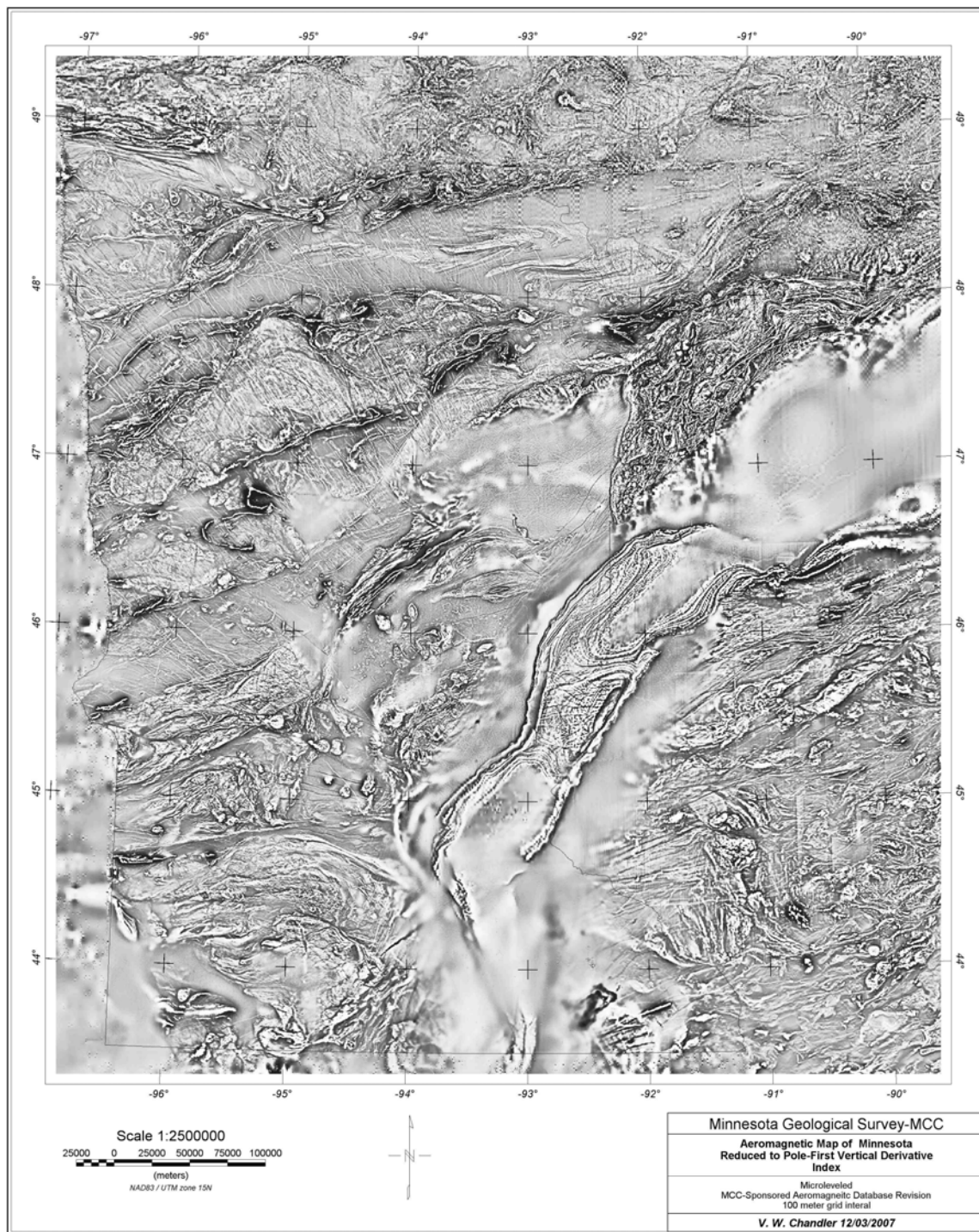


Figure 1. First Vertical derivative of the revised aeromagnetic data reduced to pole.

Geochemical and stable isotope studies of hydrothermal alteration associated with the Eagle deposit, northern Michigan

Ding, Xin, Ripley, Edward M., Li C Department of Geological Sciences, Indiana University, 1001 East 10th Street, Bloomington, IN 47405

The Eagle Ni-Cu-PGE deposit occurs in olivine-rich melagabbro, melatroctolite, and feldspathic peridotite units that were emplaced during the early stage of development of the Midcontinent Rift. U-Pb dating of baddeleyite from a feldspathic peridotite indicates a crystallization age of 1107.2 ± 5.7 Ma. Mineralization is characterized by the presence of two semi-massive sulfide zones in olivine-rich rocks that are linked by a zone of massive sulfides. Pyrrhotite, pentlandite, and chalcopyrite comprise the bulk of the sulfide mineral assemblage.

Hydrothermal alteration in the igneous rocks is locally intense. Phase relations involving serpentine, chlorite, actinolite, prehnite and pumpellyite suggest the temperatures of alteration did not exceed 300°C. Olivine in the intrusive rocks has been variably converted to mixtures of serpentine and fine-grained magnetite (Fig.1). Interstitial pyroxene and plagioclase have been altered to mixtures of serpentine, chlorite, amphibole, and lesser amounts of talc. Disseminated sulfide minerals are locally replaced by magnetite, serpentine, and chlorite. Serpentine shows a broad and distinctive compositional spectrum, with variations linked to the parent mineral which is replaced. Serpentine which replaces olivine is enriched in Mg and depleted in Al and Fe relative to serpentine that replaces pyroxene and sulfide minerals (Fig.2). Aluminum is thought to be derived from clinopyroxene, and the relatively high Al content of serpentine associated with sulfide minerals suggests that Al was a mobile element during low-temperature hydrothermal alteration. δD value of serpentine range from -85 to -109, suggesting equilibration with fluids of δD values between -58 and -82 at 300°C. The δD values suggest that evolved, long path-length meteoric water characterized by a low time integrated water/rock ratio was responsible for the alteration. Oxygen isotopic analyses of serpentine are in progress; results will aid in further constraining fluid sources.

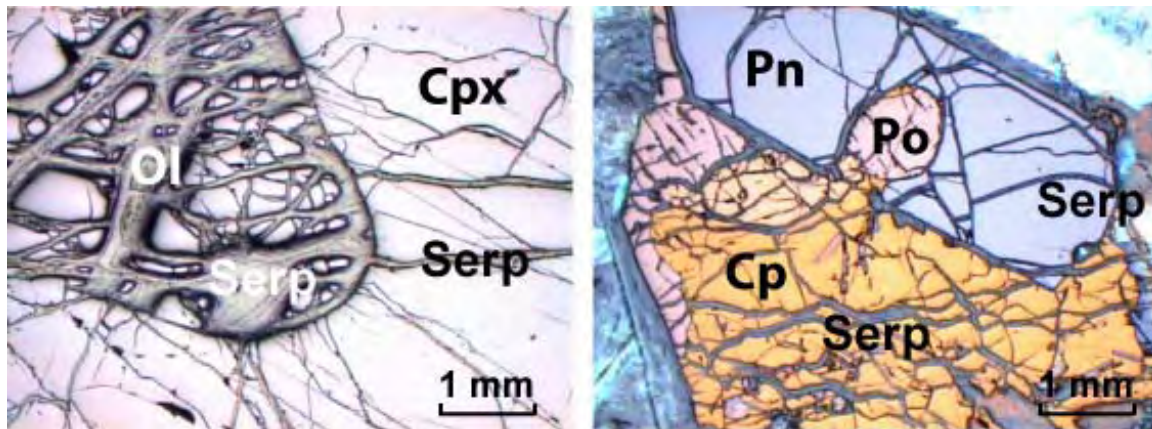
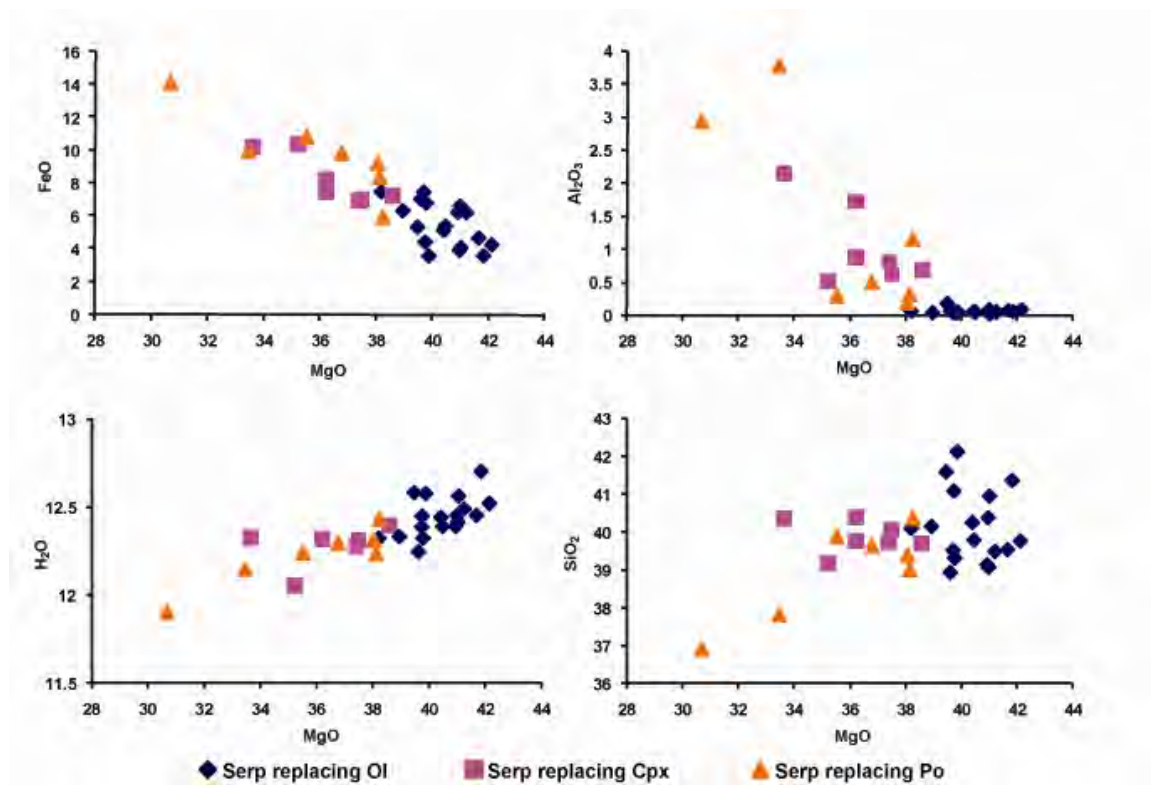


Figure 1 Photomicrographs of serpentine replacing olivine, clinopyroxene and sulfide in Eagle deposit



Properties of fluid involved in formation of natural ore in the Mesabi Iron Range, Minnesota

Elizabeth Drommerhausen, Steven Losh; Dept of Chemistry and Geology, TN 242,
Minnesota State University, Mankato MN 56001

Natural ore in the Mesabi Range has long been thought to have been formed by downward percolation of meteoric water, which dissolved non-oxide minerals (chiefly chert) from the Biwabik iron formation and oxidized, hydrated, and concentrated the remaining iron oxides. However, some investigators (e.g., Gruner, 1946) have suspected a hydrothermal origin for some if not all of the fluid that interacted with the iron formation. Morey (1999) hypothesized that the fluids responsible for formation of natural ore were driven northward and upward along an aquifer from the Penokean-aged collision zone ~100 miles south of the Mesabi Iron Range.

We are evaluating the origin and the fate of fluids involved with leaching silica and producing natural ore by fluid inclusion and cathodoluminescence techniques. In the Hibbtac pit, brecciated quartz veins lie within and next to minor high-angle fault zones that experienced movement due to volume loss that accompanied chert dissolution from iron formation; oxidation and dissolution generally took place in the hangingwalls of the faults. Because the quartz is largely confined to faults that moved as a result of dissolution and the quartz is brecciated by movement on those faults, the quartz we sampled was very likely precipitated from the same fluid that dissolved chert from the iron formation. Thus temperatures and salinities of fluid inclusions hosted by this quartz may thus constrain the source of the fluid involved with formation of natural ore.

We have also examined fluid inclusions in quartz from a 6-inch thick bedding-parallel quartz + bladed hematite vein from the LTV Number 6 pit near Aurora. The iron formation is unoxidized and gently-dipping, and bedding is slickensided, implying low-angle fault movement. Other veins in slickensided, unoxidized iron formation at this location contain carbonate minerals, but the vein we examined did not.

Preliminary fluid inclusion data from two Hibbtac quartz vein samples from one high-angle fault indicates that the fluid that dissolved silica from the iron formation. Fluid inclusions in these samples are primary, simple liquid + vapor inclusions exhibiting the same liquid:vapor ratio throughout. They are not necked or otherwise deformed. The fluid was characterized by a wide range of temperatures as indicated by homogenization temperatures (T_{homog}): two vein samples from one fault give T_{homog} of 60° to 122° C (n=6). Salinities, determined from ice melting temperatures, range from 4.5% to 19 wt% NaCl equivalent. Fluid inclusion from the quartz + hematite vein at the LTV 6 mine have similar characteristics. Fluid inclusions from a second fault at the Hibbtac mine display significantly higher homogenization temperatures, from 164° to 240° C (n=5). Clearly, nearly all of these fluids are much hotter and have much higher salinity than expected for meteoric waters that percolated a short distance downward from the paleo-surface, even during a period of warm climate. Their characteristics are those of a relatively deeply-sourced fluid.

The range in homogenization temperatures, which can vary by tens of degrees over a distance of millimeters, implies mixing of relatively warm and cool fluids during precipitation of quartz. Fluid mixing and/or episodic pulsing may manifest as alternating domains of contrasting cathodoluminescence. Cold cathodoluminescence reveals some growth zoning in quartz from the LTV Pit 6 samples.

The preliminary data in hand support the notion that the rocks presently exposed in the Mesabi Iron Range were infiltrated by warm, saline fluids that are quite similar at two locations, and in two different stages of quartz paragenesis, that are about 50 miles apart. We are continuing to obtain more data from already-sampled localities and to expand the number of sample localities throughout the Mesabi Iron Range to evaluate the nature and variability, in space in time, of properties of fluid that interacted with rocks of the Biwabik Iron Formation.

Gruner, J., 1946, The Mineralogy and Geology of the Taconites and Iron Ores of the Mesabi Range, Minnesota; St. Paul, Office of the Commissioner of the Iron Range Resources and Rehabilitation, 127 pp.

Morey, G., High-grade iron ore deposits of the Mesabi Range, Minnesota – Product of a continental-scale Proterozoic groundwater flow system; Econ. Geol. v. 94, pp. 133-141

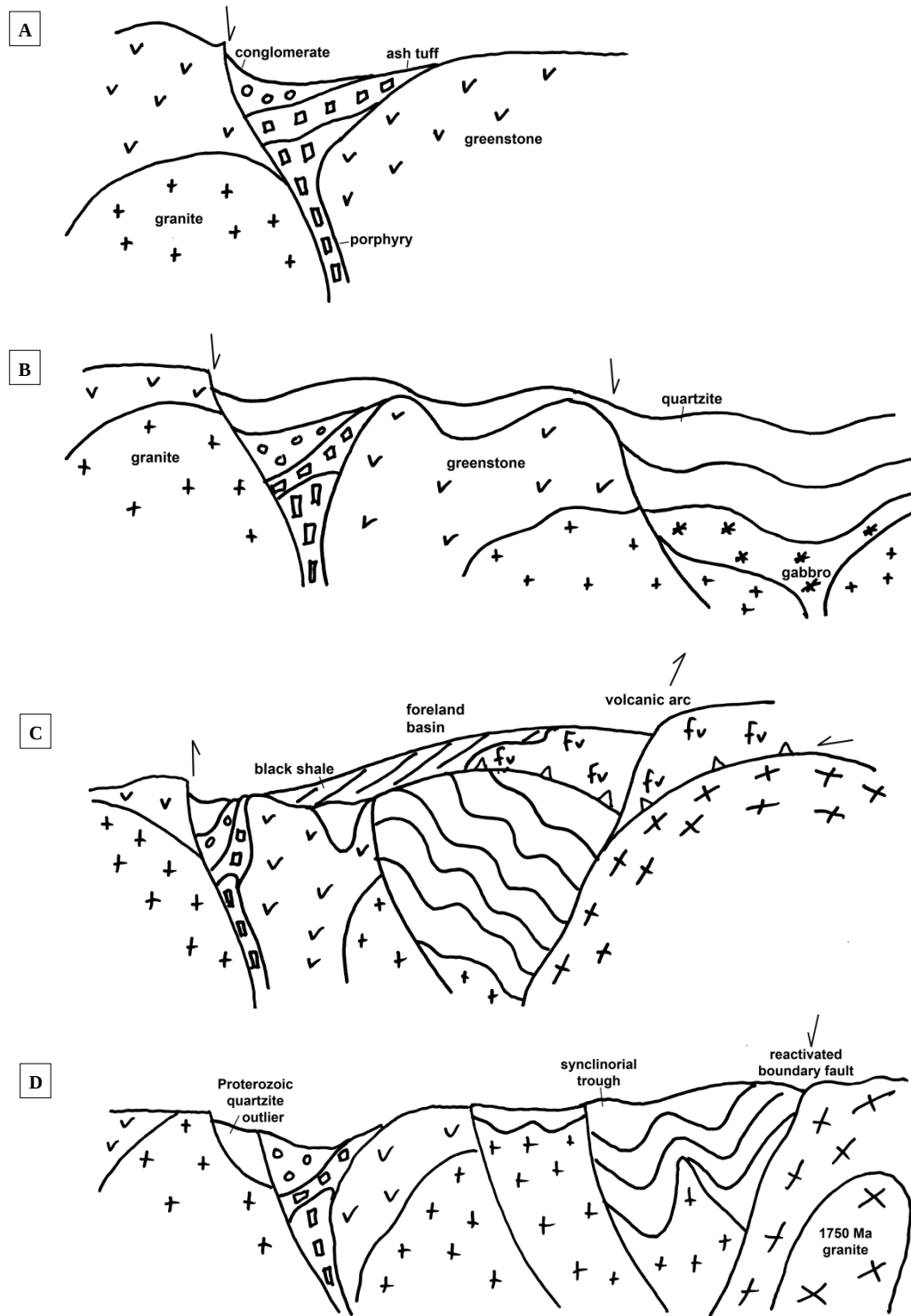
EVIDENCE FOR REACTIVATING ARCHEAN STRUCTURAL BREAKS DURING PALEOPROTEROZOIC RIFT SEDIMENTATION AND SUBSEQUENT ACCRETIONARY HISTORY “ONCE A FAULT ALWAYS A FAULT”

Norman Duke, Department of Earth Sciences, University of Western Ontario, London, ON, N6A 5B7, nduke@uwo.ca

Isolated remnants of Paleoproterozoic cover sequences are occasionally preserved along structural breaks within Archean basement, even well removed from the major tracts of sedimentary cover. Excellent examples occur in the northeast Churchill Province where Hurwitz outliers are preserved along Pykes Break on the northern margin of the Rankin Greenstone Belt as well as along similar basement faults occurring within the Kaminak Greenstone Belt. Outliers of Huronian occur along segments of the Kirkland-Larder-Cadillac-Bousquet break and the Cobalt Plate is transected by the Temagami-Ville Marie-Belleterre break in the southern Superior Province. A prime example from the Penokean Fold Belt is the outlier of Adjibik Quartzite preserved at Ropes, well interior to the Dead River-Ishpeming Greenstone Belt north of the Marquette Trough. That the Negaunee Iron Formation buttresses against the Southern Gneiss Complex, a wholly different Archean terrane-type compared to the bordering greenstones to the north, indicates reactivation of Archean subprovince boundaries played an important role in forming the major depositional troughs.

The origin of the Archean breaks stem from the terminal Neoarchean cratonization event, i.e. complex fault zones accommodating the unroofing of the voluminous granite plutons and bounding local depocenters of orogenic ash tuff and polymictic conglomerate (see Figure A). Subsequent reactivation occurred during Paleoproterozoic rifting, accommodating the deposition of thick siliciclastic cover successions (see Figure B). Closing of rift basins during the Hudsonian/Penokean collisional events re-established the Archean basement to pre-rift thicknesses by reverse shear and lead to open folding and upward increasing tectonic telescoping within the overlying sedimentary cover successions (see Figure C). As a result, Proterozoic sedimentary outliers are preserved along reactivated Archean basement break environments, while abrupt stratigraphic/structural buttressing is commonplace along the boundaries of the major sedimentary troughs (see Figure D).

Break reactivation well accounts for Proterozoic metamorphic overprinting of Archean lode gold mineralization, and may even have played a pivotal role in the late oxidation of the Negaunee siderite ores marginal to the Southern Shear, the southern boundary to the Marquette Trough. Strong brittle fracturing with associated chlorite that overprints the Southern Shear suggests this particular boundary fault had a protracted history culminating in normal displacement late in the Penokean. Could the oxidation of the Negaunee siderite bands to form supergene magnetite-martite-platey hematite ores relate to meteoric ingress as late as 1730 Ma? The primary lessons to be gleaned from the geological evidence for repeated displacements are: “once a fault, always a fault”; that these structures accommodated opposing normal/reverse displacements over time; and that they remained a focus for very different fluid types over their protracted geological history.



Figures: A - 2695-2675 Ma Neoproterozoic Orogenic Break. B - 2450-2200 Ma Paleoproterozoic Rift. C - 1850 Ma Penokean Collision. D - Post-Penokean Thermal Domes.

Toward a Common Map Legend for Ontario

R.M. Easton, M.G. Houlé, D. Rowell, and N.F. Trowell, Precambrian Geoscience Section, Ontario Geological Survey, 933 Ramsey Lake Road, 7th Floor, Sudbury, ON P3E 6B5, Canada, mike.easton@ontario.ca

Ontario encompasses over 1 million km², 3 major Precambrian geological provinces (Superior, Southern, Grenville) and a variety of younger Paleozoic rocks and Quaternary sediments. The Ontario Geological Survey (OGS) typically produces maps at several scales: detailed (1:20 000), regional (1:50 000 and 1:250 000), or provincial (1:1 000 000). Historically, creation of map legends has been individualistic, dependent on both the mapping geologist and the character and scale of the map area.

With the advent of increasing interjurisdictional collaborative mapping projects, digital collection of field data, and a focus on compilation maps, there is an increasing need for the OGS to develop a common map legend for all OGS Precambrian geology maps.

Creating a common map legend is more challenging than simply creating a standard scheme for rock nomenclature, although the latter is a necessary prerequisite. A map legend must also be able to reflect relative age relationships, formal stratigraphic nomenclature where established, be applicable to areas of well known and poorly known geology, yet be independent of map scale. Furthermore, the methodology used must be relatively easy for the end user to understand and, for hard-copy maps, must contain as few characters as possible in order to avoid clutter and be comprehensible.

This presentation presents a first attempt by the OGS to create a common map legend. At its essence is a basic 3 or 4 letter alphanumeric code: legend/colour code_rock class_root rock name[±key modifier]. For example, 5lg[bi] is a biotite granite, assigned colour code of unit 5. Comments on the merits and drawbacks of this scheme are welcomed by the authors.

During the course of developing a common map legend, specific problems were encountered with respect to existing nomenclature schemes for metamorphic, altered, and/or deformed rocks (a.k.a. composite-origin rocks) rocks. For example, is composition critical to the name (*e.g.*, marble); or texture (*e.g.*, schist); or protolith (*e.g.*, metabasalt); or mineralogy (*e.g.*, diopside marble); or a combination of factors (*e.g.*, kyanite metapelite)? Unfortunately, all recent rock nomenclature schemes for composite-origin rocks (*e.g.*, Fettes and Desmons 2007) have focused on naming such rocks at the hand sample level, not at a macroscopic scale. To address this problem, a hierarchical nomenclature scheme, is proposed, as outlined in brief in the table below.

Type	Subtype	Root Name (examples)	Optional Modifier (textural, mineralogical, descriptive)
Metamorphic	Structural	schist, gneiss, granulite	kyanite schist
	Compositional	marble, amphibolite, pelite	calcitic marble
	Textural	breccia, agmatite	
Alteration	Hybrid	migmatite	
	Hydrothermal	silicification	
	Metasomatic	fenite, skarn	
Structural	Brittle	cataclastite and related rocks	fault gouge
	Ductile	mylonite and related rocks	
	Impact	melt, breccia	

References Fettes, D. and Desmons, J. 2007. Metamorphic Rocks: A Classification and Glossary of terms, Recommendations of the International Union of Geological Sciences Subcommittee on the Systematics of Metamorphic Rocks; Cambridge University Press, Cambridge, UK, 244p.

Detrital zircon geochronology of Huronian Supergroup sandstones located within the Vernon structure, north of Espanola, Ontario

R.M. Easton, Precambrian Geoscience Section, Ontario Geological Survey, Sudbury, Ontario P3E 6B5 mike.easton@ontario.ca and **L.M. Heaman**, Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta, T6G 2E3 larry.heaman@ualberta.ca

Located north of Espanola, Ontario, the Vernon structure is a former depositional graben which preserves a near complete stratigraphic section through the Huronian Supergroup; from its contact with Neoarchean basement to the Lorrain Formation (upper Cobalt Group) (Easton 2005, 2006). The graben is bounded by Neoarchean monzogranitic rocks of the Birch Lake granite, part of the southern Abitibi subprovince, which has yielded a U-Pb zircon age of 2651 ± 1 Ma (Kamo 2006). The depositional setting of the Huronian Supergroup in the Vernon structure provides an opportunity to investigate the influence of local *versus* regional provenance sources on the composition of Huronian Supergroup metasandstones. For comparison, Rainbird and Davis (2006) provide regional data on the detrital zircon geochronology of Huronian Supergroup metasandstones from the Elliot Lake and Cobalt areas.

Samples were collected from 3 sandstone-dominated formations in the Vernon structure, from stratigraphically lowest to highest these are the Matinenda, Mississagi and Serpent formations. U-Pb zircon geochronology was conducted using laser-ablation analyses at the University of Alberta; 45 grains were analyzed from the Matinenda sample, and 36 grains each from the Mississagi and Serpent samples.

The Matinenda Formation sample was collected from the base of the formation where it overlies a package of Huronian Supergroup mafic metavolcanic and volcanoclastic rocks in Baldwin Township. Most of the near concordant grains in the sample are Neoarchean, and define 2 groupings; 1) 2600 to 2690 Ma ($n=18$), and 2) 2690 to 2740 Ma ($n=8$). The latter age range is representative of the age of volcanism and plutonism in the Abitibi greenstone belt. The younger age range images emplacement ages representative of plutonic rocks of the southern Abitibi subprovince. In addition, 4 near concordant grains gave an average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2455 ± 9 Ma, which is interpreted as representing the age of locally-sourced Huronian metavolcanic material. Rainbird and Davis (2006) document a similar population distribution of Neoarchean grains in their Matinenda Formation sample, but they did not find any Paleoproterozoic grains.

The Mississagi Formation sample was collected from the uppermost part of the formation in Porter Township. This sample has an SiO_2 content of 93 wt.%, and a Chemical Index of Alteration (CIA) value of 65. Again, the most concordant grains defined 2 groups, with 10 grains in the range from 2600 to 2690 Ma, and 5 grains in the 2690 to 2740 Ma interval. This sample also contained 4 grains in the range 2900 to 3000 Ma and 1 grain at 3320 Ma. This distribution is similar to that reported by Rainbird and Davis (2006), who also reported a population of very old grains, which only occurred in the Mississagi Formation. Roughly half of the analyzed grains in the Mississagi Formation sample were $>10\%$ discordant, in contrast to the other two samples, where significant discordance was much less common.

The Serpent Formation sample was collected from the middle of the formation in Porter Township. This sample has a SiO_2 content of 81.3 wt. %, a Na_2O content of 5.0 wt. % and a CIA value of 82; the high sodium content is typical of the formation. Although the two Neoarchean age groups are also present in this sample, the younger group (2600 to 2690 Ma) is dominant (22 grains), with only 2 grains present from the 2690 to 2740 Ma group, and 2 grains ranging from 2740 to 2790 Ma. This result differs from Rainbird and Davis (2006), who found the 2690 to 2740 Ma range dominant, as well as the presence of a sizable Geon 28 population. The dominance of the younger Neoarchean grains in the Serpent Formation in the Vernon structure may indicate that the sandstone there is sourced more locally than the Elliot Lake sample studied by Rainbird and Davis (2006).

The geochemistry of the metasandstones provides limited provenance information. The Huronian metavolcanic rocks in the Vernon area lack any diagnostic trace element signatures (such as high Cr contents) that could be detected in the sandstones. The Birch Lake granite is characterized by high SiO₂ (70-74 wt.%) and elevated thorium contents (20-50 ppm), and the metasandstones contain between 15 and 140 ppm thorium, with low uranium. Thus, plutons similar in composition to the Birch Lake granite could have provided a source for both quartz and thorium for the sandstones in the Vernon structure.

Probably the most significant result from this study is the abundance of grains in the interval from 2600 to 2690 Ma (mostly 2660 to 2680 Ma) in all 3 samples, which appear to increase in abundance up section. If the sandstones were sourced solely from the northern Abitibi subprovince, the dominant population would be expected to range from 2690 to 2740 Ma. The limited geochronology available for intrusive rocks in the southern Abitibi subprovince range in age from 2660 to 2680 Ma (*e.g.*, Prevec 1993, Krogh *et al.* 1984), suggesting that a significant portion of the detrital zircons in the sandstones are derived locally from the southern Abitibi subprovince.

A titanite grain from the Matinenda Formation sample yielded a Pb²⁰⁷/Pb²⁰⁶ age of 2139±15 Ma, similar to regional Rb/Sr ages reported from Nipissing gabbro intrusions in the Southern Province (*e.g.*, 2110±80 Ma, adjusted to current decay constants, Van Schmus 1965), perhaps reflecting post-emplacement cooling of Nipissing gabbro intrusions that were emplaced into the Huronian Supergroup at circa 2215 Ma, or a regional metamorphic event. Attempts to date the timing of regional metamorphism using staurolite grains present in lower amphibolite facies metapelitic rocks of the McKim Formation, collected from classic localities near Agnew Lake, were inconclusive, due to low U contents in the staurolite grains coupled with the effects of metamorphic retrogression on the grains.

References

- Easton, R.M. 2005. Geology of Porter and Vernon townships, Southern Province; in Summary of Field Work and Other Activities, 2005, Ontario Geological Survey Open File Report 6172, p.13-1 to 13-20.
- Easton, R.M. 2006. Geology and mineral potential of Southern Province rocks in Baldwin Township; in Summary of Field Work and Other Activities, 2006, Ontario Geological Survey Open File Report 6192, p.14-1 to 14-21.
- Kamo, S. 2006. Report on U-Pb geochronological data from the southern Abitibi Subprovince, Bannockburn–Montrose and Vernon townships, and the Grenville Front region, Thistle–Sisk townships, Ontario; internal U/Pb age report from the Jack Satterly Geochronology Laboratory for the Ontario Geological Survey, Department of Geology, University of Toronto, 22 Russell Street, Toronto, Ontario M5S 3B1, 20p.
- Krogh, T.E., Davis, D.W., and Corfu, F. 1984: Precise U-Pb zircon and baddeleyite ages for the Sudbury Structure; in Geology and Ore Deposits of the Sudbury Structure; Ontario Geological Survey Special Volume 1, p. 431-446.
- Prevec, S.A. 1993. An isotopic, geochemical and petrographic investigation of the genesis of early Proterozoic mafic intrusions and associated volcanics near Sudbury, Ontario; unpublished Ph.D. thesis, University of Alberta, Edmonton, Alberta, 223p.
- Rainbird, R.H. and Davis, W.J. 2006. Detrital zircon geochronology of the western Huronian Basin; Institute on Lake Superior Geology, Proceedings, 52, pt.1, Programs and Abstracts, 55-56.
- Van Schmus, W.R. 1965. The geochronology of the Blind River-Bruce Mines area, Ontario; Journal of Geology, v. 73, p. 755-780.

Structural and kinematic analysis of the Archean Shagawa Lake shear zone, Superior Province, northeastern Minnesota

Emerald J. Erickson., Dept. of Geology, Univ. of Minnesota-Duluth, eric1757@d.umn.edu

Vicki Hansen., Dept of Geology, Univ. of Minnesota-Duluth, vhansen@d.umn.edu

Granite-greenstone terrains exist in all Archean (3.8-2.5 Ga) cratons and are important to understanding Archean geologic processes. The debate about the formation of Archean granite-greenstone terrains features two hypotheses: 1) sagduction and diapirism caused by crustal scale density instabilities that led to sinking of greenstone basins and rise of granitic bodies and 2) arc-terrane accretion via plate tectonics processes that led to interlayered greenstone basins and volcanic arc plutons. The Superior Province in northeastern Minnesota is an Archean granite-greenstone terrain which is historically explained by arc-terrane accretion. The evolution of shear zones within greenstone terrains can provide critical insight between these hypotheses.

The steeply dipping, east striking Shagawa Lake shear zone, northeastern Minnesota, lies within a greenstone belt bordered to the north and south by granite complexes. The Shagawa Lake shear zone lies within a greenstone belt consisting of Newton Lake formation (metadiabase and greenstone), Knife Lake group (felsic volcanic tuff and metasediments) and Ely Greenstone (greenstone and iron formation). The Shagawa Lake shear zone is bordered to the north by the Vermilion Granitic Complex and to the south by the Giants Range Batholith.

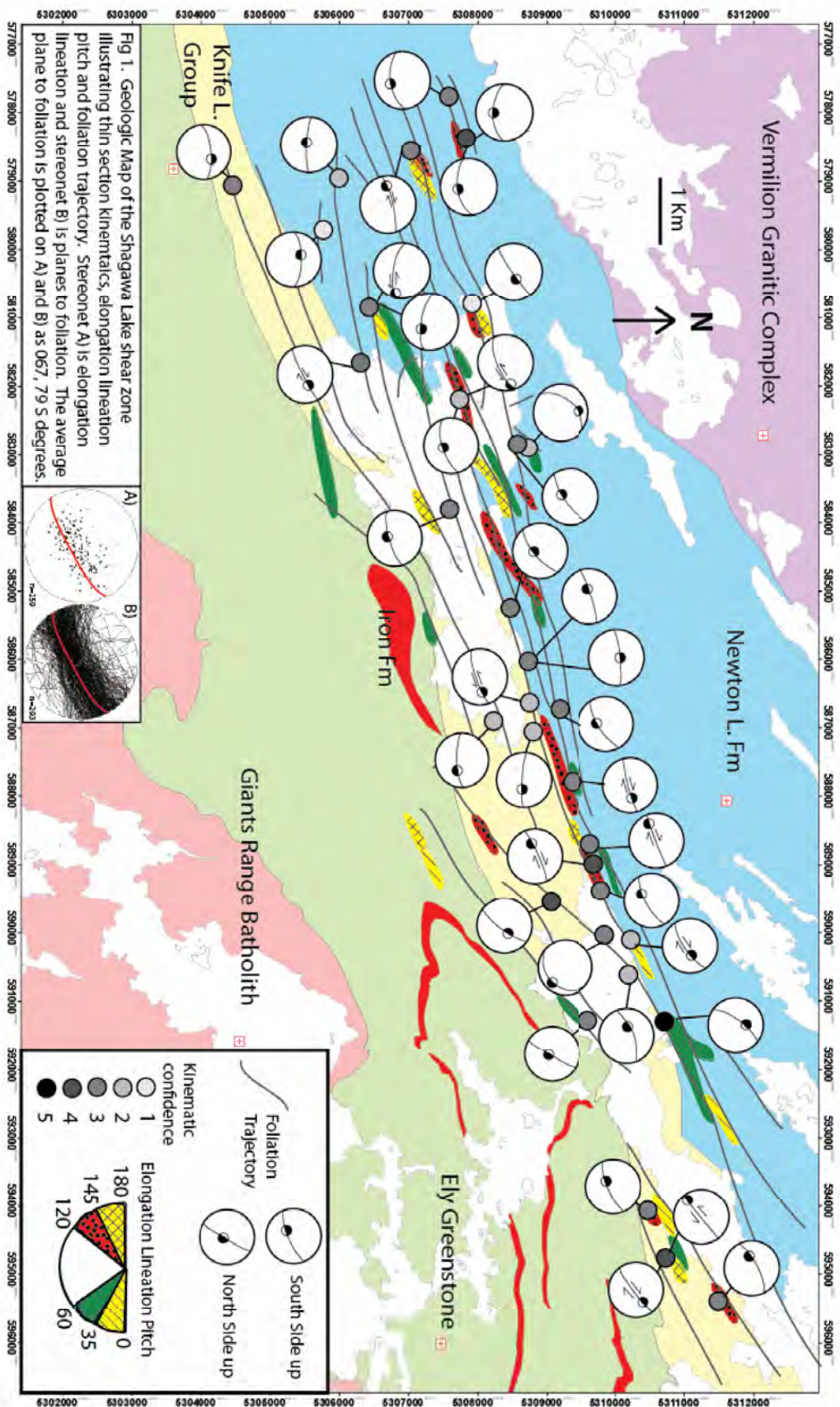
I undertook a structural and kinematic study to understand the deformation within the Shagawa Lake shear zone. This work focuses on a ~18 km long and ~3-4 km wide portion of the shear zone (Fig 1.). I compiled structural data from published Minnesota Geological Survey maps and collected structural data and oriented samples for microstructural analysis along three north-south transects.

The Shagawa Lake shear zone foliation averages 064° , 79°S . Elongation lineations are dominantly steeply plunging ($90^{\circ} \pm 30^{\circ}$) with subsidiary shallowly plunging lineations ($15^{\circ} \pm 10^{\circ}$). The average lineation is 143° , 84° . Locally dip-slip and strike-slip elongation lineations exist in the same rock. Shallow strike-slip lineations are few and overprint the penetrative elongation lineations.

In the case of both strike-slip and dip-slip lineations, sections cut normal to foliation and parallel to lineation show fabric asymmetry, whereas sections cut normal to foliation and lineation display fabric symmetry. These relations are consistent with non-coaxial shear.

Shear sense interpretations within the motion plane, normal to foliation and parallel to lineation, proved challenging. Of the 47 thin sections I was able to, with varying degrees of confidence, interpret 39. Microstructures within the Shagawa Lake shear zone 1) in the west, from north to south transition approximately from north-side-up to south-side-up, 2) towards the east both north-side up and south-side-up shear are recorded across the shear zone, 3) both right-lateral and left-lateral strike-slip shear occurs throughout and 4) zones of localized right-lateral and left-lateral strike-slip are not penetrative and probably postdate the later dip-slip elongation lineation.

The structural patterns within the Shagawa Lake shear zone are consistent with the rising of the northern and southern granitic complexes and concurrent sinking of greenstone basins forming north-side-up and south-side-up dip-slip displacement within the greenstones and volcanic sediments.



Flow fabric determination of two Mesoproterozoic midcontinent rift dike swarms, northeastern Minnesota

Fein, E. M., (Department of Geology, Kent State University, Kent, OH 44242, efein@kent.edu),
Ferré, E.C. (Department of Geology, Southern Illinois University, Carbondale, IL, 62901),
& **Holm, D. K.** (Department of Geology, Kent State University, Kent, OH 44242)

The planar geometry of mafic dikes provides an important constraint on the direction of magma flow, and their fast cooling preserves laminar flow fabrics of viscous magma, which aligns rigid grains (e.g., Cañón-Tapia, 2004). The aim of this study is to document regional-scale igneous flow patterns in two Mid-continent Rift System (MRS) dike swarms and to locate vent sources feeding these intrusions by obtaining a reliable measure of magmatic fabrics using Anisotropy of Magnetic Susceptibility (AMS). Previous thin section petrofabric analyses of aligned plagioclase phenocrysts suggested primarily lateral flow in both swarms, albeit from a relatively confined data set (Reichhoff, 1987). Another objective therefore is to assess the potential importance of lateral mass transfer in the process of intracratonic rifting and crustal evolution.

The Carlton County (CC) and Duluth dike swarms, located in and around Duluth, MN, are geographically proximal but distinct in age, strike pattern, and chemical composition. The reversely polarized (older) CC dikes intrude Paleoproterozoic metagreywackes, and are subparallel in map-view. The younger, normally polarized Duluth dikes intrude MRS volcanics, and strike somewhat irregularly. The mean orientation measured for the CC swarm is N28°E, 89°NW. Duluth swarm's mean orientation again strikes N28°E, although more variably, with shallower and more diverse dip directions ranging from ca. 70°NW to 70°SE (planes, Fig. 1).

The dike geochemistry is consistent with a mantle plume source with some input from partial melting of the continental lithosphere (Seifert & Olmsted, 2004). Both dike swarms are basalt to basaltic andesite in composition. The CC dikes are predominantly quartz tholeiite, whereas the Duluth dikes are predominantly olivine tholeiite, with major primary minerals in both swarms including: plagioclase, olivine, augite, magnetite, and ilmenite (Reichhoff, 1987).

The dikes in both swarms appear massive in outcrop and hand sample and no flow structures such as stretched vesicles were observed, making more traditional, macroscopic flow fabric measurement impossible. AMS, defined by preferred orientations of both crystallographic axes and shape preferred orientations of individual mineral grains and grain clusters, provides for delineation of rock fabrics in such macroscopically isotropic rocks (Rochette et al., 1992). The AMS technique is powerful and can measure the orientations of hundreds of grains in minutes, compared to hours of measurement using other approaches (Borradaile & Henry, 1997). This technique has been successfully applied to magma flow in dikes in studies since Knight & Walker (1988) empirically showed that AMS fabric is equal to magma transport direction in Hawaiian dikes. Since then, a basic understanding of the technique has been developed, and AMS is now accepted as a robust geologic tool for defining rock fabrics (Cañón-Tapia, 2004).

We collected two oriented samples (at differing distances from the dike margins) from 26 dikes (13 from each swarm). To date, 21 oriented samples from 19 dikes have been analyzed. For each sample site an average of 16 cubes were analyzed, with a minimum of 9 per site. AMS measurement of each cube produces a magnetic susceptibility ellipsoid, represented by a second-order tensor describing the length and orientation of three principle axes, $K_1 \geq K_2 \geq K_3$. K_1 gives the average magnetic lineation, used as a proxy for magmatic flow fabric. K_1 and K_2 determine the plane of average magnetic foliation (Rochette et al., 1992; Ferré et al., 2004).

Measurements were made using a Kappabridge KLY4-S susceptibility bridge at field intensity 300 A/m. The AMS results have a bulk magnetic susceptibility of about $1-3 \times 10^{-2}$ SI, meaning that the magnetic signal is likely dominated by the fabric of ferromagnetic phases. The AMS signal is robust as the bulk magnetic susceptibility is well within the instrument sensitivity (2×10^{-8} SI at 300 A/m; Pokorný et al., 2004). The degree of magnetic anisotropy is on average 1.04 with a standard

deviation of 0.03 for both swarms. Site means for 12 dikes in the CC swarm and 9 dikes in the Duluth swarm are plotted (Fig. 1). The open triangles indicate the swarm mean of the K_1 site means, yielding average magnetic lineation orientations for each swarm. Results for the CC swarm cluster relatively consistently and include a magnetic lineation that is sub-vertical. In contrast, results for the Duluth swarm are complex and give poor statistics; however overall the

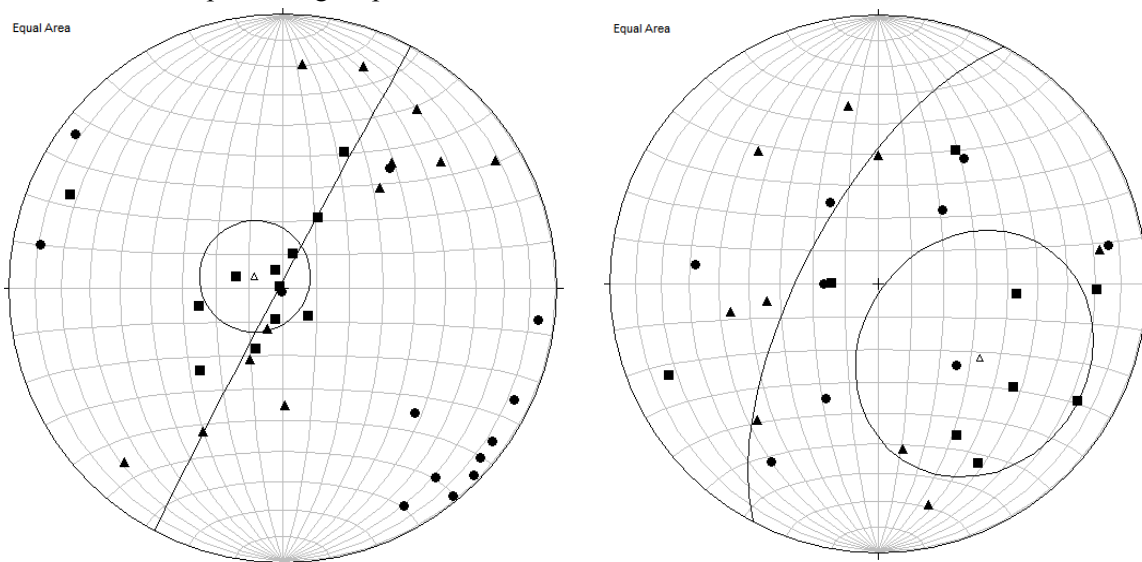


Figure 1. Site averaged AMS results for all data collected to date in lower hemisphere stereoplots for each swarm (CC left; Duluth right): K_1 =squares; K_2 =triangles; K_3 =circles. Mean dike orientation for each swarm is also plotted.

magnetic lineations are sub-horizontal or inclined. The preliminary AMS measurements suggest differing magmatic emplacement directions in the two dike swarms. The CC swarm was emplaced predominantly vertically, and the Duluth dike swarm displays more variable, oblique emplacement patterns, which may be influenced by inverse magnetic fabrics from single-domain magnetite in the Duluth swarm rocks. To independently corroborate these results, image analysis will be performed on three mutually perpendicular, oriented thin sections of a number of our samples using a software package to quantify mineral alignment as a proxy for magma flow.

- Borradaile & Henry, 1997, Tectonic applications of magnetic susceptibility and its anisotropy, *Earth-Science Reviews*, 42, 49-93.
- Cañón-Tapia, E., 2004, Anisotropy of magnetic susceptibility of lava flows and dykes: A historical account, from: Martín-Hernández, F., Lüneberg, C.M., Aubourg, C., & Jackson, M. (eds.) *Magnetic Fabric: Methods and Applications*, Geological Society, London, Special Publications, 238, 205-225.
- Ferré, E.C., Martín-Hernández, F., Teyssier, C., & Jackson, M., 2004, Paramagnetic and ferromagnetic anisotropy of magnetic susceptibility in migmatites: Measurements in high and low fields and kinematic implications, *Geophysics Journal International*, 157, 1119-1129.
- Knight, M.D. & Walker, G.P.L., 1988, Magma flow directions in Dikes of the Koolau Complex, Oahu, Determined from Magnetic Fabric Studies, *Journal of Geophysical Research*, v. 93, p. 4301-4319.
- Pokorný, J., Suza, P., & Hrouda, F., 2004, Anisotropy of magnetic susceptibility of rocks measured in weak magnetic fields using the KLY-4S Kappabridge, in: Martín-Hernández, Lüneberg, Aubourg, & Jackson, M. (eds.) *Magnetic Fabric: Methods and Applications*, Geol. Soc. London Spec. Pub. 238, 69-76.
- Reichhoff, J., 1987, Two Keweenaw basaltic dike swarms in the Duluth area, Minnesota, Unpublished M.S. Thesis, University of Minnesota Duluth.
- Rochette, P., Jackson, M., & Aubourg, C., 1992, Rock magnetism and the interpretation of anisotropy of magnetic susceptibility, *Reviews of Geophysics*, v. 30, p. 209-226.
- Seifert, K.E. & Olmsted, J.F., 2004, Geochemistry of North Shore Hypabyssal dikes and sills in the Midcontinent Rift of Minnesota: an example – the 47th Avenue sill, *Can. J. Earth Science*, 41, 829-842.

This research is supported by ILSG, GSA, Sigma Xi, and Kent State University.

Student Capstone Map from the UMD Precambrian Research Center's Field Camp: Bedrock Geology Map of Homer Lake and Adjacent Areas, Cook County, Minnesota

Shelby J. Frost¹, Natalie A. Juda², and Jim Miller³

1) Winona State University, Winona, Minnesota; 2) Macalester College, St. Paul Minnesota (presently at Golden Chalice Resources, Timmins Ontario); 3) Department of Geological Sciences, University of Minnesota Duluth

One of the four capstone mapping projects conducted during the fifth week of UMD's Precambrian Research Center's 2007 summer field camp focused on an incompletely mapped Keweenaw gabbroic complex in far northeastern Minnesota (Fig. 1). This extensive gabbroic complex, named the Brule Lake/Hovland gabbro (BLHg) by Miller et al. (2001), occurs as an east-west trending, semi-continuous intrusive unit composed of an unknown number of separate intrusions. The structural position of the BLHg complex is generally above the mafic and felsic intrusions of the Duluth Complex and reversed-polarity lavas of the NSVG and below the Eagle Mountain and Pine Mountain granophyre bodies. Vervoort et al. (2007) reported U-Pb ages for the Eagle Mtn and Pine Mtn granophyres of 1098.6 ± 3.6 Ma and 1095.3 ± 3.8 Ma, respectively. Gradational contacts between the BLHg and the overlying granophyres suggest that the BLHg may have a similar age of emplacement. These possible ages and the high structural position of the BLHg are consistent with this intrusive complex being more similar to the Beaver Bay Complex (~1096 Ma) than to the deeper-seated and older Duluth Complex (1099-1108 Ma, Paces and Miller, 1993).

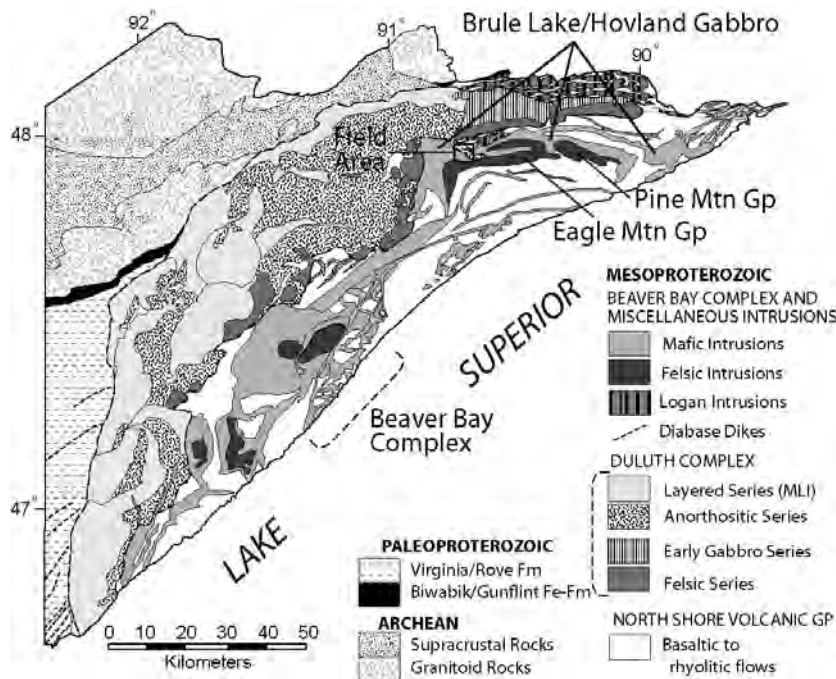


Figure 1. Generalized geology of northeastern Minnesota showing the location of the field area. Intrusive units mentioned in the text are labeled.

The western extent of the BLHg, which is where our mapping was focused (Fig. 1), was first reconnaissance mapped by Grout in the 1930's and 40's. Most of his mapping was published in MGS Bulletin 39 (Grout et al., 1959) as a series of small-scale (~1:100,000) township maps that show the generalized outcrop distribution of various rock types. In the Homer Lake area (T63N, R3W), Grout et al. (1959, Figure XXIV) documented the occurrence of locally foliated and layered gabbro, oxide gabbro, anorthositic gabbro, intermediate rocks, basalt, and hornfels. Davidson and Brunell (1977) published another reconnaissance map of the area that focused

mainly on the geology of the Brule Lake area, to the north of Homer Lake. Curiously, the geology of the Homer Lake area shown on the 1:24,000 scale Davidson and Burnell (1977) map does not show the various rock types that Grout et al. (1959) identified ringing Homer Lake. In fact, only one outcrop is shown in the Homer Lake area, which proved to be misidentified. This suggests that these Davidson and Burnell did not actually map in this area.

During the capstone week, we worked out of a base camp on Homer Lake just outside the Boundary Waters Canoe Area Wilderness (BWCAW) and made daily forays into the field by canoe. We completed five full days of field mapping as a single party of three. Jim Miller had also done two days of mapping in the previous summer to preview the area for the capstone project. Most mapping concentrated on the shoreline exposures of Homer, Axe and Whack Lakes. During the field work, over 110 outcrop stations were observed, the orientation of 50 structures were measured, and 41 hand samples were collected (petrographic study of these samples are planned for this spring).

The field data were used to interpret a map area of about 3 miles, east to west, by 1 mile, north to south. In the reconnaissance map of Davidson and Brunell (1977), which was directly integrated into the regional Duluth Complex map (Miller et al., 2001), this area was interpreted to be underlain largely by gabbroic anorthosite related to the anorthositic series of the Duluth Complex. They show olivine gabbro in the northern part. Our mapping showed there to be few if any anorthositic series lithologies in the area, except for small inclusions. Rather, we found the area to be dominated by variably foliated oxide gabbro that dips moderately (15° - 35°) to the south. The most prominent and traceable feature in the area is sheet of hornfels basalt overlain by hornfels cross-bedded, volcanogenic sandstone. This volcanic-sedimentary unit can be traced along the north shore of Homer Lake for over two miles of strike length and forms a 100m thick screen that separates two distinct conformable gabbro sequence. The intrusive rocks north of (underlying) the screen is composed of mafic to intermediate rock types grouped as the Axe Lake gabbroic sequence. The gradual progression of mafic (diabase and oxide gabbro) to intermediate (ferromonzodiorite to granophyric gabbro) rock type from north to south (upsection) implies that this may represent a differentiated sequence formed by in situ fractional crystallization. South of (overlying) the volcanic screen is a sequence of oxide gabbro to gabbro-norite that alternate between coarse-grained, poorly foliated and medium-grained, well foliated textures. This is informally termed the Homer Lake gabbroic sequence. What is perhaps the most interesting result of our mapping is that, while it shows Davidson and Brunell's (1977) interpretation to be incorrect, it actually verifies the reconnaissance mapping of Grout et al. (1959).

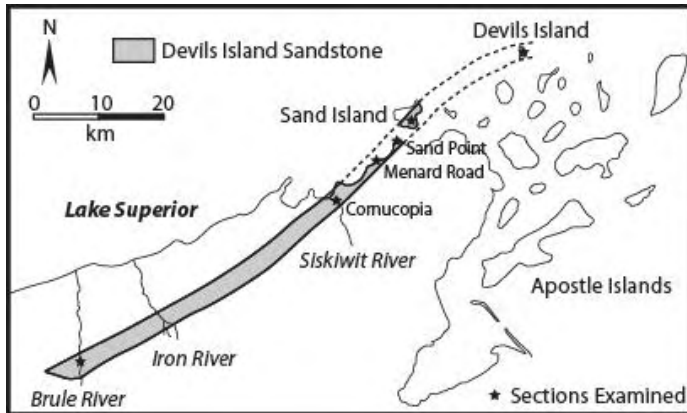
The main criteria for selecting a particular area for a capstone mapping project for the Precambrian field camp is that it be a generally a poorly mapped, but well exposed area, which previous reconnaissance mapping has shown to have a diverse and interesting geology. The Brule Lake/Hovland gabbro is one of the last poorly mapped parts of the greater Duluth Complex. Because of its location in and near the BWCAW, the BLHg will likely only become well mapped by academic-based mapping. To tease out the detailed geology of the BLHg, we plan to incrementally expand the map coverage of this intrusive complex over the coming years of the Precambrian field camp. Next year, we plan to work north and west of the current map area.

References

- Davidson, D.M., Jr., and Burnell, J.R., Jr., 1977, Reconnaissance geologic map of the Brule Lake quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map Series, M-29, scale 1:24,000
- Grout, F.F., Sharp, R.P., and Schwartz, G.M., 1959, The geology of Cook County Minnesota. Minnesota Geological Survey Bulletin, v. 39, 163 p.
- Miller, J.D., Jr., Green, J.C., Severson, M.J., Chandler, V.W., and Peterson, D.E., 2001, Geologic map of the Duluth Complex and related rocks, northeastern Minnesota. Miscellaneous Map Series, M-119, scale 1:200,000
- Paces, J.B., and Miller, J.D., Jr., 1993, Precise U-Pb ages of Duluth Complex and related mafic intrusions, northeastern Minnesota: geochronological insights to physical, petrogenetic, paleomagnetic and tectono-magmatic processes associated with the 1.1 Ga Midcontinent rift system: *Journal of Geophysical Research*, v. 98, no.B8, p. 13,997-14,013.
- Vervoort, J.D., Wirth K., Kennedy, B., Sandland, T., Harpp, K.S., 2007, The magmatic evolution of the Midcontinent rift: New geochronologic and geochemical evidence from felsic magmatism: *Precambrian Research* 157, p. 235–268.

REINTERPRETATION OF THE TRACE FOSSIL-BEARING DEVILS ISLAND SANDSTONE, KEWEENAWAN RIFT, NORTHERN WISCONSIN

GALSTON, Lynn, Geology, University of Wisconsin - Eau Claire, 105 Garfield Avenue, Eau Claire, WI 54702, galstolm@uwec.edu and **HAVHOLM, Karen G.**, Department of Geology, University of Wisconsin-Eau Claire, Eau Claire, WI 54702 and **HASIOTIS, Stephen T.**, Department of Geology, University of Kansas, Lawrence, KS, 66045



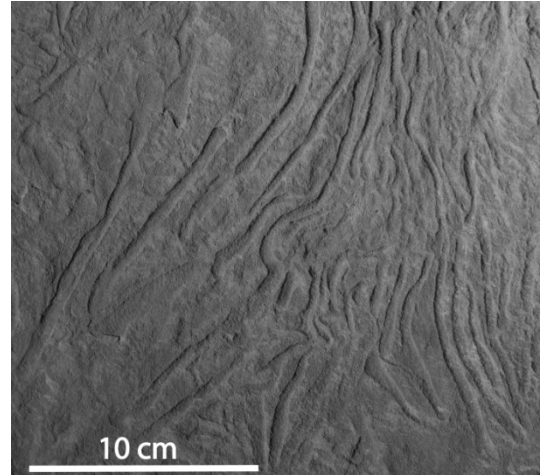
Outcrop locations, modified from Adamson, 1997

The Devils Island Sandstone is a fine-grained quartz arenite that is a late-stage Keweenawan rift-fill deposit. The unit is exposed on the coast of Lake Superior creating cliffs and sea caves on Sand and Devils Islands as well as the shoreline between Menard Road and Sand Point. There are also limited exposures on the Brule, Iron, and Siskiwit Rivers. Both the Devils Island Sandstone and the stratigraphically equivalent Hinckley

Sandstone were interpreted as a shallow lacustrine environment (Tryhorn and Ojakangas, 1972; Adamson, 1997). Identification of adhesion structures in the Hinckley Sandstone, however, indicates an environment that experienced subaerial exposure. Further studies of sedimentary structures in the Hinckley Sandstone indicate a depositional environment ranging from fluvial to eolian dune and interdune (Johnson, Beaster, Kohn and Havholm, 2001). This revised interpretation of the Hinckley Sandstone prompted re-evaluation of the Devils Island Sandstone.

Outcrops of the Devils Island Sandstone have been studied in some detail. A boat was used to access many of the outcrops, and stratigraphic sections were measured and described. Four out of five facies identified are similar to facies within the Hinckley Sandstone. Tangential cross-strata indicate a predominantly eolian dune environment with localized subaqueous features. Cross-strata dip primarily to the northeast, east and southeast. Trough cross-strata with rip-up clasts and coarser sand grains, including granules and pebbles in some localities, suggest a fluvial environment. Trough orientations indicate paleocurrent directions primarily to the northeastern quadrant. Sandy planar bedding contains sedimentary structures reflecting an environment of deposition that varied from dry (wind-ripple strata) to damp (adhesion structures) to wet (subaqueous ripple forms). Convolute bedding, including fluid-escape structures and cm- to dm-scale faults as well as folds, appears to have resulted from rapid deposition onto a saturated substrate. These facies suggest a fluvial and dune-interdune environment. The fifth facies—silty planar bedding—contains laterally continuous, thinly laminated fining-upward sequences containing mm- to cm-scale silt-sand couplets with rippled to irregular silty capping laminae and, locally, tool marks and horizons with mudcracks. This facies indicates a predominantly subaqueous environment with fluctuating energy levels, possibly lacustrine.

At one locality within the silty planar facies trace fossils are present including 1) curved to sinuous and Y-branching, cm-wide, meandering traces, and 2) sub-mm to mm-scale sinuous trails that overlap and cross over larger traces. Identification of trace fossils within the Devils Island Sandstone could serve either to constrain its age to Late Proterozoic, rather than Mid-Proterozoic, or provide rare evidence of Mid-Proterozoic multicellular life.



REFERENCES

- Adamson, K.F., 1997, Petrology, Stratigraphy and Sedimentation of the middle Proterozoic Bayfield Group, northwestern Wisconsin. Unpublished Masters Thesis, University of Minnesota, 203pp.
- Johnson, A.D., Beaster, K.F., Kohn, J.D. and Havholm, K.G., 2001, Braided-stream/eolian environment of Proterozoic Hinckley Sandstone, Keweenawan rift, east-central Minnesota. Geological Society of America Abstracts with Programs, v. 33, p. A229.
- Tryhorn, A.D., and Ojakangas, R.W., 1972, Sedimentation and petrology of the upper Precambrian Hinckley Sandstone of east-central Minnesota. In P.K. Sims and G.B. Moey, eds., Geology of Minnesota: a Centennial Volume, Minnesota Geological Survey, Minneapolis, p. 431-435.

Structural and Kinematic analysis of the Kawishiwi shear zone, Superior Province: Insight on granite-greenstone terrain tectonics and Archean crustal evolution

Sally Goodman, University of MN Duluth, Dept. of Geological Sciences, good0491@d.umn.edu

Two conflicting hypotheses have been invoked to explain the formation of Archean (~2.7 Ga) granite-greenstone terrains: 1) granite-greenstone terrains are collapsed back-arc or sutured forearc basins of subduction-driven accreted terranes, or 2) granite-greenstone terrains formed by density-driven sagduction of an insulating greenstone cover and concurrent rising of granite diapirs. Granite-greenstone terrains commonly preserve shear zones, which may reveal a history of Archean crustal evolution and tectonic processes.

A structural and kinematic analysis of the Kawishiwi Shear Zone (KSZ), within the Vermillion District, Superior Province, was conducted to evaluate the tectonic processes of granite-greenstone formation. The KSZ, broadly bounded by the Vermillion Granitic Complex to the north and the Giants Range Batholith to the south, forms one of several east-striking, steeply dipping shear zones in the Vermillion District. Metamorphism of regional rocks is generally in greenschist and amphibolite facies. The ~30km KSZ length is truncated by younger (1.1 Ga) Keeweenawan intrusive rocks in the southeast and the north-striking Waasa fault in the west. Locally, the KSZ lies within Ely Greenstone; Knife Lake Group graywackes, tuffs, and conglomerates; and the Giants Range Batholith to the south and eastern extent.

In order to understand the KSZ kinematic and structural evolution, major data collection and analysis included: 1) metamorphic foliation, elongation lineation and pitch domains from field mapping the eastern 24km x 10km KSZ and also existing geologic maps, 2) outcrop-scale and microstructural kinematic analysis from oriented rock samples, quartz c-axis petrographic fabric analysis, and 3) general metamorphic history from lithology and thin section petrography.

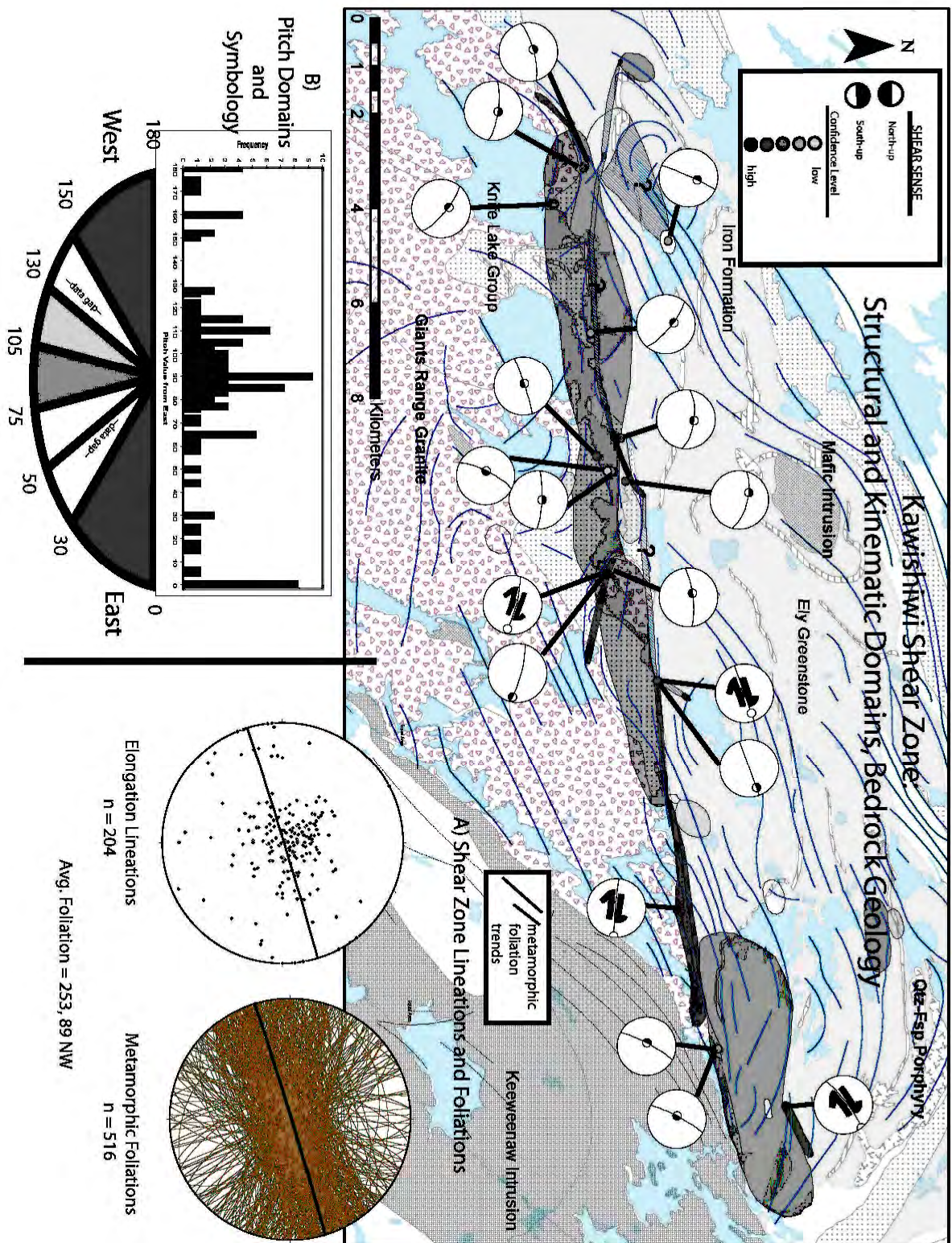
The data show that the KSZ is ~3-5 km wide and steeply dipping; it has an average foliation of 253, 89°, and a regionally dominant steeply plunging mineral elongation lineation with some gently plunging lineations (fig. A). Pitch values are bimodal; pitch domains show a distributed region of high pitch values and a narrow zone of low pitch values along strike of the KSZ (fig. B). The pillowed Ely Greenstone commonly does not have a foliation or lineation, likely due to strain partitioning around pillows. Of 55 oriented thin sections, 21 had discernible asymmetric fabrics. Asymmetric fabrics occur in foliation perpendicular, lineation parallel planes and symmetric fabrics occur in foliation perpendicular, lineation perpendicular planes; therefore, mineral elongation lineations are parallel to the motion plane or vorticity normal section, which is consistent with non-coaxial shear with *lineation forming parallel to shearing*. It follows, in the regions with high pitch values, the displacement is vertical to oblique and shear recorded was both north-side-up and south-side-up; along the narrow zone with shallow pitch, displacement is consistently dextral strike-slip.

The structural and kinematic results point to two displacement events in the KSZ: one of distributed ductile dip-slip shear (both north- and south-side-up), and a subsequent, more focused dextral strike-slip shear. The distributed and dominant dip-slip shear favors the sagduction-diapirism hypothesis whereby a high Archean geotherm dictates widespread density-driven ductile deformation of rising granites and sinking greenstone/sediment packages.

Green, J.C., Phinney, W.C., Weibler, P.W., 1966. Geologic Map of Gabbro Lake Quadrangle, Lake County, MN. MNGS: M-2, scale 1:31,680.

Green, J.C. and Schulz, K.J., 1982. Geologic Map of the Ely Quadrangle, St. Louis and Lake Counties, Minnesota. MNGS, M-50, scale 1:24,000.

Jirsa, M.A. and Miller Jr., J.D., 2004. Bedrock Geology of the Ely and Basswood Quadrangles, Northeast Minnesota. MNGS, M-148, scale 1:100,000.



MN DNR DRILL CORE EVALUATION PROJECT – THE APPLICATION OF AN XRF TO ELUCIDATE GOLD MINERALIZATION IN THE VERMILION GREENSTONE

Hanson, A.E. and **Frey, B.A.**, Minnesota Department of Natural Resources, Lands and Minerals Division, 1525 3rd Ave. E. Hibbing, MN 55746

The 2.7 Ga Vermilion Greenstone Belt is located in the southern extensions of the Wawa Subprovince, within the Superior Province of the Canadian Shield. It has a diverse setting that consists of volcanic-dominated lithologies including calc-alkaline and tholeiitic basalt flows, dacitic tuffs and banded iron formations (Larson 2004). This project focuses on a 90 square mile area of the Vermilion district from Tower, MN to just east of Ely, MN. As in the Canadian equivalents, there is evidence of lode gold deposits and volcanogenic massive sulphide deposits (Williams et al., 1991), however none of these is currently being mined in Minnesota.

The main focus of this project is to look for gold mineralization potential. This includes the establishment of gold mineralization indicators, and mineralization patterns. To date, more than thirty drill holes have been logged, with additional samples taken for analyses. As the cores were being logged, the Innov-X Vacuum Portable X-Ray Fluorescence spectrometer* (XRF) was used to complement our other activities. The XRF provides us with real-time chemistry data and allows for quick correlation between chemistry, as well as the visible and invisible, core or cuttings features. The XRF input was also useful for indicating sample intervals for further chemistry work. The goal of this project focuses on sharing the information we obtain about the gold mineralization. The information will be provided in a digital format online, including GIS maps.

There are some characteristics of the Innov-X XRF that we have to consider carefully, many of which involve interference. The XRF analyzes for multiple elements in one measurement. Hardware, software, and physics constraints require that trade-offs occur when obtaining results, however. Examples of interference include sample matrix effect, chemical matrix effect, instrument resolution, and calibration. The sample matrix effect takes the heterogeneity and/or homogeneity of the sample into account. The window through which the X-Rays are emitted is about $\frac{1}{2}$ cm², allowing only a small area to be analyzed. When we are examining drill core, this may be an advantage or disadvantage, depending on the sample characteristics. For example, we can analyze a small, unidentified grain, or do numerous analyses on an altered area leading up to a vein in order to see the chemical changes. This may be a disadvantage if we are trying to obtain a general composition of the matrix of the core. The XRF has been subject to chemical matrix effects, which occur as X-Ray absorption and enhancement phenomena, both of which involve iron in this case. We may have had lower than actual amounts of copper and elevated amounts of chromium due to the presence of iron. The effect of instrument resolution manifests when two elements have similar energy peaks, so it is especially prevalent with light elements. We cannot use the XRF for exact results because it is hard to recognize when this effect occurs.

Calibration is extremely important, and can be manipulated in various ways to obtain various results, such as detection of lighter elements, or more accurate readings for specific elements. If all samples have similar compositions, then calibration can be tweaked to optimize accuracy. This option is not available for a project such as ours with a wide range

of greenstone belt rock compositions. Our XRF is calibrated for the optimized analysis of 20 transition metals specifically. The adjustable sampling time interval can be increased to increase sensitivity and lower the detection limit, but this also reduces the numbers of samples analyzed. The use of standards is important, and their general composition should approximate that of the samples, if possible.

The software outputs analytical values for respective elements along with a “+/-“ value. The latter value will vary as the entire sample composition varies. Analytical values will not be produced unless analytical values are approximately 3 times the “+/-“ value, or more. The XRF may have a 1 ppm detection limit for gold, but it will not produce analytical values for a “+/-“ value of 3ppm, unless the sample actually has about 10 ppm Au. A lack of analytical values does not preclude gold amounts of interest.

Overall, the XRF is a very useful real-time guide, but we will not use it as a precise quantitative instrument.

Interesting Results.

The XRF was first used with our previous work in the Virginia Horn near Gilbert, MN. In that case, we found elongate as opposed to equigranular arsenopyrite crystals, within the altered dacitic porphyry, which was found to correlate strongly with elevated gold amounts.

The approximate $\frac{1}{2}$ cm² XRF sampling area is ideal for looking at the detailed mineral association related to gold mineralization. While working in the Vermilion area near Ely at the Raspberry Prospect, XRF analyses indicated that galena or rutile were the associations of choice for gold. Other areas of elevated base metals (such as molybdenum, copper, or zinc) lacked gold. Gold was also not arsenopyrite associated. XRF analyses also indicate the apparent regional tendency for fractures and shears to be associated with anomalous mercury.

The XRF does not replace geologic observations, or laboratory assay and analyses, but it offers us one more portable tool in our arsenal.

*The MN DNR does not endorse this product. The manufacturer’s name appears herein solely because it is considered essential to this report.

References

Larson, P.C., 2004, Regional Till Sampling of the Western Vermilion Greenstone Belt, Minnesota: Natural Resources Research Institute, University of Minnesota Duluth, Technical Report NRRI/TR-2004/23, 33p., 1 plate.

Williams, H.R., Stott, G.M., Heather, K.B., Muir, T.L., and Sage, R.P., 1991, Wawa Subprovince, in Thurston, P.C., Williams, H.R., Sutcliffe, R.H., and Stott, G.M., eds., Geology of Ontario: Ontario Geological Survey Special Volume 4, Part 1, p. 485-539.

IRON-FORMATION-HOSTED GOLD IN THE SUPERIOR PROVINCE OF NORTHWESTERN ONTARIO

HILL, MARY LOUISE, Department of Geology, Lakehead University, 955 Oliver Road, Thunder Bay, ON, Canada P7B 5E1 and **CHEATLE, ANDREW**, Chief Geologist, Musselwhite Mine, Box 7500, Thunder Bay, ON, Canada P7B 6S8

At Musselwhite Mine and in the Beardmore-Geraldton area, Archean iron formation hosts significant gold mineralization. Both Musselwhite and Beardmore-Geraldton lie within metavolcanic and metasedimentary belts of the Superior Province. In both locations, the iron formation is complexly folded and metamorphosed to the upper greenschist or lower amphibolite facies. These deposits can be compared to Archean iron-formation-hosted gold deposits that were mined at Homestake Mine, ND and Lupin Mine, NWT. What is the significance of iron formation as a host to gold mineralization in these deposits?

Deposit-scale analysis at Musselwhite demonstrates that gold mineralization was synchronous with amphibolite facies metamorphism and deformation. The deposit is giant in scale (more than 2 million ounces mined to date and 2 million ounces remaining in mineral reserve) with an average grade of approximately 5.5 g/t. Gold occurs primarily in a semi-pelitic unit within the iron formation, with the richest ore typically found at intersections of narrow high-strain shear zones with this particular lithology. Heterogeneity of metamorphism and deformation within the iron formation appears to be a key factor in mineralization. Strain incompatibilities caused by competency contrasts at various scales have produced enough transient permeability to allow localized fluid migration and mineralization.

In the Beardmore-Geraldton belt a network of anastomosing shear zones separates regional-scale lithons of metasedimentary and metavolcanic rock metamorphosed to the greenschist facies. The shear zones are steeply dipping with nearly horizontal transcurrent displacements. Here again, gold mineralization is linked to high-strain deformation zones. At this grade of metamorphism, iron formation has deformed in a more ductile manner than adjacent metavolcanic lithologies, and folding is common. Competency contrasts between lithologies are more pronounced during deformation at these temperatures, and this is significant to mineralization potential. Historic mining in this area has produced over 4 million ounces of gold in total, but no single mine has been a giant producer. Relationships seen at Musselwhite and other iron-formation-hosted gold deposits could have important implications for exploration in this area.

The most significant contribution of iron formation to gold mineralization in Archean metavolcanic and metasedimentary belts may be the heterogeneities in deformation produced during synchronous metamorphism and deformation of contrasting lithologies in brittle-ductile shear zones.

Whatever happened to the Logan sills? Ongoing research into the geochemistry of Midcontinent Rift-related mafic intrusive rocks south of Thunder Bay

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.

Until recently, the Mesoproterozoic Midcontinent Rift (MCR)-related gabbroic sill complexes around Thunder Bay and the Nipigon Embayment were described as the Logan Sills and considered to be a relatively homogeneous package of rocks (Stockwell et al., 1972). Recent work as part of the Lake Nipigon Region Geoscience Initiative has shown that the sills in the vicinity of Lake Nipigon can be subdivided into a number of discrete units with distinct geochemical and isotopic characteristics (Hollings et al., 2007a,b; Heaman et al., 2007). None of these sills were thought to have been part of the Logan Sill suite, which was restricted to the area south of Thunder Bay (Hollings et al., 2007a).

As part of an ongoing investigation of the MCR-related rocks south of Thunder Bay, samples of gabbroic sills and dykes were collected and analysed in order to further characterize these spatially distinct suites. The sills share a number of common characteristics. Like the sills of the Nipigon embayment, the majority of sills from this study are characterized by negative Nb anomalies, consistent with pervasive crustal contamination at depth.

The 2007 reconnaissance sampling shows that the southern sills can be divided into at least two, and possibly three, distinct suites. A mafic to ultramafic sill was identified in the Riverdale area in 2006 (Hollings et al., 2007c) and characterized by elevated Gd/Yb_n ratios (Fig. 1), comparable to the Hele and Disraeli intrusions of the Nipigon embayment. Present levels of sampling suggest that this “Riverdale sill” is restricted to a relatively small area. If the samples are from a single sill, then it must be at least 60 m thick. At one location, the Riverdale sill is cut by a ~1 m wide vertical dyke that is geochemically similar to the Nipigon sills.

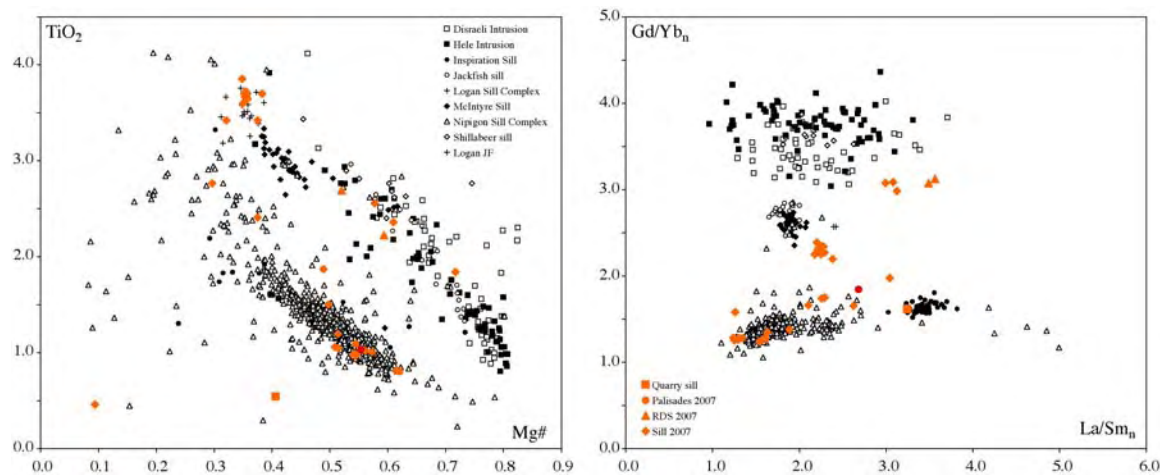


Figure 1: Major and trace element variation diagrams illustrating the geochemical affinities of the sills south of Thunder Bay. Data from Logan sills are from Hart (2003, 2005). Nipigon data are from Hollings et al. (2007a). Data for dykes south of Thunder Bay are from L. Hulbert and R. Ernst (Geological Survey of Canada, pers. comm. 2006) from samples collected by M. Smyk and J. Scott (Ontario Geological Survey), Hollings et al. (2007c) and this study.

A second sill suite is characterized by Gd/Yb_n ratios between 2 and 2.5, comparable to the Jackfish and McIntyre sills of the Nipigon Embayment. However, this suite, like the Logan sills is characterized by somewhat higher La/Sm_n ratios (Fig. 1). The elevated TiO₂ values of this sill are also consistent with the values reported for the Logan sills (Fig. 1).

The third suite is geochemically similar to the main Nipigon suite of the Nipigon Embayment (Fig. 1). It is characterized by lower La/Sm_n ratios and lower TiO₂ values for a given content of MgO. A single sample within this suite, collected from a ~1m thick sill that crops out in a package of Rove shale lies within the field of the Inspiration sills and may represent a distinct suite but additional sampling will be required to validate this. This sampling, planned for 2008, will also provide more comprehensive coverage of all the mafic intrusions south of Thunder Bay. This will help to elucidate boundaries between sill suites and individual intrusions and provide insight into mafic magmatism along the northwestern margin of the MCR.

References

- Hart, T.R. 2003. Keweenaw 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: Lithogeochemical, Assay and Compilation Data. Ontario Geological Survey, Miscellaneous Release of Data 147.
- Heaman, L.M., Easton, M., Hart, T.R., Hollings, P., MacDonald, C.A., and Smyk, M., 2007. Further refinement to the timing of Mesoproterozoic magmatism, Lake Nipigon Region, Ontario. *Canadian Journal of Earth Sciences*, 44, 1055-1086.
- Hollings, P., Hart, T., Richardson, A., and MacDonald, C.A., 2007c. Geochemistry of the Midproterozoic intrusive rocks of the Nipigon Embayment, Northwestern Ontario. *Canadian Journal of Earth Sciences*, 44, 1087-1110.
- Hollings, P., Richardson, A., Creaser, R., and Franklin, J., 2007b. Radiogenic isotope characteristics of the Midproterozoic intrusive rocks of the Nipigon Embayment, Northwestern Ontario. *Canadian Journal of Earth Sciences*, 44, 1111-1129.
- Hollings, P., Smyk, M., and Hart, T., 2007c. 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. In Woodruff, L (ed.), Proceedings and Abstracts, Institute on Lake Superior Geology 53rd Annual Meeting, Proceedings Volume 53, Part 1 – Program and Abstracts, 40-41.
- 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.

STABLE ISOTOPE GEOCHEMISTRY OF THE MUSSELWHITE AU MINE, N. ONTARIO: IMPLICATIONS FOR MINERALIZATION

ISAAC, Carissa, Lakehead University, Thunder Bay, Ontario cisaac@lakeheadu.ca and **HOLLINGS, Pete**, Department of Geology, Lakehead University peter.hollings@lakeheadu.ca

The Musselwhite mine is located on the south shore of Opapimisk Lake, approximately 720 km north of Thunder Bay. Hosted in the ~2.8Ga North Caribou Lake greenstone belt of the Sachigo Superterrane, Superior Province, the Musselwhite mine is classified as a shear hosted orogenic gold deposit, with an estimated reserve of 1.78 million ounces Au (Goldcorp, 2008). The amphibolite grade metabasalts and komatiitic metabasalts that host the mine have elevated gold concentrations with the highest gold grades hosted in iron formation contained within the volcanic pile (Hall and Rigg, 1986).

Oxygen isotope signatures from quartz samples from Musselwhite range from +12 to +14.7 per mil. These values are consistent with previous work by Otto (2002) and indicate fluid compositions that fall within both the magmatic and metamorphic range. The large overlap between the magmatic and metamorphic fluid oxygen isotope signatures have led researchers to use nitrogen isotopes to investigate the source of gold bearing fluids in orogenic gold deposits (Pitcairn et al., 2005; Jia, 2000). Nitrogen substitutes for K^+ as NH_4^+ in potassic minerals and has the advantage over oxygen and hydrogen isotopes in that it is present at low abundances in rocks. This reduces the effects of re-equilibration during successive thermal events such as metamorphism.

Twenty biotite and 30 quartz samples have been analyzed for $\delta^{15}N$, $\delta^{18}O$ and δD from the Musselwhite mine as well as 12 biotite samples from the surrounding granitoid rocks of the North Caribou Lake Greenstone Belt.

Nitrogen isotopes in biotite from the Musselwhite mine are characterized by a $\delta^{15}N$ range from -1.3 to 11.1 per mil, whereas biotite samples from granites and metasedimentary rocks adjacent to the deposit have a $\delta^{15}N$ range of -6.9 to +6.1 per mil. The range of nitrogen isotopes at Musselwhite suggests mixing between magmatic and metamorphic fluids (Figure 1).

Oxygen and hydrogen isotopic ranges for the granitoid plutonic rocks are +2.0 to +4.0 per mil and -59 to -80 per mil respectively; these values are typical of felsic plutonic rocks (Taylor, 1974). Oxygen and hydrogen isotopes of biotite samples from the mine range from +7.7 to +9.6 per mil for oxygen and -85 to -103 per mil for hydrogen. The anomalously low δD signature could be influenced by: 1) the iron content of the biotites, 2) degassing of the deposit at hypabyssal levels, 3) biologic activity.

In conclusion, the stable isotopic data generated for the Musselwhite Mine suggest the possibility for fluid mixing and indicate that magmatic fluids may have had a role in transporting gold.

References:

- Goldcorp, 2008. Goldcorp, inc. website – Musselwhite. <http://www.goldcorp.com/operations/musselwhite/>
- Hall, R. S. and Rigg, D. M., 1986. Geology of the West Anticline Zone, Musselwhite Prospect, Opapimisk Lake, Ontario, Canada. In Macdonald, A. J. Gold '86; an international symposium on the geology of gold deposits, pp. 124 -136.
- Hill, M.L.; Cheatle, A.; Liefrovich, R., 2006. Musselwhite Mine: an orogenic gold deposit in the Western Superior Province; In Programs with Abstracts, Geological Association of Canada Vol. 31, pp. 67.
- Jia, Y., 2000. Giant quartz vein systems in accretionary orogenic belts; the evidence for a metamorphic fluid origin from delta (super 15) N and delta (super 13) C studies; Earth and Planetary Science Letters, December 30, 2000, Vol. 184, Issue 1, pp. 211-224.

Otto, A. 2002. Ore forming processes in the BIF-hosted gold deposit Musselwhite mine, Ontario, Canada. M.Sc. thesis (unpublished) Freiberg University of Mining and Technology, Germany, 86 pp.

Pitcairn I. K.; Teagle, Damon A. H.; Kerrich, R.; Craw, D.; Brewer, T. S. 2005. The behavior of nitrogen and nitrogen isotopes during metamorphism and mineralization; evidence from the Otago and Alpine schists, New Zealand, Pitcairn, I. K. In: Earth and Planetary Science Letters, April 30, 2005, Vol. 233, Issue 1-2, pp.229-246

Taylor, H. P., Jr. 1974. The Application of Oxygen and Hydrogen Isotope Studies to Problems of Hydrothermal Alteration and Ore Deposition; Economic Geology and the Bulletin of the Society of Economic Geologists, Vol. 69, Issue 6, pp.843-883

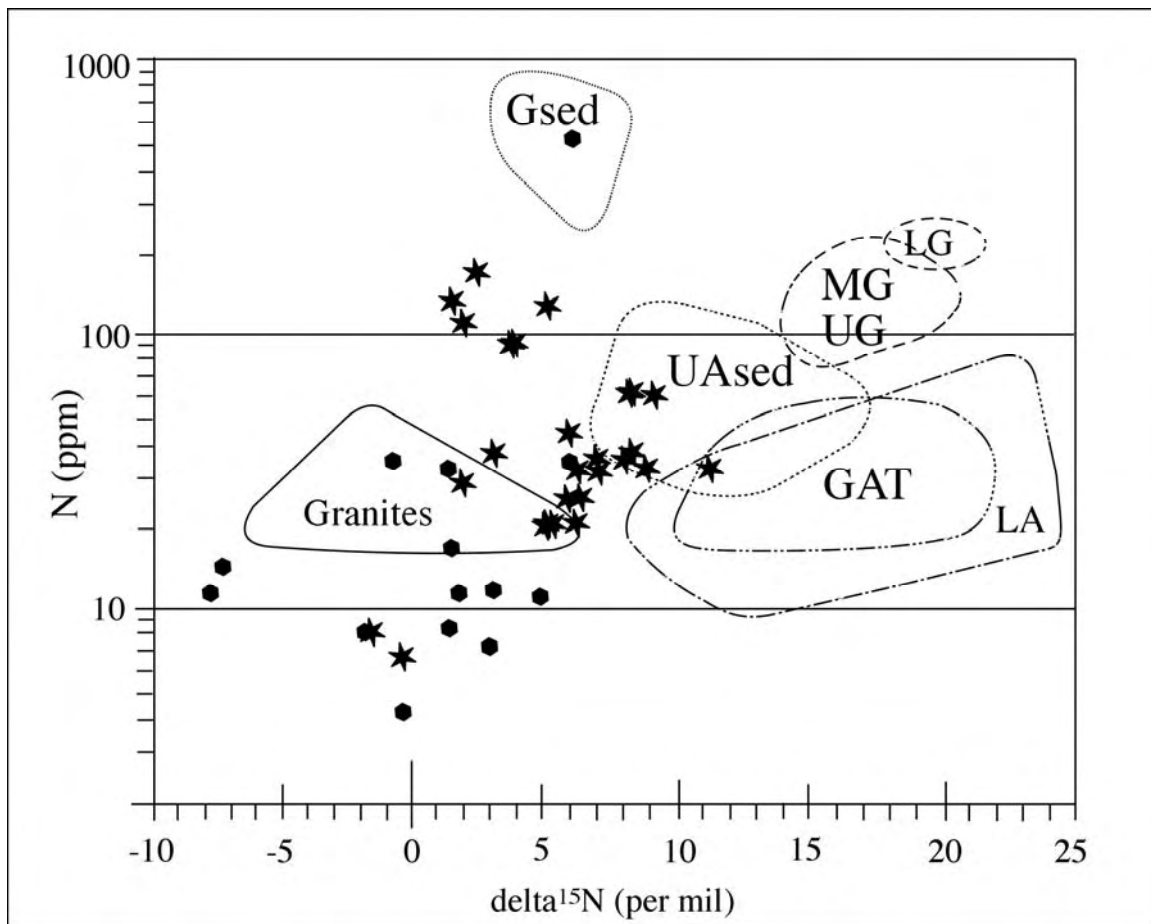


Figure 1: Plot of Nitrogen isotope data for the Musselwhite mine. Stars represent samples from Musselwhite Mine and hexagons represent regional granitoid samples. Fields for comparative data sets from Jia, 2000; Gsed = greenschist metasedimentary rocks, LG = lower Greenschist rocks, MG UG = middle-upper Greenschist rocks, GAT = Greenschist-Amphibolite Transition zone, LA = lower Amphibolite rocks, UAsed = upper Amphibolite metasedimentary rocks.

“CAPSTONE” GEOLOGIC MAPPING NEAR GABIMICHIGAMI LAKE, BOUNDARY WATERS CANOE AREA WILDERNESS, BY STUDENTS OF THE PRECAMBRIAN RESEARCH CENTER’S 2007 FIELD CAMP

Jirsa, Mark A., (jirsa001@umn.edu); **STARNS, Edward, Costello, Daniel E., Gal, Benedek, Hoaglund, Steven A., and Putz, Amanda J.**

The Precambrian Research Center—a branch of the University of Minnesota, Duluth—conducted its first season of field camp in 2007. After 5 weeks of field training, students were assigned “Capstone Projects” that provide an opportunity to create new geologic maps in areas of poorly understood geology. The four students listed above worked with the first and second authors to map in an area of the 2006 Cavity Lake forest fire in the northeastern part of the Boundary Waters Canoe Area Wilderness. The fire was the delayed result of a mega-storm in 1999 that flattened thousands of acres, reducing the woods to a tangle of downed trees and stubby new growth. The fire greatly improved access, and the subsequent rains cleaned outcrops to reveal details about the bedrock geology not previously visible. Gabimichigami Lake straddles the contact between Neoarchean and Mesoproterozoic rocks. Specifically, the mapping occurred along the north, west and east shores of the lake in parts of the U.S.G.S. Gillis Lake and Ogishkemuncie 7.5-minute quadrangles. Previous mapping was regional in scale; and although fairly accurate, it lacks detail and is quite dated (Gruner, 1941). Students were divided into two teams, each tackling a different aspect of the geology. One team (Costello and Gal) mapped the basal contact zone of the Tuscarora Intrusion, a component of the Mesoproterozoic Duluth Complex; the other team (Hoaglund and Putz) mapped the structure and stratigraphy of Neoarchean volcanogenic sedimentary rocks that form the intrusion’s footwall. The map and geologic descriptions presented here are based solely on the observations from several days of field work. Although some samples were taken, no petrographic or geochemical data were acquired.

The Neoarchean rocks consist of volcanic, volcanoclastic, and intrusive rocks informally called the Jasper Lake sequence. Regionally, the sequence consists of hornblende trachyandesitic flows and volcanogenic sedimentary strata derived from them, all intruded by dikes of similar composition. Though folded, the sequence appears to be generally southwestward-younging. It grades irregularly up-section from pyroclastic flows and breccia, to a thick package of poorly stratified volcanic conglomerate, to interbedded conglomerate, sandstone, and mudstone. Individual units of volcanic conglomerate are clast-supported, poorly sorted, and locally contain an abundance of one textural and compositional variant of trachyandesite over another. Taken together, the monolithic composition, generally poor sorting, disorganized bedding, and presence of dikes of similar composition imply that the poorly stratified conglomeratic units represent volcanic debris flows. The conglomeratic package grades irregularly to the south and west into a package of interbedded, moderately well-sorted conglomerate and volcanic sandstone, which grades further to predominantly volcanic graywacke, having graded bedding and mudstone drapes indicative of turbidite deposition. Mapping at Gabimichigami Lake was largely within the latter, presumably water-lain part of the sequence. Bedding dips steeply, and locally is overturned slightly to the south. Stratigraphic younging deduced from graded beds defines tight to open folds having northwest-trending axes, and plunges that range from northwest to southeast. No axial-planar cleavage was observed. Conglomerate layers in this package are white to brownish-gray, and clast-supported. Clasts are moderately to well rounded, moderately well sorted, and range from 1 cm to 20 cm in diameter. Clasts consist of porphyritic to aphyric hornblende dacite to trachyandesite, similar to the volcanic rocks near Jasper Lake. The presence of rare clasts of medium- to coarse-grained rocks having the same hornblende-rich composition may indicate erosion from hypabyssal intrusions in the otherwise largely volcanic source region. Graywacke is gray to light gray, fine- to medium-grained, and contains abundant feldspar and hornblende. Graded units of sandstone, siltstone, and mudstone are common. The well

developed graded bedding, flame structures, ball and pillow structures, and mudstone rip-ups indicate that sediment was deposited by turbidity currents. Metamorphic grade in the Jasper Lake sequence appears to be low greenschist facies, except in the narrow contact aureole of the Tuscarora intrusion where biotite, staurolite, and possibly andalusite occur in metapelitic beds. Quartz-chlorite veins having variable trends are common near shear zones and fold axes.

The Mesoproterozoic intrusive rocks of the Tuscarora Intrusion are divided here into 4 units; a basal contaminated zone, a heterogeneous unit, the main augite troctolite, and a northwest-trending troctolite dike. With the exception of the dike, unit contacts, magmatic foliation, and oriented xenolithic inclusions strike northeast and dip shallowly to the southeast. The basal contaminated zone contains abundant inclusions of varied size and composition, including footwall metasedimentary rocks, in a fine-grained granodioritic, noritic, or possibly ultramafic matrix. Disseminated biotite is present near the footwall, and decreases in abundance stratigraphically upward. Mineral lineation and igneous layering are present locally. The basal contact is transitional, magmatically and structurally disturbed and brecciated, and is marked by local intrusions of fine-grained felsic material emplaced into the metasedimentary footwall rocks. The heterogeneous unit consists of fine- to coarse-grained, pegmatite-rich, subophitic augite-troctolite, mela-troctolite, and poikilitic anorthositic troctolite. The texture of the rocks is variable and taxitic. The contact with the underlying contaminated zone is abrupt. The main augite troctolite is medium- to coarse-grained, modally layered, and subophitic. It locally contains pegmatitic pods that are particularly abundant in the lower parts of the unit. Inclusions of poikilitic, troctolitic anorthosite are also present. Disturbed layers of pegmatite and varitextured rock, locally enriched in specific mineral phases (olivine, plagioclase, pyroxene and oxides) are common near the inclusions. The contact with the underlying heterogeneous unit is transitional. The troctolite dike consists of fine- to medium-grained, homogeneous, poikilitic troctolite and subophitic augite-troctolite. Trachytoid texture and weak modal layering occur locally near and parallel to the subvertical contacts. The unit contains small inclusions of poikilitic troctolitic anorthosite, which may have been derived from the Anorthositic Series rocks of the Duluth Complex.

A preliminary geologic map of the Cavity Lake fire area that incorporates the student work described here will be available in July, 2008. This map will provide details about both the distribution and relative temporal framework of the Precambrian bedrock. Students enrolled in the 2008 field camp will continue mapping in the region. In addition, one student from the 2007 camp, Dan Costello, will begin thesis field work in the Tuscarora Intrusion during 2008. A final map of the area will be published after completion of these efforts. Support for mapping in the Cavity Lake fire area by the first and second authors is provided by the U.S. Geological Survey's 2007 State Geologic Mapping Element (STATEMAP) of the National Geologic Mapping Program, and the State Special Appropriation to the Minnesota Geological Survey.

REFERENCE

Gruner, J.W., 1941, Structural geology of the Knife Lake area of northeastern Minnesota: Geological Society of America Bulletin 52:1577-1642

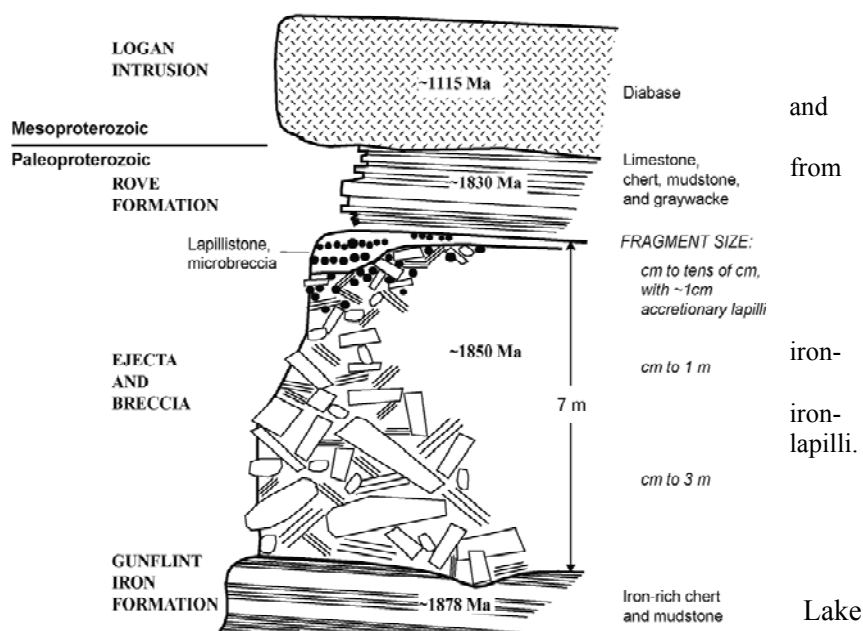
SUDBURY IMPACTITE LAYER NEAR GUNFLINT LAKE, NE MINNESOTA

Jirsa¹, Mark A., Weiblen², Paul W., Vislova³, Tatiana, and McSwiggen⁴, Peter L.

(¹ Minnesota Geological Survey (jirsa001@umn.edu); ² University of Minnesota-Twin Cities; ³ SUNY College-Oneota; ⁴ McSwiggen and Associates, St. Paul)

We present here a preliminary, largely macroscopic description of rocks inferred to contain ejecta from the ca. 1850 Ma Sudbury meteorite impact event—following the discovery of similar deposits in Thunder Bay, Ontario and Michigan that are well documented by Addison and others (2005), Cannon and Addison (2007), and Pufahl and others, (2007). The Gunflint Lake exposures lie some 480 miles (770 km) west of Sudbury, making this one of the most distant sites known to contain what is considered “proximal ejecta” from the impact. It should be noted at the onset, that only a small portion of the material described here can be considered true ejecta—the great majority of the 7 meter-thick deposit is breccia that consists of thoroughly disheveled fragments that appear to have been derived from subjacent strata. Like the deposits near Thunder Bay, the breccia is sandwiched between Gunflint Iron Formation and sedimentary strata of what has traditionally been assigned to Rove Formation. Unlike deposits near Thunder Bay, the breccia lies within the metamorphic aureole of the Tuscarora and Poplar Lake Intrusions of the Duluth Complex (ca. 1100 Ma), and is intruded by diabasic sills of the Logan Intrusions (ca. 1115 Ma; Heaman and Easton, 2005). Pervasive carbonate mineralization and metamorphism has overprinted and obscured much of the original, delicate mineralogic features, but macroscopic textures and geochemical content that convey information about protolith and depositional mechanisms are preserved. The study of these rocks underway—in the context of the other ejecta sites—will provide a more detailed geologic history of the impact event.

Figure 1—Composite and schematic sketch showing stratigraphy of Gunflint Lake impactite adjacent rocks. Approximate ages cited references. Symbols in breccia are broadly representative of fragment type and relative size: closed polygons=chert-rich formation; lines=layered, carbonate-rich formation; solid circles=



To date, the Gunflint breccia has been mapped within the broadly-folded, shallowly south-dipping sequence of Paleoproterozoic strata over a strike-distance of about 1.5 mi (2.4 km). The thickness, internal stratigraphy, and position relative to Logan Intrusions vary considerably along strike; however, the composite section shown in Figure 1 represents the gross sedimentological characteristics that are present in many exposures. Most of the deposit consists of very poorly sorted breccia containing blocks and slabs as large as 3 meters having nearly

random orientations. The breccia is crudely graded; largest blocks occur near the base, and smaller and more rounded fragments occur up-section. The contact with underlying iron-formation is abrupt and clearly unconformable, but there is surprisingly little relief on the surface at outcrop scale. The iron-formation footwall is not particularly fractured, nor is it ductily deformed: implying that neither seismic brecciation nor soft-sediment deformation, respectively, played a significant role in fragmentation. Most fragments appear to have been derived from the underlying iron-formation, though alteration and metamorphism likely destroyed some of the recognition criteria for smaller clasts in the “matrix” of large breccia blocks. The upper part of the breccia contains small to large blocks locally infilled with concentrically zoned, spherical structures as large as 1.5 cm. that are interpreted to be accretionary lapilli. The lapilli are the only fragments in the deposit presently considered to be part of the impact ejecta blanket—no grains of shocked quartz, microtektites, or other exotic clasts have been identified. A unit of bedded, and locally graded lapillistone and microbreccia caps the megabreccia in many locations. The unit contains both intact and abraded lapilli. It appears to have formed within channel-like depressions on the irregular surface of underlying breccia. The deposit is overlain by interbedded mudstone, limestone, and graded turbidite layers of the basal Rove Formation.

The breccia marks an abrupt shift in depositional facies from iron- and silica-rich to iron- and silica-poor sediments, implying a catastrophic origin. Any interpretations at this time are tentative; however, the combination of fragment size, random orientation, chaotic distribution, and apparently local derivation counter-indicates deposition by common mechanisms such as sea cliff erosion or gravity-driven debris flow. Deposition may have been the result of impact-generated tsunamis, or be more directly linked to the turbulent impact ejecta plume. The deposit resembles those described in Thunder Bay and Michigan, to which a similar depositional history has been ascribed. Crude grading in the Gunflint megabreccia implies deposition by a single, intense, and waning event. The cap of bedded lapillistone and microbreccia may be the product of channelized back-flow following tsunami run-up, reworking by secondary or tertiary tsunami waves, or settling during collapse of the ejecta plume. Water depth at the time of impact is problematic—clearly the underlying iron-formation was deposited in fairly deep water, as was the overlying Rove Formation. However, the chaotic breccia and abundance of carbonate mineralization may indicate subaerial exposure during part of the depositional history. The presence of accretionary lapilli in only the upper part of the deposit is also problematic. In the tsunami scenario, this observation could reflect hydraulic sorting that precluded lapilli deposition during wave run-up, and instead selectively washed lapilli onto the brecciated landscape as the wave (s) receded. Many other questions remain, including the nature of the substrate at the time of breccia deposition, the content of exotic (ejecta) fragments, the precise mineralogic and geochemical composition, and the origin, paragenesis, and significance of carbonate. Work to address some of these questions and integrate the results into broader interpretations of the Sudbury impact event is underway.

REFERENCES

- Addison, W.D., Brumpton, G.R., Vallini, D.A., McNaughton, N.J., Davis, D.W., Kissin, S.A., Fralick, P.W., and Hammond, A.L., 2005, Discovery of distal ejecta from the 1850 Ma Sudbury impact event: *Geology* **33**: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: *ILSG Proceedings, 53rd Annual Meeting*, v. 53, Part 1, p. 20-21.
- Heaman, L.M., and Easton, R.M., 2005, Proterozoic history of the Lake Nipigon area, Ontario: Constraints from U-Pb zircon and baddeleyite dating: *in* Easton, M., and Hollings, P., eds., *ILSG Proceedings, 51st Annual Meeting, Nipigon, Ontario, Proceedings and Abstracts*, v. 51, Part 1, p. 24-25.
- Pufahl, P.K., Hiatt, E.E., Stanley, C.R., Morrow, J.R., Nelson, G.J., and Edwards, C.T., 2007, Physical and chemical evidence of the 1850 Ma Sudbury impact event in the Baraga Group, Michigan: *Geology* **35**:827-830.

AN ARCHEAN-AGED PGE-BEARING INTRUSION, BARAGA COUNTY, MICHIGAN

JOHNSON, R., SEASOR, R. and SUSZEK, T., Rod Johnson and Associates, Inc., 1550 Baldwin Avenue, Negaunee, MI 49866

This paper describes the discovery, geology and exploration of an Archean-aged, PGE-bearing, ultramafic intrusion discovered in Baraga County, Michigan and unofficially named by the authors the Kortio Lake Intrusion (KLI).

During 1997 a program was undertaken to determine if an analog to the Lac des Isle PGE deposit of northwestern Ontario, Canada might exist on the southern side of the Mid-continent Rift within the Northern Complex granite-greenstone terraine of the Upper Peninsula of Michigan. Initial inspection was concentrated upon known appinitic intrusions in northern Marquette County. Lack of any evidence of mineralization within the surface exposures of these bodies led to the decision to move the search to the far western boundary of the granite-greenstone terraine with the intent of prospecting the entire area, from western Baraga County to eastern Marquette County.

Coarse-grained hornblendite intrusions were identified in an area previously believed to be underlain by amphibolites. Also discovered were glacial float boulders of coarse-grained hornblendite containing several percent pyrite and chalcopyrite. The outcrops that were the source of the glacial float were located. These outcrops exhibited easily identified copper staining, as malachite, along with varying amounts of pyrite, chalcopyrite and nickel-bearing sulfides. The northern edge of KLI is located immediately west and southwest of Kortio Lake (aka Little Summit Lake), 3 kilometers (2 miles) south of Herman, Baraga County, Michigan

A review of available geochemical and airborne magnetic surveys further supported the interpretation that the area had potential for hosting PGE and copper nickel mineralization. Reconnaissance mapping of the surrounding area indicated the potential for an intrusion of appreciable size. It was determined that the complex was approximately 4,300 meters (14,000 feet) long, in a north-south direction and in excess of 3,200 meters (10,500 feet) wide, east to west. Detailed geologic mapping and outcrop prospecting and sampling was undertaken. That effort defined a hornblendite intrusion that has a surface expression of 4,300 meters (14,000 feet) long and a range in width of from 1,600 meters (5,250 feet) to 300 meters (1000 feet). Several areas of mineralization were identified in the prospecting and sampling phase.

Field relationships indicate that the KLI is a late Archean-aged intrusive that is truncated, on its southern end, by the Great Lake Tectonic Zone (GLTZ). Mapping indicated that the hornblendite intrusion had been intruded by a later, but nearly contemporaneous, fine to medium grained diorite. The contact zone between the hornblendite and diorite ranges from sharp to gradational and numerous locations exhibit areas where the diorite contains variable-sized, autoliths of hornblendite.

The KLI is intruded by dikes of probable Archean age (Metachewan?) and numerous east-west trending Keweenaw age diabase dikes. Also noted are narrow granitic pegmatite dikes and small intruded plugs ranging from granitic to dioritic in composition. The intrusion is also crossed by numerous shear zones and faults with unknown, but probable minor displacement. The structural relationships have yet to be determined.

The hornblendite intrusion is a highly variable rock, both in texture and in content of primary and accessory minerals. Textures range in grain size from fine-grained, nearly aphanitic, to pegmatitic and include equigranular, porphyritic and breccia phases. Coarse-grained zones have hornblende crystals that range up to 4 cm in size. The coarse-grained zones generally contain an appreciable amount of biotite. Other primary accessory minerals of note occur within distinct zones. There are surface exposures of coarse-grained hornblendite that contain up to 25% of coarse-grained, interstitial carbonates. Other exposures of the coarse-grained hornblendite commonly contain visible apatite. Some areas of the hornblendite contain appreciable amounts of magnetite.

Mineralization in outcrop and glacial float consists of pyrite and chalcopyrite. Grain size of the sulfides ranges from microscopic to blebs in excess of 2.5 cm in size. Analysis of the mineralized samples indicated the presence of nickel, platinum, palladium and gold in amounts that are well above background levels. The distribution of mineralization indicates magmatic segregation into layers. Although minor mineralization has been found within the diorite intrusion, and within veins and shear zones that cut it, the bulk of the mineralization is found within the hornblendite and that rock has been the focus of the exploration efforts.

During 2004 a geochemical survey utilizing a field-portable X-ray fluorescence analyzer yielded metal contents in outcrop of up to 7% copper, 0.3% nickel, 0.6% chromium and 0.1% cobalt. Select hand samples have yielded up to 500 parts per billion of combined platinum group metals by fire assay. The project moved forward with an airborne survey in 2005 and a drilling project in 2006.

During the summer of 2005 a helicopter-borne time domain EM and aeromagnetic survey was flown with excellent results in outlining the extent of the KLI with magnetics and the identification of numerous E-M conductors within the intrusive body. A total of 450 line kilometers were completed.

During the summer of 2006 six diamond drill holes totaling 941 meters (3,088 feet), from three locations, were completed in the area of the original discovery of PGE mineralization. A seventh hole was drilled, with a total length of 365 meters (1,197 feet), to test an area of very high magnetism.

Results of the diamond drilling confirmed the presence of copper and nickel mineralization that contains varying anomalous amounts of platinum, palladium and gold. PGE minerals have been identified by electron microscopy. The assay results indicated the potential for greater concentrations, at economic levels, within the body.

Structural and Kinematic Analysis of the Mud Creek Shear Zone, Northeastern Minnesota; Implications for Archean (2.7 Ga) Tectonics

Karberg, Susan M., University of Minnesota – Duluth, Duluth, MN 55812, karbe002@d.umn.edu

Granite-greenstone terrains preserve large tracts of stable Archean continental crust and as such they may hold the only tangible record of Archean tectonic processes. Granite-greenstone terrains include granitoid bodies surrounded by layered, folded, felsic to ultramafic volcanic and volcanoclastic greenstone belts, commonly cut by shear zones or faults. Researchers suggest two hypotheses for the formation of Archean continental crust: (1) sagduction/diapirism, in which crustal density instabilities cause greenstone sequences to sink into basins as granitoid bodies rise (Anheusser et al., 1969), and (2) volcanic arc accretion, in which modern-style plate tectonic processes drive the accretion and imbrication of island arcs and associated basins. Although the Superior Province is widely accepted as a result of transpressional volcanic arc terrane accretion, no robust evidence exists that dismisses the sagduction/diapirism hypothesis and there is a lack of strong arguments for the plate tectonics processes of volcanic arc terrane accretion.

The Archean age Mud Creek shear zone, located between two Archean granitic bodies, offers an excellent location to examine the sagduction/diapirism and arc accretion hypotheses. The Mud Creek shear zone lies within a greenstone belt between the Vermilion Granitic Complex to the north and the Giants Range Batholith to the south. The supracrustal rocks between the two granitic bodies consist of basalt flows, tuff, iron formation, greywacke, slate, conglomerate, felsic lava and pyroclastics flows (Peterson and Jirsa, 1999). The Mud Creek shear zone defined on recent geologic maps is an area approximately 14 km in length and 1 km wide, however foliation and elongation lineation occur throughout the 15 km by 7 km study area that encloses the shear zone. Therefore the Mud Creek Shear zone in this study is considered the larger deformed area.

The goal of this study is to examine foliation, elongation lineation, and microstructural kinematic evidence to understand the process or processes which controlled the deformation of the Mud Creek shear zone. I compiled existing structural data including bedding, foliation and lineation orientations from geologic maps, collected additional new foliation and elongation lineation orientations, and oriented samples for microstructural analysis.

Foliation orientations are consistently near vertical, ranging from steeply north-dipping to steeply-south dipping, trending northeast-southwest. Generally, bedding parallels foliation. Pillow basalts are not foliated, but pillow rims record evidence of shear, most likely due to strain partitioning around the strong pillow cores. Motion direction is unknown due to a general lack of the third dimension, but most pillows appear flattened into pancake-like shapes which are elongate in map view in the same orientation as other foliated rock types. In some locations outside of the study area pillows are stretched out into vertical pencil-like columns which parallel the vertical elongation lineation seen throughout the Mud Creek shear zone. Foliation trend lines are drawn in figure 1. The pattern shows the continuity of foliation orientation throughout the Mud Creek shear zone, dominantly northeast-southwest.

Elongation lineation occurs in all rock types, with the exclusion of some pillowed basalt. Pillow basalt may be too strong and strain is likely to be partitioned around pillows, leaving little to no record of visible elongation lineations. Orientations of elongation lineations range from shallow strike-slip to steep dip-slip. Shallow lineations are rare and occur as an overprint to dip-slip lineations or in confined zones. Vertical lineations ($90^\circ \pm 10^\circ$) are dominant throughout foliated rock types, and also observed on the compositional layering of banded-iron-formation. Figure 1 contains a map of elongation lineation pitch showing the dominantly vertical aspect of displacement, but also shows pockets or zones of moderately east, moderately west, and shallow strike-slip displacement.

Microstructural analysis reveals interesting spatial patterns (figure 2): 1) south-side-up displacement is dominant in the northwest portion of the study area, 2) north-side-up displacement is dominant in the southeast portion of the study area, and 3) a central zone records both displacement domains, including individual samples that record both domains. Individual samples that record both domains have a penetrative fabric (S-C foliations) that indicates south-side-up displacement, and a less penetrative fabric confined to small zones recording north-side-up displacement (S-C foliations).

Results from microstructural analysis support the sagduction/diapirism hypothesis, with rise of the southern granitic complex, followed by rise of the northern granitic complex. Cross-cutting relationships indicate later strike-parallel dextral displacement occurred along narrow zones (<1km wide) of previously formed foliation planes. Other samples record shallow to moderate elongation lineation orientation that record sinistral displacement confined to the northwest corner of the study area.

References:

Anhaeusser, C.R., Mason, R., Viljoen, M.J., Viljoen, R.P., 1969. A reappraisal of some aspects of Precambrian shield geology. GSA Bulletin 80, pp.2175-2200.

Peterson, D.M. and Jirsa, M.A., 1999. Bedrock geologic map and mineral exploration data, western Vermilion district, St Louis and Lake counties, Northeastern Minnesota. University of Minnesota.

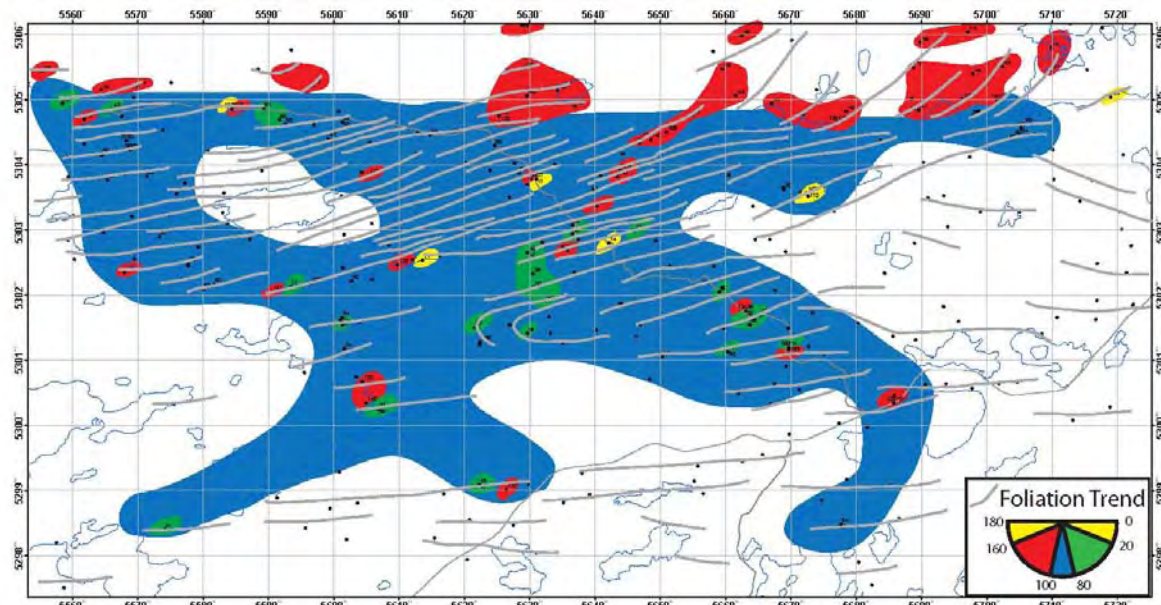


Figure 1. Schematic map of the Mud Creek shear zone with foliation trends (grey) and elongation lineation pitch zones (colors).

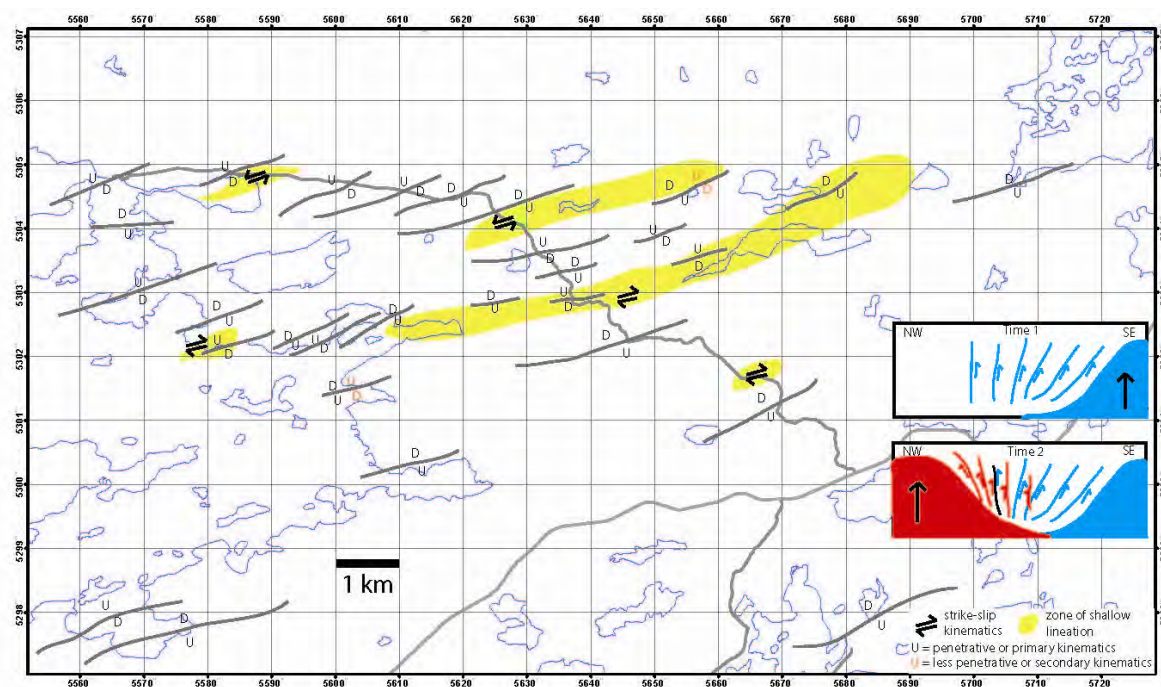


Figure 2. Sample kinematics within the Mud Creek shear zone. D = down, U = up. Includes interpretive cartoon cross section from NW-SE.

Using mineralization to evaluate small-scale controls on shale permeability in the Nonesuch Formation

Natalie King

Department of Geosciences, Colorado State University, Fort Collins, CO 80523-1482

Mineralization in the Nonesuch Formation, which hosts the White Pine stratiform copper deposit, is being used to evaluate controls on paleopermeability. Relatively little work has been done on characterizing the controls on permeability in shales, despite their importance in fluid migration and accumulation in sedimentary basins. This study will improve understanding of controls on shale permeability that affect both the formation of sediment-hosted ore deposits and the integrity of petroleum top seals.

Cores through the Nonesuch Fm, three from northern Wisconsin, outside the main stratiform copper mineralization, and three from the upper peninsula of Michigan within the zone of mineralization of the White Pine stratiform copper deposit, were logged noting stratigraphy, color, texture, mineralogy, grain size, organic content, laminations, bedding, and other sedimentary structures. Four representative cores, two from the mineralized zone and two from the unmineralized zone, were sampled for petrographic and whole rock geochemical analyses.

Initial results from geochemical analyses, indicate three geochemically distinct groups in the Michigan cores; above the ore zone, well-mineralized ore horizons, and poorly mineralized ore horizons. The poorly mineralized horizons show a positive Cu to S trend that increases downward in the lower stratigraphic sections in the Nonesuch Fm. Above the ore zone, As concentrations are slightly higher than in the ore zone. Preliminary point counting data show a positive correlation between organic content and Cu concentrations. These data support fluid movement through the lower Nonesuch Fm that in turn indicates that there was paleopermeability in the lower Nonesuch Fm. Further work will examine small-scale controls such as grain and organic orientation, grain size, and mineral content to characterize these paleo-fluid pathways and establish small-scale controls on shale permeability.

Structural and metamorphic history of the Burntside Lake shear zone with possible implications for Archean granite-greenstone formation

J.N., Koester, J.W., Goodge, V.L. Hansen, Department of Geological Sciences, University of Minnesota-Duluth, Duluth MN 55812, koest036@d.umn.edu

There is much debate as to the origin of Archean granite-greenstone terranes. In an effort to understand the genesis of these ancient terranes, it is helpful to focus on the boundaries between greenstone and granite bodies. The Burntside Lake shear zone represents a good location to study the relative importance of vertical and horizontal displacement because it lies at the boundary between a greenstone terrane, the Newton Lake formation, and a granite body, the Vermilion granitic complex. In an effort to better understand the origin of granite-greenstone terranes in this area, my study addressed the structural and kinematic evolution of the shear zone and used metamorphic petrology to evaluate crustal displacements across the zone.

The Burntside Lake shear zone lies at the boundary of the Wawa and Quetico subprovinces of the Superior Province. The Superior Province represents one of the largest tracts of Archean crust preserved in the rock record. The classic interpretation of the Superior Province is that it involved a process similar to island-arc accretionary tectonics occurring today (1-7). However, other Archean granite-greenstone terranes are interpreted as being born of sagduction/diapirism, in which greenstone units blanket underlying granites to induce a density instability. Due to this instability, granite bodies will rise while greenstone units sink into inter-granitoid basins (8-9). Through further study of structural boundaries in granite-greenstone terranes we can hope to learn more about processes active in the Archean.

Fieldwork was conducted along an 8 km length of the Burntside Lake shear zone which stretches 50 km from the Vermilion fault in Minnesota northeastward to Ontario. The shear zone strikes between N30E to N50E. During fieldwork, orientation data were collected from both foliations and lineations to aid in understanding the structural regime recorded in rocks of the study area. In addition to these fabric data, 106 samples were collected for petrographic study as hand samples and thin sections. Of these, 19 were selected from different field locations to be cut into thin sections. Thin sections were used to study microfabrics and metamorphic mineral assemblages.

My study of the Burntside Lake shear zone focuses on the interaction between a granitoid body and a greenstone body. The shear zone is characterized by vertical to nearly vertical south-dipping foliation orientations, only a down-dip lineation was observed (Fig. 1). Dominant rock types collected in the field are biotite schists and chloritic greenstones. On the thin section scale, foliations vary from planar to anastomosing. Foliation is defined by the alignment of biotite, chlorite and hornblende. Elongate needles of hornblende, biotite, and chlorite define lineations. However, in a few samples, quartz is elongated as well. S-C' fabrics in biotite and chlorite were used to determine sense of shear, along with sigma grains when applicable. These microfabrics were poorly preserved and in some thin sections completely ambiguous, resulting in very few samples having definitive petrofabrics with which to interpret shear sense. However, north-side-up shear sense dominate rocks in the field area.

Mineral assemblages present in the field area indicate a low to intermediate metamorphic grade associated with the shear zone. On the north side of the zone, peak mineral assemblages include garnet-biotite and hornblende-plagioclase. To the south of the fault, chlorite is the dominant peak metamorphic mineral. Using electron microprobe analysis to obtain mineral chemistry, I was able to determine metamorphic temperatures in the shear zone for eight samples. To the north of the fault, garnet-biotite pairs record a temperature of about 550 °C, whereas hornblende-plagioclase records an average temperature of 700 °C. The temperatures recorded by these two geothermometers show a 150 °C difference. This difference may be real, or may be an artifact of the calibrations chosen. Additionally, the plagioclase grains analyzed may record igneous temperatures or some intermediary temperature that

represents neither a purely igneous or metamorphic temperature. To the south, chlorite compositions record temperatures between 150 – 330 °C.

In conclusion, the Burntside Lake shear zone represents a nearly vertical to vertical zone of deformation approximately 1.5 km wide. Through kinematic analysis of microfabrics the zone appears to have a north-side-up sense of shear (please see caveats noted above), as interpreted from thin sections.

Rocks to the north side of the shear zone were metamorphosed in the upper greenschist to lower amphibolite facies, whereas the south side of the shear zone records lower greenschist-facies. Thus, metamorphism recorded on both sides of the fault agrees with a north-side-up sense of shear, determined from microstructures.

Further work on must be done to allow for a greater understanding of the complex history recorded in the rocks defining the Burntside Lake shear zone. Specifically, work to further constrain pressure/temperature, and kinematics including timing between the conflicting senses of shear apparent in some of the samples utilized in this study. And lastly, a comparison study of the many shear zones in the area to understand any relation/timing relationships that may exist.

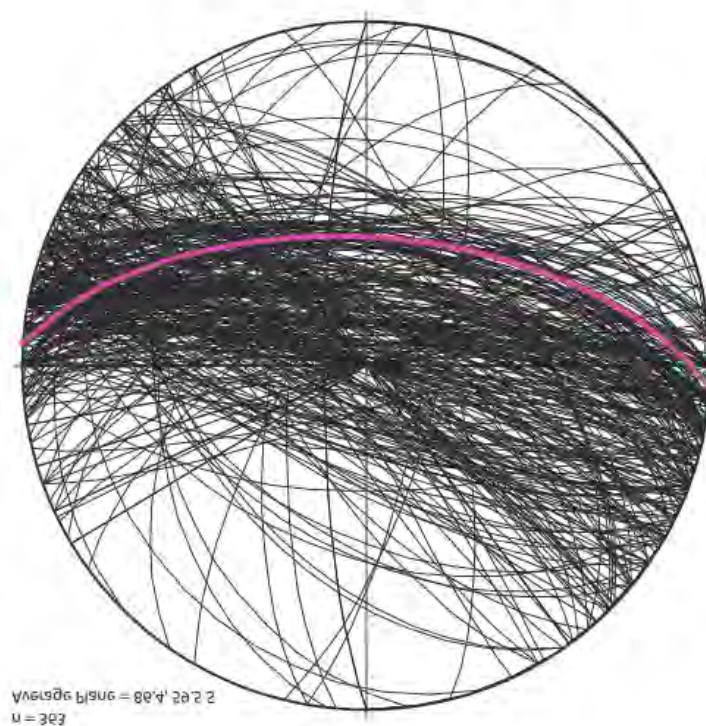


Figure 1: Equal area stereoplots of foliation orientations from the Burntside Lake Shear zone (compilation of my orientations as well as those compiled by 10-11)

References:

- (1) Card, K.D., 1990, P. Research, 48, 99-156. (2) Cawood, P.A., Kroner, A., Pisarevsky, S., 2006, GSA Today, 16, 7, 4-11. (3) Jirsa, M.A., Southwick, D.L., Boerboom, T.J., 1992, Can. J. E. Sci., v. 29, p. 2146-2155. (4) Tabor, J.R., Hudleston, P.J., 1991, Can. J. E. Sci., 28, 292-307. (5) Bauer, R.L., Bidwell, M.E., 1990, Can. J. E. Sci., 27, 1521-1535. (6) Hudleston, P.J., Schulta-El, D., Southwick, D.L., 1988, , Can. J. E. Sci., 25, 1060-1068. (7) Bauer, R.L., Hudleston, P.J., Southwick, D.L., 1992, Can. J. E. Sci., 29, 208 2103. (8) McGregor, A.M., 1951, Trans Geol. Soc. S. Africa, 54, 27-70. (9) Rey, P.F., Philippot, P., Thebaud, N., 2003, P. Research, 127, 43-60. (10) Green, J.C., Schulz, K.J., 1983, MGS Univ. MN. (11) Sims, P.K., Mudrey, M.G., Jr., 1978, MGS Univ. MN.

Strategies for Drilling Unconsolidated Material and Historic Underground Mine Workings: Examples from Hibbing Taconite Company's 2007 Diamond Drilling Campaign

Jared D. Lubben^{1,2}

¹ Hibbing Taconite Company, P.O. Box 589, Hibbing, MN 55746

² Cliffs Technology Group, 550 E. Division Street, Ishpeming, MI 49849

As mining efforts at Hibbing Taconite advance north-eastward along the strike of the Biwabik Iron Formation, diamond drilling information is critical for evaluating the potential of new mine areas. To the east of Hibbing Taconite's current open pit mine operations, significant obstacles related to prominent rock stockpiles, strong oxidation trends, and historic underground mine workings are encountered during diamond drilling. These problematic zones typically overlie ore-strata and are encountered in almost every drill hole. Consequently, new ideas and drilling strategies are required to penetrate these zones.

Over the summer of 2007, Hibbing Taconite completed its annual diamond drilling program within areas hosting the prominent historic underground mining operations. The focus of this report is two-fold: Different lines of evidence used for drill hole targeting and positioning will be explained while various drilling methods and strategies used to reach target depths for drill holes under the 2007 program will be discussed.

Mineral Zonation and Stratigraphy of the Tilden Hematite Deposit

Helene M. Lukey, Senior Staff Geologist. Cliffs Technology Group, Cliffs Mining Service Company, Ishpeming, MI 49849

Hypogene alteration zones have been described as a precursor to high-grade hematite deposits in Australia, Brazil and elsewhere. This alteration described as being below or distal and is typically magnetite-carbonate-silicates reflecting Mg-Fe metasomatism. This paper describes the mineral zonation and possible structural control on mineralogic variation within the Tilden Mine. In contrast to the high-grade deposits, these variations are not peripheral to the ore bodies but are the ore.

The deposit occurs within the Negaunee Iron Formation, along the southern margin of the Paleoproterozoic Marquette Range Supergroup basin. The regional structure is a fault bounded west plunging syncline within the crustal scale Great Lakes Tectonic Zone, which forms the boundary between Archean granite-greenstone and gneissic terranes. Local structure consists of the second order anticlines and synclines with variable northwest and southwest plunges. The interaction of sedimentation and diagenesis within growth fault controlled basins, along with a metamorphic and/or hydrothermal overprint has resulted in a complex series of ore types.

For modeling purposes, the deposit has been divided into geologic domains based on both lithology and metallurgical response in the laboratory and in the plant. Mineralogic variation is recognized within individual mineral grains; at blast pattern (10 to 15 meter) and development drill hole (100 meter) scales.

A simplified stratigraphic column consists of the Main Pit Carbonate domain (martite-magnetite-various carbonates±silicates) in the core of the Main Pit anticline overlain by the Martite domain (martite+local goethite) and the West Hematite domain (microplaty hematite+goethite). The Clastic domains consist of quartz-rich lenses with variable matrix material within a variety of iron formation types. Although variable, the domain stratigraphic thicknesses are 100 to 200 meters.

These compositional and associated textural variations affect plant efficiency and product quality, and are critical factors for ore reserve modeling, ore control and mine planning decisions.

THE SEELEY SLATE AND BARABOO INTERVAL SEDIMENTATION

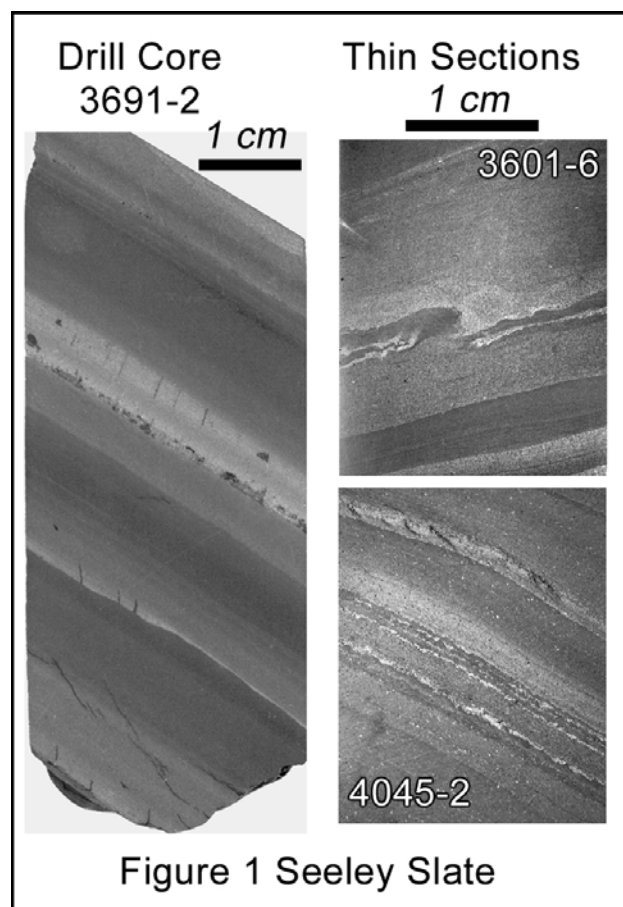
MEDARIS, L. G. Jr and DOTT, R. H. Jr., Dept. of Geology and Geophysics, University of Wisconsin-Madison, Madison, WI 53706, medaris@geology.wisc.edu

The Baraboo Interval represents a major episode of sedimentation between 1700 and 1630 Ma in the Lake Superior region. In the Baraboo Range, the type area, the Baraboo Quartzite is overlain conformably by ~120 m of gray slate, the Seeley Slate, which in turn is overlain by ~300 m of dolomite and discontinuous iron formation, the Freedom Formation. These two formations occur only in the subsurface in the hinge of the Baraboo syncline and have been described previously from exposures in underground iron mines, now abandoned, and drill cores by Weidman (1904) and from drill cores by Leith (1935), Schmidt (1951), and Geiger (1986). Because information on the Baraboo Interval comes largely from the prominent Baraboo Quartzite and correlative quartzites, we have undertaken a new study of the Seeley Slate to gain further insight into the nature of Baraboo Interval weathering and sedimentation.

During exploration for iron ore in 1907, the Oliver Iron Mining Company obtained numerous drill cores from the Freedom Formation and Seeley Slate in the western part of the Baraboo Range along the axis of the Baraboo syncline. Access to these drill cores was provided by the WGNHS, and samples of gray slate, shown by the driller logs as occurring beneath iron formation, were selected from nine drill cores for detailed investigation.

The Seeley is a gray slate with cleavage discordant to stratification in most cores. At least a small percentage of quartz silt is dispersed among phyllosilicate minerals even in the most homogeneous appearing intervals, which range up to several centimeters in thickness. Lamination visible in most cores is defined by lighter-colored concentrations of quartz silt, which vary in thickness from 0.5 to about 1 cm. Rare, coarser laminae have quartz grains up to 0.2 mm in diameter. A small percentage of silty laminae show discernible graded bedding (e.g. Fig. 1, core 3691-2). Soft sediment deformation by depositional loading is evident in core 3601-6; some other laminae were contorted slightly by cross-cutting cleavage (core 4045-2). Although most deformation was ductile, brittle cracking is evident in a few silty laminae (core 3691-2).

As determined by petrographic examination and XRD and EMP analyses, the Seeley slate consists predominantly of quartz and $2M_1$ muscovite, with subordinate rutile, pyrite, chlorite [repidolite, $(Mg_{3.5-2.9}Al_{2.8-2.9}Fe_{5.7-6.2})_{12}(Si_{5.3}Al_{2.7})_8O_{20}(OH)_{16}$], and



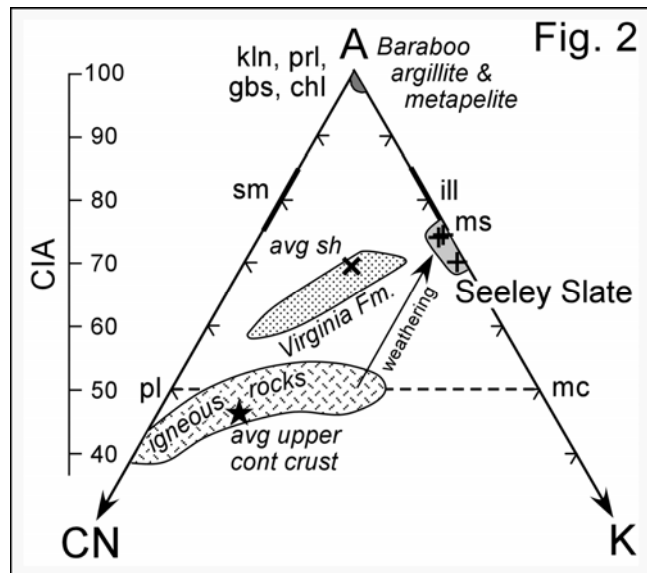
tourmaline [schorl, $(\text{Mg}_{0.2-0.3}\text{Na}_{0.8-0.7})(\text{Fe}_{1.5-1.8}\text{Mg}_{1.5-1.2})_3\text{Al}_6\text{Si}_6(\text{BO}_3)_3(\text{OH})_4$]. Locally, siderite $[(\text{Fe}_{0.86}\text{Mn}_{0.01}\text{Mg}_{0.05}\text{Ca}_{0.08})\text{CO}_3]$ occurs with quartz and muscovite in fine laminae.

The Seeley slate has an unusual composition for shale; four samples of typical slate are virtually devoid of CaO and Na_2O , contain 4.0 - 6.8 wt% FeO , 1.9 - 2.0 wt% MgO , 0.60 - 0.69 wt% TiO_2 , and plot near the composition of muscovite in an Al_2O_3 - CaO + Na_2O - K_2O molar projection (Fig. 2). The composition of the Seeley slate may have resulted from extensive weathering of granite (Fig. 2). Although the Seeley Slate is relatively mature, having a CIA index of 70 to 74, it is much less mature than argillite and metapelite in the Baraboo Quartzite.

The Seeley Slate contrasts markedly with the underlying and overlying formations. The red Baraboo Quartzite below was deposited initially by braided streams followed by shallow marine tidal and wave processes. The inferred marine transgression continued during Seeley deposition in a deeper, quieter setting on a marine shelf. Occasional density currents carried quartz

silt and rare sand into the otherwise mud-dominated environment. The overlying Freedom Formation was probably deposited in the same setting, which was now starved of clastic input so that dolomite and iron-rich facies could accumulate chemically.

Baraboo Interval strata accumulated as a sedimentary wedge on the southern passive margin of a Proto-North American craton. With a total thickness of about 1500 m and extending at least 1000 km east-west, they comprise a significant stratigraphic package, which includes one of the youngest known Banded Iron Formations in the world. The red color due to hematite cement in the Baraboo and correlative Sioux and Barron Quartzites indicates an oxygenic atmosphere, and the extreme compositional maturity of both the quartzites and their interstratified pelitic layers resulted from intense chemical weathering of the source terrain of these clastic sediments. In contrast, the gray color, mineralogy, and bulk composition of the Seeley Slate imply deposition of less intensely weathered detritus in a reducing environment as compared to the Baraboo Quartzite,.



References

- Geiger, C.A. (1986) *Geosci. Wis.* 10, 28-36
 Leith, A. (1935) *Kansas Geol. Soc. Guidebook*, 9th Ann. Field Conf., 320-322
 Schmidt, R.G. (1951) M.S. thesis, Univ. Wis. – Madison, 40 pp.
 Weidman, S. (1904) *WGNHS Bull.* 13, 190 pp.

The Inaugural Season of the Precambrian Field Camp at the University of Minnesota Duluth

Miller, James D., Dept. of Geological Sciences, University of Minnesota Duluth, Duluth, MN 55812 (mille066@umn.edu)

Peterson, Dean M., Natural Resources Research Institute at UMD, 5013 Miller Trunk Hwy., Duluth, MN 55811 (dpeters1@nrri.umn.edu), and

Hudak, George J., Department of Geology, University of Wisconsin Oshkosh, Oshkosh, WI 54901(hudak@uwosh.edu)

This past summer, the Precambrian Research Center at UMD ran the first season of a one-of-a-kind field camp. The camp teaches students mapping techniques that are best suited to field studies of Precambrian rocks of the Canadian Shield. By all measures, the camp was a rousing success.

The Precambrian field camp was attended by 15 students - four from UMD and the remaining mainly from schools throughout Minnesota and Wisconsin. Jim Miller (MGS), Dean Peterson (NRRI) and George Hudak (UW-Oshkosh) served as full-time instructors, with assistance on various projects by Terry Boerboom (MGS), Val Chandler (MGS), John Goodge (UMD), Mark Jirsa (MGS), Howard Mooers (UMD), Mark Severson (NRRI), and Nigel Wattrus (UMD). The six credit course ran for six weeks from mid-July to late August. Although students worked six days a week, commonly 10-hour days, and often under very hot and humid conditions, they consistently kept a positive attitude throughout.

The first two weeks of the camp were run out of UMD. Daily mapping exercises included 1) structural and outcrop mapping at Thompson Dam, 2) an introduction to geophysical field methods (gravity, ground magnetics, seismic), 3) mapping mafic cumulate rocks of the Duluth Complex at Spirit Mountain, and 4) mapping intrusive and volcanic rocks along the North Shore near Tettegouche State Park. The latter exercise included a day of canoe mapping along Lake Superior.

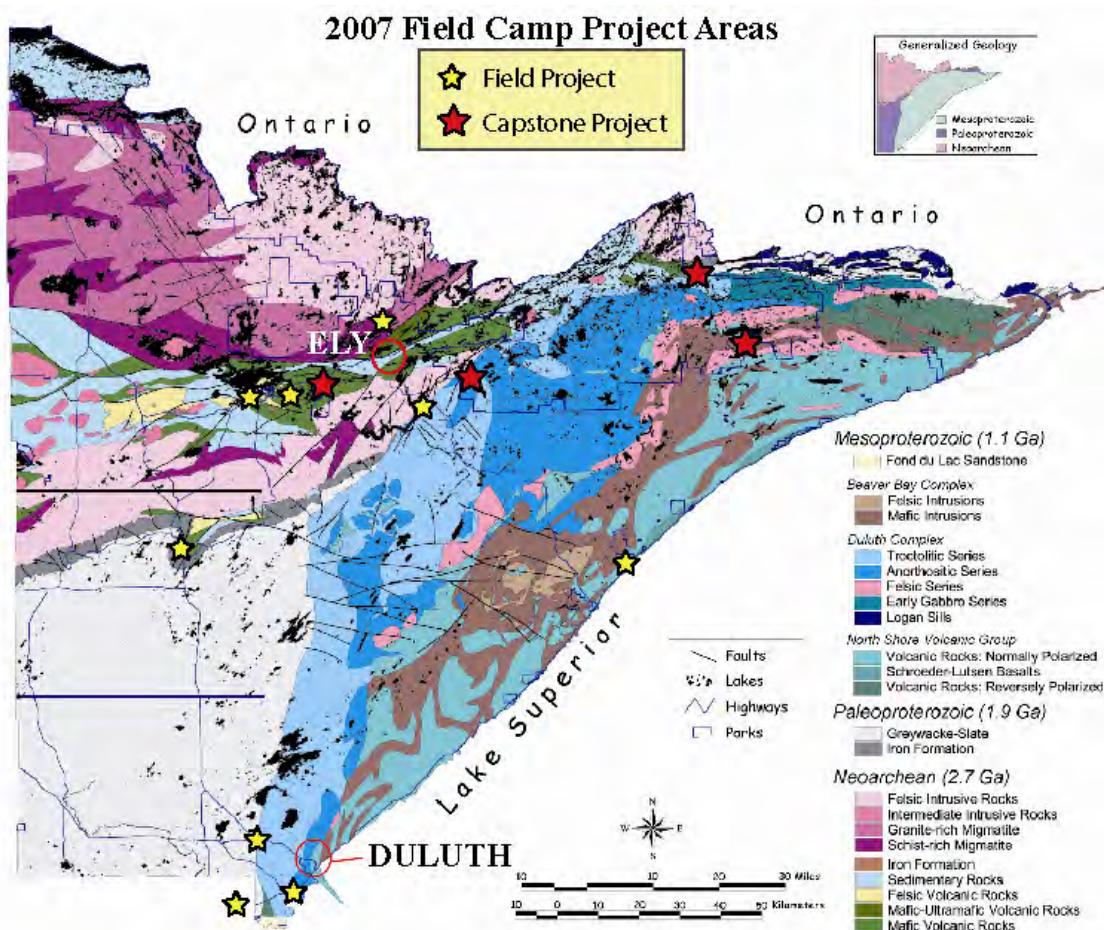
For weeks 3 and 4, we moved the camp to Vermilion Community College in Ely. There students started with a stratigraphic correlation project along the Biwabik Iron-formation, that included core logging and measuring section in one of the taconite mine pits. Next, students conducted a two-day project of mapping along the basal mineralized contact of the Duluth Complex. At the end of the third week, we arranged an evening of mapping by lamplight along the main adit of the Soudan Iron Mine. During week 4, students conducted a multifaceted mapping project on greenstone belt geology and overlying glacial geology in the Fivemile Lake area west of Ely.

The true highlights of the summer were the capstone mapping projects during Week 5. Here, students chose field mapping projects that entailed detailed bedrock mapping in previously unmapped wilderness areas, most in the BWCA. George Hudak mentored three students on mapping greenstone belt geology in the Twin Lakes area west of Ely. Mark Jirsa led four students into the BWCA off the Gunflint Trail, which had been intensely burned over in the Cavity Lake Fire of July 2006. Jim Miller worked with two students in the eastern prong of the Duluth Complex in the Homer Lake area off the Caribou Trail. Dean Peterson supervised a group of five students in mapping project of a gabbroic macrodike in the Nickel Lake-Gabbro Lake area of the BWCA. Upon returning to UMD for the final week, students worked on digitally compiling their capstone mapping data into ArcView and then creating geologic maps in Illustrator. These maps are on display in this year's poster session.

The true measure of the success of the camp is how the student have taken advantage of this experience to better their academic and career goals. Of the 15 students, five have secured jobs with exploration companies, six are pursuing Master's degrees (four at UMD, two at Lakehead University in Thunder Bay), three are currently finishing their undergraduate degrees with one planning to attend UMD next term. Many of the students have expressed to us how beneficial this camp has been to them, not only in teaching them particular field methods best suited to Precambrian terranes, but moreso in giving them the confidence to work with this type of geology, which we all know can be challenging.

Being the only open field camp in the US that focuses on the unique attributes of Precambrian shield geology, we believe that UMD's Precambrian field camp fills a very important niche in geological field education. Moreover, we hope this camp helps to reverse the alarming degradation of field geology as a primary component of geological education in many US schools. The art and science of observing and interpreting rocks in the field is still at the core of all geological endeavors and deserves a preeminent place in all geology curriculum. It is our mission to provide students with the tools and techniques that will start them on a life-long path of looking at rocks in the field, especially those of the Precambrian.

To see photos from last year's camp or download the geologic maps that were produced from the capstone projects and are on display at this meeting, please visit the PRC website (www.d.umn.edu/prc).



BEDROCK GEOLOGY OF THE FOOTWALL TO THE SOUDAN IRON FORMATION SOUTH OF TWIN LAKES, ST. LOUIS COUNTY, NORTHEASTERN MINNESOTA

MOOSAVI, S., JOHNSON, T. K., WENDLAND, C., ANDERSON, A., HUDAK, G. J.,
Precambrian Research Center, University of Minnesota – Duluth, Duluth, MN 55811,
hudak@uwosh.edu

The Ely Greenstone Formation of the Vermilion District of northeastern Minnesota is made up of a steeply north- to southwest-dipping sequence of Neoarchean supracrustal and associated intrusive rocks folded about the Tower-Soudan anticline. Recent mapping in the Vermilion District has concentrated in the area between the Soudan Mine (to the west) and Armstrong Lake (to the east; Hudak et al., 2002; Peterson and Patelke, 2003; Heine, 2005; Hoffman, 2007; Hudak et al., in prep.). The Lower Member of the Ely Greenstone (EGLM) is composed of submarine calc-alkalic and tholeiitic basalt and basalt-andesite sheet lava flows, pillow lava flows and pillow breccias with associated basalt to andesite tuffs and lapilli tuffs, along with subordinate rhyodacitic to rhyolitic lava flows, lapilli tuffs and tuffs, with minor intercollated epiclastic rocks and iron formations (Schulz, 1980; Southwick et al., 1998; Hudak et al., 2002, Hoffman, 2007). The EGLM has been subdivided into the older, largely shallow submarine Fivemile Lake Sequence (FLS) and the younger, deep submarine Central Basalt Sequence (CBS; Peterson and Patelke, 2003). The Soudan Iron Formation Member (EGSM) comprises Algoma-type cherty iron formation, massive to pillowed basalt lava flows, polymict epiclastic rocks and minor associated felsic tuffs (Peterson and Patelke, 2003). The Soudan Member is overlain by the Upper Member of the Ely Greenstone (EGUM). The EGUM is composed of poorly vesiculated tholeiitic basalt lava flows locally interlayered with Algoma-type iron formation lenses (Schulz, 1980; Southwick et al., 1998). Near Tower and Soudan, the EGUM is commonly interstratified with the Lake Vermilion Formation (LVF: greywacke, slate, conglomerate, and dacite tuff), and the Gafvert Lake Sequence (GLS: subaerial to submarine dacite to trachyandesite lava flows, tuffs, and intrusions; locally, the LVF unconformably overlies EGLM and EGSM strata (Southwick et al., 1998; Peterson and Patelke, 2003).

Detailed (1:5000 scale) geological mapping (Moosavi et al., 2007) occurred in the eastern part of the Vermilion District during August, 2007 as one of four capstone projects associated with the Precambrian Research Center field school. The mapping extended from about 1.5km south of Twin Lakes to the southern shoreline of Twin Lakes, and had the goal of increasing our understanding of the stratigraphy, hydrothermal alteration, and structural geology in this poorly understood part of the Vermilion District. The steeply north-dipping, east-west striking stratigraphic sequence is locally cut by east- east-northeast-trending, typically dextral shear zones composed of chlorite schist. The southwestern part of the field area comprises sparsely to moderately vesicular basalt and andesite lava flows which are correlative with the Eagle's Nest Basalts (Jirsa et al., 2001). These lava flows are overlain by what we interpret as the CBS, which comprises a 1.0 to 1.5km thick sequence of exceptionally well-preserved sparsely- to moderately vesicular pillowed and massive basalt lava flows and associated hyaloclastite that are locally interlayered with 10-50m thick rhyodacite to rhyolite tuffs and lapilli tuffs. Locally, 20-40m thick polymict breccias occur near the top of the CBS. These are compositionally and

texturally similar to breccias observed by Hudak et al. (in prep.) near the top of the CBS south of Sixmile Lake. Overlying interbedded Algoma-type iron formations, felsic tuffs and felsic lava flows are correlative with the EGSM. A sharp contact exists between the EGSM and stratigraphically overlying dacite to rhyodacite tuffs which we interpret as the GLS. This supracrustal sequence is intruded by fine- to coarse-grained, ophitic gabbro sills. These sills are correlative with gabbro sills mapped in the Soudan Mine area (Peterson and Patelke, 2003) and near Needleboy and Sixmile Lakes (Hudak et al., in prep.), and may represent hypabyssal intrusions which fed the overlying EGUM basalt lava flows. Synvolcanic hydrothermal alteration south of Twin Lakes is variable. Basalt and andesite volcanic rocks are generally moderately altered to an epidote-chlorite-actinolite-quartz alteration assemblage. Felsic rocks are commonly sericite-altered. Near the top of the CBS, mafic to intermediate volcanic rocks are strongly altered to an epidote-quartz $\pm$ garnet (andradite) assemblage similar to that observed in the uppermost 50m of the CBS in the vicinity of Sixmile Lake (Hudak et al., in prep.).

References

- Heine, J., 2005, Gafvert Lake Reconnaissance Mapping Project: Natural Resources Research Institute Technical Report NRRI/TR-2005/20, 12 p.
- Hoffman, A. T., 2007, 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, 295 p..
- 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.
- Jirsa, M. A., Boerboom, T. J., and Peterson, D. M., 2001, Bedrock Geological Map of the Eagles Nest Quadrangle, St. Louis County, Minnesota: Minnesota Geological Survey, Miscellaneous Map Series M-114, 1:24000 scale.
- Moosavi, S., Johnson, T., Wendland, C., Anderson, A., and Hudak, G., 2007, Bedrock Geology Map of the Footwall to the Soudan Iron Formation South of Twin Lakes, St. Louis County, Northeastern Minnesota: Precambrian Research Center, Geological Map Series Map 2007-4, Natural Resources Research Institute, University of Minnesota-Duluth.
- 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.

GEOCHEMISTRY OF SEDIMENTARY ROCKS ASSOCIATED WITH THE MUSSELWHITE GOLD DEPOSIT, NORTHWESTERN ONTARIO

MORAN, PATRICK; FRALICK, PHILIP; HILL, MARY LOUISE, HOLLINGS, PETE,
Department of Geology, Lakehead University, Thunder Bay, Ontario, Canada, P7B 5E1,
pcmoran@lakeheadu.ca

The Musselwhite gold deposit, 100% owned and operated by Goldcorp Inc., has cumulatively produced in excess of 2 million ounces since 1997 and has a projected mine life through 2013. It is situated in the North Caribou Lake metavolcanic/metasedimentary belt in the central northwestern portion of Superior Province, approximately 430 km northwest of Thunder Bay. The belt occurs along the contact between the North Caribou Terrane and the Island Lake Domain, with a large, crustal-scale deformation zone forming its eastern margin. The Musselwhite gold deposit is hosted by amphibolite grade rocks dominated by banded iron formation (BIF). This study primarily focuses on the Northern Iron Formation (NIF) metasedimentary assemblage, host to the majority of gold mineralization at Musselwhite

Stratigraphic and geochemical analyses suggest that the lithologies of the NIF assemblage were deposited on Mesoarchaean mafic to ultramafic volcanic rocks forming the ocean-floor. The NIF assemblage and another iron formation lower in the stratigraphy, the Southern Iron Formation (SIF), record hydrothermal regimes associated with, and interrupted by, eruptive volcanic activity. The stratigraphically lowest lithologies in the NIF assemblage, meta-argillite, quartz-grunerite BIF, and magnetite-dominant BIF, were deposited in deep, calm water, in association with venting hydrothermal fluids. These ancient chemical sediments are analogous in geochemistry to modern day deposits in places such as the Red Sea and East Pacific Rise. Differing Eu content between chert and magnetite layers indicate that rhythmically changing temperature variations drove the hydrothermal system, imparting the banded nature. The quite chemically pure chert and magnetite layers of the lower portion of the NIF assemblage contrast with silicate-dominant banded iron formation; the silicate-dominant BIF increases in importance stratigraphically upwards. It represents a decreasing hydrothermal system and/or an increase in the rate of clastic sedimentation. Hornblende-garnet and biotite-garnet schists were formed by metamorphism of mudstones composed of eroded material. The sediment that formed the hornblende-garnet schist is the same sediment that composes the siliciclastic component of the silicate-dominant NIF. Similarly the biotite-garnet schist represents a mudstone, but unlike the hornblende-garnet schist, it is primarily derived from intermediate to felsic source rocks. Lastly the garnet-quartzite represents metamorphosed sandstone eroded from the same intermediate to felsic igneous source rocks as the biotite-garnet schist. Just as there is an overall increase in clastic content upwards through the approximately 30 m thick sedimentary succession there is also a change from more mafic sourced debris to a more intermediate/felsic source.

The majority of samples collected from Musselwhite did not experience significant remobilization of typically immobile elements. This is indicated by the relatively linear geochemical ratios between the immobile elements in question (Al_2O_3 , TiO_2 , Zr, U, Th, etc).

Even elements that are commonly more mobile (K_2O , Na_2O , etc) appear to have remained relatively immobile at Musselwhite. The only samples that show significant geochemical change are from shear zones. The gold mineralization is primarily associated with shear zones within the siliciclastic-rich, upper NIF assemblage, where pyrrhotite (possibly originally pyrite) replaced iron oxides and iron silicates. This indicates that the control on areas of gold mineralization was a combination of: 1) the presence of structural zones allowing gold-bearing fluids to move through the NIF, which could act as a geochemical trap for gold; and 2) structural conditions in the siliciclastic-rich NIF that favoured hydrothermal fluid involvement with this unit.

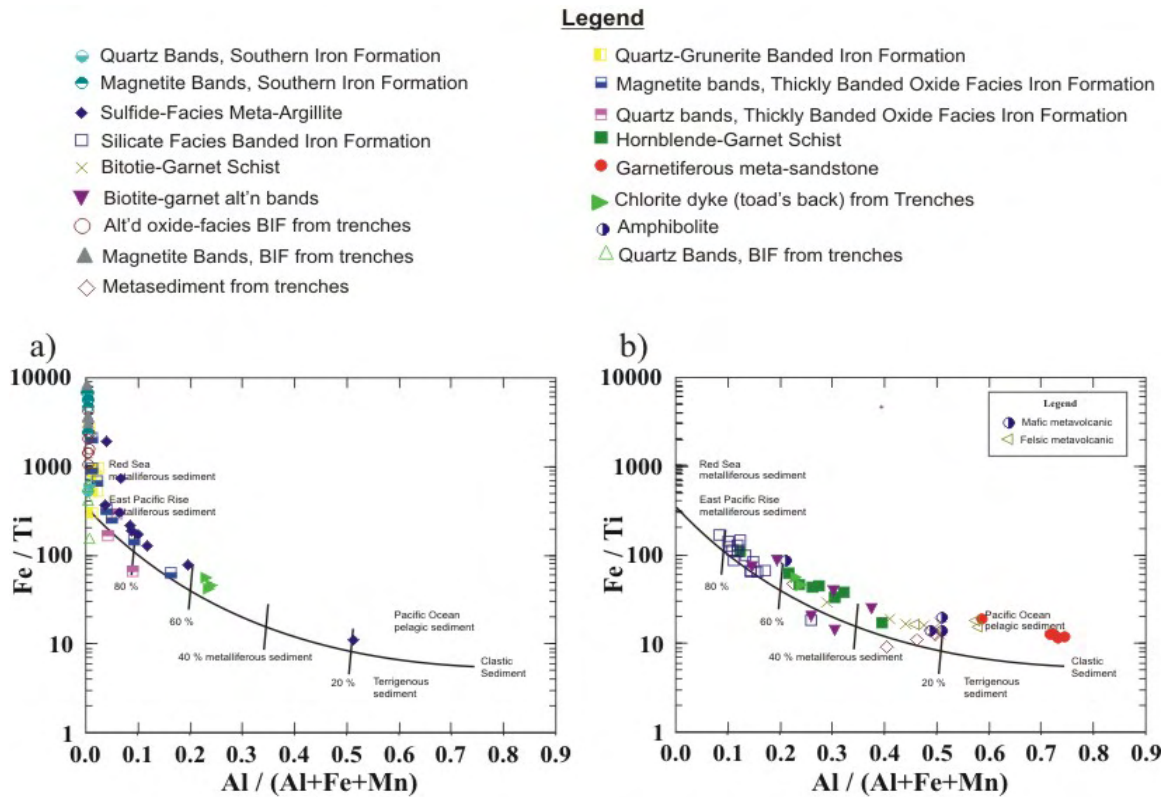


Figure 1. Discrimination diagram for estimating the amount of exhalative versus siliciclastic sedimentary material in samples. The amount of siliciclastic material increases toward the lower right and amount of chemical precipitates increase toward upper left. There is an overall trend toward more siliciclastic material higher in the stratigraphy. a) This diagram shows chemically dominated samples from the Musselwhite gold deposit b) Siliciclastic dominated samples from units above those in Fig. 1a. Four mafic and three felsic metavolcanic samples are plotted on Fig. 1b for comparison. Note samples plot above the mixing line, in 1a and 1b, which is the result of lower Ti in the original clays.

ON-LINE ELECTRONIC ACCESS TO INSTITUTE ON LAKE SUPERIOR GEOLOGY PUBLICATIONS

M.G. Mudrey, Jr., 106 Ravine Road, Mount Horeb, WI 53572 USA
(mgmudrey@mhtc.net)

Peter Hollings^s Department of Geology, Lakehead University, Thunder Bay, ON P7B 5E1, Canada (peter.hollings@lakeheadu.ca) (*corresponding author*)
Lura E. Joseph, Geology Library, 223 Natural History Building, 1301 W Green, Urbana, IL 61801, USA (luraj@uiuc.edu)

Mark Jirsa, Minnesota Geological Survey, 2642 University Ave., St. Paul, MN 5514 USA 55114 (jirsa001@umn.edu)

Jo Kalliokoski, 1010 7th Ave., Houghton, MI 49931

Authors are **Present** and *Emeriti* Secretaries/Treasurers of the Institute during the last 25 years and one librarian (Joseph) who helped the Institute to compile, index and create search mechanisms for its varied publications

In the past 54 years, over 16 gigabytes of abstract, field trip guides and supplemental information from more than 100 individual documents have been produced as part of the annual proceedings of the Institute on Lake Superior Geology (ILSG). These include comprehensive volumes on mineral properties, combined abstract and field guides, and field guides published by sponsoring organizations. During the past three years students at Lakehead University and other volunteers have scanned and digitized these volumes. Use of optical character recognition (OCR) software has allowed the Institute to make the digital files searchable. By use of proprietary software from Cvision[®] Technologies, Inc, this quantity of information was compressed in PDF format to less than 600 megabytes, approximately 3600 compression ratio. The documents can be opened and read directly in Adobe Reader[®] and other software with read PDF compatibilities. The documents can be directly accessed for download at no cost at <http://www.lakesuperiorgeology.org/>

Work on the scanning consisted of direct scanning to PDF and scanning to tiff format images. PDF and tiff images were cleaned, and where necessary (particularly with older, yellowed, and mimeographed documents) extensively enhanced to improve readability. Where necessary, colored maps and illustrations were treated separately. The documents were then compressed. Compression to 5 megabytes was achieved from a 1.5 gigabyte original scan.

To accompany the online collection of ILSG publications, a searchable index was created by Joseph - geology librarian at University of Illinois, Urbana-Champaign (UIUC)
<http://search.grainger.uiuc.edu/ilsg/>

Work on the database project progressed in the following steps during summer and fall of 2007:

- A bibliography was created from information available from GeoRef[®]. The references were subsequently parsed and imported into an Excel[®] database. Many entries were missing from GeoRef[®], and gaps were filled in from the collection at UIUC, from PDFs as they were added to the ILSG web site, and via Interlibrary Loan. Each reference was checked for accuracy, and edited for consistency of the source field information for each volume. In addition, information was added to fields that are unlikely to be included in commercial indexes, such as type (oral presentation, poster, guidebook, address, or other), meeting location, and meeting date, and the speakers and titles of presentations for which abstracts are unavailable.
- The completed Excel[®] database was imported into an Access database and loaded on a library server at UIUC.
- A search engine that had been created in-house to search other library databases was modified to search the ILSG database. The Access[®] database can be easily updated. At some time in the future, key words could also be added to the database to enhance search results; however that would be a major project. There are currently over 2400 references in the index.

The database can be searched by entering search terms into any or all of the following fields: author, title, source (including volume number), publication year, meeting location and/or meeting dates. In addition, there is a drop-down menu to search a type of reference (oral presentation, poster, guidebook, and so forth). The results can be sorted by author, publication year, type, meeting location, or meeting date. The default sort is by author. The default for type is “any.” If no search terms are entered, the results will include all references, one hundred at a time. This is useful for browsing. Each of the search fields can be searched for either “all of the terms” or “any of the terms.” Searching of phrases is beyond the capability of this search engine. Wildcards (truncation symbols such as *) are not used; however, truncation is automatic: that is, a partial word will return results. For example, “Eidu” in the author field will return references by Eidukat, and “mineral” in the title field will return references with “mineral,” “minerals,” “mineralization,” and so forth. Case (upper or lower) is not recognized, so is not important.

The database format and search capabilities will be demonstrated in a poster presentation.

A complete list containing such information as author, editor, chairperson, and sponsoring organization is maintained by:

MTU Archives & Copper Country Historical Collections
 J. Robert Van Pelt Library
 Michigan Technological University
 Houghton MI 49931
 Phone: 906-487-2505
 e-mail: copper@mtu.edu

Photocopies of most back volumes can be ordered from the MTU Archives at the prevailing copy rate.

Multi-element Geochemical Signature of Copper Mineralization at the White Pine Mine, Midcontinent Rift System, Western Upper Peninsula, Michigan

MUVI-TJIKALEPO, Muatala H., BORNHORST, Theodore J., and ROBINSON, George W., A. E. Seaman Mineral Museum, Michigan Technological University, Houghton, MI 49931 and **WILLIAMS, W.C.**, Phoenix, AZ 85048

The lower beds of the Nonesuch Shale and uppermost beds of the Copper Harbor Conglomerate host a giant stratiform copper deposit at the White Pine Mine. The ore body yielded roughly 2.0 billion kilograms of copper and 50 million ounces of silver from 198 million tons of ore from 1953 to 1996 (an average grade of 1.14 % copper and 0.25 ounces of silver per ton) (Johnson et al., 1995). Whereas the White Pine deposit has been the subject of both basic and in-depth geologic studies, heretofore there has not been a multi-element geochemical investigation. For this study, samples were selected from drill core to avoid the problems of geochemical mobility in surface exposures. A systematic vertical section through the ore body was obtained from 5 holes at the White Pine Mine. The holes were from both the center and edge of each deposit. A total of 387 samples (includes areas not discussed here) were analyzed for 64 elements by Activation Laboratories in Toronto, Canada. Copper ore samples are defined here as those samples with 0.2 % Cu or more. At the White Pine Mine, the weighted average for the samples used in this study have a copper content of 1.22 % Cu which is similar to the average grade in mined ore of 1.14 % Cu. The geochemical character of the White Pine copper ore is given in Table 1. Several elements (Cu, Ag, As, Hg, Ba, Br, Ca, Cd, Fe, K, Mn, Na, Ni, Pb, Re, S, V, Zn, U) were selected for more in-depth study (Muvi-Tjikalepo, 2007).

At the White Pine Mine, distribution of Ag, Hg, and Re closely parallel that of Cu. Arsenic does not appear to correlate well with the vertical changes in the amount of Cu. The vertical distributions of Pb and Cd appear to correlate well with each other, but not with Cu. The vertical variation of Zn shows no significant correlation to that of Pb-Cd. The contents of Zn and Ni appear to be closely related to one another and slightly resemble Cu. The vertical variations of Ba and Br appear to be irregular and/or nearly constant throughout and show no significant correlation to the distribution of Cu. The geochemical profiles of Ca and Fe appear to show an antithetic relationship with each other and appear unrelated to the distribution of Cu. The Mn concentration is more or less constant throughout the vertical ore column, and shows a weak relationship with Cu and a moderate connection with Ca. The vertical distribution of S displays a clear relationship with that of Cu. The geochemical profiles of both K and Na show no significant resemblance to the geochemical profiles of Cu, and their vertical distributions appear more or less homogenous throughout the ore column. The geochemical profiles of U closely parallel those of Cu, except in the uppermost part of the mineralized column where the U content appears to rise slightly with a corresponding slight drop in Cu. The V content on the other hand appears to be largely constant.

In comparison to the Kupferschiefer ore horizon and the ore shale of the Zambian Copperbelt, the White Pine occurrence is geochemically dominated by Cu and Ag. In ore shale of the Zambian Copperbelt the metal association is Cu and Co. The association of metals in the Kupferschiefer shale and Zambian Copperbelt shale are relatively more polymetallic than White Pine.

Acknowledgements

This study was partially funded by Phelps Dodge Exploration (currently Freeport-McMoRan Copper & Gold), a Fulbright Fellowship to Muvi-Tjikalepo, and Michigan Technological University. The drill core from the White Pine Mine was obtained by Bornhorst during the time of mine closure through the generous assistance of Dr. Rod Johnson.

Table 1: Weighted average values of elemental concentrations in copper ore from the White Pine Mine. Copper ore is defined as those samples with a minimum copper of 0.2 %. Weighted average determined by weighting using the total thickness of the interval sampled in the core. For the White Pine Mine, 49 samples covered 69 ft of core defined as ore. The number of digits listed is not necessarily significant on the basis of accuracy or precision. The QA/QC program included blind duplicate samples, a blind “blank” sample run with each batch, blind geochemical reference samples, laboratory duplicate samples, and laboratory geochemical reference standards. Raw and QA/QC data are given in Muvi-Tjikalepo (2007).

Cu %	1.22		
Al %	5.54	Mn ppm	1216
Ag ppm	10.9	Mo ppm	1.1
As ppm	5.6	Na %	1.47
Au ppb	<2	Nb ppm	16.3
Ba ppm	621	Nd ppm	31
Be ppm	2	Ni ppm	51
Bi ppm	0.2	P %	0.08
Br ppm	4.5	Pb ppm	11
Ca %	2.10	Pr ppm	7.8
Cd ppm	7.8	Rb ppm	46.6
Ce ppm	52	Re ppm	0.15
Co ppm	33	S %	0.32
Cr ppm	79	Sb ppm	0.6
Cs ppm	6.1	Sc ppm	17.0
Dy ppm	6.6	Se ppm	1.3
Er ppm	3.9	Sm ppm	7.2
Eu ppm	1.63	Sn ppm	3
Fe %	4.58	Sr ppm	120
Ga ppm	22.2	Ta ppm	0.9
Gd ppm	7.0	Tb ppm	1.1
Ge ppm	0.3	Te ppm	0.3
Hf ppm	6.1	Th ppm	6.8
Hg ppb	92	Ti %	1.77
Ho ppm	1.3	Tl ppm	0.82
In ppm	<0.1	Tm ppm	0.46
Ir ppb	<5	U ppm	2.4
K %	2.14	V ppm	133
La ppm	25.7	W ppm	<1
Li ppm	43.7	Y ppm	30.6
Lu ppm	0.5	Yb ppm	3.5
Mg %	2.16	Zn ppm	117
		Zr ppm	237

References Cited

- Johnson, R.C., Andrews, R.A., Nelson, W.S., Suszek, T., and Sikkila, K. 1995. Geology and mineralization of the White Pine copper deposits: unpublished Copper Range Company Report.
- Muvi-Tjikalepo, M.H. 2007. Stratigraphy and trace element distribution in the lower Nonesuch Formation of the Michigan segment of the North American Mid-continent Rift System, Gogebic-Ontonagon Counties, Michigan: M.S. Thesis, Michigan Technological University, 133 p.

Northern Michigan Geologic Repository Association

The geological repository facilities in Marquette are full-to-overflowing. There is no room for new cores or samples. Furthermore, the state cannot provide permanent, ongoing funding. The Northern Michigan Geologic Repository Association (NMGRA) is being created as a not-for-profit-organization to provide support for repository efforts in the Northern Peninsula to collect geologic cores, samples, specimens, and associated documents relating to the geology and house, materials collected in the State of Michigan. These materials will be catalogued and preserved for charitable, educational, scientific, and literary purposes. NWGRA will work in cooperation with scientific, professional, educational, governmental, social and philanthropic organizations to advance mutual concerns and activities. As a not-for-profit-organization, your contributions will be tax deductible.

PolyMet Mining: NorthMet Cu-Ni-Co-PGE Project, Hoyt Lakes, Minnesota, USA

Richard Patelke, Project Geologist, PolyMet Mining

LOCATION: NorthMet is 70 miles north of Duluth in the heart of the world-class Mesabi Iron Range District of northeastern Minnesota. It is one of at least ten deposits in the region.

STORY: Drilling for Cu-Ni-Co-PGE began with US Steel in 1969, with work by PolyMet since 1998. There are 371 drill holes over 285,757 feet with 34,186 multi-element assays. The Project includes the former LTV Steel Mining Company taconite iron ore concentrator, the “Erie plant,” idle since 2001 and now wholly owned by PolyMet. The Erie plant comprises a 100,000 tpd concentrator and associated facilities, such as a tailings basin with 28 years of capacity at PolyMet's intended initial production of 32,000 tpd. Also included are a rail fleet, shops, office buildings, and ready access to power and water. The plant is ready to run NorthMet ore after simple refurbishment, installation of flotation equipment, and construction of the hydromet facility.

A bankable feasibility study was completed in 2006, permits and financing are expected in late 2008, with construction commencing immediately thereafter, concentrate production will begin in 2009, followed closely by hydrometallurgical processing, and ultimately copper metal production along with Ni-Co hydroxide and PGE concentrate.

GEOLOGY: The NorthMet deposit is a large, disseminated sulfide, Cu-Ni-Co-PGE ore body in the Keweenawan Duluth Complex. It is hosted in grossly layered troctolitic rocks overlying metamorphosed greywackes. There are seven igneous stratigraphic units divided and recognized by texture and basal ultramafics. All intrusive and country rock units dip gently to the southeast.

DEPOSIT: The main ore zone is in the basal igneous stratigraphic unit with local extension of mineralization into the overlying unit. A secondary ore zone (the “Magenta Zone”) in the upper units in the western part of the deposit crosses stratigraphy. The Magenta Zone is copper and PGE-rich and sulfur poor relative to the rest of NorthMet. Mineralization is chalcopyrite, cubanite, pyrrhotite, and pentlandite. PGE are correlated with copper. The deposit is open along strike and down-dip, with continuing drilling expected to add resource in both directions. NorthMet has a resource (2007) of 638 million tons measured and indicated, 252 million tons inferred, and reserves of 275 million tons proven and probable at a grade of 0.28% Cu, 0.08% Ni, 0.008% Co, and 0.337 g/tonne Pt + Pd + Au.

DISPLAY: Four core boxes displaying stratigraphic and mineralization suites, poster with cross-sections, maps, and photos.

Keweenawan apparent polar wander path: new observations, new ideas

L.J. Pesonen Department of Physics, Laboratory for Solid Earth Geophysics, PB 64, 00014 University of Helsinki, Finland (lauri.pesonen@helsinki.fi)

The Keweenawan apw track (the “Logan Loop”) of Laurentia has been considered to be the best documented Precambrian apw-sequence in the world. However, even after nearly 50 years of work, the cause of the pole motion is still debated.

Here we present new observations extracted from the literature. We focus on two cases, (i) the Logan intrusions and (ii) the Mamainse Point volcanics. These units are of prime importance since, unlike many other Keweenawan units, they record two to three successive reversals (at least the latter case) thus being crucial in testing the various models of the Logan Loop.

Mamainse Point Volcanics. Palmer (1970) pointed out that in the Mamainse Point section there are four “magnetostratigraphic” units, which are from oldest to youngest: R2-N2-R1-N1. Of the reversals the oldest one (R2-N2) is *asymmetric* in a similar manner as in most Keweenawan units: R inclinations are steep upward whereas N inclinations are moderate shallow downward.

Recently, Swanson-Hysell et al. (2006) have given new evidences that the older reversal is not asymmetric if one considers the data *in time progression* (flow by flow) and not as mean values. Following this principle, they interpret the asymmetry as a rapid motion of Laurentia from high to nearly equatorial latitudes. This idea cast doubt that the asymmetry is due to a hypothetical non-dipole field as suggested by Pesonen and Nevanlinna (1981). There are some support for their idea. First, a close look of the Fig. 19 of Palmer (1970) shows also a streaking in reversed polarity (R2) inclinations, from steep values to shallow ones. Unfortunately, we don’t know if Palmer’s data correspond the stratigraphic order. There are more examples where time progression of the pole can be notified along the western arm of the Logan Loop, such as in Osler volcanics, where the pole of the lower R units is distinctly older than that of the upper R units (Fig. 1). Also, the pole of Logan R sills seem to be older than that of dykes (which cut the sills; Fig. 1). However, there are also contrasting evidences. For example, the N-poles of the Portage Lake lava sequence, when plotted in stratigraphic order (Books, 1972), do not plot *along* the track but make an oval *across* it, resembling typical secular variation pattern (Donadini 2007). Secondly, there are also some evidences of “back-and-forth” movement of the pole along the apw-track. Another problem is the age of the Mamainse Point volcanics, since according to Davis et al. (1995) the upper part of the lower R2 unit is ca. 1096 Ma, some 15-20 Ma younger than other R polarity poles, such as the Logan sills (ca. 1110 Ma). The only way to reconcile this is that the dated flow is an intrusive (sill) but even in this case, the pole will make back-and-forth movement along the track which is against the plate motion model. We have proposed that the major part of the loop, the asymmetry, and the back-and-forth movement can all be explained in terms of the fluctuating non-dipole field (Pesonen et al., 2006).

Pigeon River dykes. Hollings et al. (2007) have pointed out that in the Pigeon River area (Ontario), there are three cross-cutting dyke swarms. Recently, one dyke from the the Pigeon River swarm has yielded an U-Pb age of 1141 ± 20 Ma (Heaman et al., 2007) which is markedly older than the generally accepted age of the Keweenawan igneous units (1115-1087 Ma). In addition, Hollings et al. (2007) point out that geochemically the Thunder Bay (and south of it) sills are distinct from Lake Nipigon sills. These results call for a relook at the paleomagnetic data base if there are supporting evidences for their observations. Fig. 1 shows the poles from three, supposed to be nearly coeval (1115-1087 Ma), Keweenawan igneous areas in the northern part of the Lake Superior. These are Pigeon River (triangles), Thunder Bay (squares) and Lake Nipigon (circles). The dual polarity poles are derived of dykes (small symbol) and sills (large symbol), respectively. All the rock units have been paleomagnetically studied by three to six authors (Dubois, Robertson&Fahrig, Pesonen, Palmer, Halls and Stott, Middleton et al.; see references) thus allowing a consistency check to be made. The result is somewhat surprising: in the case of

N-polarity data, there are no marked differences between poles from the three areas and the consistency check is excellent. In the case of R-polarity data, there is a slight tendency that the Nipigon sills and dykes are the oldest (in the sense of apw; Fig. 1), the Thunder Bay sills and dykes are next and the Pigeon River sills are the youngest units. Most important, the pole of the Pigeon River R-polarity dykes, recently dated at 1141 ± 20 Ma, differ from other R poles. Unfortunately, data from only three dykes are so far available but the consistency between the two studies (Robertson and Fahrig, 1971; Pesonen, 1979) is good. It is noteworthy that this R polarity pole, if indeed of 1141 Ma old, cannot be matched with the coeval 1141 Ma Abitibi poles (either N or R). If the Pigeon River R-pole stands in future studies (more data urgently needed), the new pattern of Keweenawan-Abitibi poles does not allow a simple western arm of the Logan Loop to be drawn but requires, a more complex apwp. Alternatively, the complex pattern of poles may reflect a rapidly oscillating non-dipole field prevailing during the (oldest) R polarity epoch. The R2-N1 asymmetry in the Coldwell Complex (1108 Ma), and the new, surprisingly “young” age, 1104 Ma, for an R-polarity Nipigon sill with steep upward inclination (Halls and Stott, 2005; Fig. 1) requires also a back-and-forth movement of the pole along the apw-track, in support of an fluctuating non-dipole field model. The new poles from the coeval dykes from Central Arizona, being 14° apart from the Lake Superior area (Fig. 1) can also be interpreted in terms of an oscillating non-dipole field, although they are not yet dated with modern standards (Donadini, 2007).

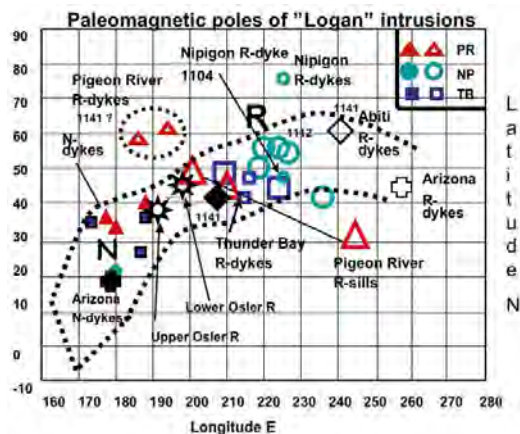


Figure 1. Paleomagnetic poles of Keweenawan intrusions from Pigeon River (PR), Lake Nipigon (NP) and Thunder Bay (TB) areas. Large (small) symbols denote sills (dykes) and open (closed) symbols denote R (N) polarities, respectively. Some key ages are added. Also shown are the ca. 1140 Ma old poles from the Abitibi dykes, Ontario (both polarities) and new results from the Central Arizona dykes (both polarities). The dotted swathe is the western arm of the Logan Loop.

References

- Books, K.G. (1972). USGS Surv.Prof. Pap., 760, 42 p.
- Davis, D. et al., 1995. ILSG, 41, 9-10.
- Donadini, F. (2007). PhD thesis, Univ. of Helsinki, 188 p.
- DuBois, P.M., 1962. Geol.Surv. Can. Bull. 71, 1-75.
- Halls,H.C.&Pesonen, L.J (1982). GSA Mem., 156, 173-201.
- Halls,H.C.&Stott, G (2005). OGS Open file report, 617, 52 p.
- Heaman, L. M. et al. (2007). CJES, 44, 1-32.
- Hollings, P. et al. (2007). CJES, 44, 389-412.
- Middleton, R.S. et al. (2004). JGR-B, 109, 2103, doi:10/1029
- Palmer, H.C. (1970). CJES, 7, 1410-1436.
- Pesonen, L.J., 1979. Bull. Geol. Soc. Finl. 51, 27-44.
- Pesonen, L.J.&Nevanlinna, H., (1981). Nature, 294, 436-439.
- Robertson, W.A.&Fahrig, W., 1971. CJES, 8, 1355-1372.
- Swanson-Hysell, N. et al. (2006). GSA Abstracts, 38, 398

GEOLOGICAL MAP OF THE NORTHERN SOUTH KAWISHIWI INTRUSION AND SURROUNDING AREAS, DULUTH COMPLEX: ST. LOUIS AND LAKE COUNTIES, NORTHEASTERN MINNESOTA

PETERSON, Dean (*Natural Resources Research Institute, University of Minnesota Duluth*)

The recent boom in metal prices has brought about a worldwide resurgence in the exploration for virtually all mineral commodities, and the Lake Superior district has certainly seen its share of these exploration dollars. In the Duluth Complex of northeastern Minnesota, five companies are actively working on Cu-Ni-PGE properties in the Partridge River (Polymet Mining, Teck-Cominco) and South Kawishiwi (Franconia Minerals, Duluth Metals Limited, and Encampment Minerals) intrusions. Such mineral exploration relies on published geological information (maps, reports) from geological surveys and/or academic organizations. The publication of a new bedrock geological map of the northern South Kawishiwi intrusion (SKI) and adjacent areas has been one of the author's research projects over the last several years. Such work, *if it is completed correctly*, adds important knowledge that can be directly integrated into the detailed databases that the companies maintain for their properties. The caveat (*if it is completed correctly*) relates to how seamless the published data can be incorporated into exploration programs, resource calculations, and mine plans. For this project, geologic units that the companies use to define the igneous stratigraphy of the SKI (based on ~700 drilled within the map sheet) have been used to define the map units of the basal zone of the SKI.

The author's mapping has evolved from a geological mapping study of a small area (to understand magma inflow into the SKI) into a comprehensive geologic mapping and compilation project (~105,000 acres) to answer some of the fundamental questions on the origin of the extensive known and undiscovered Cu-Ni-PGE mineralization in the northern portion of the SKI. Such an increase in scope is needed due to the economic significance of the published resource estimates (>\$140 billion) from this area. To date, over 15,000 outcrops, 1,400 structural measurements, and 12,500,000 meters of elevated contour lines have been integrated into the comprehensive GIS database. The new map area includes the geology from each of the seven major lithologic units in the area: the footwall Late Archean Giants Range batholith and Paleoproterozoic Biwabik Iron and Virginia Formations; the enclosing Mesoproterozoic Anorthositic Series rocks; and the Troctolitic Series Bald Eagle (BEI) and SKI intrusions and the arcuate Nickel Lake Macrodiike that links the BEI and SKI.

A new insight of this work has been the recognition that the northern SKI is not a shallowly dipping sill but rather a southwest trending funnel-like body. Such an interpretation leads to the conclusion that the eastern contact of the SKI, which previously was interpreted as the top of the intrusion, is a basal contact, and thus has great potential for hosting Cu-Ni-PGE mineralization at depth.

The map presented in the 2008 ILSG poster session should be viewed as an update, as there are still several large areas that are yet to be mapped in detail.

References

- Foose, M.P., and Cooper, R.W., 1978, Preliminary geologic map of the Harris Lake area, northeastern Minnesota: U.S. Geological Survey Open-File Report 78-385, 24 p., 1 plate, scale 1:12,000.
- Green, J.C., Phinney, W.C., and Weiblen, P.W., 1966, Geologic map of Gabbro Lake quadrangle, Lake County, Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-2, scale 31,680.
- Miller, J.D., Green, J.C., Severson, M.J., Chandler, V.W., and Peterson, D.M., 2001, Geological map of the Duluth Complex and related rocks, Northeastern Minnesota: Minnesota Geological Survey, Miscellaneous Map M119, scale 1:200,000.
- Miller, J.D., Jr., Severson, M.J. and Foose, M.P., 2005, Bedrock geology of the Babbitt Northeast quadrangle, St. Louis and Lake Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-160, scale 1:24,000.
- Peterson, D.M., Patelke, R.L., and Severson, M.J., 2004, Bedrock geology map and Cu-Ni mineralization data for the basal contact of the Duluth Complex west of Birch Lake, St. Louis and Lake Counties, Northeastern Minnesota: Natural Resources Research Institute, Map Series NRRI/MAP-2004-02, scale 1:10,000.
- Peterson, D.M., Albers, P.B., and White, C.R., 2006, Bedrock Geology of the Nickel Lake Macrodiike and Adjacent Areas: Lake County, Northeastern Minnesota: Natural Resources Research Institute, Map Series NRRI/MAP-2006-04, scale 1:10,000.
- Peterson, D.M., 2006, Digital Base for Geological Mapping within the Northern South Kawishiwi Intrusion: Lake and St. Louis Counties, Northeastern Minnesota: Natural Resources Research Institute, Map Series NRRI/MAP-2006-01, scale 1:20,000.
- Phinney, W.C., 1967, Reconnaissance geologic map of part of the Kangas Bay quadrangle: Minnesota Geological Survey file map, scale 1:24,000.
- Tharalson, E., Sweet, G., Boisjoli, T., Lentz, B., Fellows, T., and Peterson, D., 2007, Geological Map of the Nickel Lake Macrodiike and Northern Bald Eagle Intrusion, Lake County, Northeastern Minnesota: Precambrian Research Center Map Series PRC/MAP-2007-01, scale 1:10,000.

A Study of the Paragenetic Stages of Mineral Growth in Complex Iron Ores at the Tilden Mine and Development of a Mine Scale Model for Application to Ore Treatment Methods

Natalie J. Pietrzak¹, Norm Duke¹, Glenn Scott² and Helen Lukey²

¹Earth Sciences Department, University of Western Ontario, London, Ontario N6A 5B7 Canada

²Cliffs Technology Group, Cliffs Mining Services Company, Ishpeming, 49849, Michigan, USA.

The Tilden Mine in Negaunee, Michigan is owned and operated by the Cleveland-Cliffs mining company. The Tilden operation is mining a segment of the Negaunee Iron Formation that is stratigraphically located within the Proterozoic aged Marquette Range Supergroup (Lougheed, 1983).

Cleveland-Cliffs currently experiences a reduction in pellet quality when processing ore mined from various locations within the Tilden pit. From a geological prospective, factors that can effect the plant operation and pellet quality are related to mineralogy and mineral textures. In previous work, the Tilden ore body has been divided into a series of geologic domains based on lithology, structure and metallurgy. Five principle domains have been outlined using the major metadiabase horizons as markers: 1) Northwest Domain; 2) CDIII-West Pit Domain; 3) Main Pit Domain; 4) Intrusive Domains and; 5) Main Pit Footwall Domain. These domains are then further subdivided based on ore type, ore lithology and metallurgy (Lukey et al., 2007).

Focus of this Phd thesis is to characterize the mineralogical domains at pit scale. With the results of this thesis, the Tilden staff can determine the mineralogical variations that affect their pellet production quality. The main objectives of this project include: 1) to determine ore composition and textures of the metallurgically classified domains and; 2) characterize the mineralogical variations and separate primary, metamorphic and/or hydrothermal stages.

Lougheed, M.S., 1983, Origin of Precambrian Iron-Formations in the Lake Superior Region: Geological Society of America Bulletin, v. 94, p. 325-340.

Lukey, H.M., Johnson, R.C., and Scott, G.W., 2007, Mineral Zonation and Stratigraphy of the Tilden Haematite Deposit, Marquette Range, Michigan, USA: Iron Ore Conference.

VERMILION DISTRICT, NE MINNESOTA

SARTORELLI, A. K., Department of Geology, University of Wisconsin Oshkosh, Oshkosh, WI 54901, sartoa61@uwosh.edu

ANDERSON, A., Precambrian Research Center, University of Minnesota – Duluth, Duluth, MN 55811

HUDAK, G. J., Department of Geology, University of Wisconsin Oshkosh, Oshkosh, WI 54901

Locating volcanic vents can be problematic because many of the physical features that characterize active volcanism (eruptions, volcanoes, hydrothermal and fumarolic activity) are no longer present. Ancient submarine lava flows appear to have formed with similar morphologies to modern submarine lava flows (Jones, 1968; Moore, 1975; Dimroth, et al., 1978; Cas and Wright, 1987; Walker, 1992; Kennish and Lutz, 1998; Batiza and White, 2000); therefore, detailed mapping and facies analysis are essential tools for evaluating: 1) proximity to ancient vent sites; 2) the water depth in which ancient submarine lava flows formed; and 3) the paleotopography associated with the genesis of ancient lava flows. Evaluating such features is necessary to accurately reconstruct ancient volcanic environments (Dimroth et al., 1978; Walker, 1992), and can provide important information useful for locating natural resources in ancient volcanic rocks (Cas, 1992; Gibson et al., 1999; Franklin et al., 2005).

Detailed (1:500 to 1:5000 scale) volcanic facies mapping was performed in the Fivemile Lake Sequence of the Lower Member of the Neoarchean Ely Greenstone Formation (EGLM; Peterson and Patelke, 2003) immediately west of Fivemile Lake in the Vermilion District of northeastern Minnesota during August and September, 2007. The purpose of this mapping (which was performed as part of an Undergraduate Student – Faculty Collaborative Research Grant from the University of Wisconsin Oshkosh) was threefold: 1) to further document the distribution of various flow morphologies (sheet lavas, pillow lavas) in the EGLM; 2) to utilize facies analysis in an attempt to determine ancient volcanic vent locations in the EGLM; and 3) to further evaluate the hypothesis that increased thicknesses of hyaloclastite deposits (glassy fragmental rocks) associated with ancient submarine lava flows appear to correlate directly with increasing proximity to ancient vent sites and anomalous base metal mineralization (Newkirk et al., 2001; Hudak et al., 2002a). The mapping included making detailed observations, descriptions, and measurements of pillow morphology, pillow strike, pillow dip and topping directions, pillow bud orientations, pillow dimensions (maximum, minimum, and average pillow horizontal and vertical dimensions), and thickness of interpillow hyaloclastite deposits. Petrographic studies were performed after the mapping to further evaluate the mineralogical and textural characteristics of these extremely well preserved ancient pillow lavas.

Our detailed mapping indicates that the region immediately south and west of Fivemile Lake is composed of pillow lavas which were erupted from two separate pillow volcanoes. Pillow budding directions indicate that the oldest pillows were formed in a shallow submarine environment and flowed east from a volcanic vent or vents located west of Fivemile Lake, whereas younger pillow flows flowed west from a shallow submarine volcanic vent or vents located east of the study area. Based on previous studies by Newkirk et al. (2001) and Hudak et al. (2002), this vent or vents may have been located along a north-northeast-trending synvolcanic structure immediately east and northeast of Fivemile Lake. It appears that our

detailed pillow measurements are able to distinguish the products of overlapping pillow volcanoes that were active approximately 2.7 billion years ago.

References

- Batiza, R., and White, J. D. L., 2000. Submarine Lavas and Hyaloclastite: *in* Sigurdsson, H. (editor in chief), *Encyclopedia of Volcanoes*: Academic Press, San Diego, p. 361-381.
- Cas, R. A. F., 1992. Submarine volcanism: eruption styles, products, and relevance to understanding the host-rock successions to volcanic-hosted massive sulfide deposits: *Economic Geology*, v. 87, p. 511-541.
- Cas, R. A. F., and Wright, J. V., 1987. *Volcanic Successions*: Chapman and Hall, London, 528 p.
- Dimroth, E., Cousineau, P., Leduc, M., and Sanschagrin, Y., 1978. Structure and organization of Archean subaqueous basalt flows, Rouyn-Noranda area, Quebec, Canada: *Canadian Journal of Earth Science*, v. 15, p. 902-918.
- Franklin, J. M., Gibson, H. L., Jonasson, I. R., and Galley, A. G., 2005. Volcanogenic massive sulfide deposits: *Society of Economic Geologists 100th Anniversary Volume*, p. 523-560.
- Gibson, H. L., Morton, R. L., and Faculty Member, 1999. Submarine volcanic processes, deposits, and environments favorable for the location of volcanic-associated massive sulfide deposits: *in* Barrie, C. T. and Hannington, M. D., 1999, *Volcanic-Associated Massive Sulfide Deposits: Processes and Examples in Modern and Ancient Settings*, *Reviews in Economic Geology*, v. 8, p. 13-51.
- Hudak, G. J., Heine, J., Newkirk, T. T., Odette, J., and Hauck, S., 2002a. Comparative Geology, Stratigraphy, and Lithogeochemistry of the Fivemile Lake, Quartz Hill, and Skeleton Lake VMS Occurrences, Vermilion District, NE Minnesota: *Natural Resources Research Institute Technical Report NRRI/TR-2002/03*, 390 p.
- Jones, J. G., 1968. Pillow lava and pahoehoe: *Journal of Geology*, v. 76, p. 485-488.
- Kennish, M. J., and Lutz, R. A., 1998. Morphology and distribution of lava flows on mid-ocean ridges: a review: *Earth Science Reviews*, v. 43, p. 63-90.
- Moore, J. G., 1975. Mechanism of formation of pillow lava: *American Scientist*, v. 63, p. 269-277.
- Newkirk, T. T., Faculty Member, and Hauck, S. A., 2001. Preliminary lava flow morphology studies at the Fivemile Lake VMS prospect, Vermilion District, NE Minnesota: implications for volcanic processes, volcanic paleoenvironments, and VMS exploration: *Geological Society of America Abstracts and Programs*, v. 33, no. 6, p. A-398.
- Peterson, D. M., and Patelke, R. L., 2003. National Underground Science and Engineering Laboratory (NUSEL): Geological Site Investigation for the Soudan Mine, NE Minnesota: *NRRI Technical Report NRRI/TR-2003/29*, 88p.
- Walker, G. P. L., 1992. Morphometric study of pillow size spectrum among pillow lavas: *Bulletin of Volcanology*, v. 54, p. 459-474.

Geochemistry of the Sudbury Impact Layer, Northern Michigan: Implications for the Nature of the Source Materials

K.J. Schulz and W.F. Cannon, U.S. Geological Survey, Reston, VA 20192
(kschulz@usgs.gov, wcannon@usgs.gov)

We have analyzed selected materials from the Sudbury impact layer in Northern Michigan for major and trace elements including rare earth elements (REE). Samples include accretionary lapilli, black, possibly devitrified glass fragments, vitric-rich breccia, and matrix from chert breccia. Major element concentrations are variable in these samples; however, most element concentrations vary inversely with increasing SiO_2 content. Matrix from a chert breccia at the base of the Hiawatha Graywacke in the Iron River-Crystal Falls district has the lowest SiO_2 (61.1 %) and highest FeO_t (24.5 %) and P_2O_5 (1.44 %) contents that probably reflect the presence of a significant component of the Riverton Iron-Formation that directly underlies the breccia. Two black, possibly devitrified glass fragments from drill core at L'Anse have the highest SiO_2 contents (~ 95 %) and concomitantly low concentrations of all other major elements. The other samples show a range of SiO_2 content from about 71 to 82 %. A distinctive characteristic of all but one of these impact layer samples is very low CaO (after removal of secondary carbonate) and Na_2O contents (Fig. 1a).

The trace element concentrations of the impact layer samples in Michigan also tend to decrease in abundance with increasing SiO_2 content. However, the samples mostly have similar ratios of relatively immobile trace elements (e.g., Zr/TiO_2 , Zr/Nb , Th/Hf , Sc/Yb). Chondrite-normalized REE patterns are similar for all impact layer samples and are characterized by enriched light-REE ($[\text{La}/\text{Yb}]_n = \sim 8$ to 20) and no to moderate negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.65 - 0.94$). Chondrite-normalized extended trace element patterns also are similar for most of these impact layer samples and have prominent negative anomalies for Ba, Nb, Ta, Sr, and Ti, and no to negative P anomalies (Fig. 1b). The low Sr abundance complements the low CaO and Na_2O content and suggests a very low plagioclase component in the impact layer samples. All of the samples have a relatively high U/Th ratio (0.46-7.43; mean = 1.94 versus 0.26 for average upper crust) that probably reflects secondary redistribution of uranium. In addition, the accretionary lapilli are anomalously enriched in Y, and two samples also are enriched in V and Cr. These enrichments may reflect secondary carbonate complexing, precipitation from seawater under appropriate redox conditions and/or prior enrichment of source materials. The most iron-rich sample is also anomalously enriched in V. The compositional similarity of the accretionary lapilli and vitric-rich breccia samples (Fig. 1) suggests that the composition of the impact layer materials primarily reflects that of the source materials at the site of impact.

Compared to the Onaping Formation, which represents the impact-related fallback breccia at Sudbury (Ames et al., 2002), the impact layer samples in Michigan have higher SiO_2 , FeO_t and K_2O contents, and lower abundances of the other major elements particularly CaO and Na_2O (Fig. 1a). The abundances of most trace elements also are generally lower in the Michigan impact layer samples, but their chondrite normalized patterns are very similar to those of the Onaping Formation with the exception of prominent depletions of Ba, Sr and Ti (Fig. 1b).

The low abundances of Ca, Na, Sr, and Ba in the Michigan impact layer samples are interpreted as a primary feature reflective of the original source material. Such low abundances are not common of most crustal rocks, but are characteristic of sediments derived from intensely

weathered terranes in which Ca, Na, and Sr are selectively leached from weathering profiles. This suggests that the dominant source material for the impact layer was most likely sediments derived from an intensely weathered terrane. Carbonaceous shales in the Onaping are not depleted in Ca, Na, Sr and Ba, but shales in the Iron River-Crystal Falls district of Michigan are characterized by low abundances of these elements and have overall trace element patterns similar to those of the Sudbury impact layer samples (Fig. 1b). We suggest that similar sediments also were present in the Sudbury area at the time of impact and form the dominant component of the material ejected distally from the impact site. This conclusion is supported by the results of impact modeling studies that predict that the upper crustal portion of the shock-melted target rock volume at Sudbury would be ejected away from the crater area and produce lithological and chemical variations with radial distance from the crater in which deep basement components would dominate near the crater (i.e., Sudbury Igneous Complex) and upper crustal sedimentary components would increasingly dominate farther from the crater center.

Ames, D.E., Golightly, J.P., Lightfoot, P.C., and Gibson, H.I., 2002, Vitric compositions in the Onaping Formation and their relationship to the Sudbury Igneous Complex, Sudbury structure: *Economic Geology*, v. 97, p. 1,541-1,562.

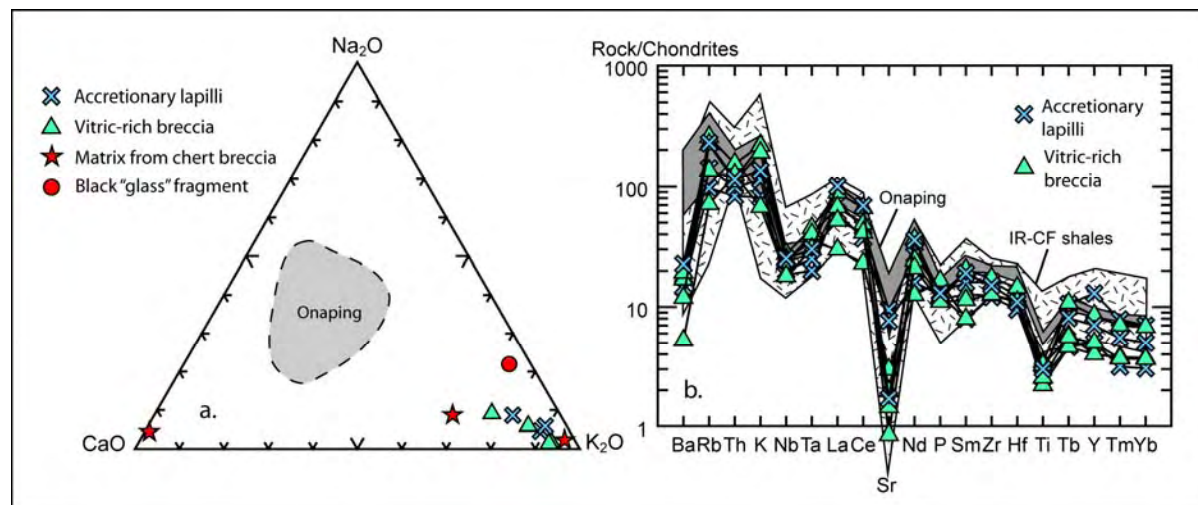


Figure 1. a) CaO-Na₂O-K₂O diagram for the Sudbury impact layer samples, Michigan and the Onaping Formation, Ontario, and b) chondrite-normalized extended trace element patterns for accretionary lapilli and vitric-rich breccia samples, Michigan. Also shown in 1b are fields for samples from the Onaping Formation, Ontario (Ames et al., 2002) (gray field) and shales from the Iron River-Crystal Falls (IR-CF) basin, Michigan (Schulz, unpublished data) (stippled field).

Penokean Massive Sulfide Deposits: Age, Geochemistry, and Paleotectonic Setting

K.J. Schulz¹, S.W. Nicholson¹, and W.R. Van Schmus²

¹U.S. Geological Survey, Reston, VA 20192 (kschulz@usgs.gov) (swnich@usgs.gov)

²University of Kansas, Lawrence, KS 66045 (rvschmus@ku.edu)

The Paleoproterozoic volcanic terrane that extends across northern Wisconsin eastward into northern Michigan hosts a number of copper-zinc±lead±gold massive sulfide deposits including Crandon and the recently discovered Back Forty deposit. These deposits collectively contain more than 100 million tons of identified base- and precious-metal mineralization and represent a large but still mostly undeveloped resource.

The age of the volcanic terrane in northern Wisconsin is constrained between about 1890 and 1860 Ma by the dating of mostly intrusive rocks within the belt (Sims et al., 1989); however, published ages have not been available for the massive sulfide deposits. We have analyzed zircons from two samples from the Back Forty deposit, Menominee County, Michigan; a quartz porphyry from the footwall and a feldspar porphyry that intrudes the deposit. Zircon fractions from the two samples cluster within error along a common concord and regression through the origin defines a U/Pb age of 1874 ± 4 Ma (Fig. 1). This age is within error of an unpublished U/Pb zircon age (~ 1870 Ma) determined for the Lynne deposit in Wisconsin (R. Thorpe, personal communication to T. DeMatties, 1995) and firmly establishes that massive sulfide formation within the Wisconsin volcanic terrane was contemporaneous with iron formation deposition in the foreland basins in Michigan and Minnesota.

To expand on our previous geochemical studies of the volcanic rocks hosting the Bend and Pelican massive sulfide deposits in northern Wisconsin, we have now analyzed volcanic rocks from the Flambeau, Thornapple (Eisenbrey), Lynne, Ritchie Creek, and Back Forty deposits. These results show that the felsic volcanic rocks hosting the Bend, Pelican, Ritchie Creek and Back Forty deposits, located in the central and eastern parts of the terrane, have similar orogenic calc-alkaline compositions and are characterized by strong enrichments in highly incompatible trace elements including Th (Fig. 2) and light REE ($[La/Yb]_n \sim 6-15$). In contrast, the felsic volcanic rocks hosting the Flambeau and Thornapple deposits, both located in the western part of the volcanic terrane, are much less enriched in Th (Fig. 2) and other incompatible trace elements ($[La/Yb]_n \sim 3-6$). The volcanic rocks hosting the Lynne deposit have compositions that are mostly transitional between the other two groups (Fig. 2). The enriched Th and light REE of the Bend, Pelican, Ritchie Creek and Back Forty felsic volcanic rocks are similar to calc-alkaline felsic volcanic rocks in continental back-arc and intra-arc rifts such as the Taupo volcanic zone in North Island, New Zealand; whereas, the compositions of the Flambeau and Thornapple felsic volcanic rocks are comparable to felsic rocks in oceanic (Kermadec) and evolved island arc (Kuroko) back-arc basins (Fig. 2). The enriched trace element chemistry of the volcanic rocks in the central and eastern portion of the volcanic terrane in Wisconsin and Michigan suggests that continental basement is more widespread in the terrane than previously recognized. Paleozoic massive sulfide deposits associated with similar enriched calc-alkaline felsic volcanic rocks that formed in extensional continental arc settings are generally characterized by a significant lead content (e.g., Bathurst deposits; Yang and Scott, 2003). In contrast, the Penokean massive sulfide deposits are generally lead-poor, with the

exception of the Lynne deposit. The reason for lead-poor nature of the Penokean deposits remains a topic of investigation.

References cited:

- Sims, P.K., Van Schmus, W.R., Schulz, K.J., and Peterman, Z.E., 1989, Tectono-stratigraphic evolution of the Early Proterozoic Wisconsin magmatic terranes of the Penokean Orogen: Canadian Journal of Earth Sciences, v. 26, p. 2,145-2,158.
- Yang, K., and Scott, S.D., 2003, Geochemical relationships of felsic magmas to ore metals in massive sulfide deposits of the Bathurst Mining Camp, Iberian Pyrite Belt, Hokuroku District, and the Abitibi Belt: Economic Geology Monograph 11, p. 457-478

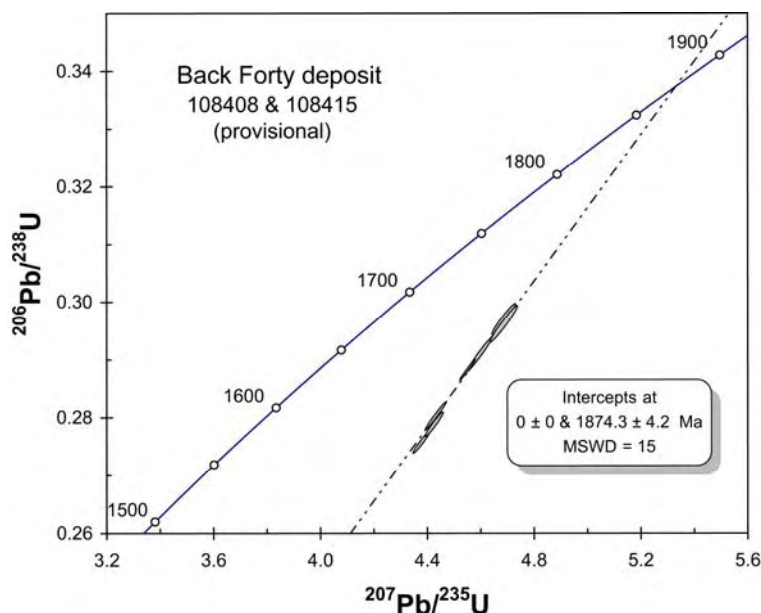


Figure 1. Concordia diagram for zircon fractions from footwall quartz porphyry (108415) and cross cutting feldspar porphyry (108408), Back Forty massive sulfide deposit, Menominee County, Michigan.

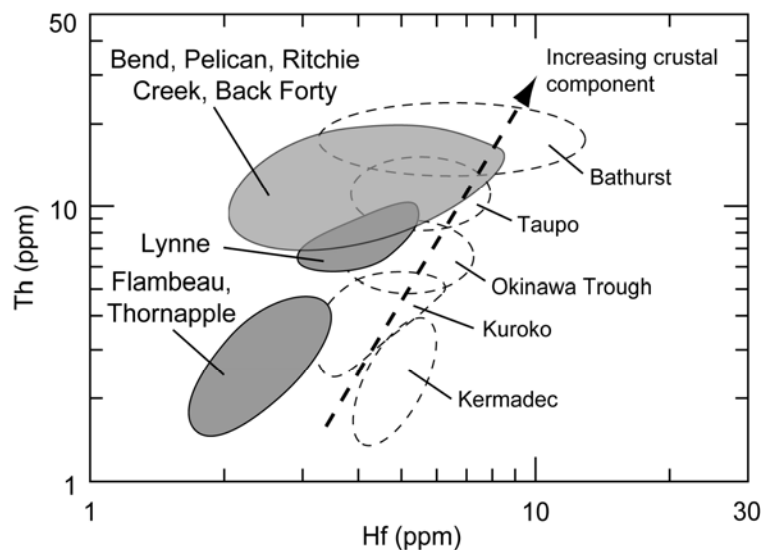


Figure 2. Th vs Hf diagram for felsic volcanic rocks hosting Penokean massive sulfide deposits. Also shown are fields for more recent felsic volcanic rocks from extensional back-arc settings ranging from oceanic (Kermadec, SW Pacific) to evolved island arc (Kuroko, Japan) to continental (Taupo, NZ and Bathurst, NB).

GEOLOGICAL MAP OF THE NICKEL LAKE MACRODIKE AND NORTHERN BALD EAGLE INTRUSION: LAKE COUNTY, NORTHEASTERN MINNESOTA

THARALSON, Erik (Department of Geological Sciences, University of Minnesota Duluth, Minnesota)¹

SWEET, Gabriel (Department of Geology, Macalester College, Minnesota)²

BOISJOLI, Troy (Department of Geology, St. Norbert College, Wisconsin)³

LENTZ, Brian (Department of Geoscience, Winona State University, Minnesota)⁴

FELLOWS, Tyler (Department of Geosciences, University of Wisconsin-Milwaukee, Wisconsin)

PETERSON, Dean (Natural Resources Research Institute, University of Minnesota Duluth)

1 – Currently employed by Encampment Minerals, Ely Minnesota

2 – Currently MS student, Lakehead University, Thunder Bay, Ontario

3 – Currently employed by Cameco Mining, Saskatchewan

4 – Currently employed by Golden Chalice Resources, Timmins, Ontario

The Precambrian Research Center's (PRC) 2007 Precambrian field camp culminated in the mapping and publication of a series of bedrock geological maps from four areas in northeastern Minnesota. These "Capstone" projects were completed in areas of Minnesota where either previous mapping was only reconnaissance scale or in historically previously mapped areas (> 40 years ago) that are adjacent to ongoing research mapping projects.

The new bedrock geology map of the Nickel Lake Macrodiike and northern Bald Eagle intrusion of the Duluth Complex (presented in the poster session) is the result of seven days of field mapping by the authors in 2007. This map was created by PRC Field Camp students under the supervision and guidance of Dr. Dean Peterson, NRRI Senior Research Associate. The purpose of this map is to aid understanding the nature of the Nickel Lake Macrodiike and its pertinence to Cu-Ni-PGE mineralization in the South Kawishiwi Intrusion (Peterson and Albers, 2007). Additionally, this map will extend the range of Dr. Peterson's ongoing project to map in the northern half of the SKI.

Access to the 641 outcrops mapped for this project was provided by extensive canoe shoreline mapping and traverses in the bush (approximately 300 kilometers of total mapping traverses). Mapping was completed at 1:5,000 and 1:10,000 scales and reduced for this map to 1:10,000. The new geologic information was integrated with previous data compiled from Green et al., (1966) and Peterson et. al., (2006) to form the foundation of the final published map.

References

Green, J.C., Phinney, W.C., and Weiblen, P.W., 1966, Geologic map of Gabbro Lake quadrangle, Lake County, Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-2, scale 1: 31,680.

Peterson, D.M. and Albers, P.B., 2007, Geology of the Nickel Lake Macrodiike and its association with Cu-Ni-PGE mineralization in the northern South Kawishiwi Intrusion, Duluth Complex, northeastern Minnesota: Institute on Lake Superior Geology, 53rd Annual Meeting, Trip #4, Field Trip Guidebook, Lutsen, Minnesota, Volume 53.

Peterson, D.M., Albers, P.B., and White, C.R., 2006, Bedrock Geology of the Nickel Lake Macrodiike and Adjacent Areas: Lake County, Northeastern Minnesota: Natural Resources Research Institute, Map Series NRRI/MAP-2006-04, scale 1:10,000.

The Effect of Magmatic Volatile Phase Separation Linked to Intrusion of the Duluth Complex: Solution to Anomalous Os Isotopic Compositions of the Virginia Formation?

WILLIAMS, Curtis D., RIPLEY, Edward M., LI, Chusi, Department of Geological Sciences, Indiana University, 1001 East 10th Street, Bloomington, IN 47405, cuwillia@indiana.edu

Both pyrite- and pyrrhotite-bearing pelitic rocks of the 1.85 Ga Virginia Formation show Re and Os isotopic ratios consistent with a mixing event at ~1.1 Ga. Initial $^{187}\text{Os}/^{188}\text{Os}$ ratios suggest that mixing must have involved a component with a near-chondritic Os isotopic ratio. The data can be simply interpreted to reflect the interaction of the Virginia Formation with mantle-derived (chondritic) magmas of the Duluth Complex. However, the Virginia Formation rocks in question occur one and one half kilometers or more from the Duluth Complex, are only slightly recrystallized and have never been in direct contact with magma. Fluid inclusions in layer-parallel quartz veins hosted by the Virginia Formation are characterized by pressure corrected (2 kb) homogenization temperatures between 500 and 600°C. Together with oxygen isotope values of the quartz (5 ‰-6 ‰), the data suggest that magma-derived fluids may have been responsible for the Re-Os isotopic disturbance.

In order to further constrain this premise we have undertaken LA-ICP-MS analysis of individual fluid inclusions and have evaluated the expected compositional variations of fluid derived from a mafic magma. We have utilized the program MELTS (Ghiorso and Sack, 1995) to evaluate the compositional variations expected in derivative melts and the program Magmatic-Volatile-Phase (Candela and Piccoli, 1995) to estimate concentrations and ratios of elements in a fluid produced from H₂O-saturated magma. A high-Al, olivine tholeiite was used as the parental magma, with initial H₂O content varied between 0.2 and 2.0 wt%.

At 75% fractional crystallization of a parental melt with 0.2 wt% H₂O, the fluid produced is very Fe-rich (~4.9 wt%) with $\text{Fe} \geq \text{Na} > \text{Ca} > \text{K} > \text{Mn} \geq \text{Mg}$ (assuming 1:1 Na melt-fluid partitioning). Fluids produced from 75% fractional crystallization and up to 1.0 wt% initial H₂O show less pronounced differences between elements, with 1.2 wt% Fe, 1.1 wt% Na, 0.7 wt% Ca, 0.48 wt% K, 0.12 wt% Mn and 10ppm Mg. Fluids produced during equilibrium crystallization are also high in Fe, but Na and Ca display similar concentrations, and Mg concentrations for all starting H₂O concentrations exceed 0.5 wt%. Relative concentrations also vary with $\text{Mg} \geq \text{K} > \text{Mn}$.

Between 1.0 and 1.2 wt% initial H₂O, the derivative melts become saturated in H₂O at variable crystallization intervals (85-51%, respectively) and exsolve a volatile phase. As in the case at 75% fractional crystallization, Fe is the dominant cation in these fluids, followed in order of decreasing concentration by Ca, K, Mn and Mg. As initial H₂O is increased to 2.0 wt%, Fe concentrations rises (~2.2 wt%) such that $\text{Fe} \gg \text{Ca} > \text{K} > \text{Mn} > \text{Mg}$.

Modification of the starting melt composition was also varied via assimilation of Virginia Formation (melt minimum $\text{Qz}_{(50)}\text{-Ab}_{(24)}\text{-Mu}_{(24)}\text{-H}_2\text{O}_{(2)}$). The assimilation of 10% Virginia Formation leads to the production of a volatile phase with less Fe (~3 wt%), but higher Ca (~1.1 wt%) and K (0.47 wt%). Both fractional and equilibrium crystallization of the contaminated

starting composition show decreases between element concentrations as H₂O content of the starting melt increases.

To evaluate the initial Cl/H₂O ratio of a melt, the program Magmatic-Volatile-Phase was used which incorporates this parameter along with the evolution of H₂O in the melt. These models suggest a parental melt with 1.0 to 2.0 wt% H₂O_(i) will produce a Fe-rich vapor similar to that modeled indirectly by MELTS between 1.0 and 1.2 initial wt% H₂O, with the exception of lower Ca concentrations.

Our fluid inclusion analyses show Fe concentrations in excess of 1.3 wt%, while Na and K reach 0.16 wt% and 0.04 wt% respectively. Mg concentrations peak around 1700 ppm, while Ca is low or below detection limit. Compositions of the fluid inclusions are very similar to modeled results, which are consistent with the premise that interaction with magmatically-derived fluids was responsible for the anomalous Os isotopic signatures recorded in sulfide-bearing rocks of the Virginia Formation.