

57TH ANNUAL MEETING



INSTITUTE ON LAKE SUPERIOR GEOLOGY

ASHLAND, WISCONSIN MAY 18-21, 2011



PROCEEDINGS VOLUME 57

PART 1 – PROGRAMS AND ABSTRACTS



INSTITUTE ON LAKE SUPERIOR GEOLOGY

**57TH ANNUAL MEETING
MAY 18-21, 2010
ASHLAND, WISCONSIN**

HOSTED BY:

NORTHLAND COLLEGE

**TOM FITZ
Chair**

Proceedings Volume 57

Part 1 – Program and Abstracts

Edited by: Tom Fitz, Allison Mills, Kristi Wilson, Cassandra Bodette, and Drew Cramer

Cover Photo: Intrusive breccia in the Mellen Intrusive Complex, Mellen, WI

57TH INSTITUTE ON LAKE SUPERIOR GEOLOGY

CONTENTS OF PROCEEDINGS VOLUME 57:

PART 1: PROGRAM AND ABSTRACTS

PART 2: FIELD TRIP GUIDEBOOK

TRIP 1: IGNEOUS STRATIGRAPHY OF THE LAYERED SERIES AT DULUTH - TYPE INTRUSION OF THE DULUTH COMPLEX

TRIP 2: MIDCONTINENT MICROCOSM

TRIP 3: GEOLOGY OF THE BAYFIELD PENINSULA: KEWEENAWAN BAYFIELD GROUP AND PLEISTOCENE DEPOSITS

TRIP 4: GEOLOGY AND REMEDIATION AT THE ASHLAND/NORTHERN STATES POWER SITE

TRIP 5: BAD RIVER WATERSHED CULVERT RESTORATION PROGRAM

TRIP 6: GEOLOGY OF COPPER FALLS STATE PARK

TRIP 7: GEOLOGY OF THE MONTREAL RIVER MONOCLINE

TRIP 8: THE ARCHEAN/PALEOPROTEROZOIC UNCONFORMITY NEAR DENHAM, MINNESOTA

TRIP 9: GRANITIC, GABBROIC, AND ULTRAMAFIC ROCKS OF THE KEWEENAWAN MELLÉN INTRUSIVE COMPLEX

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

LaMaskin, T.A., 2011, Testing models of late Paleoproterozoic Penokean orogenesis in the Great Lakes Region, U.S.A. using sedimentary provenance: planning the investigation [abstract]: Institute on Lake Superior Geology Proceedings, 57th Annual Meeting, Ashland, WI, v. 57, part 1, p. 53-54.

Published by the 57th 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 57 PART 1— PROGRAM AND ABSTRACTS

Previous Institutes on Lake Superior Geology, 1955-2010.....	iv
Sam Goldich and the Goldich Medal.....	vi
Past Goldich Medalists and the 2010 Goldich Medal Recipient.....	viii
Goldich Medal Committee.....	viii
Citation for 2010 Goldich Medal Recipient	ix
ILSG Student Research Fund	xi
Student Paper Awards.....	xii
Eisenbrey Student Travel Awards	xiii
Report of the Chairs of the 56 th Annual Meeting	xv
2011 Board of Directors	xvii
2011 Session Chairs.....	xvii
2011 Student Paper Awards Committee.....	xvii
2011 Banquet Speaker	xviii
Program.....	xix
Schedule of Events	xx
Schedule of Talks and Posters	xxi
Abstracts	xxviii
Author Index	97

PREVIOUS INSTITUTES ON LAKE SUPERIOR GEOLOGY, 1955-2010

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

28	1982	International Falls, Minnesota	D.L. Southwick
29	1983	Houghton, Michigan	T.J. Bornhorst
30	1984	Wausau, Wisconsin	G.L. La Berge
31	1985	Kenora, Ontario	C.E. Blackburn
32	1986	Wisconsin Rapids, Wisconsin	J.K. Greenberg
33	1987	Wawa, Ontario	E.D. Frey and R.P. Sage
34	1988	Marquette, Michigan	J. S. Klasner
35	1989	Duluth, Minnesota	J.C. Green
36	1990	Thunder Bay, Ontario	M.M. Kehlenbeck
37	1991	Eau Claire, Wisconsin	P.E. Myers
38	1992	Hurley, Wisconsin	A.B. Dickas
39	1993	Eveleth, Minnesota	D.L. Southwick
40	1994	Houghton, Michigan	T.J. Bornhorst
41	1995	Marathon, Ontario	M.C. Smyk
42	1996	Cable, Wisconsin	L.G. Woodruff
43	1997	Sudbury, Ontario	R.P. Sage and W. Meyer
44	1998	Minneapolis, Minnesota	J.D. Miller, Jr. and M.A. Jirsa
45	1999	Marquette, Michigan	T.J. Bornhorst and R.S. Regis
46	2000	Thunder Bay, Ontario	S.A. Kissin and P. Fralick
47	2001	Madison, Wisconsin	M.G. Mudrey, Jr. and B.A. Brown
48	2002	Kenora, Ontario	P. Hinz and R.C. Beard
49	2003	Iron Mountain, Michigan	L.G. Woodruff and W.F. Cannon
50	2004	Duluth, Minnesota	S.A. Hauck and M. Severson
51	2005	Nipigon, Ontario	P. Hollings and M.C. Smyk
52	2006	Sault Ste. Marie, Ontario	R.P. Sage and A.C. Wilson
53	2007	Lutsen, Minnesota	L.G. Woodruff and J.D. Miller, Jr.
54	2008	Marquette, Michigan	T.J. Bornhorst and J.S. Klasner
55	2009	Ely, Minnesota	J.D. Miller, Jr., G.J. Hudak, D.M. Peterson
56	2010	International Falls, Minnesota	P. Hollings, P. Hinz, M. Smyk, M. Jirsa, and T. Boerboom

SAM GOLDICH AND THE GOLDICH MEDAL

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

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

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

Reference:

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

Prepared by various Goldich Medal Awardees, 2007



INSTITUTE ON LAKE SUPERIOR GEOLOGY GOLDICH MEDAL

PAST GOLDICH MEDALISTS

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

2011 GOLDICH MEDAL RECIPIENT

Dean M. Rossell

Kennecott Exploration Company
Salt Lake City, Utah

GOLDICH MEDAL COMMITTEE

Serving for the meeting years shown in parentheses

Al MacTavish, Industry member - Chair (2008-2011)

Mary Louise Hill, Academic member (2009-2012)

Laurel Woodruff, Government member (2010-2013)

CITATION FOR 2011 GOLDICH MEDAL RECIPIENTS

Dean M. Rossell

It is my privilege and great pleasure to introduce Dean Rossell as this year's Goldich Medal recipient. Dean has been an ILSG contributor and stalwart attendee of its meetings and field trips since his student days many years ago. Dean grew up in Minneapolis, and graduated from the University of Minnesota-Duluth in 1979, studying under some of the early recipients of the Goldich Medal (Ralph Marsden, Dick Ojakangas, and John Green). Immediately after graduation he got a temporary job in Nevada, and that summer, by tracing boulders up dry washes, was the co-discoverer of what soon thereafter became the Trout Creek barite mine. But he promptly returned to the Lake Superior region, graduating from Michigan Technical University in 1983, studying under the aegis of another Goldich medalist, Ted Bornhorst. His M.Sc. thesis was entitled "Alteration of the Deer Lake Peridotite in the Vicinity of the Ropes Mine, Marquette County, Michigan." This grew out of his summer student work at that old gold mine, which Callahan Mining Corp. was putting back into production after nearly a century of abandonment. After graduating from MTU, he spent the next seven years as an exploration geologist for Resource Exploration, Inc. out of Marquette, working for Bill Bodwell. His wife Karen also worked in the Resource Exploration office in those days as a draftsman. Dean himself never spent much time in the office, though. His work for clients during this period included: re-logging all drill core and re-interpreting the Keweenaw Western Syncline sediment-hosted chalcocite deposit, Michigan; mapping, sampling and drilling VMS base metal and shear zone-hosted gold targets in the Archean Ramsay-Lake Gogebic greenstone belt, Michigan; initiating and carrying out field exploration and drilling on numerous grassroots-developed gold targets in the Archean greenstones and felsic intrusives of the Virginia Horn, Minnesota; and drilling for platinum group elements near the Reserve Mining property in the Duluth Complex, Minnesota. In short, he came up the old fashioned way, doing the field work in numerous exploration programs, mapping, sampling and drilling rocks around the Lake Superior region.

Beginning in 1991 Dean worked as a contract geologist for Kennecott Exploration Company out of Crystal Falls, Michigan, initially doing mapping and field sampling in the search for Proterozoic sedex base metal deposits. It was during this time that he alertly found a nickel-copper sulfide-bearing boulder in a logging roadcut that led to a complete change in direction of that program. A few months later, he was the first to discover nickel-copper mineralization in the BIC layered mafic intrusion, and he strongly advocated an investigation of the Yellow Dog peridotite.

In 1995 Dean gained permanent status with Kennecott and carried on with his tireless and imaginative efforts to explore for base metals in Keweenaw Rift-related terranes on both sides of the border. His investigations eventually led to the discovery of the Eagle nickel-copper-PGE deposit at the Yellow Dog peridotite in 2002, the result of a nearly single-handed effort on his part. This very high grade Michigan deposit has now received its permits for underground mining, and promises to be an important contributor to the economy of the Upper Peninsula.

In the early days of 21st Century exploration for nickel-copper in the Black Sturgeon district of Ontario, he acquired and tested one of the known ultramafic intrusions (Kitto), and tested others in elsewhere in Ontario that he is still not authorized to talk about. He carried his ideas into Minnesota, leading Kennecott to search for mineralization in buried ultramafic intrusions in the Animikie Basin. Again with the imagination and persistence that are his hallmarks, this work eventually led to discovery of the Tamarack deposit in Carlton County, Minnesota. Several years of drilling turned up only anomalous Ni-Cu values at Tamarack, but Dean's careful persistence eventually paid off with Kennecott's announcement in June 2008 of a long drill intercept of very high grade nickel-copper. This deposit is currently being intensively evaluated by Kennecott, and Tamarack has the promise of being a larger version of the Eagle deposit in Michigan.

Dean and his family are now based in Salt Lake City, but he still doesn't spend much time in the office. That's not where the rocks are. He has been to nearly every part of the world where one can see the right rocks. In fact, his title in Kennecott's Project Generation Group is "Global Nickel Specialist", and he's now internationally regarded as an expert on exploration for ultramafic-hosted Ni-Cu-PGE deposits. Despite the competitive secrecy that surrounds such efforts, Dean has shared his expertise and knowledge with others in the geologic community when able. As is the case with most company geologists, Dean has had to be restrained in publishing his work, but has made the scientific aspects of it known at ILSG meetings: Duluth, 2004 (Eagle deposit presentation and abstract), Nipigon 2005 (Eagle deposit poster session). He also published on the Eagle deposit at the AIME-SEG meeting in Salt Lake City in 2005 (presentation and abstract), and prepared and led the field trip to the BIC intrusion at the Marquette ILSG in 2008. He has also contributed more indirectly, getting Kennecott to provide access and thesis research funds for graduate students studying the geology of the Eagle and Tamarack deposits, and he has been an important supporter of student involvement in the ILSG. Although his base is now in Utah, he still spends most of his time in the Lake Superior region, something not likely to change anytime soon.

Dean Rossell is a standout in the ranks of exploration geologists: a real minefinder, and one who gives back to the community of his peers (especially the ILSG community), as well. Please join me in congratulating Dean as the 2011 recipient of the Goldich Medal of the Institute on Lake Superior Geology.

Doug Duskin
April, 2011

ILSG STUDENT RESEARCH FUND

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

- The ILSG Board of Directors will be responsible for selecting a minimum of two awards each year. The ILSG Treasurer will issue the awards.
- The ILSG Student Research Fund is available for undergraduate or graduate students working on geology in the Lake Superior region.
- The applications are due to the ILSG Secretary by August 31st of each year. Awards will be made by October 1st of each year.
- Names of the award recipients will be announced at the next annual meeting and posted on the ILSG website.
- Details of the application process can be found on the ILSG web site.
- The proposal will need to be signed by researcher's supervisor.

In 2010 the ILSG Board of Governors awarded one \$500 award from the Student Research Fund. The winner is listed below, along with a description of his research project.

Scott Scheiner (Kent State University) – *Source regions of sediments in the Animikie Basin*

Scott is working with Dan Holm (Kent State University) and Terry Boerboom (Minnesota Geological Survey) studying the geochemistry and clast mineralogy the greywacke and turbidite sequences of the Animikie basin to determine the source of the sediments.

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.

STUDENT PAPER AWARDS

The student paper committee comprised of Graham Wilson (*Chair, Turnstone Geological Services Ltd.*) Jim Miller (*University of Minnesota – Duluth*) and Anthony Pace (*Ontario Geological Survey*) yet again had a difficult job of selecting among the 16 student oral and poster presentations. The following students were granted awards of \$200 each, in recognition of their excellence of research and presentation:

Andrew Ryan

Petrographic and geochemical analysis of a Nipigon diabase sill

Ryan, Andrew J. and Zieg, Michael J., Department of Geography, Geology, and the Environment, Slippery Rock University, Slippery Rock, PA

Steve Hoaglund

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

Hoaglund, S.A.^{a*}, Miller, J.D.^a, Crowley, J.L.^b, and Schmitz, M.D.^b

^a Department of Geological Sciences, University of Minnesota Duluth, Duluth, MN,

^b Department of Geosciences, Boise State University, Boise, ID

Victoria Stinson

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

Stinson, Victoria R. and Hill, Mary Louise, Lakehead University, 955 Oliver Road, Thunder Bay, Ontario

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.

The following 28 students were awarded travel grants to help defray the cost of meeting attendance. Award amounts varied by travel arrangement and distance from \$75-\$300. We think this is a record number of annual awards, thanks largely to generous contributions from corporate and individual sponsors.

Robert Cundari—Lakehead University, Thunder Bay, ON

Adam Fage—Lakehead University, Thunder Bay, ON

Maura Kolb—Lakehead University, Thunder Bay, ON

Seamus Magnus—Lakehead University, Thunder Bay, ON

Sean O'Hare—Lakehead University, Thunder Bay, ON

Raya Puchalski—Lakehead University, Thunder Bay, ON

Robert Scott—Lakehead University, Thunder Bay, ON

Steve Siemieniuk—Lakehead University, Thunder Bay, ON

Victoria Stinson*—Lakehead University, Thunder Bay, ON

James Blount—Lawrence University, Appleton, WI

Rachel Carver—Lawrence University, Appleton, WI

Suzanne Craddock—Lawrence University, Appleton, WI

Sarah Ehlinger—Lawrence University, Appleton, WI

Meaghan Gallagher—Lawrence University, Appleton, WI

Megan Luedtke—Lawrence University, Appleton, WI

Sarah Shay—Lawrence University, Appleton, WI

Amanda Van Lankvelt*—Lawrence University, Appleton, WI

Levi Markwood—Slippery Rock University, PA

Andrew Ryan*—Slippery Rock University, PA

Dan Cervin—University of Minnesota, Duluth, MN

Avery Cota—University of Minnesota, Duluth, MN

Dan Foley—University of Minnesota, Duluth, MN

Shelby Frost**—University of Minnesota, Duluth, MN

Steve Hoaglund*—University of Minnesota, Duluth, MN

Cabin Ross—University of Minnesota, Duluth, MN

Stephanie Theriault—University of Minnesota, Duluth, MN

Michael Totenhagen—University of Minnesota, Duluth, MN

Natalie Pietrzak—University of Western Ontario, London, ON

**Also recipient of 2010 STUDENT PAPER AWARD*

***Also recipient of 2009 STUDENT RESEARCH GRANT*

REPORT OF THE CHAIRS OF THE 56TH ANNUAL MEETING
INSTITUTE ON LAKE SUPERIOR GEOLOGY
INTERNATIONAL FALLS, MINNESOTA

The 56th Annual Institute on Lake Superior Geology on May 19-22, 2010 was a cross-border meeting with an international team of co-chairs. The meeting in International Falls was chaired by Mark Jirsa, Terry Boerboom, Mark Smyk, Peter Hinz and Pete Hollings. Despite this the meeting was a great success with a total of 171 registrants, including 30 students.

The two-day technical session held at the Holiday Inn on Thursday and Friday included 23 talks and 17 posters presentations, including 11 oral and 5 poster presentations by students. This year's Goldich Medal recipients were Bill Addison and Greg Brumpton whose tireless work in the Thunder Bay area led to the first recognition of the ejecta layer from the Sudbury impact. Bill and Greg were presented their medals at the annual banquet by another Goldich Medalist, Bill Cannon from the USGS. Fittingly, the evening banquet talk was presented by Dr. Bevan M. French of the Smithsonian Institution who discussed his work on meteor impacts.

The meeting offered eight field trips that highlighted various aspects of the geology and ore deposits of two countries. Pre-meeting field trips included ***Mineral deposits of the Rainy River area*** led by Wally Rayner and C.J. Baker (*Rainy River Resources*), and Craig Ravnaas (*Ontario Geological Survey*), a one-day trip on ***Geology of the Archean succession at Atikokan*** led by Phil Fralick (*Lakehead University*) and Denver Stone (OGS) and ***Structural geology along the Quetico fault*** led by Howard Poulsen (*Consultant*) and Dyanna Czeck (*UW-Milwaukee*). On Friday afternoon following the completion of the technical session, two field trips were offered. The first took participants on a boat trip through the ***Archean geology of Voyageurs National Park and Little America gold mine*** led by Chris Hemstad (*Boreal Explorations*) while Mark Jirsa (MGS) led a group to the ***Ash River neutrino detector laboratory and the Archean Vermilion Granitic Complex***. Post-meeting trips included a ***Transect through the Quetico-Wabigoon subprovince boundary*** led by Mark Jirsa (*Minnesota Geological Survey*) and Chris Hemstad (*Boreal Exploration*), ***Mineral deposits of the Mine Centre – Rainy Lake area*** led by Peter Hinz (OGS) and last, but not least, ***Geology and environmental issues of the Steep Rock mine*** led by Andrew Conly (*Lakehead University*) and Rob Purdon (*Ontario Ministry of Natural Resources*).

The Institute's Board of Directors met on May 20, 2010. The meeting was called to order by Chair Peter Hinz. The meeting was attended by George Hudak, Ted Bornhorst, Jim Miller, Mark A. Jirsa - Treasurer (2011), Pete Hollings, Terry Boerboom and Mark Smyk.

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

1. Accepted report of the Chairs for the 55th ILSG, Ely, Minnesota; as printed in the Proceeding Volume (Miller), and minutes of last Board meeting, May 7, 2009 (Hollings)
2. Received, discussed, and accepted 2009-2010 ILSG Financial Summary (Jirsa).

3. Received, discussed, and accepted 2009-2010 report of the Secretary (Hollings).
4. Approved Hollings to continue as Institute Secretary (this was later presented to the membership and approved)
5. Approved Peter Hinz as on-going ILSG Board member
6. Discussed application process for ILSG Student Research Awards. Hollings to revise the application to be a two-page form, not including references, figures or tables. Application dates to remain unchanged
7. Approved Ashland, Wisconsin at the site for the 57th annual ILSG meeting. The meeting will be hosted by Tom Fitz with help from Jim Miller, Laurel Woodruff and Bill Cannon.
8. Discussed and approved replacing Terry Boerboom as the “member from government” on Goldich Committee (end of term 2010) with Laurel Woodruff
9. It was agreed that the Institute would adopt the following policy “The Institute will not distribute email advertisements for ‘for-profit’ organizations or individuals. The institute will post links for such organizations on the Institute web site and will include a logo and brief notice in the annual proceedings in return for a donation”. Hollings to prepare a new page on the web site highlighting institute sponsors and donors.

The co-chairs would like to thank all the sponsors for their support of the meeting, all those who helped us organize and run the meeting, the Backus Community Center who put together a magnificent banquet on very short notice using community volunteers, and to all presenters and participants without whom the meeting could not have happened. We never cease to be amazed by the patience, enthusiasm, and passion of the membership of the ILSG.

Respectfully submitted,

Pete Hollings, Mark Smyk, Peter Hinz, Terry Boerboom and Mark Jirsa
Co-Chairs, 56th Institute on Lake Superior Geology

2011 BOARD OF DIRECTORS

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

Tom Fitz, Chair (2011-2014)

Northland College
Ashland, Wisconsin

Peter Hinz, (2010-2013)

Ministry of Northern Development, Mines and Forestry
Thunder Bay, Ontario

George Hudak, (2009-2012)

NRRI, Duluth

Ted Bornhorst, (2008-2011)

Michigan Technological University
Houghton, Michigan

Mark A. Jirsa, Treasurer (2008-2011)

Minnesota Geological Survey
St. Paul, Minnesota

Peter Hollings, Secretary (2010-2013)

Lakehead University
Thunder Bay, Ontario

2011 SESSION CHAIRS

Marcia Bjørnerud, Lawrence University

Bill Cannon, U.S. Geological Survey

Todd LaMaskin, Wisconsin Geological Survey

Mark Jirsa, Minnesota Geological Survey

George Hudak, Natural Resources Research Institute

Jim Miller, University of Minnesota – Duluth

Peter Hollings, Lakehead University

Mark Smyk, Ontario Geological Survey

2011 STUDENT PAPER AWARDS COMMITTEE

Elizabeth Gordon, University of Wisconsin – Parkside (Chair)

Laurel Woodruff, U.S. Geological Survey

James Shannon, MMG – Minerals and Metals Group

Thursday Evening Awards Banquet
with Keynote Address by:

Dr. Huifang Xu
(University of Wisconsin – Madison)

Banded Iron Formations: Unique
Products from the Interactions between
Komatiites and Seawater of the Early Earth



PROGRAM

SCHEDULE OF EVENTS

TUESDAY, MAY 17

- 4:00 p.m. – 9:00 p.m.: Registration
- 4:00 p.m. – 9:00 p.m.: Cash bar is open

WEDNESDAY, MAY 18 (ALL TRIPS DEPART AND RETURN TO THE AMERICINN)

- 7:30 a.m. – 6:00 p.m. Field Trip 1 – Duluth Layered Series trip
(Rendezvous in Duluth at 9:00)
- 8:00 a.m. – 6:00 p.m. Field Trip 2 – Midcontinent Microcosm
Field Trip 3 – Bayfield Peninsula
- 4:00 p.m. – 10:00 p.m.: Registration continues
- 7:00 p.m. – 10:00 p.m.: Poster Session, Ice-breaker social at AmericInn

THURSDAY, MAY 19

- 8:00 a.m. – 12:00 p.m.: Registration Continues
- 8:10 a.m. – 11:40 a.m.: Technical Session I
- 11:40 a.m. – 1:15 p.m.: Lunch break. Lunch on your own.
- 1:15 p.m. – 4:40 p.m.: Technical Session II
- 6:00 p.m. – 7:00 p.m.: Social mixer and cash bar
- 7:00 p.m. – 9:30 p.m.: Banquet, awards ceremony, and keynote address

FRIDAY, MAY 20 (ALL TRIPS DEPART AND RETURN TO THE AMERICINN)

- 8:00 a.m. – 11:40 a.m.: Technical Session III
- 11:40 a.m. – 1:15 p.m.: Lunch break. Lunch on your own.
- 1:15 p.m. – 2:40 p.m.: Technical Session IV
- 3:00 p.m. – 6:00 p.m.: Field Trip 4 – Ashland Lakefront Site
Field Trip 5 – Bad River Watershed Culverts
Field Trip 6 – Copper Falls Hike
- 6:30 p.m. – 9:00 p.m.: Barbecue at Northland College. Shuttle vans to/from
AmericInn provided.

SATURDAY, MAY 21 (ALL TRIPS DEPART AND RETURN TO THE AMERICINN)

- 8:00 a.m. – 5:00 p.m.: Field trip 7 – Montreal Monocline
Field Trip 8 – Unconformity at Denham, MN
Field Trip 9 – Mellen Complex

End of meeting.

SCHEDULE OF TALKS AND POSTER SESSIONS

THURSDAY, MAY 19

Technical Session I: Regional geology and geophysics, Archean stratigraphy and structure. Session Co-chairs: Marcia Bjørnerud and Bill Cannon

- 8:10 Introductory comments
- 8:20 **Bruce A. Brown and Peter Schoephoester**
Preserving Wisconsin's mining history: Building a GIS-based mined-lands inventory as a resource for planning, environmental management, future mineral exploration, and historical research
- 8:40 **Val W. Chandler and Richard S. Lively**
Application of the horizontal-to-vertical spectral ratio (H/V) passive seismic method in Minnesota
- 9:00 **Mark A. Jirsa, Terrence J. Boerboom, Val W. Chandler, John H. Mossler, Anthony C. Runkel, and Dale R. Setterholm**
Highlights of the new Bedrock Geologic Map of Minnesota
- 9:20 **John M. Esch**
Bedrock topography, glacial drift thickness and bedrock outcrop maps, Upper Peninsula of Michigan
- 9:40 Coffee Break and Poster Session
- 10:00 **H. Paul Gilbert**
Stratigraphic investigation of the Neoarchean Bird River Belt, Southeast Manitoba, Canada
- 10:20 **Paul Geller*, Phil Fralick, Mary Louise Hill, and Patricia Gillies**
A review of the Western Superior Lithoprobe Line 3
- 10:40 **Brittney Swoffer* and Mary Louise Hill**
A deformation history of the Ivanhoe Lake Fault
- 11:00 **Robert J. Scott*, Maura J. Kolb, and Mary Louise Hill**
Comparison of microscale and regional scale structural control on gold mineralization in the North Caribou greenstone belt, Superior Province, northwestern Ontario
- 11:20 **Victoria Stinson* and Mary Louise Hill**
Microstructural control on gold mineralization in greenschist to amphibolite facies metamorphism, Greenstone, Ontario

11:40 a.m. – 1:15 p.m.: Lunch break. Lunch on your own.

Technical Session II: Paleoproterozoic geology and mineral deposits

Session Co-chairs: Todd LaMaskin and Mark Jirsa

- 1:15 **Introductory Comments**
- 1:20 **Amanda Van Lankvelt*, David Schneider , Keiko Hattori, and John Biczok**
Neoproterozoic magmatism in the NW Superior Craton: Granitoids of the North Caribou Terrane
- 1:40 **Michael A. DeVasto*, Dyanna M. Czeck, and Prajukti Bhattacharyya**
Quantifying deformation fabrics and chemistry across small granitic ductile shear zones from Mountain, Wisconsin
- 2:00 **Thomas W. Buchholz, Al Falster, and William B. Simmons**
Compositional trends in chevkinite group minerals from the Wausau Complex, Marathon County, WI.
- 2:20 **Todd A. LaMaskin**
Testing models of late Paleoproterozoic Penokean orogenesis in the Great Lakes Region, U.S.A. using sedimentary provenance: planning the investigation
- 2:40 **Coffee Break and Poster Session**
- 3:00 **Michael R. Easton, and Larry M. Heaman**
Detrital zircon geochronology of Matinenda Formation sandstones (Huronian Supergroup) at Elliot Lake, Ontario: Implications for uranium mineralization
- 3:20 **Phillip Larson, John Swenson, and Marsha Patelke**
The Biwabik Iron Formation: geochemical and textural evidence for deposition of iron-formation in a Paleoproterozoic epeiric sea
- 3:40 **Steph Theriault*, Jim Miller, Mike Berndt, and Ed Ripley**
The mineralogy, spatial distribution, and isotope geochemistry of sulfide minerals in the Biwabik Iron Formation
- 4:00 **Michael Totenhagen*, Penny Morton, and Phil Larson**
Characterization of gangue minerals in lower cherty ores of the Biwabik Iron Formation at United Taconite LLC
- 4:20 **Thomas Waggoner, Doug Duskin, Musa Karakus, and John Gartner**
Pyroclastic Magnetite Bombs in the Hemlock Formation, Iron County, Michigan
- 6:00 – 7:00 **Poster Session during Social Mixer**

FRIDAY, MAY 20

Technical Session III: Paleoproterozoic to Mesoproterozoic geology and mineral deposits. Session Co-chairs: George Hudak and Jim Miller

- 8:10 Introductory comments
- 8:20 **Breanne Beh* and Phil Fralick**
Depositional Processes Operating on the Paleoproterozoic Gowganda Ice Margin: an example from the Marquette, Michigan area
- 8:40 **Philip Fralick and Kamil Zaniwski**
Sedimentology of a wet, pre-vegetation floodplain assemblage: the Mesoproterozoic Outan Island Formation, Sibley Group, Ontario, Canada
- 9:00 **Carl Christian*, Peter Hollings, and Mark Smyk**
Chemistry and petrology of Midcontinent Rift-related intrusive rocks of the Sibley Peninsula, Ontario
- 9:20 **Robert Cundari*, Peter Hollings, and Mark Smyk**
Compilation and reevaluation of the geochemistry of Midcontinent Rift-related intrusive rocks around Thunder Bay, Ontario
- 9:40 Coffee Break and Poster Session
- 10:00 **Mark Smyk, Peter Hollings, and Robert Cundari**
The Pillar Lake volcanics: new insights into an enigmatic Mesoproterozoic volcanic suite near Armstrong, Ontario
- 10:20 **Dayton N. Ryan*, James D. Miller, and Jeffery D. Vervoort**
The geochemical evolution of the Sonju Lake intrusion: an assimilation-fractional crystallization model
- 10:40 **Dan Cervin*, Penny Morton, Jim Miller, and Richard Patelke**
Characterization of precious metal occurrences in the NorthMet deposit of the Partridge River Intrusion, Duluth Complex, Minnesota, USA
- 11:00 **Daniel J. Foley*, and James D. Miller**
Petrology and Cu-Ni-PGE mineralization of the Bovine Igneous Complex, Baraga County, Northern Michigan
- 11:20 **Erik R. Tharalson* and Thomas Monecke**
Geology and mineralization of the Serpentine Cu-Ni deposit, Duluth Complex Minnesota
- 11:40 – 1:15: Lunch break. Lunch on your own.

Technical Session IV: Midcontinent Rift mineral deposits

Session Co-chairs: Peter Hollings and Mark Smyk

- 1:15 Introductory comments
- 1:20 **Brian D. Goldner and James D. Miller**
Petrology of the Ni-Cu-PGE-mineralized Tamarack Intrusion, Aitkin and Carlton Counties, Minnesota
- 1:40 **Allan D. MacTavish, Geoffrey J. Heggie, V. Roland Goodgame, Justin R. Johnson, Anthony E. Beswick, William E. Stone, and Keith P. Watkins**
Platinum-Palladium-Copper-Nickel Mineralization at the Thunder Bay North Deposit, Ontario
- 2:00 **Dean Peterson, Phil Larson, Gabriel Sweet, and Jack Gibbons**
The Mineral Exploration Trifecta
- 2:20 Presentation of student awards

* Indicates eligibility for Student Paper Award.

If presenter is not the first author, then the name of the presenter is underlined.

POSTER PRESENTATIONS

Regional Geology and Geophysics

- 1) **Val W. Chandler, and Richard S. Lively**
Upgrade of the gravity and rock properties databases at the Minnesota Geological Survey
- 2) **Mark A. Jirsa, Terrence J. Boerboom, and Val W. Chandler**
Bedrock Geologic Map of Minnesota—Precambrian Geology

Archean and Paleoproterozoic Geology

- 3) **Jakob Wartman*, Ron Morton, George Hudak, and Cory Hercun**
Physical volcanology and hydrothermal alteration of the Rainy River Gold Project, Northwestern Ontario
- 4) **Ryan Rague and Steven Losh**
Fluid flow events in the Biwabik Iron Formation, Minnesota

- 5) **Brittany Saylor*, Jonathan Stencil, Michael DeVasto, and Prajukti Bhattacharyya**
Whole rock geochemical analyses of sheared granitic rocks from Mountain, Wisconsin
- 6) **Jolene T. Traut* and Dyanna M. Czeck**
Using cleavage refraction and microstructural evidence to determine the relative rheology of naturally deformed quartzites and phyllites from Baraboo, Wisconsin

Midcontinent Rift Rocks

- 7) **Terrence J. Boerboom and John C. Green**
Bedrock geologic maps of the Grand Marais and Kadunce River Quadrangles, North Shore of Minnesota
- 8) **Eric J. Carlson, Terrence J. Boerboom, Corey J. Holton, Kyle W. Kubitza, Lucy Mulvey, and Eric Scheurer**
Mesoproterozoic bedrock in the Kadunce River Quadrangle, NE Minnesota—Precambrian Research Center capstone
- 9) **Katherine Cummings* and Marcia Bjørnerud**
Possible eukaryotic microfossils in the 1.1 Ga Copper Harbor Formation, Michigan
- 10) **Evgeniy V. Kulakov, A.V. Smirnov, and J.F. Diehl**
Paleomagnetism and Paleointensity as recorded by 1.08 GA Lake Shore Traps (Keweenaw Peninsula, Upper Michigan)
- 11) **Elisa J. Piispa, Aleksey V. Smirnov, and Lauri J. Pesonen**
Paleomagnetism of Midcontinent Rift rocks from the northern shore of Lake Superior (Ontario, Canada): Preliminary results

Midcontinent Rift Mineral Deposits

- 12) **Laetitia Amissé* and Sarah J. Barnes**
Role of Te-As-Bi-Sb (TABS) in the distribution of PGE and formation of PGM: Application to the Duluth Complex
- 13) **Matthias Queffurus* and Sarah J. Barnes**
The use of S/Se ratios in magmatic Ni-Cu-PGE sulfide deposits and its implications for exploration: Example of the Duluth Complex, Minnesota, USA
- 14) **Cabin Ross*, George Hudak, Ron Morton, Tom Quigley, and Bob Mahin**
Preliminary stratigraphy and physical volcanology associated with the Paleoproterozoic Backforty VMS deposit, Menominee County, Michigan

- 15) **Jillian E. Votava and Theodore J. Bornhorst**
Towards a geochemical characterization of native copper ores of the Keweenaw Peninsula, Michigan

Quaternary Geology and Geological Education

- 16) **Maverick Deschamp* and Jennifer McGuire**
The uptake of lead by Brassica rapa; implications for hunting in agricultural fields
- 17) **Corrie T. Floyd*, Kent M. Syverson, and Christina M. Hupy**
Using LiDar data and ArcGIS to evaluate subtle glacial landforms associated with the early Chippewa and Emerald Phase ice-margin positions, Barron County, Wisconsin
- 18) **George Hudak, Stephen Monson Geerts, Larry Zanko, April Severson, Allison Severson, and Bryan Bandli**
The Minnesota Taconite Workers Health Study: Environmental study of airborne particulates - 2011 update
- 19) **William Bajjali, Cole Holstrom, and Dan Fuller**
Comparing sources of high salinity of two Urban Streams and their effects on Superior Bay in City of Superior
- 20) **Stephen Mattox**
Using Credit-by-Exam to Connect Advanced High School Geology Courses to University Geology Programs: Lessons Learned from a State-wide Pilot Study in Michigan

Precambrian Research Center Field Camp

- 21) **Ryan Birkmeier, Tyler Boley, Brittnee Brannan, Ryan Doucette, Mark Jirsa, and Aubrey Lee**
Geologic mapping of Neoproterozoic rocks near Ogishkemuncie Lake, by students of the Precambrian Research Center's 2010 field camp
- 22) **Jim Miller, Ben Brooker, Max Hadley, Levi Markwood, Jeff Olson, and Alex Tomlinson**
2010 Precambrian Field Camp Mapping in the Jack Lake Area, Cook County, Northeastern Minnesota

- 23) **Amy L. Radakovich, Charlie T. Parent, , Molly E. Partridge, Andrew D. Ritts, Rita Pierce, and George J. Hudak**
Reconnaissance Bedrock Geological map of the northern part of Sudan Underground Mine State Park and the northwestern part of Lake Vermilion State Park, St. Louis County, Minnesota
- 24) **Alexandra M. Vallowe, Ernest J. Thalhamer, Damon L. Rhoades, and Dean M. Peterson**
Surface and subsurface geologic maps of the Soudan Underground Mine State Park, St. Louis County, Northeastern Minnesota

* Indicates eligibility for Student Paper Award



ABSTRACTS

Role of Te-As-Bi-Sb (TABS) in the distribution of PGE and formation of PGM: Application to the Duluth Complex

Laetitia Amissé and Sarah J. Barnes

*Sciences de la Terre, Université du Québec à Chicoutimi, 555 Bld. de l'Université,
Saguenay, Québec, Canada G7H 2B1 laetitia.amisse1@uqac.ca and [Sarah-Jane Barnes@uqac.ca](mailto:Sarah-Jane.Barnes@uqac.ca)*

Platinum-group elements (PGE) are commonly present in minerals such as pyrrhotite, pentlandite and chalcopyrite (BMS) crystallized from sulfide liquid. However, recent studies of deposits have shown that while much of the Re, Os, Ir, Ru, Rh are in solid solution in BMS, Pt and in some cases Pd are absent of these phases. The general observation shows that Pt and Pd are present in platinum-group minerals (PGM) with elements like tellurium, arsenic, bismuth and antimony (TABS). In some cases the PGM are closely associated with BMS but there are some examples where they are not. This raises the question of what role these elements play in collecting PGE.

More and more authors think that TABS have an effect on the behavior of Pt and Pd. Some authors (Dare et al., 2010) suggest that PGE may crystallize as PGM directly from the sulfide liquid. Others authors (Hanley, 2007; Holwell and McDonald, 2010) suggest that TABS are derived from country rocks and formed an immiscible TABS liquid where collected PGE.

However, one difficulty in testing these hypotheses is that TABS especially Bi and Te are present at very low concentrations in crustal rocks and are volatiles, which makes them difficult to determine. Some authors (Hall and Pelchat, 1997) introduce a more sensitive routine method for determining TABS based on hydride generation and inductively coupled plasma-mass spectrometry (HG-ICP-MS).

This study will consist of two parts. The first will consist developing the HG-ICP-MS at laboratory of “Université du Québec à Chicoutimi” to obtain better detections limits. This second part will investigate whether TABS have redistributed or collected PGE at the Dunka Road deposit of the Duluth Complex.

REFERENCES

- Dare, S.A.S., Barnes, S.J., and Prichard, H.M., 2010a, The distribution of platinum group elements (PGE) and other chalcophile elements among sulfides from the Creighton Ni–Cu–PGE sulfide deposit, Sudbury, Canada, and the origin of palladium in pentlandite: *Mineralium Deposita*, doi 10.1007/s00126-010-0295-6.
- Hall, G.E.M., and Pelchat, J.C., 1997, Determination of As, Bi, Sb, Se, and Te in Fifty Five Reference materials by Hydride Generation ICP-MS: *Geostandards Newsletter*, v. 21, p.85–91.
- Hanley, J.J., 2007, The role of arsenic-rich melts and mineral phases in the development of high-grade Pt–Pd mineralization within komatiite-associated magmatic Ni–Cu sulfide horizons at Dundonald Beach South, Abitibi subprovince, Ontario, Canada: *Economic Geology*, v.102, p. 305–317.
- Holwell, D.A., and McDonald, I., 2010, A review of the behavior of platinum group elements within natural magmatic sulfide ore systems: the importance of semimetals in governing partitioning behavior: *Platinum Metals Review*, v. 54, p. 26–36.

Comparing sources of high salinity of two urban streams and their effects on Superior Bay in City of Superior

William Bajjali, Cole Holstrom, and Dan Fuller

University of Wisconsin-Superior, Department of Natural Sciences, Superior, WI

A study of water quality was conducted for Newton and Faxon Creeks that run through an urban area in the city of Superior and discharge into Hog Island Inlet (HII) and Superior Bay, respectively.

Faxon Creek was monitored for comparison purposes and recorded salinity concentrations much higher than that of Newton Creek. The chloride concentration was greater than that of Newton Creek and much higher than the secondary maximum contaminant level established by the Environmental Protection Agency. Water salinity of the creeks is attributed mainly to the chloride and sodium concentrations.

Both Newton and Faxon Creeks revealed different chemical makeups. Faxon Creek reveals that all ion concentrations in its water are higher than in Newton Creek with the exception of sulfates and nitrates. The average chloride:sulfate ratio is 13.5 times higher in Faxon Creek than in Newton Creek. Nitrate concentrations in Newton Creek are almost 4 times the natural abundance of nitrate in natural water and the phosphorous is 3 to 4 times the recommended concentration value set by EPA.

A geochemical model reveals that the water of HII is the result of a mixing ratio of about 90 % of Lake Superior water and 10 % of Newton Creek water. The source of water contaminations in Newton Creek originate mainly from the discharge of treated wastewater from Murphy Oil with minimum contributions from surface runoff. The source of contamination in Faxon Creek is mainly due to urban surface runoff that is influenced by road deicing practices.

Depositional processes operating on the Paleoproterozoic Gowganda ice margin: an example from the Marquette, Michigan area

Breanne Beh and Philip Fralick

Department of Geology, Lakehead University, 955 Oliver Road, Thunder Bay, ON, P7B 5E1, philip.fralick@lakeheadu.ca

Glacial sediments of the Huronian Supergroup outcrop along the north shore of Lake Huron and were likely deposited on what is thought to have been a divergent continental margin (Fralick and Miall 1981; 1989). The glaciogenic Enchantment Lake Formation, part of the Chocolay Group of the Marquette Range Supergroup, is chronostratigraphically correlated to the Huronian Supergroup based on U-Pb age determination on detrital zircon, 2317 ± 6 Ma, and diagenetic xenotime, 2133 ± 11 Ma (Vallini et al. 2005). As the Gowganda is the thickest and most commonly preserved of the three Huronian glacial events it is reasonable to assume it correlates to the Enchantment Lake Formation.

Two metamorphosed stratigraphic sections were logged on the north side of the Dead River Basin located near Marquette, Michigan. According to the mapping discussed in a United States Geological Survey professional paper (Puffett 1974), the sections are identified as the Enchantment Lake Formation of the Marquette Range Supergroup. Puffett's (1974) map shows that the Enchantment Lake is underlain by Archean rocks to the north, indicating the sections young to the south.

The logged sediments were grouped into ten lithofacies: 1) Shale, 2) Siltstone, 3) Siltstone with coarse grains, 4) Diamictite, 5) Fine sandstone, 6) Hummocky cross-stratified sandstone, 7) Coarse sandstone, 8) Granule to small pebble conglomerate, 9) Pebble conglomerate and 10) Boulder lense. These lithofacies are probably a subaqueous glacial outwash fan. The presence of an iceberg dumped boulder mound (Fig 1A) as well as hummocky cross-stratification (Fig 1B) indicates that deposition on the fan was occurring in an open water setting. Siltstone is the most common sediment throughout the logged section. It makes up the matrix of the diamictite as well as the conglomerates. In some locations, it is also interbedded with fine- and coarse-grained sandstone. The fact that the siltstone occurs in conjunction with the majority of the other lithofacies indicates that it is likely the background sediment deposited from suspension settling of subaqueous outwash material. Resedimentation events such as small slumps and debris flows are thought to account for the incorporation of coarse-grained lithofacies in the predominantly siltstone succession. In particular, these resedimentation events probably produced the siltstone with coarse grains lithofacies as these layers represent a mixing of two separate grain-size populations in a manner not compatible with traction current deposition (Fig 1C). Throughout the section, stringers of coarse-grains as well as small lag deposits indicate that current reworking of the sediments has occurred by removing the finer grains (Fig 1D). Currents created by the glacial outwash would have been incapable of creating this winnowing effect because they were sediment laden. The erosive currents were likely geostrophic currents generated in the open water environment during storm events.

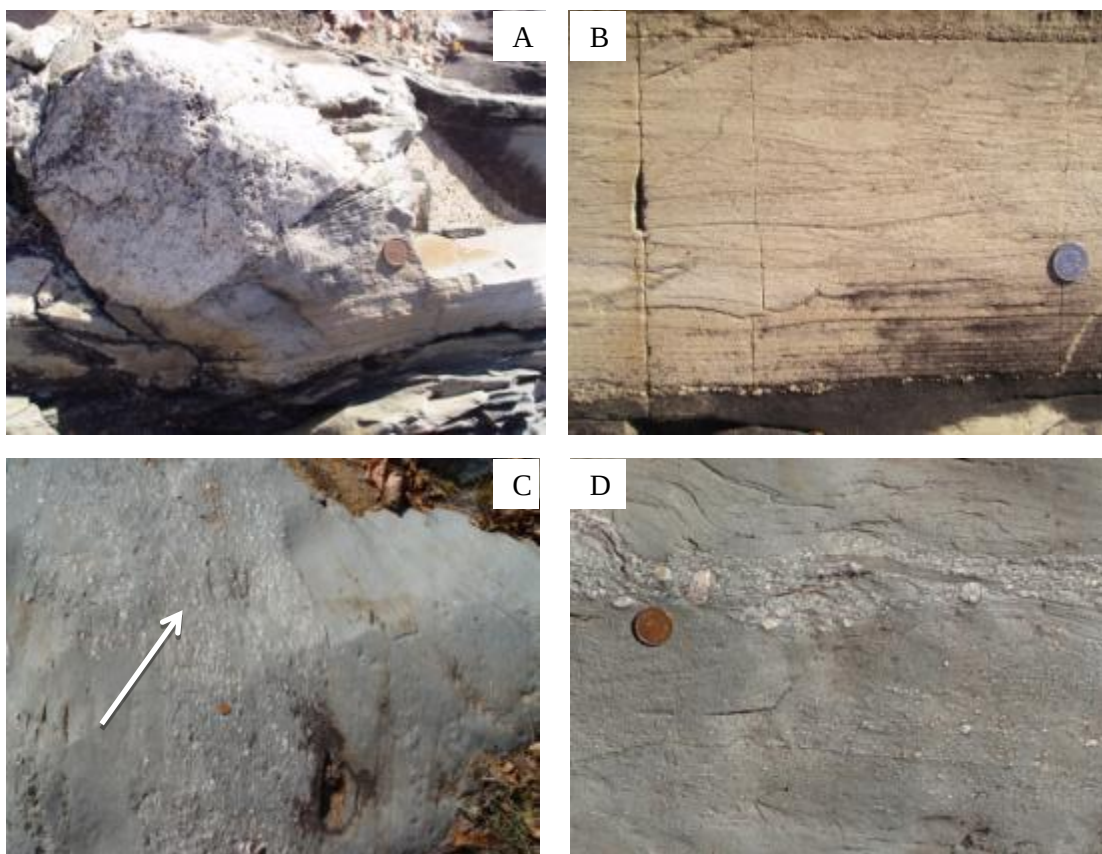


Figure 1. A) A cobble from the boulder mound compressing underlying sediments. B) Hummocky cross-stratification. C) Siltstone with coarse grains indicated by the arrow. D) A small lag deposit of granule to small pebble conglomerate.

REFERENCES

- Fralick, P.W., and Miall, A.D. 1981, Grant 84: Sedimentology of the Matinenda Formation, in Pye, E.G., ed., Geoscience Research Grant Program, Summary of Research 1980 – 1981: Ontario Geological Survey, Miscellaneous Paper 98, p. 80-89.
- Fralick, P.W., and Miall, A.D., 1989, Sedimentology of the Lower Huronian Supergroup (Early Proterozoic), Elliot Lake area, Ontario, Canada: *Sedimentary Geology*, v. 63, p. 127-153.
- Puffett, W.P., 1974, Geology of the Negaunee quadrangle, Marquette County, Michigan: U.S. Geological Survey, Professional Paper 788, 53 p.
- Vallini, D.A., Cannon, W.F., and Shulz, K.J. 2005, New age data for the Chocoday Group, Marquette Range Supergroup: implications for the Paleoproterozoic evolution of the Lake Superior and Lake Huron regions: *Institute on Lake Superior Geology 51st Annual Meeting, Proceedings and Abstracts*, v. 1, p. 64.

Geologic mapping of Neoarchean rocks near Ogishkemuncie Lake, by students of the Precambrian Research Center's 2010 field camp

Ryan Birkmeier¹, Tyler Boley¹, Brittnee Brannan¹, Ryan Doucette¹, Mark Jirsa², and Aubrey Lee¹

¹2010 Field Camp Students, Precambrian Research Center, Natural Resources Research Institute, University of Minnesota Duluth, 5013 Miller Trunk Highway, Duluth, Minnesota 55811

²Minnesota Geological Survey (MGS), University of Minnesota, 2642 University Avenue W., St. Paul, Minnesota 55114

This presentation shows the results of mapping Neoarchean bedrock in the Ogishkemuncie Lake area (Fig. 1) by 5 students of the Precambrian Research Center field camp.

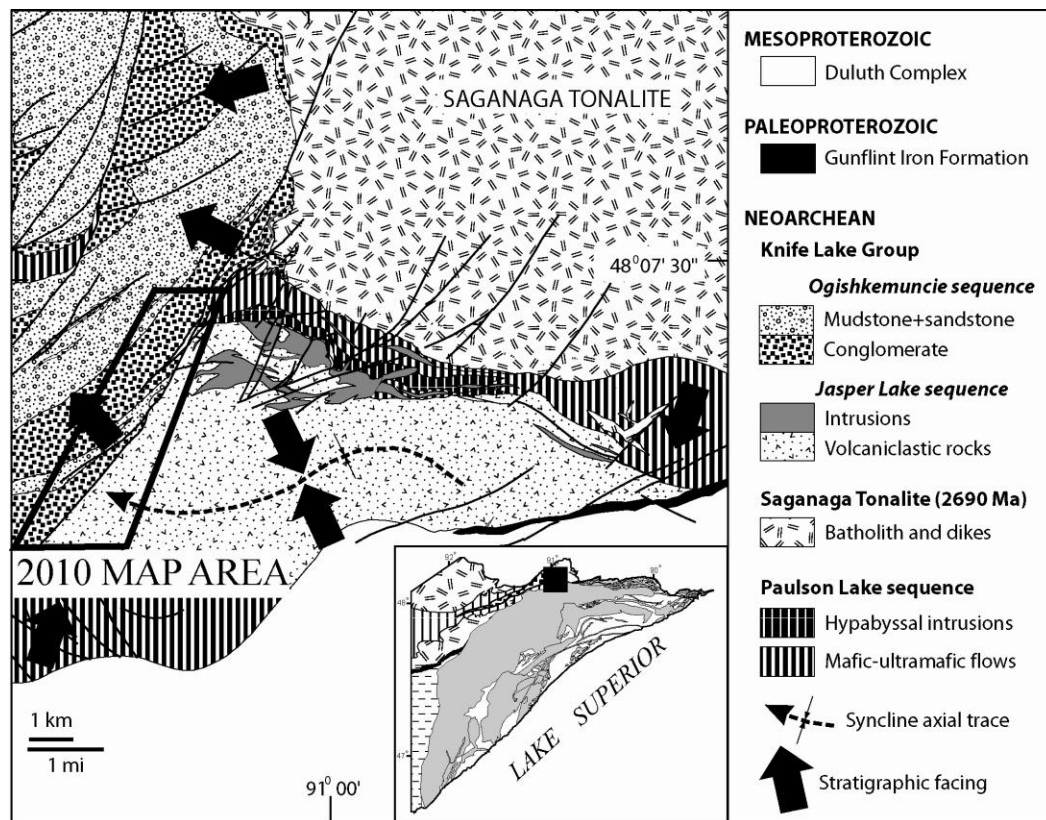


Figure 1. Simplified geology of the Cavity Lake fire area (modified from Jirsa and Starns, 2008), showing location of 2010 mapping near Ogishkemuncie Lake.

The Precambrian Research Center—a branch of the University of Minnesota, Duluth—conducted its 4th season of field camp in 2010. The final phase of training is a “Capstone Project” that provides students an opportunity to create new bedrock geologic maps in areas of poorly understood geology. The students were charged with mapping the area to help unravel the complexity and construct a sequence of depositional and deformation events

Based on prior mapping, Ogishkemuncie Lake lies along a complex unconformity that is marked locally by paleosaprolite and dissected by faults. The unconformity is overlain by the Ogishkemuncie Lake sequence, consisting of conglomerate and other strata containing sedimentary structures indicating deposition by alluvial fan, fluvial, and fluvial-lacustrine (or marine) processes, and syn- and post-depositional faulting. The unconformity is underlain by the Paulson and Jasper Lake sequences composed of metabasalt, metagabbro, trachyandesite and trachyandesitic volcanic conglomerate. An offset at the south end of the lake between the trachyandesite and volcanic conglomerate units, combined with a shear fabric containing sigma-shaped clasts indicates a component of right-lateral displacement along an anastomosing fault zone in and adjacent to Ogishkemuncie Lake. Carbonate alteration and multiple cycles of quartz veining are pervasive along the fault zone. The exposure of the trachyandesite unit in the southwest and northeast of the lake are evidence of a large synform. The Ogishkemuncie conglomerate contains clasts derived from the Paulson Lake and Jasper Lake sequences, together with abundant clasts of Saganaga Tonalite, recently dated at ~2690 Ma (Driese and others, 2011). The clast-supported, moderately-sorted deposits in the Ogishkemuncie sequence are indicative of braided stream deposition. The sequence also contains lenses of matrix-supported debris flow deposits indicative of alluvial fans. The conglomeratic strata are locally interlayered with units of graded mudstone and sandstone that may represent deposition in standing water in a fluvial-lacustrine system. These findings are consistent with the evolution of a pull-apart basin in which braided streams flowing along the basin axis were temporally dammed by transgressing alluvial fans (Fig. 2).

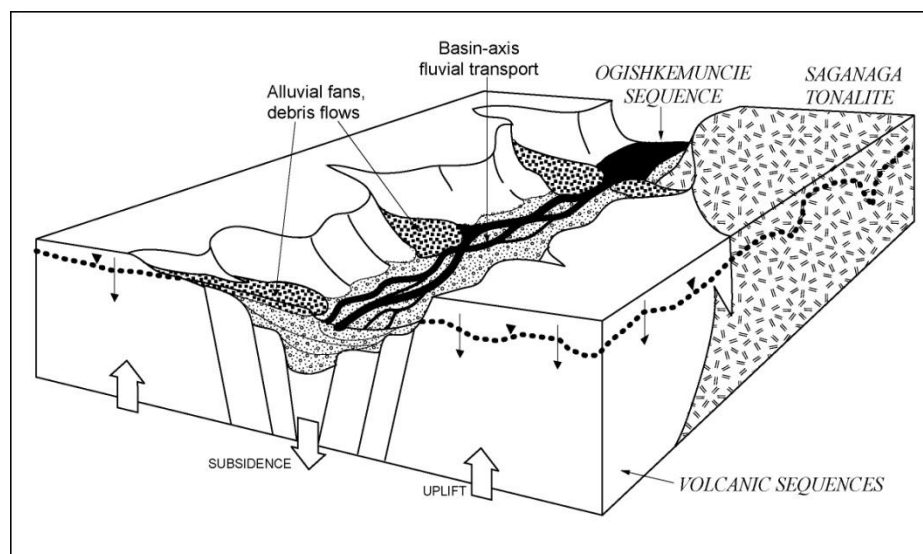


Figure 2. Model representing deposition of the Ogishkemuncie Lake sequence prior to regional deformation and metamorphism (from Driese and others, 2011); north is toward upper right of figure.

REFERENCES

- Driese, S.G., Jirsa, M.A., Ren, M., Sheldon, N.D., Brantley, S.L., Parker, D., and Schmitz, M., 2011, Neoproterozoic paleoweathering of tonalite and metabasalt: Implications for reconstructions of 2.69 Ga early terrestrial ecosystems and paleoatmospheric chemistry: *Precambrian Research*, in press.
- Jirsa, M.A., and Starns, E., Geologic map of the Cavity Lake Fire Area: MGS Open-File Report 08-05.

Bedrock geologic maps of the Grand Marias and Kadunce River Quadrangles, North Shore of Lake Superior, Minnesota

Terrence J. Boerboom¹ and John C. Green²

¹Minnesota Geological Survey, boerb001@umn.edu

²University of Minnesota-Duluth, jgreen@d.umn.edu

The Minnesota Geological Survey has continued ongoing mapping of the bedrock geology of 7.5' quadrangles adjacent to the shore of Lake Superior as part of the USGS STATEMAP program, resulting to date in eighteen published 1:24,000 scale maps from Duluth to beyond Grand Marais, in addition to 10 quadrangles already published under the former USGS COGEOMAP program. The Grand Marais and Kadunce River quadrangles (Boerboom and Green, 2010; Boerboom and Green, 2011) are the most recent of these geologic maps (figures 1 and 2). All maps in this series are available as plotter printed maps, or as PDF and GIS shapefiles at the MGS website (www.mnngs.umn.edu).

Outcrop mapping was augmented by over 100 sets of high-quality water well cutting samples, collected at 10 foot intervals by McKeever Well Drilling of Little Marais, Minnesota. These provided a crucial glimpse of the volcanic stratigraphy in the third dimension as well as information where the bedrock is poorly exposed.

The area of this map lies in the central portion of the northeast limb of the 7-10 km thick North Shore Volcanic Group (NSVG), which include abundant felsic volcanic rocks (e.g. the Devil Track, Maple Hill, Kimball Creek, Devil's Kettle, Trout Lake, and unnamed units of rhyolite, and the Kadunce River icelandite) as well as andesitic to mafic lava flows (e.g. the Red Cliff basalts and the Marr Island Lavas). In addition there are several thin hypabyssal diabase dikes and sills emplaced into the volcanic rocks, and near the northern margin of the maps the volcanic rocks are intruded by largely felsic rocks related to the Duluth Complex (e.g. Pine Mountain granophyre). This mapping has refined the volcanic stratigraphy of the NSVG in this area, working down-section towards the base of the northeast limb of the NSVG. This work has also shown that the lavas in and near Grand Marais have been pervasively intruded by diabase dikes, likely along fault planes, that now separate much of the volcanic rocks into isolated blocks which are disheveled and rotated to varying degrees. Minor amounts of hybrid felsic magmas, likely related to emplacement of the diabase, are also present.

In keeping with prior work, the NSVG is subdivided into informal lithostratigraphic packages separated by major compositional changes, by intrusions or faults across which correlation is tenuous, or where thick flows or flow sequences form mappable units. The informal lithostratigraphic packages shown on these maps include the Grand Marais felsites (rhyolite and icelandite), the Croftville lavas (which includes the Pincushion Mountain trachybasalt of Green, 2002), the Devil Track and Maple Hill rhyolites, the Red Cliff basalts, the Kimball Creek rhyolite, the Kadunce icelandite, the Marr Island lavas, and the Brule River lavas. The Brule River lavas contain a substantial proportion of felsic volcanic rocks including the Devil's Kettle rhyolite (1,097.7 ± 1.7 Ma: Davis and Green, 1997), and the newly named Trout Lake rhyolite.

The Devil Track and Kimball Creek rhyolites are interpreted as rheoignimbrites with large aspect ratios, i.e. long strike length compared to flow thickness (Green and Fitz, 1993). The aphyric Devil Track rhyolite flow, the largest felsic flow in the NSVG, is approximately 250 meters thick and extends at least 40 km west and inland from the mouth of Devil Track River (and an unknown distance to the east, beneath Lake Superior). This flow is inferred to have been either a hot superliquidus lava flow or possibly a thick, hot rheoignimbrite that flowed and underwent complete recrystallization after deposition (Green and Fitz, 1993). The Kimball Creek rhyolite is estimated to be the second largest felsite flow in the North Shore Volcanic Group, with an aspect ratio similar to the Devil Track rhyolite. It exhibits fiamme textures and tightly folded flow layering which are restricted to the top and bottom of the unit, but the majority of the exposures are fine-grained uniform rhyolite that do not contain recognizable flow structures (Green and Fitz, 1993).

Intrusive rocks in these map areas consist of thin dikes and subconformable sills most likely related in timing to the Beaver Bay Complex, and deeper-seated granophyric rocks that are part of the Pine Mountain granophyre (1,095.3 ± 3.8 Ma; Vervoort and others, 2007).

Although this long-term mapping project is on hold for the 2011 field season, the Minnesota Geological Survey has plans to resume mapping in 2012, working east up the shore towards the Canadian border.

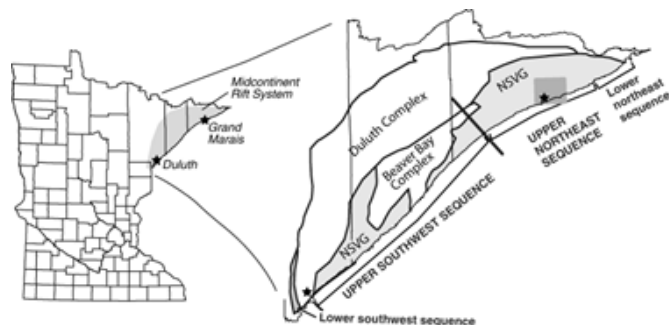


Figure 1 (left). Location map showing the extent of the Keweenaw Midcontinent Rift System in Minnesota, and the locations of the Grand Marais and Kadunce River quadrangles (dark gray boxes).

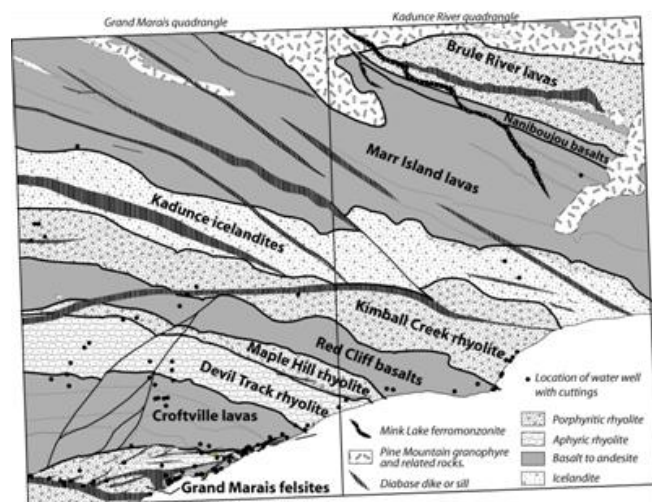


Figure 2 (right). Simplified geologic map of the Grand Marais and Kadunce River quadrangles, showing the names of the major lithostratigraphic units discussed in the text

REFERENCES

- Boerboom, T.J., and Green, J.C., 2010, Bedrock geology of the Grand Marais quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map Series Map M-189, scale 1:24,000.
- Boerboom, T.J., and Green, J.C., 2011, Bedrock geology of the Kadunce River quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map Series Map M-190, scale 1:24,000.
- Davis, D.W., and Green, J.C., 1997, Geochronology of the North American Midcontinent rift in western Lake Superior and implications for its geodynamic evolution: *Canadian Journal of Earth Science*, Volume 34, No. 4, April 1997, p. 476-488.
- Green, J.C., and Fitz, T.J. III, 1993, Extensive felsic lavas and rheognimbrites in the Keweenaw Midcontinent Rift plateau volcanics, Minnesota: petrographic and field recognition: *Journal of Volcanology and Geothermal Research*, v. 54, p. 177-196.
- Green, J.C., 2002, Volcanic and sedimentary rocks of the Keweenaw Supergroup in northeastern Minnesota, in Miller, J.D., Jr., Green, J.C., Severson, M.J., Chandler, V.W., Hauck, S.A., and Wahl, T.E., *Geology and mineral potential of the Duluth Complex and related rocks of northeastern Minnesota*: Minnesota Geological Survey Report of Investigations 58, p. 94-102.
- Vervoort, J.D., Wirth, K., and Kennedy, B., 2007, The magmatic evolution of the Midcontinent rift. New geochronologic and geochemical evidence from felsic magmatism: *Precambrian Research*, vol. 157, no. 1-4, p. 235-268.

Preserving Wisconsin's mining history: Building a GIS-based mined-lands inventory as a resource for planning, environmental management, future mineral exploration, and historical research

Bruce A. Brown and Peter Schoephoester

Wisconsin Geological and Natural History Survey, 3817 Mineral Point Road, Madison, WI 53705

A comprehensive statewide inventory of metallic and nonmetallic mining sites has never been compiled for Wisconsin. A GIS-based inventory, including current and historic sites would be useful to planners, developers, and environmental regulators as a guide to potential hazards such as improperly abandoned shafts and drill holes, areas of potential subsidence, sites that may require additional reclamation, and possible sources of surface and groundwater contamination. Access to documents and maps of historical lead-zinc and iron mining areas would also be of interest to historians. A complete inventory of metallic and nonmetallic mining sites could provide a guide to undeveloped resources for the future.

Many of the pieces necessary to assemble a statewide inventory already exist or are in various stages of preparation. The WGNHS recently completed scanning, editing, and georeferencing more than 1400 section maps from the Wisconsin Mineral Development Atlas. This data set contains maps of hundreds of underground zinc mines and crevice lead mines dating from the 1820s to 1978. More than 28,000 exploration drilling logs were recently scanned and added to this data set. A Mines, Pits, and Quarries database (MPQ) currently under construction will contain locations, geologic information, and engineering test data for current and recently active aggregate and industrial mineral mines. It will also incorporate the historic WGNHS Road Materials Survey, which provides a record of aggregate mining and exploration activity back to the early 1900s. Historic nonmetallic and metallic sites compiled by the U.S. Geological Survey in the Mineral Resource Data System (MRDS) and by the former U.S. Bureau of Mines in the Mineral Availability System and Mineral Industry Location System (MAS/MILS) have been integrated into the MPQ GIS. WGNHS is also in the process of constructing a locational database for the mineral exploration and engineering cores stored at the sample repository in Mt. Horeb, WI.

Several important historical data sets still need to be inventoried and evaluated. Examples that will require significant work are the extensive collection of documents and paper maps related to Iron mining and exploration in the Gogebic Range, Florence District, Baraboo District, and the Mayville Ironstone mines. This material has significant local and statewide historical value, and contains locations of long forgotten potential hazards as well as valuable geologic data. We are beginning to sort and evaluate this material to prioritize documents that need to be scanned or digitized to include in the statewide inventory.

The age and fragile condition of many of these documents requires that they be handled carefully in the scanning process. The WGNHS does not have staff and facilities for archiving, and after essential data is captured, many original documents are being transferred to the UW Archives or appropriate regional archive centers of the State Historical Society where they can be preserved while still available for research.

Compositional trends in chevkinite group minerals from the Wausau Complex, Marathon County, WI.

Thomas W. Buchholz¹, A. U. Falster², and W. B. Simmons²

¹1140 12th Street North, Wisconsin Rapids, Wisconsin 54494,

²Department of Earth and Environmental Sciences, University of New Orleans, New Orleans, Louisiana 70148

The Wausau Syenite Complex (WSC) is composed of four plutons, from the oldest (1565 Ma $\pm$ 3-5) (Van Wyck, 1994), most alkalic Stettin Pluton, through the younger and progressively less alkalic and more silicic Wausau and Rib Mountain Plutons, to the youngest (1505.9 $\pm$ 2.7 Ma) (Dewane & Van Schmus, 2007), most silicic Nine Mile Pluton.

Over the last several years chevkinite group minerals have been identified from three sites within the Wausau Complex. Chevkinite group minerals are complex titanosilicates, most of which contain Light Rare Earth Elements (LREE, La to Eu), Ca and Fe as essential components. Extensive substitution often allows the incorporation of significant Nb, Ta, Th, HREE and Zr, among other elements.

Recently chevkinite group minerals (probably either chevkinite-(Ce) or perrierite-(Ce) have been identified from three sites within the Wausau Complex. The first occurrence noted is at a site just north of the Aspirus Hospital in Wausau, where phases of the Wausau Pluton near a contact with a large quartzite xenolith were exposed by quarrying to cut back a hillside. Small pegmatoidal veins and clots are exposed in the approximate center of the cut and are largely composed of feldspars, quartz, an unidentified amphibole, zircon and locally abundant grains of a usually more-or-less altered chevkinite-group mineral. Accessory minerals include apatite, monazite and allanite-(Ce). Both mafic and more felsic phases of the veins carry chevkinite-group minerals. The grains generally present a mottled, altered appearance that is probably the result of post-emplacement hydrothermal alteration. These altered grains range in color from dark yellow through reddish hues to dark glassy black. Highly altered grains are chalky white in color. Careful examination of heavy mineral separates nonetheless resulted in finding unaltered material suitable for analysis.

The second occurrence is in a long-abandoned and overgrown quarry or borrow pit located near the SE corner of CTH O and U in the Stettin Pluton. The small, poorly exposed pegmatites at this site include sparse, small glassy brown prismatic crystals of a chevkinite-group mineral associated with quartz, microcline, albite, biotite, aegerine, ilmenite, probable rhabdophane-(Ce), unusually heavy-rare-earth-element enriched xenotime-(Y), an unidentified amphibole, fayalite, an euxenite-like Y-Nb oxide phase, and magnetite.

The third occurrence is in heavy mineral separates prepared from a fine-grained, miarolitic phase of a locally megacrystic mafic dike cutting Nine Mile granite in the Ladick quarry. Clearly younger than the host granite, the mafic dike may be similar in age to a dike of similar material in the Koss quarry, classified as meladiorite, with a K-Ar age of 1307.2 $\pm$ 41 Ma (Cordua, 2004). Associated minerals include amphiboles, biotite, chlorite, fluorapatite, and very rare columbite- and monazite-group species.

Most samples examined are metamict, so no XRD determination could be made as to whether the chevkinite-group minerals are chevkinite-(Ce) or perrierite-(Ce), two chemically similar members. However, the samples were analyzed by electron microprobe (EMP), and when CaO vs. FeO is plotted as suggested by MacDonald & Belkin (2002) the compositions

from all three sites clearly fall into the chevkinite field, providing strong evidence that the mineral in question in all three cases is probably chevkinite. EMP analysis also shows that chevkinite-group minerals from each site exhibit a distinct chemical composition based on the ratios of Nb + Ta versus Ti + Fe_{total} (Fig. 1). The most Nb + Ta-depleted samples are from the “Ladick meladiorite”. Samples most enriched in Nb + Ta are from the “Aspirus felsic syenite phase”, whereas those from the “Aspirus melasyenite phase” and the “Stettin syenite” exhibit intermediate Nb + Ta contents. While the range in chemical variation is relatively small, it likely reflects the abundance of these elements in the respective melts, thus the degree of fractionation. A chondrite-normalized plot of LREE contents shows overall relatively small variations in the LREE; all sites track rather closely with the exception of Eu. The observed greater Eu anomaly for the Stettin and Ladick samples is likely due to greater substitution of Eu²⁺ in plagioclase. Hence, the “Ladick meladiorite” dike, though probably significantly younger and not part of the WSC, is chemically similar and thus may have originated from a similar source as the intrusive centers of the WSC.

REFERENCES

- Cordua, William S., 2004, Enigmatic 1300 – 1400 Ma Mafic Pluton from the Koss Pit, Marathon County, WI [abstract]: Institute on Lake Superior Geology Proceedings, 50th Annual Meeting, Duluth, MN, v. 50, part 1, Program and Abstracts, p. 48-49
- 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, p. 215-234.
- Macdonald, R., Belkin, H.R., 2002, Compositional variation in minerals of the chevkinite group: *Mineralogical Magazine*, v. 66, p. 1073-1098.
- Van Wyck, N., 1994, The Wolf River A-type magmatic event in Wisconsin: U/Pb and Sm/Nd constraints on timing and petrogenesis. [abstract]: Institute on Lake Superior Geology, 40th Annual Meeting, Houghton, MI, v. 40, part 1, Program and Abstracts, p. 81-82.

Geochemistry and petrology of Midcontinent Rift-related intrusive rocks of the Sibley Peninsula, Ontario

Christian Carl¹, Peter Hollings¹, and Mark Smyk²

¹Department of Geology, Lakehead University 955 Oliver Road Thunder Bay, ON P7B 5E1 Canada

²Ontario Geological Survey, Ministry of Northern Development, Mines and Forestry, Suite B002, 435 James St. South Thunder Bay, ON P7E 6S7 Canada

The 300 km² Sibley Peninsula projects south into Lake Superior approximately 30 km east of Thunder Bay, Ontario. The geology of the peninsula consists of Southern Province assemblages, including intrusive rocks of the ~ 1.1Ga Midcontinent Rift. Due to their location within Sleeping Giant Provincial Park, the Sleeping Giant Sill (SGS) and the numerous dikes on the Sibley Peninsula have not been geochemically sampled nor classified. With permission from Ontario Parks, this study was undertaken to classify the Sibley Peninsula dikes and the SGS based on their geochemistry and to determine relative ages of the SGS and dikes of various orientations.

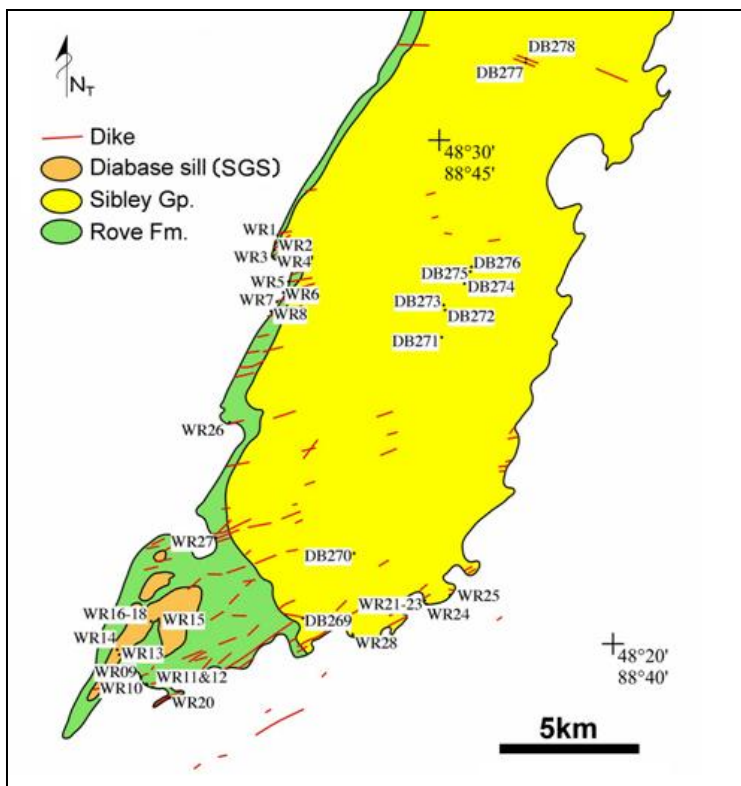


Figure 1: Map of sample locations (Hollings et al., 2010).

Thirty-four dike samples and five SGS samples were collected and analyzed for whole rock geochemistry at the Geoscience Laboratories (Fig. 1). Dikes with three different orientations were sampled: 1) numerous ~070°-striking dikes, which represent the majority of

the dikes on the peninsula, 2) two 110°-striking dikes and 3) two 029°-striking dikes. The ~070°-striking dikes were classified as Pigeon River Dikes based on Mg# versus TiO₂ and Gd/Yb_n versus La/Sm_n discrimination diagrams (Fig. 2). The 110°-striking dikes plotted near or within fields defined for ultramafic intrusions of the MCR (Hollings et al., 2007). However, due to their orientation, they are unlikely to be feeders to any of the ultramafic assemblages found in the Nipigon Embayment, northeast of the study area. The 029°-striking dikes also plotted in the field defined for mafic / ultramafic sills and intrusions on the Mg# versus TiO₂ plot and in the field defined for Nipigon Sills on the Gd/Yb_n versus La/Sm_n diagram (Fig. 2). Although these dikes are geochemically similar to Osler volcanic rocks of the neighbouring Black Bay Peninsula, they were just 18 and 20 cm wide, respectively, and tapered eastward, making them unlikely candidates as feeders to Osler volcanic rocks. Discrimination diagrams show that the SGS is of Logan affinity and now represents the easternmost recognized Logan Sill (Fig. 2). The thickness of the SGS was determined to be 194 m, making this the thickest known Logan Sill.

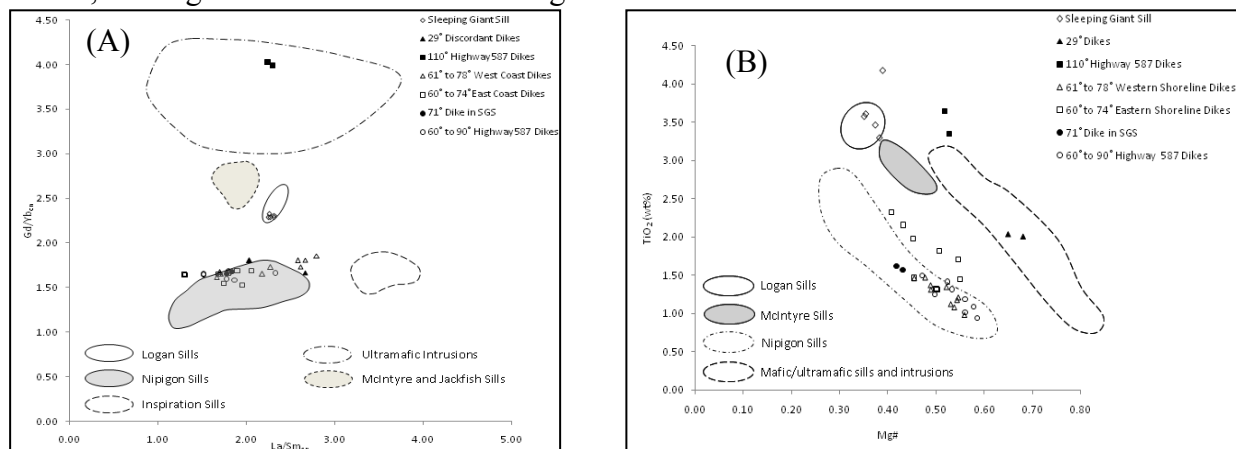


Figure 2. (A) Plot of Gd/Yb_n versus La/Sm_n. Fields from Hollings et al (2007). Normalizing values of Sun and McDonough (1989). (B) Plot of Mg# versus TiO₂. Fields from Hollings et al. (2007).

Cross cutting relationships indicate that the ~070°-striking dikes are younger than both the SGS and the 029°-striking dikes. The SGS and the 029°-striking dikes had lower silica and higher magnesium weight percentages than the ~070°-striking dikes, which may suggest that more primitive magmas were locally emplaced earlier. The ~070°-striking dikes displayed the largest negative niobium anomalies which could indicate an increase in contamination of magma sources over time, since these dikes were the youngest intrusions observed in this study.

REFERENCES

- Hollings, P., Hart, T., Richardson, A., and MacDonald, C., 2007. Geochemistry of the Midproterozoic intrusive rocks of the Nipigon Embayment, Northwestern Ontario. *Canadian Journal of Earth Sciences*, 44: 1087-1110.
- Hollings, P., Smyk, M.C. and Carl, C. 2010. Geochemistry of Midcontinent Rift-Related Dikes on the Sibley Peninsula, Thunder Bay: A Preliminary Report; Summary of Field Work and Other Activities 2010, Ontario Geological Survey, Open File Report 6260, p.10-1 to 10-3.
- Sun, S. and McDonough, W., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. *Magmatism in the Ocean Basins*. Geological Society, Special Publication No. 42, pp. 313-345.

Mesoproterozoic bedrock in the Kadunce River Quadrangle, NE Minnesota—Precambrian Research Center capstone

Eric J. Carlson, Terrence J. Boerboom, Corey J. Holton, Kyle W. Kubitza, Lucy Mulvey, and Eric Scheurer

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

The Precambrian Research Center (PRC) field camp culminates in several ‘capstone’ mapping projects located in different geological terranes in northeastern Minnesota. One of the 2010 PRC capstone projects was focused on mapping an area within the Midcontinent rift system, mainly in lava flows that are part of the North Shore Volcanic Group, intruded by thin diabase dikes and sills likely related to the Beaver Bay Complex. The mapping crew consisted of 4 students (Carlson, Holton, Kubitza, and Scheurer), one teaching assistant (Mulvey) and an instructor (Boerboom). After a day of orientation the students/TA/instructor were broken into three pairs who mapped independently, and the pairings were switched on a daily basis. Since this capstone had the luxury of staying indoors, all outcrop data (outcrop areas, structure, lithology, etc.) was entered into a GIS database file each evening.

This capstone project was chosen to augment a concurrent mapping project by the Minnesota Geological Survey in the Kadunce River 7.5’ quadrangle, which is located on the shore of Lake Superior just east of Grand Marais (figure 1). The information and geologic interpretations obtained by this capstone project were incorporated into a geologic map published by the Minnesota Geological Survey (Boerboom and Green, 2011).

Most of the exposures within this capstone project area are located either on the shore of Lake Superior, or in the many small streams which are incised into the adjacent highlands. Bedrock is well exposed in these streams, particularly on the slopes that face Lake Superior, affording an excellent opportunity to view flow features within the strata of the lava flows. Outside of the stream valleys outcrops are restricted to scattered exposures in topographically high areas, which are typically overgrown clearcuts of various generations. All of the students had a turn locating not only the sporadic outcrops, but also ourselves, in the highland bush country.

The map area is dominated by felsic lava flows, including the Devil Track and Maple Hill rhyolites, the Kimball Creek rhyolite, and the Kadunce icelandite. In addition to these felsic flows, the map area included the entire thickness of the Red Cliff basalt flows, and the uppermost basalt flow of the Marr Island lavas, a thick series dominated by volcanic rocks of andesitic composition that also includes some thinner flows of tholeiitic basalt. The stratigraphy of the volcanic pile is more or less perpendicular to the trend of the stream valleys, which enabled us to correlate map units from one stream to the next.

One of the challenges was the seemingly simple task of differentiating the Kadunce icelandite from the overlying Kimball Creek rhyolite, since both have very similar macroscopic textures with nearly identical phenocryst assemblages and only subtle variations in the textures of the matrix. As mappers we learned to identify volcanic flow features such as amygdaloidal flow tops, pipe vesicles, etc., and subsequently identified several flow contacts within the individual units. During the map compilation stage we were supplied aeromagnetic data that was used to infer the extension of small diabase dikes exposed in the river channels; however we were slightly overzealous in using the magnetic data and did end

up accidentally incorporating some areas of known volcanic exposures into the diabase dike units. Data collected during field work, including outcrop locations, lithology, structure, flow contacts, etc., was digitized using Arcmap software, which was also used for construction of the final geologic map.

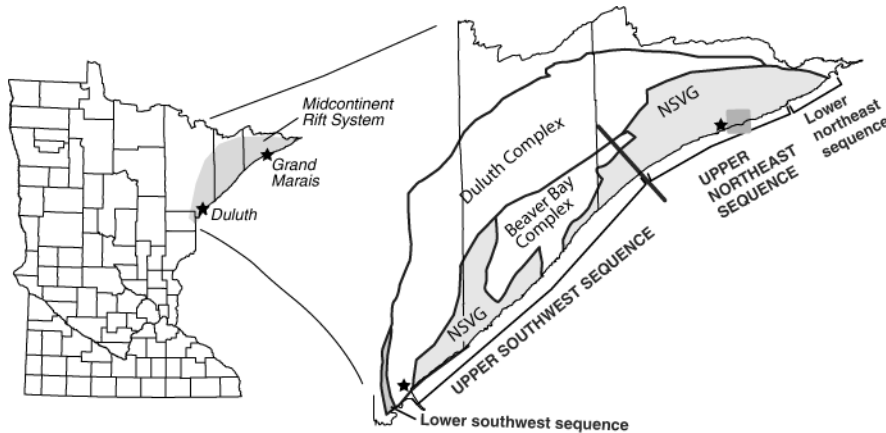


Figure 1 (left). Location map showing the extent of the Keweenawan Midcontinent Rift System in Minnesota, and the locations of the capstone mapping project (Kadunce River quadrangle).

REFERENCE

Boerboom, T.J., and Green, J.C., 2011, Bedrock geology of the Kadunce River quadrangle, Cook County, Minnesota: Minnesota Geological Survey Miscellaneous Map Series Map M-190, scale 1:24,000.

Characterization of precious metal occurrences in the NorthMet deposit of the Partridge River Intrusion, Duluth Complex, Minnesota, USA

Dan Cervin¹, Penny Morton¹, Jim Miller¹, and Richard Patelke²

¹ *Department of Geological Science, University of Minnesota Duluth, Duluth, MN, 55812*

² *PolyMet Mining, PO Box 475, County Road 666: Hoyt Lakes, MN 55750*

The NorthMet deposit is a Cu-Ni-PGE magmatic sulfide ore body located along the northwestern margin of the Partridge River Intrusion (PRI), which is part of the 1.1 Ga Duluth Complex. PolyMet Mining Company is currently seeking a permit to develop an open pit mine at the site, which is about 7 miles south the town of Babbitt, MN. During pilot-plant test runs by PolyMet, approximately 75% of the total mass of precious metals (mostly Pd, Pt, Au) known to exist from assay data were recovered; total sulfide recovery was 90%. In a sulfide flotation beneficiation process, it is assumed that precious metals are contained within sulfide minerals as small (micron-sized) platinum group minerals (PGM), as Au-Ag minerals and alloys, or in solid solution. The 75% recovery implies that many precious metal mineral and alloy phases (PMM) may not be hosted by sulfide minerals.

Building on a summary report of PGM occurrences in the Duluth Complex by Severson and Hauck (2003), this study seeks to more completely characterize the mineralogical and textural occurrences of PMM in the NorthMet ore feed and concentrates. This information is not only of importance to the beneficiation of NorthMet ores, but also to the understanding of the metallogenesis of PGE-Au in magmatic sulfide deposits. The energy dispersive spectrometer-equipped scanning electron microscope at University Minnesota Duluth was used in backscatter electron composition mode (BEC) to conduct detailed compositional scanning of polished thin sections to locate PMM.

As the 75% precious metal recovery would predict, NorthMet PMM primarily occur in association with sulfide minerals. Of the 347 PMM investigated in this study, 234 (67%) were hosted by sulfide minerals (mostly chalcopyrite and pentlandite), either as inclusions or at sulfide grain boundaries (Fig. 1). The remaining 33% (133) of PMM were found in a variety of primary silicates, secondary silicates, and apatite (Fig. 1). Forty-four percent of sulfide-hosted PMM are located at sulfide grain boundaries, 56% occur as inclusions in sulfide. However, 3D studies by Godel et al. (2010) indicate that most PGM observed as inclusions in sulfides in 2D studies are in fact boundary occurrences. Boundary PMM are susceptible to isolation from a sulfide host by silicate alteration minerals, these isolated PMM are presumably unrecoverable by sulfide flotation beneficiation processes. The preliminary conclusions of this study are:

1) The lower recoveries of precious metals relative to base metals in NorthMet ores is largely due to PMM boundary occurrences being lost to tailings because they are isolated in gangue minerals or are broken off of sulfide grains during comminution.

2) The occurrence of PMM in secondary silicates (chlorite, amphibole, sericite) that appear to be replacing sulfide minerals implies that PGM-Au-Ag can be isolated from a sulfide host by post-magmatic deuteric fluids causing sulfide dissolution.

3) PMM that appear to be hosted in primary silicates occur in very close association with fine-grained, interstitial sulfide minerals (generally <0.5 mm distant). Many PMM that appear to be hosted in primary silicates in SEM BEC images most likely have a sulfide association that is not always apparent in 2D SEM imagery. A preliminary spot check of primary silicate PMM occurrences with transmitted and reflected light microscopy indicates

that sulfides, which are not visible in SEM images, are visible as opaque minerals below the surface of the polished thin sections. Additional petrographic study is needed to confirm whether PMM actually occur in primary silicates without associated sulfide or secondary minerals, for if this is the case, this would have profound implications for the metallogenesis of PGE.

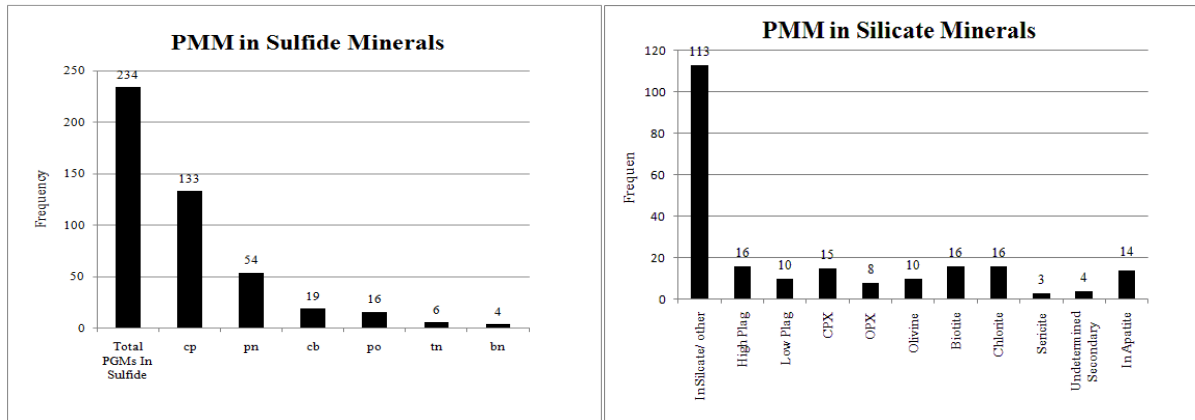


Figure 1: Frequency of PMM occurring in various types of sulfide and silicate minerals in NorthMet ores; cp=chalcopyrite, pn=pentlandite, cb=cubanite, tn=talnakhite, bn=bornite; High Plag= An >60, Low Plag=An <60, cpx=clinopyroxene, and opx=orthopyroxene.

REFERENCES

- Godel, B., Barnes, Sara J., Barnes, Stephen J., Maier, W.D., 2010, Platinum Ore in Three Dimensions: Insights from High Resolution X-ray Computed Tomography; *Geology*, v. 38, no. 12, pp.1127-1130.
- Severson, M., Hauck, S., 2003, Platinum Group Elements and Platinum Group Minerals in the Duluth Complex, Natural Resources Research Institute Technical Report NRRI/TR-2003/37, University Minnesota Duluth, 312 p.

Application of the horizontal-to-vertical spectral ratio (H/V) passive seismic method in Minnesota

Val W. Chandler and Richard S. Lively

Minnesota Geological Survey, 2642 University Ave., St. Paul, MN 55114

chand004@umn.edu

Determining the thickness of unconsolidated materials over bedrock is a common and sometimes difficult geologic problem. It is especially difficult in areas of Minnesota where glacial deposits may be over 200 meters thick and few drill holes penetrate to bedrock. Test drilling in such deep sediment can be prohibitively expensive, seismic soundings can also be slow and costly, and most electrical resistivity methods do not penetrate deeply enough. Recent technological advances in seismometers has opened a window for passive seismic data acquisition, also known as the horizontal-to-vertical -spectral ratio method (HVSr or H/V). This method relies solely on ambient seismic noise, and shows great promise for rapidly and inexpensively estimating the thickness of unconsolidated deposits over bedrock.

The H/V method uses continuous, background vibrations in the subsurface to estimate the fundamental resonant frequency of a layer of unconsolidated materials. Data collection and processing was developed (largely in Europe) to delineate areas of high-risk for earthquake damage (SESAME, 2004). If the acoustic impedance (density*seismic velocity) at the overburden-bedrock contact differs by a factor of at least 2, the thickness (Z) of the unconsolidated materials can be estimated by the relationship:

$$Z=af_0^b$$

Where f_0 is the fundamental resonant frequency (for shear waves) of the unconsolidated sequence, and a and b are parameters that are empirically determined for a given region.

Although the theory behind the H/V method is still developing, it appears that the behavior of shear waves (transversely vibrating body waves) and Rayleigh waves (backward-rolling surface waves) near the fundamental resonant frequency of the overburden layer are the principal components. At this frequency, the horizontal component of shear waves tend to maximize and the vertical component of Rayleigh waves tend to minimize. When the average horizontal spectrum of seismic noise is divided by the corresponding vertical spectrum, a pronounced peak results at the resonant frequency. This resonant frequency is used in the above equation to compute an overburden thickness.

In Minnesota, passive seismic data have been acquired at over 180 sites in northeastern, east-central, and southeastern parts of the state, with encouraging results. Through analysis of data from 34 sites with bedrock control from drill holes, we have obtained parameters for the above equation ($a=130.96$, $b=-1.3304$) specific to Minnesota. Estimates from the data of depth to bedrock have an error of 15-20% over depths ranging from a few meters to greater than 150 meters.

We have found that the H/V method must be used with appropriate caution. For example, some relatively poor H/V results are obtained in parts of southwestern Minnesota, where thick regolith and unusually dense tills may complicate the simple, sharply contrasting 2-layer model that is preferred for this kind of analysis. Although, the H/V method cannot match seismic refraction profiling for overall accuracy and amount of derived information

per line, the advantage of passive seismic is seen in rapid data collection, low field deployment costs, and ease of data analysis. For example, at a bedrock depth of around 500 feet, H/V depth estimates are obtained within 20 minutes, and are accomplished by a single individual and possibly a vehicle. In comparison, only one or two seismic refraction soundings per summer day would be possible at these depths, and this usually with a crew of 3-4 individuals, at least two large vehicles, and an energy source. Finally, a 3 component, broadband seismograph that is designed for H/V surveying is small, light weight and costs a fraction of that required for a conventional multi-channel seismic profiling system. All things considered the H/V method should prove to be a powerful tool for geologic and depth to bedrock studies, and geo-engineering investigations in the Lake Superior region.

ACKNOWLEDGEMENTS

Professor Justin Revenaugh at the University of Minnesota, and the IRIS consortium generously supported the pilot stages of this study in various ways and information on equipment and techniques from John Lane of the U.S. Geological Survey is greatly appreciated. This study was supported by the Minnesota Legislature through the County Geologic Atlas Program of the Legislative and Citizens Commission on Minnesota Resources. Additional support was through the State Special Appropriation of the Minnesota Geological Survey.

REFERENCES

SESAME (Seismic Effects assessment using Ambient Excitations), 2004, Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations. Measurements, processing and interpretation, WP12 European commission - Research general directorate project no. EVG1-CT-2000-0026 SESAME, report D23.12, 62 pp.

Upgrade of the gravity and rock properties databases at the Minnesota Geological Survey

Val W. Chandler and Richard S. Lively

Minnesota Geological Survey, 2642 University Ave., St. Paul, MN 55114

chand004@umn.edu

Gravity and rock property data have been a significant resource for geological investigations in Minnesota. Used in conjunction with the upgraded, aeromagnetic database, the gravity and rock property data at the Minnesota Geological Survey (MGS) have been foundational to mapping of Precambrian bedrock geology. During 2009-2011 the MGS has upgraded these databases, with significant additions of new and preexisting data that have become available over the last decade as well as improving the location information for better usage in a digital environment.

Much of the upgrade of the gravity database involved relocating stations with subsequent recalculation of the Bouguer Anomaly. Many of the older stations had location errors of 200 meters or more made when the data was originally digitized from the field maps. Field numbers and other logistical information were lost during this early digitization. To remedy this, the original gravity location data were imported into an ArcGis environment. The points were compared with locations shown on the original field maps, which were usually located at spot elevations. The point locations were moved to match what was shown on the field maps. The original station numbers were also restored and, if available, other information was added, including observers, date of acquisition, and the meter that was used. If the field materials were missing, the stations were at least moved to their most likely position along roads and trails. The re-computed Bouguer anomaly values equate to differences of up to 0.15 milligals for most of the pre-existing stations, although differences up to 0.25 milligal error exist for some of the oldest stations. In addition 2,000 new gravity stations were added to the database. Of these, 878 stations were acquired at spacings of 100-250 meters in 1979 along seismic reflection lines in west-central Minnesota. The remaining stations were acquired in 2003-2010 as part of various Statemap and County Atlas mapping in northeastern and southwestern Minnesota. Many of these latter stations lie within large coverage gaps in the earlier data.

The rock properties database has been expanded from 4161 to over 8800 entries. The new database includes determinations for over 5125 densities, 6890 magnetic susceptibilities, and 980 measurements of Natural Remnant Magnetization (NRM). Most entries are based on individual measurements from hand or core samples. The new density data also include 739 determinations that were based on seismic refraction velocities. These produce density estimates for materials that were underrepresented in the previous release, including glacial deposits, Cretaceous rocks, Paleozoic rocks, and Keweenawan sandstones. In addition, results from cuttings and core samples acquired by previous investigators resulted in several thousand magnetic susceptibility and several hundred density measurements being added to the database. Finally, the location of many rock property sample sites have been improved through GIS overlays with detailed topographic bases and precisely mapped locations of outcrop.

The upgraded gravity and rock property databases, which are web-accessible, represent a significant improvement over the previous available versions. They should serve the needs of the MGS and the broader geological community for many years to come.

ACKNOWLEDGEMENTS

University of Minnesota students Jack Barland and Roger Morrison provided valuable assistance throughout much of the data compilation. This study was supported by the Minnesota Legislature through the Minerals Coordinating Committee and the Minnesota Department of Natural Resources.

Possible eukaryotic macrofossils in the 1.1 Ga Copper Harbor Formation, Michigan

Katherine Cummings and Marcia Bjørnerud

Geology Department, Lawrence University, 711 E Boldt Way, Appleton WI 54911

bjornerm@lawrence.edu

Unusual and possibly biogenic cm-scale features have been found on the bedding plane of a siltstone layer within the ca. 1.1 Ga Copper Harbor Formation, the lowermost of the rift-filling sedimentary units of the Midcontinent Rift. The Copper Harbor Formation includes cobble- to boulder-conglomerates, sandstones, siltstones and mudstones, representing alluvial fan, braided stream, and ephemeral lake environments within the axial valley of the Midcontinent Rift (Elmore 1984). Calcified cabbage-sized stromatolites occur at several horizons in the upper part of the Copper Harbor formation; some of these grew on top of a substrate of mud, while others encrusted cobbles and boulders (Elmore, 1984; Planavsky and Bjørnerud, 2006).

The newly discovered features were found in a siltstone layer between two stromatolitic horizons at Horseshoe Harbor, near Copper Harbor, Keweenaw County, Michigan. In plan view, the enigmatic features are circular to slightly elliptical with a diameter of 0.3-1.0 cm (Fig.1). Many have a transecting lenticular element or septum that cuts across them in a 'theta' geometry. These septa lie at random orientations in the ca. 25 x 30 cm bedding plane slab in which more than 50 of the features were found.

In cross section, the features are funnel-shaped, narrowing downward to a blunt tip. In several of the features, the funnel terminates in a mm-scale crystal of calcite (Fig 2). Finer calcite cements the fine-grained material in the interior of the features and also defines the edges of the funnel shapes. Petrographic and XRD analyses indicate that the rest of the interior material is silt-sized quartz and feldspar together with minor clay (halloysite) and iron oxides, the same minerals found in the surrounding rock. SEM imaging of the material inside and outside the features similarly revealed no obvious differences in grain size or texture. Some of the funnel-shaped elements have a crude layering defined by iron oxides, but it is not easily traceable from the enclosing rock. The layering could either be primary or a product of post-depositional pressure dissolution.

These features do not resemble any common sedimentary or diagenetic structures. They are unlikely to be dewatering structures since there is no evidence of 'soft-sediment' distortion of the surrounding layering. Their consistent and unusual shapes make it seem unlikely that they are concretions or similar structures.

A National Academy of Sciences workshop (Knoll, 1999) proposed the following criteria for identifying microbial fossils in Precambrian rocks: 1) *Provenance* [the source and geologic context of the parent rock must be firmly established]; 2) *Age* [the parent rock must have a reasonably well constrained age]; 3) *Indigenosity* [the features must be embedded in the rock matrix]; 4) *Syngenicity* [the features must have been formed at the same time as the parent rock]; and 5) *Biogenicity* – the features must be definitively biological. The features from the Copper Harbor Formation meet the first four of these criteria; the last, of course, is the most difficult to establish unambiguously.

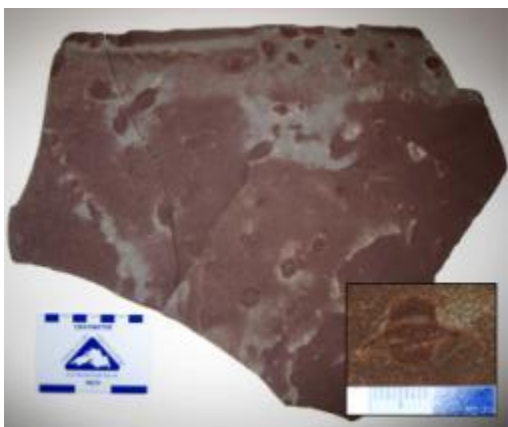


Fig. 1: The siltstone slab with unusual bedding plane features. Lower right: Close-up of one feature, highlighting the transecting element.

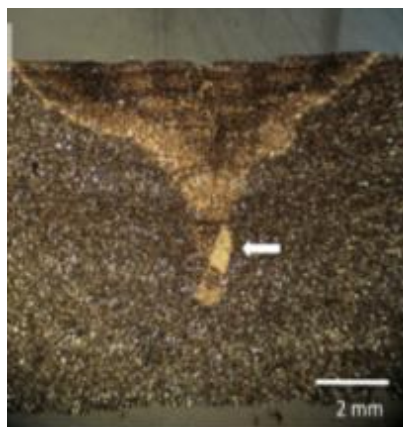


Fig. 2: Thin section (cross-polarized light) of one of the features in cross section, showing calcite crystal at terminal end of the funnel (arrow).

If they are biogenic, it seems most likely that the features represent either body or trace fossils of a eukaryotic organism (Andrew Knoll, personal communication, 2010). They are far too large to have been formed by single prokaryotes, and their symmetry and consistent geometry would seem improbable for colonies of individuals.

Eukaryotic organisms were diverse and well-established by Mesoproterozoic time in the marine realm, but there are fewer reports of eukaryotic terrestrial biota (Knoll et al. 2006). Fedonkin and Yochelson (2002) described fossils of colonial eukaryotes on bedding surfaces of freshwater siltstones within the 1.5 Ga Appekunny Fm. of the Belt Series in Montana. In a study of the 1.1-1.2 Ga Torridonian sequence of Scotland, similar both in age and depositional setting to the Copper Harbor Formation, Prave (2002) argued for a diverse terrestrial fluvial and lacustrine ecosystem, based on extensive and well-preserved microbial crusts and evidence for unusually cohesive sandy sediment.

The Copper Harbor stromatolites indicate that in spite of the high-energy sedimentary environment, there was an active lacustrine ecosystem within the valley of the Midcontinent Rift at ca. 1.1 Ga, perhaps seeded via wind transport of dormant reproductive structures (Planavsky and Bjørnerud, 2002). The newly discovered features described here may indicate an even greater degree of biodiversity than previously recognized. The Midcontinent Rift is already renowned for its unparalleled volcanic effusion rates and world-class copper deposits; perhaps it should also be re-examined for clues to the early colonization of the continents by Life.

REFERENCES

- Elmore, R., 1984. The Copper Harbor Conglomerate: A late Precambrian fining-upward alluvial fan sequence in northern Michigan. *Geol. Soc. America Bulletin* 95, 610-617.
- Fedonkin, M., & Yochelson, E., 2002. Middle Proterozoic 1.5 Ga *Horodyskia moniliformis*: Oldest Known Tissue-Grade Colonial Eucaryote. *Smithsonian Contrib. Paleobiology* 94.
- Knoll, A., ed., 1999. *Size Limits of Very Small Organisms: Proceedings of a Workshop*. Washington, D.C: National Academy Press. 164 pp.
- Knoll, A., Javaux, E., Hewitt, D., and Cohen, P., 2006. Eukaryotic organisms in Proterozoic oceans. *Philosophical Transaction of the Royal Society* 361, 1023-1038.
- Planavsky, N., and Bjørnerud, M., 2004. Blowing in the Wind: The Copper Harbor stromatolites revisited. *Proceedings of the Institute on Lake Superior Geology* 50, 137-138.
- Prave, A., 2002. Life on land in the Proterozoic: Evidence from the Torridonian rocks of northwest Scotland. *Geology* 30, 811-814.

Compilation and reevaluation of the geochemistry of Midcontinent Rift related intrusive rocks around Thunder Bay, Ontario

Robert Cundari¹, Peter Hollings¹, and Mark Smyk²

¹*Department of Geology, Lakehead University 955 Oliver Road Thunder Bay, ON P7B 5E1 Canada*

²*Ontario Geological Survey, Ministry of Northern Development, Mines and Forestry, Suite B002, 435 James St. South Thunder Bay, ON P7E 6S7 Canada*

Recent geochemical, geochronological, and geophysical data have provided further insight into the relationship of Midcontinent Rift (MCR)-related intrusive units south of Thunder Bay (e.g. Hollings et al., 2010). These data have shown that the intrusive relationships are more complicated than previously thought and further work is needed in order to understand these relationships and put them in context within the MCR. The initial phase of this study will: 1) identify the issues surrounding the intrusive units within the study area and how they may potentially be resolved; and 2) present preliminary findings of a geochemical compilation for MCR rocks in Canada, with particular focus on indices of fertility for Ni-Cu-PGE deposits.

Mapping focused around the Arrow River has revealed an extension of the recently recognized Devon basalts (Cundari, 2010). Outcrops on the western bank of the Arrow River exhibited an amygdaloidal texture and a cracked “elephant skin” flow-top texture similar to Devon basalt outcrops observed ~4 km to the west, suggesting that the unit may be significantly more extensive than previously recognized. A $\text{La}/\text{Sm}_{\text{cn}}$ ratio of 2.98 and a $\text{Gd}/\text{Yb}_{\text{cn}}$ ratio of 3.13 are well within the range ($\text{La}/\text{Sm}_{\text{cn}} = 2.6$ to 3.1 ; $\text{Gd}/\text{Yb}_{\text{cn}} = 3.0$ to 3.4) for the unit (Cundari, 2010), supporting this interpretation. Digital elevation models will also be generated in order to help correlate laterally extensive volcanic units and sills.

Additional geochemistry and reinterpretation of geological maps suggest that a broadly northeast-trending dyke swarm, hitherto collectively termed Pigeon River dykes, may in fact comprise two distinct trends: one trending northeast and the other trending east-northeast. Dating by Heaman et al. (2007) revealed a considerable range of ages for Pigeon River dykes (i.e. east-northeast-trending 1078 ± 3 Ma Arrow River dyke and the northeast-trending 1141 ± 20 Ma Rita Bolduc dyke), suggesting that it may be possible to subdivide the Pigeon River swarm. Although preliminary data suggest that there are no significant geochemical variations between the two orientations, closer examination of the geochemistry, as well as additional detailed field work, is planned to further investigate this question.

A detailed compilation of existing data sets, comprising ~2400 data points of spatially referenced samples with whole rock geochemical analyses (including ~800 samples with fire assay PGE data), has been undertaken. This database represents all major MCR units in Canada and is currently being analyzed in order to investigate geochemical variations in these rocks. Only preliminary interpretations of these data sets have been undertaken (e.g. Hollings et al., 2007a, 2010). Detailed study of these data sets will be conducted, particularly in regard to PGE mineralization. Preliminary observations suggest that Logan sills display broadly higher Cu/Pd ratios than those of the Nipigon sills, the Osler volcanic rocks and the ultramafic intrusions of the Nipigon Embayment (Figure 1). Samples from a detailed traverse through the Osler Group stratigraphy undertaken by Hollings et al. (2007b) have been

reanalyzed for PGE in order to look for detailed variation in one of the few MCR-related sequences in Canada where the stratigraphy is well-understood. This study will allow for investigations in PGE distribution over a ~3 million-year interval and the implications for possible Cu-Ni-PGE mineralization.

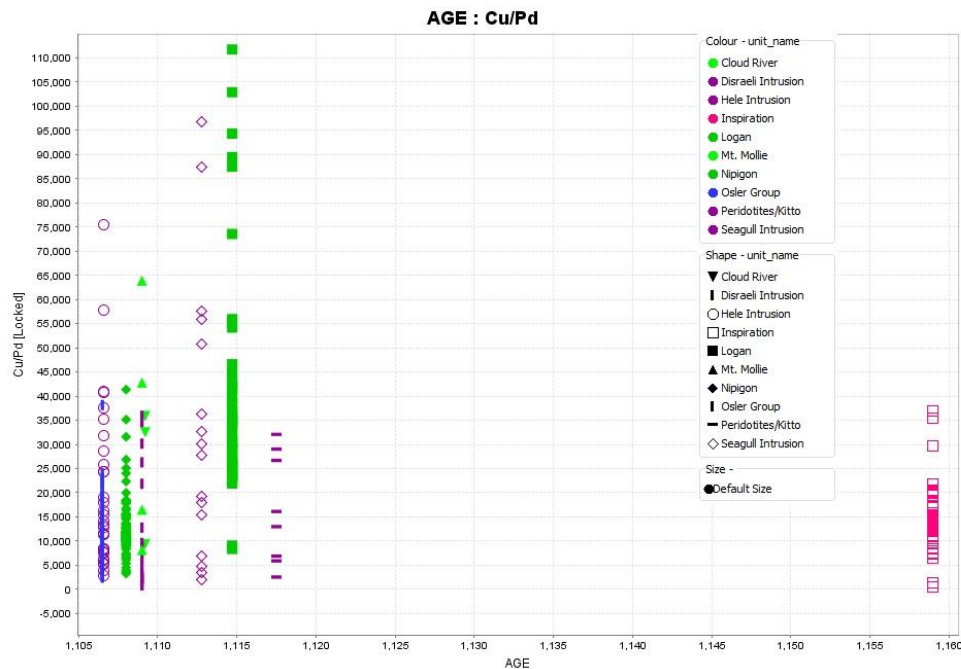


Figure 1: Age versus Cu/Pd graph. Median age dates were taken from Heaman et al. (2007).

REFERENCES

- Cundari, R. 2010. The Geology and Geochemistry of the Devon Volcanics, South of Thunder Bay, Ontario. Unpublished honours thesis. Lakehead University, 62p.
- Heaman, L.M., Easton, R.M., Hart, T.R., Hollings, P., MacDonald, C.A., Smyk, M., 2007. Further refinement to the timing of Mesoproterozoic magmatism, Lake Nipigon Region, Ontario. *Canadian Journal of Earth Sciences* 44, p.1055–1086.
- Hollings, P., Hart, T., Richardson, A., MacDonald, C.A., 2007a. Geochemistry of the Mesoproterozoic intrusive rocks of the Nipigon Embayment, northwestern Ontario: evaluating the earliest phases of rift development. *Canadian Journal of Earth Sciences* 44, p.1087–1110.
- Hollings, P., Fralick, P., Cousens, B., 2007b. Early history of the Midcontinent Rift inferred from geochemistry and sedimentology of the Mesoproterozoic Osler Group, northwestern Ontario. *Canadian Journal of Earth Sciences* 44, p.389–412.
- Hollings, P., Smyk, M., Heaman, L.M., and Halls, H., 2010. The geochemistry, geochronology, and paleomagnetism of dikes and sills associated with the Mesoproterozoic Midcontinent Rift near Thunder Bay, Ontario, Canada. *Precambrian Research*, v.183, Issue 3, p.553- 571.

The geochemical evolution of the Sonju Lake intrusion: an assimilation-fractional crystallization model

Dayton, R.N.^{1*}, Miller, J.D.¹, and Vervoort, J.D.²

¹Department of Geological Sciences, University of Minnesota Duluth, Duluth, MN 55812 USA

²School of Earth and Environmental Sciences, Washington State University, Pullman, WA 99164, USA

The Sonju Lake Intrusion, located within the Beaver Bay Complex near Finland, MN, is the most completely differentiated intrusion related to the Midcontinent Rift System (Stevenson, 1974; Wieblen, 1982). The Sonju Lake intrusion exhibits a cumulate stratigraphy consistent with closed system differentiation of tholeiitic magma by fractional crystallization (Stevenson, 1974; Miller et al., 1993; Miller and Ripley, 1996). The Finland granite, composed of micrographic-textured ferromonzonite to leucogranite, forms the hanging-wall to the Sonju Lake intrusion. Field relationships from outcrop and drill core through the Sonju Lake intrusion and the overlying Finland granite show a cyclic to irregularly gradational contact. This relationship, the smooth compositional variations across the felsic-mafic contact, and the parallel zonation of the two subunits of the Finland granite with the strike of the mafic cumulates of the Sonju Lake intrusion are consistent with the Finland granite being a late stage felsic differentiate of the Sonju Lake intrusion (Miller and Green, 2002; Miller and Ripley, 1996). However, geophysical modeling of gravity and aeromagnetic data implies a volume of granophyre that approaches that of the Sonju Lake intrusion and therefore greatly exceeds the volume of felsic material that could be accounted for by differentiation of a mafic body of that size (Miller et al., 1990).

Miller and Ripley (1996) suggested that the Finland granite was emplaced first and acted as a density barrier to the upward movement of the mafic Sonju Lake magma. Since underplating of the mafic magma would be expected to cause melting in the lower portions of the Finland granite, the lithologically and chemically gradational contact between the two bodies might instead represent a mixing zone between the mafic magma of the upper Sonju and the partially melted base of the Finland granite. The major and minor element geochemistry of the Finland granite resembles an extreme differentiate of the Sonju Lake intrusion and precludes using lithogeochemical data to evaluate the extent of mixing between mafic and felsic magmas. However, because the granite has an isotopic signature that is distinct from the mafic rocks of the Sonju (Vervoort et al., 2007, and this study), a radiogenic isotope study has a better chance of assessing the extent of assimilation of the partially melted Finland granite by the Sonju Lake intrusion and the effect of this assimilation on the compositional evolution of the well differentiated Sonju Lake intrusion.

The Finland granite and Sonju Lake intrusion have distinct and identifiable isotopic compositions of Nd. Samples from the leucogranite range from -3 to -3.6 ϵ_{Nd} at 1096 Ma with an average of -3.4 ϵ_{Nd} for five samples (Vervoort and Green, 1997, Vervoort et al., 2007, this study). Samples from the Sonju Lake intrusion, below the cumulus arrival of apatite, range from 1.47 to -1.62 ϵ_{Nd} . The rocks above and including the uppermost cumulate layer of the Sonju Lake intrusion consistently exhibit decreasing values of ϵ_{Nd} with increasing stratigraphic height closer to the Finland granite. If the consistent isotopic signature of the leucogranite (-3 to -3.6 ϵ_{Nd}) is taken as the initial ϵ_{Nd} of the Finland granite as a whole, it is clear that the underlying quartz ferromonzodiorite, with ϵ_{Nd} compositions of -1.7 to -2, contains a more radiogenic Nd component attributable to the Sonju Lake intrusion.

The quartz ferromonzodiorite may be a late-stage differentiate of the Sonju Lake intrusion that assimilated non-radiogenic Nd from the Finland granite. An assimilation-fractional crystallization model is presented to evaluate Nd isotopes in the upper portions of the Sonju Lake intrusion and overlying Finland granite (Fig. 1). Anomalous negative ϵ_{Nd} values for samples from the SLI-1 core that profiles the felsic-mafic contact west of the main exposure area are enigmatic.

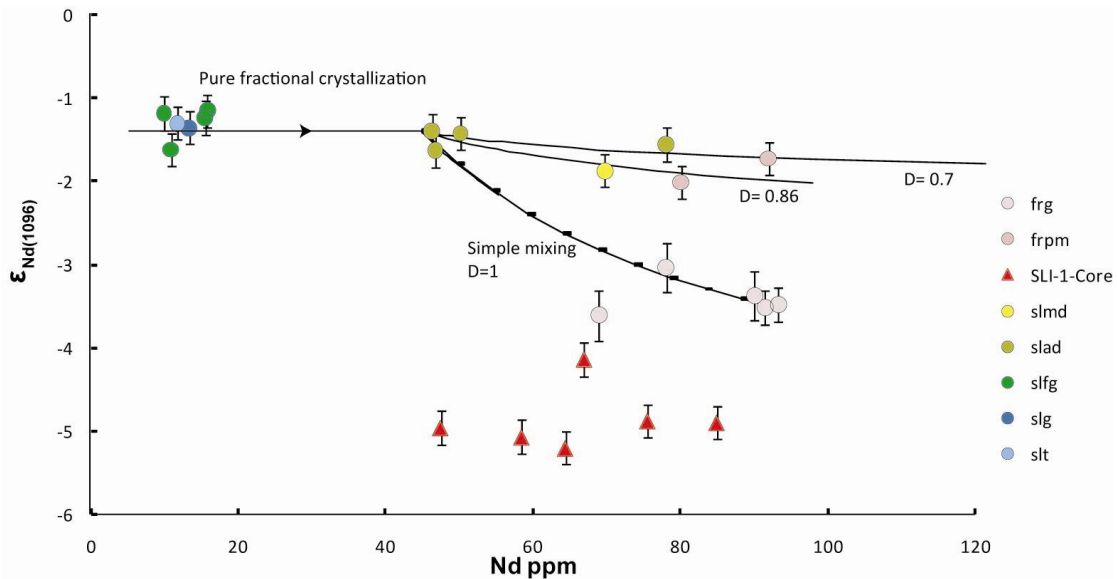


Figure1. Concentration of Nd vs. $\epsilon_{\text{Nd}(1096)}$ showing AFC model curves and simple mixing curve for identical end members. Ticks on mixing curve are 10% increments.

REFERENCES

- Miller, J.D., Jr, Schaap, B.D., and Chandler, V.W., 1990, The Sonju Lake intrusion and associated Keweenaw rocks: Geochemical and geophysical evidence of petrogenetic relationships. 36th Annual Institute on Lake Superior Geology, p. 66–68.
- Miller, J.D., Jr., Green, J.C., Chandler, V.W., and Boerboom, T.J., 1993, Geologic map of the Finland and Doyle Lake quadrangles, Lake County, Minnesota. Minnesota Geological Survey Miscellaneous Map Series M-72, 1:24,000 scale.
- Miller, J.D., Jr., and Ripley, E.M., 1996, Layered intrusions of the Duluth Complex, Minnesota, USA. in Cawthorne, R.G. (ed.): Layered Intrusions: Amsterdam, Elsevier, p. 257–301.
- Miller, J.D., Jr., Green, J.C., 2002. Geology of the Beaver Bay Complex and related hypabyssal intrusions. in Miller, J.D. Jr., Green, J.C., Severson, M.J., Chandler, V.W., Hauck, S.A., Peterson, D.E., and Wahl, T.E., 2002, Geology and mineral potential of the Duluth Complex and related rocks of northeastern Minnesota. Minnesota Geological Survey Report of Investigations 58, pp. 106–143
- Stevenson, R.J., 1974. A mafic layered intrusion of Keweenaw age near Finland, Minnesota. M.S. Thesis, University of Minnesota Duluth, 160 pp.
- Vervoort, J.D., Wirth, K., Kennedy, B., Sandland, T., and Harpp, K.S., 2007. The magmatic evolution of the Midcontinent rift: new geochronologic and geochemical evidence from felsic magmatism, *Precambrian Research* 157, p. 235–268
- Vervoort, J.D., Green, J.C., 1997. Origin of evolved magmas in the Midcontinent rift system, northeast Minnesota: Nd-isotope evidence for melting of Archean crust. *Canadian Journal of Earth Science*. 34, p. 521–535.
- Weiblen P.W., 1982, Keweenaw intrusive igneous rocks. Geological Society of America Memoir 156, p. 57–82

The uptake of lead by *Brassica rapa*; implications for hunting in agricultural fields

Maverick Deschamp and Jennifer McGuire

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

According to the Center for Disease Control and Prevention, about 1 in 22 children in America have high levels of lead in their blood. Research has shown that the long-term effects of elevated concentrations of lead in the blood of children can be severe including learning disabilities, decreased growth, hyperactivity, impaired hearing, and brain damage. In 1987 Minnesota banned the use of lead shot for hunting waterfowl because it concluded that the use of lead shot was killing waterfowl and poisoning their predators. However, lead is used in other forms of hunting and thus may also be significant in the environment suggesting it should also be removed from use. To test this hypothesis, I grew *Brassica rapa*, a fast growing wild mustard plant, exposed to varying amounts of lead in its soil. The contamination was lead shot that would be commonly used in hunting and recreational shooting. In total, 10 plants were grown to maturity with lead ranging from 0-20 grams per pot. The plants and the soil from which they were grown, with remaining lead shot removed, were then digested using EPA method 3050B, a rigorous hydrochloric and nitric acid digestion that accesses all environmentally available elements, and analyzed using an ICP-AES. The data shows that the plants and soil increased in total lead corresponding with the amount of lead per pot. This result shows that with increased lead present, the plants and soil become enriched in lead and potentially pose a greater risk to consumers.

Quantifying deformation fabrics and chemistry across small granitic ductile shear zones from Mountain, Wisconsin

Michael A. DeVasto¹, Dyanna M. Czeck¹, Prajukti Bhattacharyya²

¹Dept. of Geosciences, University of Wisconsin-Milwaukee, P.O. Box 413, Milwaukee, WI 53201.

²Dept. of Geography and Geology, University of Wisconsin-Whitewater, Upham 119, Whitewater, WI 53190

INTRODUCTION

Deformation processes in ductile shear zones can be profoundly affected by the presence of fluids (Wawrzyniec et al., 1999). Fluid-rock interaction also has potential for causing volumetric changes in shear zones, which are important to consider during kinematic analyses (Ramsay and Graham 1970). The purpose of our study is to develop a way to systematically and quantitatively describe textural and chemical changes across small-scale ductile shear zones, which may be indicative of the presence of fluids during deformation.

The small (cm scale) shear zones in deformed granite of the Mountain Shear Zone (MSZ) in Mountain, Wisconsin are ideal for this study for a variety of reasons. 1) Sims et al. (1989) conducted a detailed study of the MSZ, allowing for a more detailed structural analysis. 2) Granite is an excellent rock to study microtextures due to its isotropy and simple mineralogy and chemistry. 3) The scale of these shear zones is ideal for a high resolution sampling method in order to achieve a complete geochemical dataset through the strain gradient.

GEOCHEMISTRY

Tracking geochemical changes across the strain gradient can act as an indicator of fluid-rock interactions during deformation and volume loss (Newman and Mitra, 1992; Yonkee et al., 2003). Bialek (1999) summarizes the inconsistency in results between many studies, which indicate that ductile shear zones may or may not have significant fluid input and volume change. These inconsistencies may be due to lack of resolution in the chemistry data, which typically are only collected in the protolith and shear zone. Therefore, we plotted individual elemental chemistry, determined through x-ray fluorescence, with respect to distance from the shear zone (Yonkee et al. 2003). This method provides more information than the commonly used isocon method, which lacks spatial relevance and may misrepresent elements with small changes in concentration.

Our granitic shear zones have a variety of geochemical gradients. Preliminary results in one shear zone show relatively no major element chemical changes. Preliminary results in another shear zone from the same outcrop show enrichments in Fe₂O₃, MgO, Al₂O₃ and K₂O with depletion in SiO₂ and Na₂O. CaO, P₂O₅, and TiO₂ concentrations vary along the transect, but show no obvious trend with respect to the shear zone. In comparison, the isocon method indicates minor depletions/enrichments in SiO₂, Fe₂O₃, MgO, and Al₂O₃, whereas other analyzed elements remained “immobile”.

A GIS TECHNIQUE TO QUANTIFY FABRIC FORMATION

Microstructures may be indicative of fluid interaction and localized volume loss, offering a different, yet largely descriptive, approach to studying fluid-rock interaction during

deformation. To completely convey the importance of microstructures there needs to be a method to quantify various features. Li et al. (2008) developed a semi-automatic digitizing model within ArcGIS to improve the ease of tracing crystal grain boundaries. We have expanded the use of this model by applying it to deformed polymineralic rocks. Because this model works within a GIS, we can build a spatial database of microstructural information, including mineralogy and deformation fabrics, which can be queried for statistical and geospatial information. The average nearest neighbor tool is a good example of what even a simple spatial analysis can do. Running this tool yields a plethora of information, most notably the nearest neighbor index (figure 1), which will indicate whether the distribution of grains is statistically either clustered or dispersed. Our data show that quartz and plagioclase are both significantly dispersed outside of the shear zone, yet abruptly change to a “less-dispersed” pattern inside the shear zone.

The significance of this spatial distribution still needs to be determined. This study will help to establish a quantitative method for thin section fabric analysis. Moreover, insight from this information will allow us to find a potential link between textural and chemical analyses in deformed rocks.

REFERENCES

- Bialek, D. 1999. Chemical changes associated with deformation of granites under greenschist facies conditions: the example of the Zawidów Granodiorite (SE Lusatian Granodiorite Complex, Poland). *Tectonophysics* 303, 251-261.
- Li, Y., Onasch, C. M. and Guo, Y. 2008. GIS-based detection of grain boundaries. *Journal of Structural Geology* 30, 431-443.
- Newman, J. and Mitra, G. 1993. Lateral variations in mylonite zone thickness as influences by fluid-rock interactions, Linville Falls fault, North Carolina. *Journal of Structural Geology* 15, 849-863.
- Ramsay, J. G. and Graham, R. H. 1970. Strain variation in shear belts. *Canadian Journal of Earth Sciences* 7, 786-813.
- Sims, P. K., Klasner, J. S. and Peterman, Z. E. 1990. The Mountain Shear Zone, Northeastern Wisconsin –A Discrete Ductile Deformation Zone Within the Early Proterozoic Penokean Orogen. *Geologic Survey Bulletin, Precambrian Geology of Lake Superior Region*, A1-A15.
- Wawrzyniec, T., Selverstone, J. and Axen, G. J. 1999. Correlations between fluid composition and deep-seated structural style in the footwall of the Simplon low-angle normal fault, Switzerland. *Geology* 27, 715-718.
- Yonkee, W. A., Parry, W. T. and Bruhn, R. L. 2003. Relations between progressive deformation and fluid-rock interaction during shear-zone growth in a basement-cored thrust sheet, Sevier orogenic belt, Utah. *American Journal of Science* 303, 1-59.

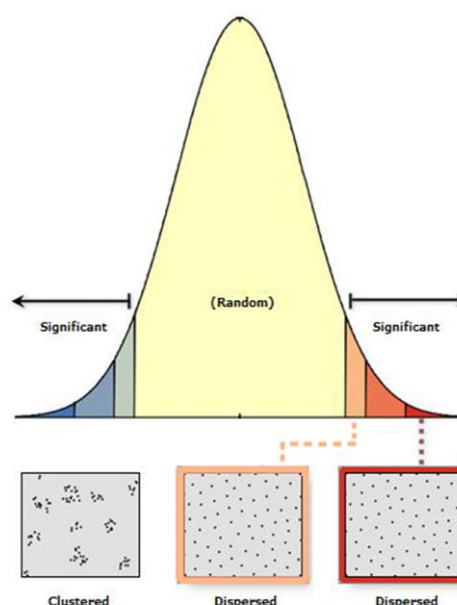


Figure 2: ArcGIS graphical output for the calculated Nearest Neighbor Index. A) corresponds to inside the shear zone. B) corresponds to samples outside of the shear zone.

Detrital zircon geochronology of Matinenda Formation sandstones (Huronian Supergroup) at Elliot Lake, Ontario: Implications for uranium mineralization

R.M. Easton¹ and L.M. Heaman²

¹*Precambrian Geoscience Section, Ontario Geological Survey, Sudbury, Ontario P3E 6B5
mike.easton@ontario.ca*

²*Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta, T6G 2E3
larry.heaman@ualberta.ca*

Between 1956 and 1996, 12 mines in the Elliot Lake camp produced 138,500 tonnes of uranium metal at an average grade of 763 ppm U (900 ppm U₃O₈). The uranium ore was hosted in quartz pebble conglomerate beds within the lower part of the Matinenda Fm near the base of the Paleoproterozoic Huronian Supergroup. The Matinenda Fm is composed almost entirely of trough and planar cross-stratified, greenish to buff, coarse-grained sandstones deposited in a braded fluvial system (Fralick 2003). The ore-conglomerates occur mainly in NW-oriented valleys (Roscoe 1969), with current direction from the NW (McDowell 1957; Pienaar 1963). Numerous workers (see Roscoe 1969 for list) have suggested a paleoplacer origin for the mineralized conglomerates, however the location and distance of the source region is problematic. McDowell (1957) suggested a source 225 to 400 km to the W-NW of Elliot Lake (roughly the Wawa greenstone belt), but previous detrital zircon studies of the Matinenda Fm near Sault Ste. Marie and Espanola (Rainbird and Davis 2006, Easton and Heaman 2008) indicate a dominant zircon population ranging from 2650 and 2670 Ma, not the >2700 Ma zircons expected for a Wawa greenstone belt source.

Due to increased exploration interest in the camp, in 2009 the Ontario Geological Survey began compilation mapping in the camp (Easton 2009, 2010). As part of this study, 4 Matinenda Fm sandstones were collected to better understand its provenance. U-Pb isotopic analyses were carried out using laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) at the University of Alberta. The samples were collected from a 180 m thick section of the Matinenda Fm exposed along a hydro transmission line west of Pecors Lake on the south limb of the Quirke Lake syncline. Two samples are from the Ryan Member, one 5 m below and the other 7 m above the mineralized Main Conglomerate Bed (09RME-0344 and 09RME-0343, respectively). A third sample (09RME-0342) is from the lower part of the Stinson Member, roughly 75 m above the Main Conglomerate Bed. The fourth sample (09RME-0129) is from the uppermost Stinson Member, roughly 10 m below the unexposed contact with the overlying McKim Formation.

The Ryan Member samples adjacent to the Main Conglomerate Bed (09RME-0344 and 09RME-0343) give near identical weighted average ²⁰⁷Pb/²⁰⁶Pb ages of 2648.9±4.3 (MSWD=2.1, n=100) and 2648.5±6.3 (MSWD=2.2, n=118), respectively. The youngest concordant grains are 2620 and 2634, and the oldest grains are 2776 and 2684 Ma, respectively. Sample 09RME-0344 contained 4 concordant grains between 2702 and 2776 Ma. Sample 09RME-0343 contained a significantly higher proportion of discordant grains, perhaps due to metamict effects related to the underlying uranium mineralization. Sample 09RME-0342, located roughly 85 m above the base of the formation, has a weighted average ²⁰⁷Pb/²⁰⁶Pb age of 2638.5±5.2 (MSWD=0.55, n=72), but contains younger grains (2546 Ma) and 3 Mesoarchean grains which give an upper intercept age of 2836±31Ma. The stratigraphically highest sample, 09RME-0129, has peaks at 2657 and, with a minor peak at 2708, suggesting a slightly more diverse provenance. The grains between 2640 to 2710 Ma give a weighted average ²⁰⁷Pb/²⁰⁶Pb of 2667.4±4.0 (MSWD=8.9, n=79). The youngest concordant grain is 2580 Ma and there are 4 concordant grains between 2706 and 2760 Ma.

These results are consistent with the recently obtained 2687±2 Ma age of felsic metavolcanic rocks at Elliot Lake (Easton 2010), and with the ages of Archean granitic rocks NE of Elliot Lake that indicate emplacement between 2620 and 2670 Ma (J. Ayer, Ontario Geological Survey, personal communication 2011), all consistent with local sourcing. The age and geochemical data are consistent with nearby Archean granites being an important source component, as suggested by Roscoe (1969). The ages are younger than those typical of the Abitibi or Wawa greenstone belts and contrast with those from other sandstone units in the Huronian Spg which show a more diverse provenance consisting of mixed

<2700 and >2700 populations and a variety of Mesoarchean grains (Rainbird and Davis 2006; Easton and Heaman 2008).

Geochemistry of the sandstones (Table 1) confirms the observations of Fralick (2003). The presence of monazite is reflected in LREE enrichment and the presence of negative Eu anomalies throughout the Matinenda Fm. This contrasts with the lack of Eu anomalies in units immediately overlying the Matinenda Fm. The increase in SiO₂ and decrease in Al₂O₃ and K₂O in the better sorted upper Stinson Member is consistent with the observed decreased clay mineral content in this unit, however, Th and total REE content do not decrease, indicating that heavy mineral content was unchanged. The low K₂O and high CIA value for sample 09RME-0129 may indicate that this sample underwent minor metasomatism compared to sample 09RME-0341, located only 5 m higher in the section. The Huronian metavolcanic rocks in the area lack any diagnostic trace element signature (such as high Cr) that could be detected in the sandstones. In summary, local sourcing of the Matinenda Fm means that the character of the adjacent Archean basement needs to be accounted for in exploration.

Table 1. Summary of geochemical data for Matinenda Formation samples along the study transect. All samples are sandstones, except for sample 09RME-0318 which is an uraniferous quartz-pebble conglomerate bed. Geochronology samples are indicated in bold. Ratios listed are those used by Fralick (2003). Data from GeoLabs, Ontario Geological Survey, Sudbury. Abbreviations: CIA = chemical index of alteration.

Sample	SiO ₂ wt.%	Al ₂ O ₃ wt.%	K ₂ O wt.%	Zr ppm	Th ppm	Total REE (ppm)	La/ Sm	Gd/ Yb	Al/ K	Zr/ Hf	Ce/ Th	Zr/ TO ₂	CIA	
0341	-	5.79	.50	.42	2	9	89	.7	2.1	.8	5	.8	20	3
0129	-	5.11	.02	.37	1	4	71	.8	2.9	.2	6	.0	10	9
0342	-	4.17	.28	.04	3		9	.3	1.8	.5	4	.8	25	1
0343	-	8.67	2.87	.64	7		6	3.8	4.9	.9	5	.3	15	6
0318	-	7.16	.13	.32	70	112	759	3.4	2.4	.2	7		09	0
0344	-	9.88	2.04	.28	7	7	1	0.3	6	.9	5	.2	41	6

REFERENCES

- Easton, R.M. 2009. Compilation mapping, Pecors-Whiskey Lake area, Superior and Southern provinces; *in* Summary of Field Work and Other Activities, 2009, Ontario Geological Survey, Open File Report 6240, p.10-1 to 10-21.
- Easton, R.M. 2010. Compilation mapping, Pecors-Whiskey Lake area, Superior and Southern provinces; *in* Summary of Field Work and Other Activities, 2010, Ontario Geological Survey, Open File Report 6260, p.8-1 to 8-12.
- Easton, R.M. and Heaman, L.M. 2008. Detrital zircon geochronology of Huronian Supergroup sandstones located within the Vernon structure, north of Espanola, Ontario; 54th Institute on Lake Superior Geology, Proceedings, v.54, pt.1, p.21-22.
- Fralick, P.W. 2003. Geochemistry of clastic sedimentary rocks: ratio techniques; *in* Geochemistry of sediments and sedimentary rocks: Evolutionary considerations to mineral deposit-forming environments, D.R. Lentz, editor; Geological Association of Canada, GeoText 4, p.8-103.
- Pienaar, P.J. 1963. Stratigraphy, petrology, and genesis of the Elliot Group, Blind River, Ontario, including the uraniferous conglomerate; Geological Survey of Canada, Bulletin 83, 140p.
- 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.
- Roscoe, S.M. 1969. Huronian rocks and uraniferous conglomerates in the Canadian Shield; Geological Survey of Canada, Paper 68-40, 205p.

Bedrock topography, glacial drift thickness and bedrock outcrop maps, Upper Peninsula of Michigan

John M. Esch, Michigan Dept. of Environmental Quality, Office of Geological Survey, P.O. 30256, Lansing, MI 48909, eschj@michigan.gov

Few studies exist concerning the thickness of the glacial drift, the underlying bedrock surface topography or the distribution of outcrops in Michigan. Newly assembled bedrock topography, glacial-drift thickness and bedrock outcrop maps were constructed using traditional depth to bedrock data from water, oil and gas, and mineral wells. Due to the sparse well control over much of the Upper Peninsula, nontraditional bedrock elevation sources such as bedrock shorelines and outcrops, SSURGO county soil data, waterfalls, quarries, aerial photos and General Land Office surveyor's plats were also used (Esch, 2011).

In the Upper Peninsula, the bedrock surface consists of high relief resistant bedrock highlands and cuestas as well as lowlands and deep bedrock valleys. The bedrock surface in places has well defined drainage networks with tributaries as well as long linear valleys. The bedrock surface has been sculpted by hundreds of millions of years of preglacial erosion and by paleo-river channels cut into it during the numerous glacial ice advances over the last 2.5 million years. There may also be local relationships between of certain bedrock valleys and scarps with jointing and deeper bedrock structures.

The Upper Peninsula is characterized by two distinct bedrock surface regions. In the western Upper Peninsula, Precambrian crystalline bedrock forms large, high relief bedrock uplands with bedrock elevations generally greater than 1000 feet above mean sea level (amsl). Archean Granite and Gneiss generally form bedrock highlands. In fact Mount Arvon consisting of Archean Granite and Gneiss in eastern Baraga County has the highest land surface and bedrock elevation in the state at 1979 feet amsl. The Portage Lake Volcanics and the Copper Harbor Conglomerate form a prominent bedrock and land surface ridge along their extent. This contrasts with the eastern Upper Peninsula where bedrock consists of less resistant Paleozoic sedimentary rocks with elevations generally less than 1000 feet amsl and lower relief. Cuestas and bedrock valleys are the dominant bedrock features in the eastern Upper Peninsula. Bedrock valleys are most numerous in eastern Chippewa County. The Niagaran cuesta and Cambro-Ordovician Sandstone cuestas are especially prominent bedrock features. Locally, the Stonington Formation/Big Hill Dolomite and Black River Formation form lower relief and less extensive cuestas. The Mackinaw Breccia forms localized bedrock highlands north of the Mackinaw Straits. Broad bedrock lowlands generally occur over the Jacobsville Sandstone except at the northern part of Sugar Island in Chippewa County.

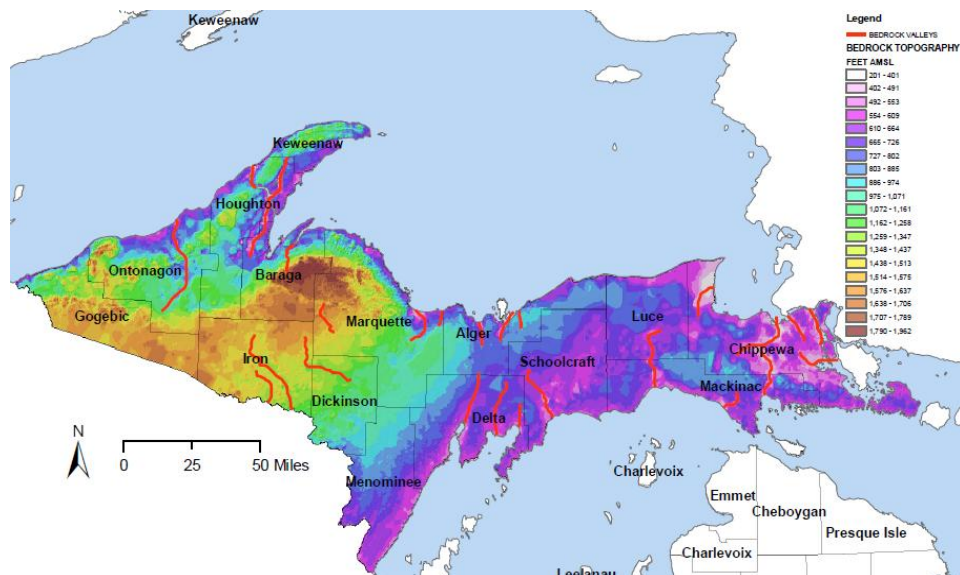
One of the lowest bedrock locations in the Upper Peninsula at 200 feet amsl occurs in a deep bedrock valley at Rudyard in Chippewa County. This bedrock valley runs from Brimley on Lake Superior past Rudyard to St. Martin Bay on Lake Michigan. It has some of the thickest drift in the Upper Peninsula at 435 feet thick. Parts of the Waiska and the Pine Rivers overlay this bedrock valley. Another deep bedrock valley underlies the Sturgeon River valley in Baraga and Houghton Counties near Pelkie. The bottom of the bedrock valley is around 200 feet amsl and drift is 400 feet over it. It is unclear if there is any relationship between the deep bedrock valleys in the eastern Upper Peninsula and the deep north-south troughs on the floor of the east side of Lake Superior which are at a much lower elevation.

Drift thickness ranges from nonexistent at bedrock outcrops to 450 feet. It averages 40 feet thick but can change thickness abruptly over short distances. Drift is locally thicker overlying bedrock valleys, broad bedrock lowlands, along the back cuesta lowlands and over end moraines. This contrasts with the Lower Peninsula where drift averages 270 feet thick and is up to 1,320 feet thick which is the thickest glacial drift on land in North America.

The land surface topography in the Upper Peninsula generally mimics the underlying bedrock topography. Modern drainage often overlies broad bedrock lowlands, bedrock valleys and back cuesta lowlands. In eastern Menominee, western Delta and southwestern Marquette counties the bedrock is a surprisingly smooth downward sloping surface to the southeast. The bedrock formations are Trenton, Black River and Prairie du Chien. In parts of this area the land surface mimics this southeast sloping surface.

These maps will assist geologists in understanding glacial lobe dynamics, in seismic data processing for oil and gas exploration, bedrock geology mapping, in aggregate and mineral exploration. These maps should be especially helpful for ground-water exploration in the highly variable drift and generally limited aquifer areas over crystalline bedrock in the western Upper Peninsula and for finding potential glacial aquifers in bedrock valleys.

Figure 1: Upper Peninsula of Michigan bedrock topography and major bedrock valleys



REFERENCES

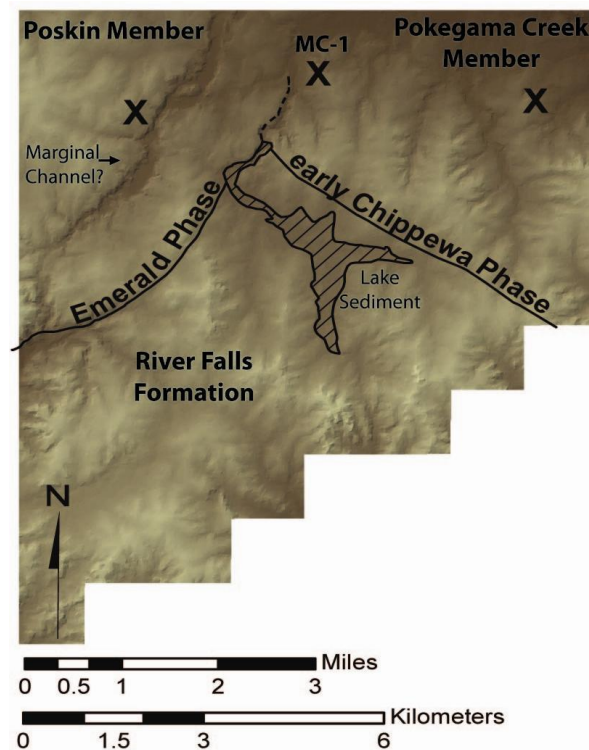
Esch, John, M., 2011, Michigan bedrock topography, glacial drift thickness and bedrock outcrop maps, Geological Society of America Abstracts with Programs, Vol. 43, No. 1, p. 56

Using LiDAR and ArcGIS to evaluate subtle glacial landforms associated with the Early Chippewa and Emerald phase ice-margin positions, Barron County, Wisconsin

Corrie T. Floyd¹, Kent M. Syverson¹, and Christina M. Hupy²

¹Department of Geology, ²Department of Geography and Anthropology, University Wisconsin-Eau Claire, Eau Claire, WI 54702-4004, floydct@uwec.edu

Glacial landforms in Barron County, Wisconsin, are a result of at least four glacial advances during the Pleistocene Epoch (2.58 to 0.012 Ma) (Johnson, 1986; Syverson and others, 2011). During the early Chippewa and Emerald Phases (Late Wisconsin Glaciation, 31-17 ka), till of the Pokegama Creek and Poskin Members of the Copper Falls Fm. were deposited over till of the River Falls Fm. (Illinoian Glaciation, >130 ka). These tills are all reddish-brown, sandy, and lithologically indistinguishable. Johnson (1986) was unable to map the location of the Emerald Phase ice margin using glacial geomorphology because these till surfaces do not display obvious glacial landforms in the field. Johnson used Late Wisconsin lake sediment in the northwest-flowing Fourmile Creek valley as evidence for the



Emerald Phase ice-margin position (Fig. 1). In addition, Fourmile Creek makes a 90-degree bend, and Johnson (1986) attributed this to flow along the Emerald Phase ice margin. LiDAR data obtained from the Barron County Land Information Office was used to evaluate the early Chippewa and Emerald Phase ice-margin positions proposed by Johnson (1986).

High-resolution terrain models have been generated using the LiDAR data. The point spacing of the data is about 3 ft, and compared to ground truth points, the root mean square error (RMSE) of the survey is 0.29 ft. Even with LiDAR's high resolution, primary glacial landforms are lacking on till surfaces in the 90 sq km study area.

However, ArcMap's 3D analyst tools and ArcScene's 3D visualization capabilities reveal three distinct fluvial channels incised in the Poskin and Pokegama

Creek till surfaces (Fig. 1). Longitudinal and cross-sectional profiles were generated to study channel morphology. These meltwater channels are sinuous, 900 to 1000 ft long, and reach maximum depths of 20 ft. They are different from modern channels because they cut across drainage divides, are sub-parallel to the land contour in some places, and typically appear abruptly on the landscape with little area for water catchment. Channel MC-1 (Figs. 1, 2) is an example of a lateral meltwater channel formed during deglaciation from the early Chippewa Phase ice maximum. Overall, these channels are evidence for a younger, less-modified landscape impacted by the Late Wisconsin Glaciation as compared to the River

Falls Fm. till surface from the Illinoian Glaciation which lacks fresh glaciofluvial and glacial landforms. LiDAR data did not reveal a sharp landform-assemblage difference between the Late Wisconsin and Illinoian till surfaces.

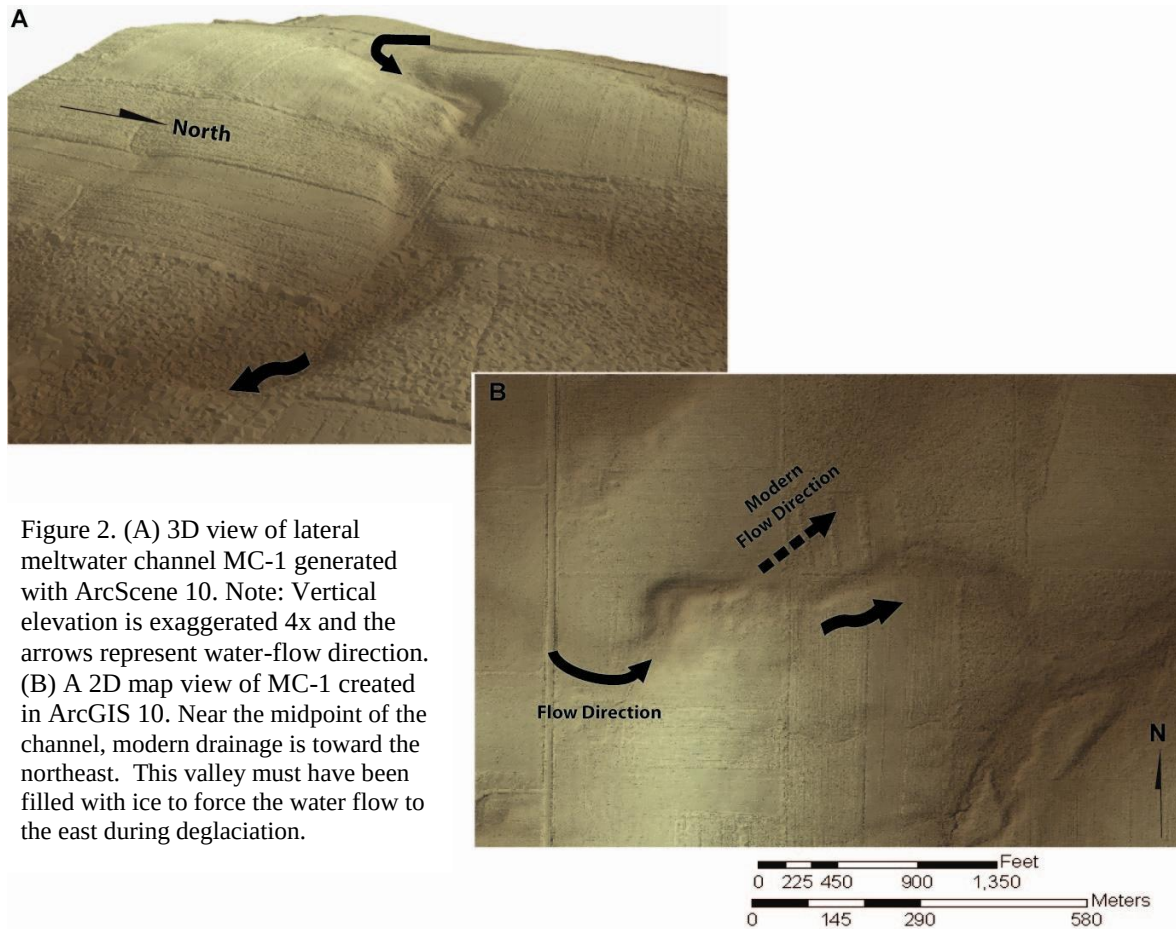


Figure 2. (A) 3D view of lateral meltwater channel MC-1 generated with ArcScene 10. Note: Vertical elevation is exaggerated 4x and the arrows represent water-flow direction. (B) A 2D map view of MC-1 created in ArcGIS 10. Near the midpoint of the channel, modern drainage is toward the northeast. This valley must have been filled with ice to force the water flow to the east during deglaciation.

REFERENCES

- Johnson, M.D., 1986, Pleistocene Geology of Barron County, Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 55, 42 p.
- Syverson, K.M., Clayton, L., Attig, J.W., and Mickelson, D.M., eds., 2011, Lexicon of Pleistocene Stratigraphic Units of Wisconsin: Wisconsin Geological and Natural History Survey Technical Report 1, 180 p.

Petrology and Cu-Ni-PGE mineralization of the Bovine Igneous Complex, Baraga County, Northern Michigan

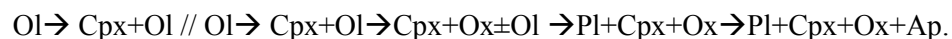
Daniel J. Foley¹ and James D. Miller¹

¹*Department of Geological Sciences, University of Minnesota Duluth, Duluth, MN 55812*

The Bovine Igneous Complex (BIC), located 8 km southeast of the town of L'Anse, Michigan, is a small basin-shaped mafic/ultramafic intrusion emplaced in the southwestern part of the Baraga Basin. Although age dating of the intrusion has so far been unsuccessful, the BIC intrusion was very likely emplaced during the early magmatic stage of Midcontinent Rift development, given its similarities to other early stage intrusions, such as Tamarack (MN) and Eagle (MI).

Investigated by Kennecott as a possible Cu-Ni-PGE prospect, the intrusion has undergone extensive exploration drilling since 1995. This work has shown the intrusion to be weakly to moderately mineralized with Cu-Ni-PGE-enriched sulfides. Metal tenors provided by initial drilling averaged less than .5% Cu and Ni, and less than 350 ppb Pt and Pd (Rossell, 2008). For this study, which is part of Dan Foley's MS thesis, two drill cores that profile the BIC (08BIC044 and BIC01-01) were investigated for their petrographic attributes, cryptic mineral compositions, and whole rock geochemistry. A detailed (1:6,000) re-mapping of the BIC was also conducted for this study.

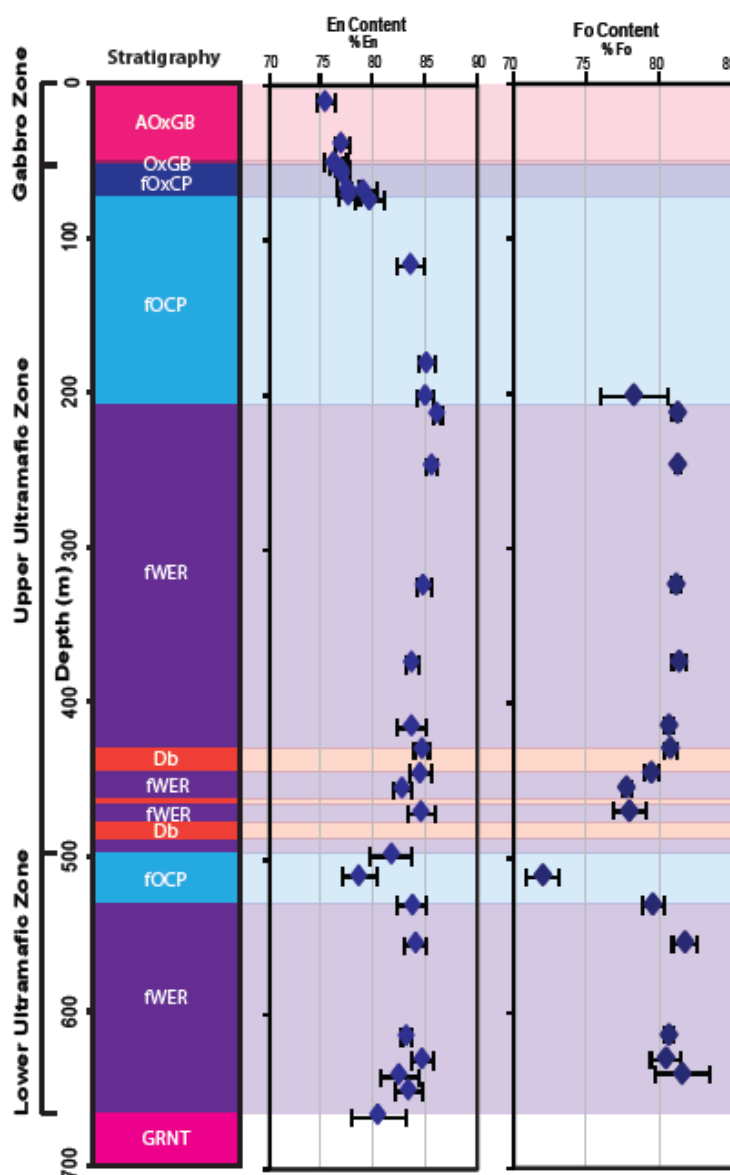
Preliminary field and petrographic studies by Rossell (2008) interpreted the intrusion to be a simple three unit system composed of a basal wehrlite/melagabbro, overlain by a clinopyroxenite/gabbro, and finally an oxide gabbro. Field mapping, core logging, and petrography conducted for this study have found that the lithostratigraphy of the BIC is a somewhat more complicated. The stratigraphy can be subdivided into three main zones – a lower ultramafic zone, an upper ultramafic zone, and a gabbro zone, each of which can be further subdivided by cumulate mineralogy. As profiled in core 08BIC044 (Fig. 1), the lower ultramafic zone is in sharp contact with a footwall of granitic gneiss at about 670m. A medium fine-grained feldspathic wehrlite (Ol cumulate with intercumulus Cpx and Pl) occurs at the basal contact and gradually coarsens up section and becomes less feldspathic. At about 525m, augite abruptly increases in mode and becomes granular to create a feldspathic olivine pyroxenite (Cpx+Ol cumulate with intercumulus Pl). The contact with the base of the upper ultramafic zone, at about 500m, is marked by the abrupt reappearance of feldspathic wehrlite that is vari-textured and contains abundant inclusions of chert and carbonate. Several fine-grained mafic dikes cut the lower 70 meters of this heterogeneous wehrlite. Above the uppermost dike, a more homogeneous, medium-grained feldspathic wehrlite (Ol cumulate with intercumulus Cpx and Pl) persists up to about 205m, at which point cumulus augite reappears and the modal rock type becomes a feldspathic olivine clinopyroxenite (Cpx+Ol cumulate with intercumulus Pl). At about 75m, an abrupt increase in the Fe-Ti oxide mode to about 10% and a loss of olivine generates a feldspathic oxide clinopyroxenite (Cpx+Ox±Ol cumulate with intercumulus Pl). Soon thereafter (~ 60m), plagioclase becomes abundant (>50%) and lath-shaped to create an oxide gabbro (Pl+Cpx+Ox cumulate). Apatite becomes a cumulus phase at about 50m to create an uppermost cumulate of Pl+Cpx+Ox+Ap. Outcrops of apatitic oxide gabbro, at presumably higher stratigraphic levels than seen in drill core, contain patches of interstitial granophyre. Assuming upward-directed crystallization, this igneous stratigraphy implies a cumulus paragenesis of:



The cumulus regression evident at the lower and upper ultramafic zone contact and the heterogeneous nature of the basal upper ultramafic zone strongly implies that this contact demarks two major magma emplacement events.

Further evidence of two episodes of magma emplacement come from mineral chemical data on olivine and augite. Cryptic variations of Fo and En components through core 08BIC044

(Fig. 1) show trends that are consistent with two major episodes of emplacement followed by fractional crystallization. The base of each ultramafic zone is characterized by decreased En content of postcumulus augite which is consistent with chilling of a parental magma. Fo content of olivine in the lower ultramafic zone remains elevated, which is consistent with chilling of primocrystic olivine. Olivine at the base of the upper ultramafic zone shows a decrease in Fo suggesting reequilibration of a new magma pulse with the resident magma. As both the lower and upper ultramafic zone wehrlites transition into olivine clinopyroxenites, both Fo and En decrease, which is consistent with progressive iron enrichment due to fractional crystallization. Interestingly, the upper ultramafic zone and overlying gabbro zone progress to more evolved cumulates, but the cryptic variation is more muted than in the lower ultramafic zone. Noting that the upper ultramafic cumulates are more adcumulate (i.e. contain less postcumulus minerals) than the lower ultramafic zone cumulates, the more subdued cryptic variation of the upper cumulates may be due to a lower trapped liquid shift.



A suite of 27 samples have been submitted for lithogeochemical and assay analyses, but the results were not available at the time of this writing. We hope to report on the geochemical data at the meeting. The whole rock geochemistry will be used to evaluate whether the two magma pulses involved similar parental magma composition. Analyses of wehrlite from the base of the lower ultramafic zone and mafic dikes from the base of the upper ultramafic zone will be evaluated as potential candidates for chilled parent magma compositions. The geochemical data will also be used to evaluate the history of sulfide saturation and metallogenesis during the crystallization of the BIC magma(s).

Figure 1. Lithostratigraphy and cryptic variation of Fo in olivine and En in augite in DDH 08BIC044. Unit abbreviations are fWER- feldspathic wehrlite, fOxCP- feldspathic olivine clinopyroxenite, Db-diabase, fOxCP – feldspathic oxide clinopyroxenite, OxGB – oxide gabbro, AOxGB – apatitic oxide gabbro

REFERENCES

Rossell, D., 2008. Geology of the Keweenaw BIC Intrusion. 54th Annual Institute on Lake Superior Geology, Part II: Field Trip Guidebook, pp. 181-193.

Sedimentology of a wet, pre-vegetation floodplain assemblage: the Mesoproterozoic, Outan Island Formation, Sibley Group, Ontario, Canada

Philip Fralick¹ and Kamil Zaniewski²

¹*Department of Geology, Lakehead University, P7B 5E1, Thunder Bay, Ontario, Canada
philip.fralick@lakeheadu.ca*

²*Department of Geography, Lakehead University, P7b 5E1, Thunder Bay, Ontario, Canada
Kamil.Zaniewski.lakeheadu.ca*

Descriptions of fluvial systems operating prior to significant terrestrial macrophyte vegetation have concentrated on assessing the impact of plant evolution on channel style. This is probably in part due to the scarcity of well-developed floodplain successions in fluvial assemblages of these ages. Those studies that do exist are concerned with depositional process on semi-arid and arid floodplains, which can be modeled by comparison with the recent. This investigation adds to the knowledge base on wet, pre-vegetation floodplain deposits and processes with a description of a continuous succession of drill-core through an extensive, 1,400 Ma, delta-top channel-floodplain assemblage. This succession forms the upper portion of the Outan Island Formation in the central portion of the one kilometer thick Sibley Group, present in northwestern Ontario, Canada. The sub-aerial floodplain deposits are dominated by flaser to lenticular bedded, fine-grained sands to shales, with abundant small shale rip-up clasts. Iron oxide-rich, millimeter-thick shale laminae denote exposure surfaces. Soft-sediment deformation of these units is ubiquitous with loading and injection features the most prominent. Where soft sediment deformation is minor the layering appears lenticular, with the ripple laminated, fine-grained sandstones able to maintain their appearance. However, significant sections of the core suffer more severe deformation with the layering developing a wispy appearance. Thicker medium-grained sandstones, representing crevasse splays, commonly have protocols (very immature soils) developed in their upper portions. Geochemistry indicates downward movement of meteoric water through the upper portions of the crevasse splays. Well-laminated sediments with wave ripples and only rarely containing rip-up clasts and soft-sediment deformation were deposited in floodplain ponds. These sub-aqueous units are commonly orange or green rather than the ubiquitous red of the sub-aerial deposits. Reduction spots centered on specks of carbon, which is probably of organic origin, indicate that life did exist on the sub-aerial surface, but the highly oxidizing nature of the sedimentary environment led to little preservation of this material other than the prolific, transported carbon specks. These deposits differ from post-vegetation floodplain sediments in having: 1) better preservation of layering without rootlet bioturbation; 2) dominance of rippled sand on the floodplain, probably due to lack of vegetation induced baffling; 3) large-scale generation of small, intraformational clasts, possibly as a result of less rootlet binding; 4) desiccation crack fills consisting of soil pedes and locally derived intraclasts, probably delivered due to erosion of the floodplain surface during rainfall events; 5) ubiquitous soft-sediment deformation features in sub-aerial deposits; and, 6) well-laminated, oxidized sediment that accumulated in floodplain ponds.

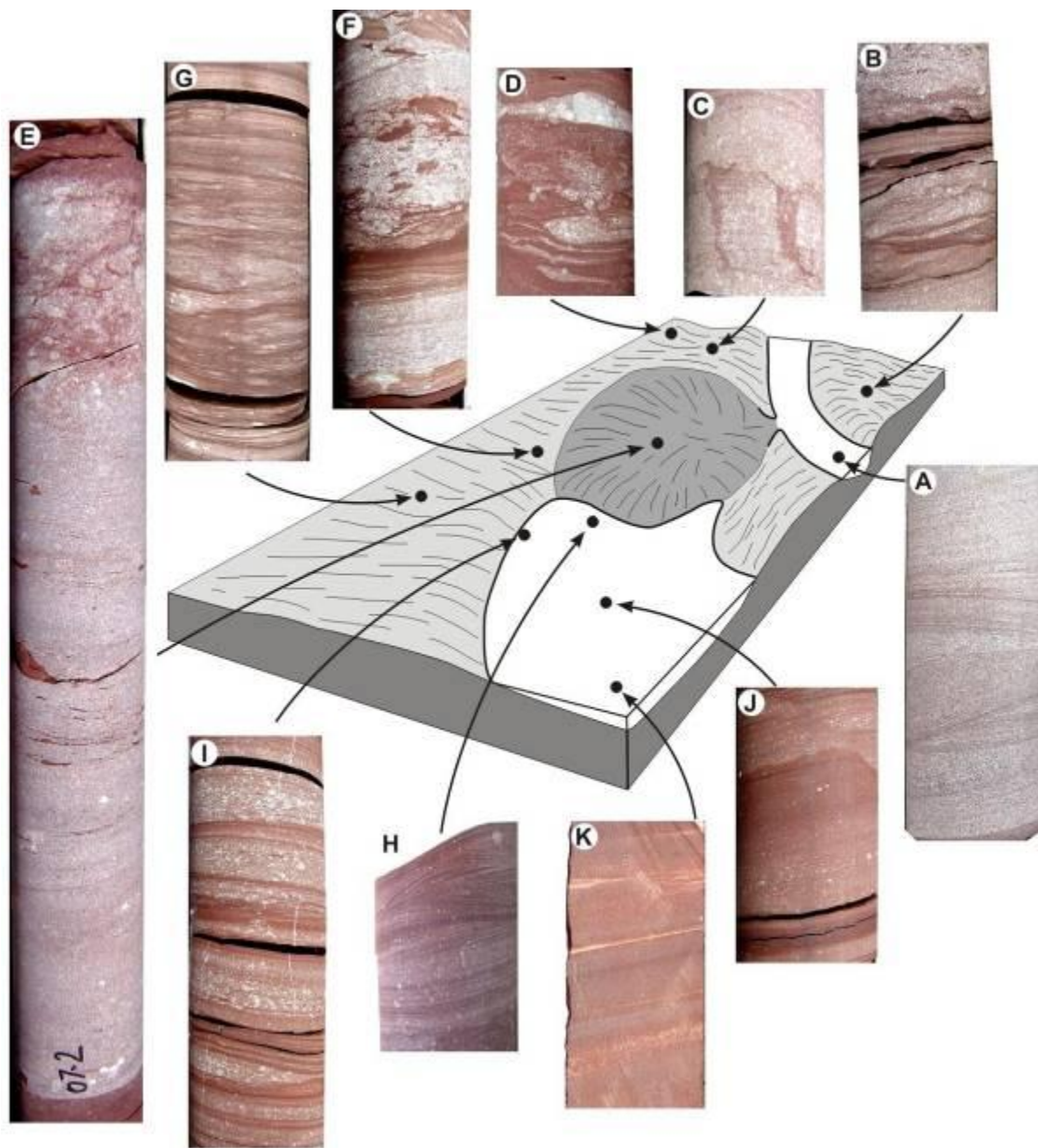


Figure 1. Diagram showing the types of layering developed in various sub-environments of the depositional system. A- Main Channel; B and C- Levee; E and F- Proximal to Distal Crevasse Splay; H- Wave reworked Crevasse Splay; D and G- Floodplain; I, J and K- Floodplain Pond.

A review of the western Superior lithoprobe line 3

Paul Geller, Phil, Fralick, Mary Louise Hill, and Patricia Gillies

Lakehead University Department of Geology 955 Oliver Road, P7B 5E1, Thunder Bay, Ontario, Canada. pgeller@lakeheadu.ca

The Lithoprobe project was a Canada-wide project that had a multi-disciplinary approach to mapping the deep crust. Line 3 of the Western Superior transect crosses from the Eastern Wabigoon Subprovince into the Quetico Subprovince. The transect passes through two terranes of the Eastern Wabigoon Subprovince: the Onaman-Tashota Terrane and the Beardmore-Geraldton Belt. The Onaman-Tashota Terrane is a patchwork of igneous intrusive and extrusive rocks. The Beardmore-Geraldton Belt is a collection of interlayered metasedimentary and metaigneous units. The Quetico Subprovince is metasedimentary, primarily composed of metaturbidites intruded by felsic igneous rocks and migmatized in places.

The seismic section does not follow a straight-line but instead has an east-west jog to the otherwise north-south trend (Figure 1). This, as well as the related areas of low data confidence, has important ramifications for the interpretation. Gravity data was used in collaboration with surface geology to add an extra degree of robustness to the investigation of structures at depth. A structure is present, dipping at approximately 12° to the south at the boundary between the Quetico Subprovince and the Wabigoon Subprovince. Structures inferred to be the Paint Lake Fault and the Jellicoe River Fault appear below the surface expression of these features, with dips of approximately 86°. Other features that seem to appear in the section must be dismissed at present as they occur in areas of low confidence.

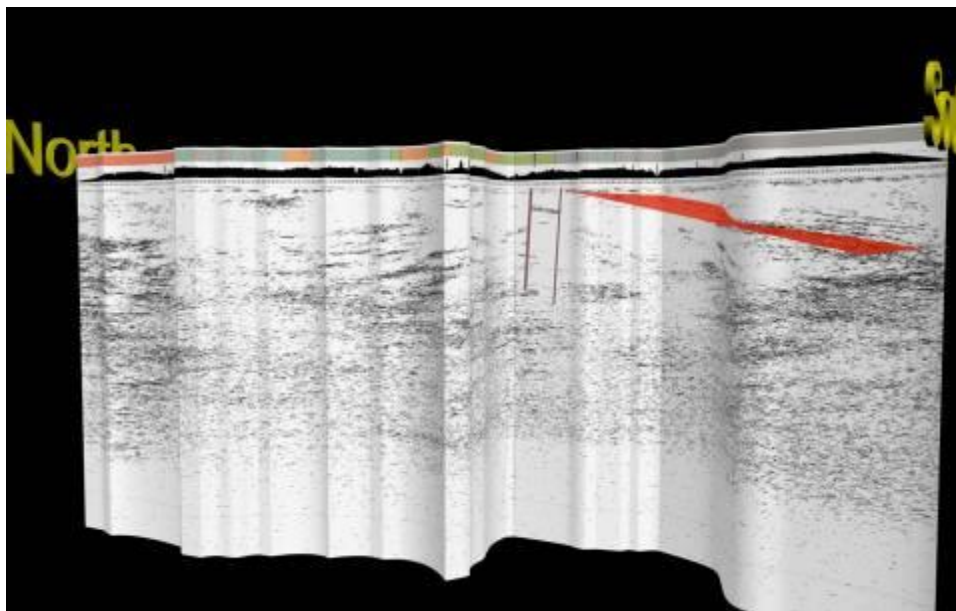


Figure 1. A 3D representation of the seismic line from surface to approximately 48 km depth, with associated geology and interpreted geology.

Stratigraphic investigation of the Neoarchean Bird River Belt, SE Manitoba, Canada

H. Paul Gilbert

Manitoba Geological Survey 360-1395 Ellice Ave. Winnipeg Manitoba Canada R3G 3P2

The Neoarchean Bird River Belt (BRB) is located in the Bird River Subprovince within the southwestern Superior Province, between flanking older cratonic blocks — the 3.0-2.87 Ga North Caribou Superterrane to the north and the 3.4-2.8 Ga Winnipeg River Subprovince to the south (Percival et al., 2006). The BRB consists of diverse volcanic and sedimentary rocks in two structural panels (north and south), separated by the relatively younger turbiditic Booster Lake Formation that extends through the centre of the belt. The calcalkaline north panel rocks (ca. 2733 Ma) are akin to modern subduction-related rocks at active continental margins, whereas the tholeiitic sequence in the south panel (ca. 2725 Ma) documents incipient rifting in an extensional tectonic regime (Fig. 1). The arc-type rocks are flanked to both north and south by mid-ocean-ridge basalt (MORB)-type sequences that are interpreted as relatively older than the arc-type rocks, and may be associated with early arc rifting in a back-arc setting (Gilbert et al., 2008).

The north and south panel rocks, although distinguished by different composition and age, have broadly similar internal stratigraphies. The south panel contains a lower felsic volcanic sequence overlain by voluminous pillowed mafic flows and an upper, diverse volcano-sedimentary assemblage. The north panel is also interpreted to consist of a lower felsic volcanic sequence – Peterson Creek Formation (PCF), overlain by varied sedimentary and volcanic rocks – the Diverse Arc assemblage (DAA), which includes a pillowed amygdaloidal andesite member at the base. The PCF is a felsic volcanic complex composed mainly of volcanic fragmental rocks and subordinate rhyolite flows. A spherulitic zone within massive flows that extends laterally within the PCF for over 20 km represents a stratigraphic break where rapid chilling was associated with alteration and penecontemporaneous devitrification (Fig. 2).

Compositionally distinctive, intrusive (and possibly extrusive) sanukitoid-type rocks (Fig. 1) are interpreted as late- or post-DAA in age. Whereas these rocks intrude the DAA as well as Booster Lake Formation rocks, sporadic clasts of apparent sanukitoid type within some DAA conglomeratic deposits suggest the deposition of DAA rocks and Booster Lake Formation turbidites may have been, in part, contemporaneous. Detrital zircon U-Pb data that indicate maximum depositional ages for the DAA (2706 ± 23 Ma) and Booster Lake Formation (2712 ± 17 Ma) are consistent with this model (Gilbert, 2008). Overlap of sanukitoid-type magmatism with late volcanism is also supported by the occurrence of syn-volcanic sanukitoid massive to fragmental volcanic rocks with an inferred igneous age between 2715 Ma and 2723 Ma in the contiguous Rice Lake belt, north of the BRB (Anderson, 2008).

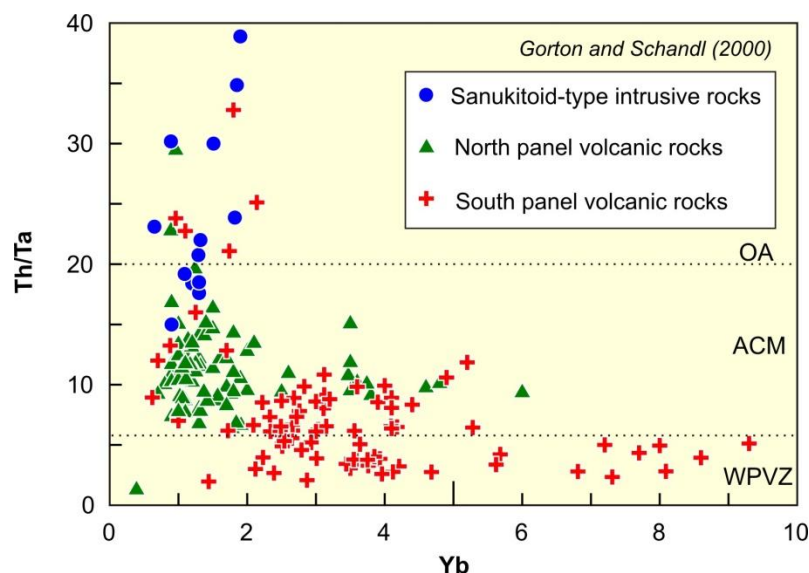


Figure 1. Th/Ta vs Yb plot of mafic to intermediate volcanic rocks in the Bird River Belt north and south panels, and late sanukitoid-type intrusive rocks. OA = Oceanic arc; ACM = Active continental margin; WPVZ = Within-plate volcanic zone.

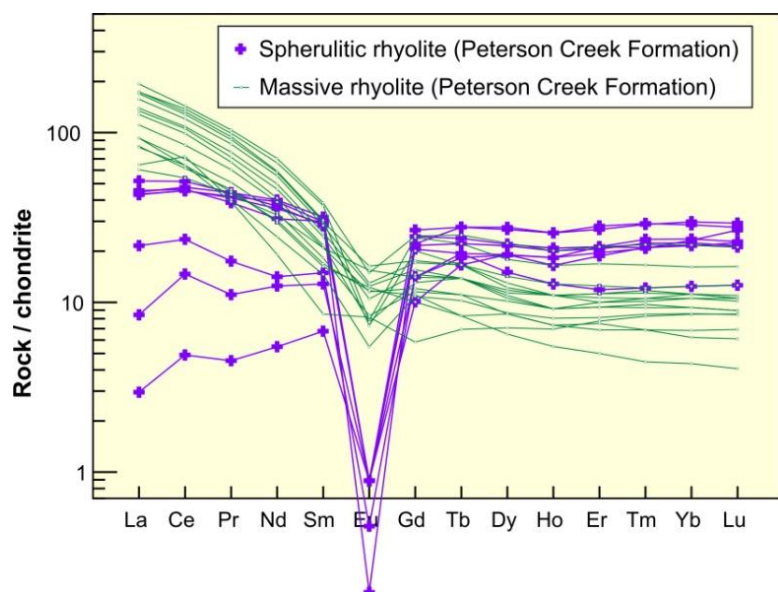


Figure 2. Chondrite-normalized REE plot of massive and spherulitic rhyolite (PCF).

REFERENCES

- Anderson, S. D. 2008. Geology of the Rice Lake area, Rice Lake greenstone belt, southeastern Manitoba (parts of NTS 52L13, 52M4); Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Geoscientific Report GR2008-1, 97 p.
- Gilbert, H.P., 2008: Stratigraphic investigations in the Bird River greenstone belt, Manitoba (part of NTS 52L5, 6); in Report of Activities 2008, Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, p.121-138.
- Gilbert, H.P., Davis, D.W., Duguet, M., Kremer, P.D., Mealin, C.A. and MacDonald, J. 2008: Geology of the Bird River Belt, southeastern Manitoba (parts of NTS 52L5, 6); Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Geoscientific Map MAP2008-1, scale 1:50 000 (plus notes and appendix).
- Percival, J.A., McNicoll, V. and Bailes, A.H. 2006: Strike-slip juxtaposition of ca. 2.72 Ga juvenile arc and >2.98 Ga continent margin sequences and its implications for Archean terrane accretion, western Superior Province, Canada; Canadian Journal of Earth Sciences, v. 43, p. 895–927.

Petrology of the Ni-Cu-PGE-mineralized Tamarack Intrusion, Aitkin and Carlton Counties, Minnesota

Brian D. Goldner*¹ and James D. Miller²

¹Department of Geological Sciences, University of Minnesota Duluth, Duluth, MN 55812

*Present Address: Rio Tinto Exploration, 224 N 2200 W Salt Lake City, UT, 84116

gold0334@umn.edu

²Department of Geological Sciences, University of Minnesota Duluth, Duluth, MN 55812

mille066@umn.edu

The Tamarack intrusion is an unexposed mineralized ultramafic intrusion located near the town of Tamarack, about 50 miles west of Duluth, Minnesota. Rio Tinto Exploration (previously Kennecott Exploration) has been conducting exploration drilling of the Tamarack intrusion for Cu-Ni-PGE sulfide deposits since 2001. The intrusion was emplaced into black slates of the Paleoproterozoic Animikie Basin during the early magmatic stage of the 1.1Ga Midcontinent Rift and a new U-Pb baddeleyite age reported here yields an age of 1105.6 ± 1.3 Ma. Drilling and geophysical data indicate that the Tamarack intrusion has a tadpole-like shape that is about 13 km long and is between 1 and 4 km wide (Fig. 1). The narrow tail area of the intrusion, which is the site of greatest exploration drilling, is composed of exclusively of ultramafic rock types. The wider “body” area at the southeastern end of the intrusion is composed of a wider variety of rock types ranging from lherzolite to granophyric gabbro. Core logging, petrographic observations, mineral chemical analyses, lithogeochemical analyses, and XRF scanning of drill core were employed on four drill cores from the Tamarack intrusion to evaluate its emplacement and crystallization history.

Core logging and petrography in three cores from the tail area shows that this part of the intrusion can be subdivided into two texturally and modally distinct units of olivine cumulates – a lower Feldspathic Lherzolite Unit composed of coarse-grained olivine mesocumulates with poikilitic pyroxenes and plagioclase, and an upper Lherzolite Unit composed of medium-grained olivine mesocumulates to adcumulates. The contact between the two lherzolite units was investigated all three cores. In one, the contact occurs across a meter-thick zone of intense alteration; in another, it shows the two lherzolite lithologies irregularly interlayered; and in a third, the feldspathic lherzolite is contains gabbroic inclusions of unknown origin.

The one 268-m-long drill core investigated from the body area ends in an olivine mesocumulate similar to the upper Lherzolite Unit of the tail area. At 225m, the lherzolite gives way up section to a 10m-thick interval of intergranular olivine websterite (Cpx+Opx+Ol cumulate) which in turn gives way to an intergranular lherzolite (Ol+Cpx+Opx cumulate). At 210m, plagioclase abruptly increase in mode (~50%) and changes from poikilitic to granular resulting in a gabbro. Granular augite and orthopyroxene persist into the gabbro, oxide increase to about 5 vol. %, but olivine disappears. This gabbro is interpreted to a Pl+Cpx+Opx $\pm$ Ox cumulate. The upper 50 meters of the core (below a 59m-thick cap of till) contains interstitial to irregular segregations of granophyre and shows the reappearance of olivine.

Disseminated Ni-Cu-PGE sulfide mineralization is present throughout most of the lithologies studied here, but is particularly abundant in the tail area at the basal contact of the

Feldspathic Lherzolite unit and in a zone straddling the contact between the two lherzolite units.

Whereas mineral chemical and whole rock data within the feldspathic lherzolite and lherzolite units found in the tail of the intrusion show little cryptic variation, the chemical attributes of lithologies in the body areas show evidence extreme differentiation. Olivine composition ranges from Fo₈₄ in the lowermost lherzolite and becomes progressively evolved to Fo₁₀ in the uppermost granophyric gabbronorite. Other mineral and whole rock data both show smooth gradations from the lherzolite to the gabbronorite which are consistent with these lithologies having formed from one parental magma by fractional crystallization in a closed system.

The main petrologic conclusions of this study are:

1) The two lherzolitic units in the tail area formed from a similar high-Mg olivine tholeiitic parent magma. The composition of this parent magma is estimated from subtracting 30% Fo₈₉ olivine phenocryst composition from a chilled margin found at the basal contact of the Feldspathic Lherzolite unit. The resulting composition is comparable to other picritic compositions found at the base of MCR-related Mamainse Point Volcanics.

2) The emplacement of the lower feldspathic lherzolite preceded that of the upper lherzolite in the tail area. The differences in texture and modal mineralogy between the two lherzolite units are attributed to the more rapid cooling of the earlier feldspathic lherzolite creating an orthocumulate in contrast to the more adcumulate upper lherzolite.

3) The sulfide mineralization straddling the lherzolite contact in the tail area is attributed to country rock assimilation and S contamination of the leading edge of the lherzolite parent magmas during the two main episodes of emplacement. The sulfide mineralization in upper part of the Feldspathic Lherzolite is thought to be related to downward infiltration of sulfide liquid from the overlying Lherzolite unit magma upon its emplacement into the semi-molten core of the Feldspathic Lherzolite.

4) Finally, the well differentiated lithologic sequence comprising the body area is interpreted to have resulted from closed-system fractional crystallization of the second magma pulse that created the upper Lherzolite unit in the tail area (Fig. 1).

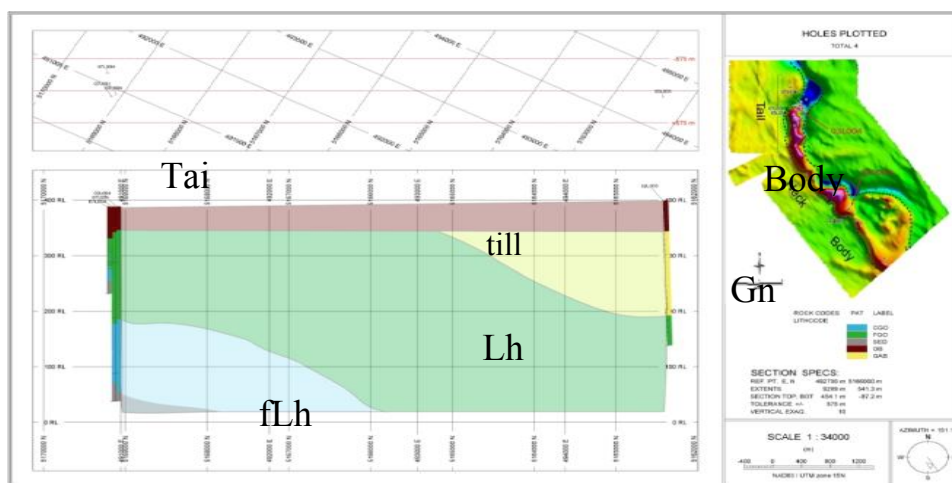


Figure 1. Possible correlation of lithologies between the tail and body of the Tamarack intrusion. fLh – feldspathic lherzolite unit; Lh – lherzolite unit; Gn – gabbronorite unit

The Minnesota Taconite Workers Health Study: Environmental study of airborne particulates - 2011 update

George Hudak¹, Stephen Monson Geerts¹, Larry Zanko¹, April Severson¹, Allison Severson¹, Bryan Bandli²

¹Natural Resources Research Institute, 5013 Miller Trunk Highway, Duluth, MN, 55811

²Department of Geological Sciences, University of Minnesota Duluth, 229 Heller Hall, 1114 Kirby Drive, Duluth, MN 55812

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

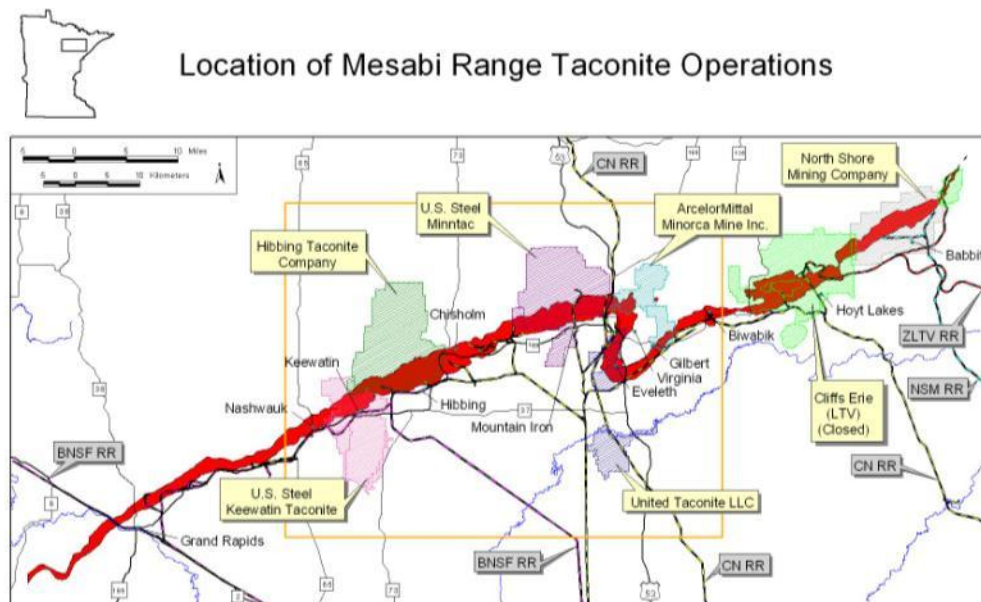


Figure 1. Locations of taconite processing plants on the Mesabi Iron Range being sampled during this study (after Oreskovich and Patelke, 2006)

Air sampling is performed within taconite operations, MIR communities, and non-MIR communities by NRRI scientists during both winter and summer seasons. Sampling at taconite operations takes place at four locations: 1) secondary crushers; 2) magnetic

separators/concentrators, agglomerators/ ball drums, and the kiln/pellet discharge area. Sampling within MIR communities takes place on the rooftops of public buildings, whereas sampling in non-MIR communities occurs on rooftops or in remote locations so that background air quality can be evaluated. Airborne particulate are collected using a microorifice uniform deposit impactor (MOUDI) (Marple et al., 1991), which enables size-fractionated particulate collection, and a total suspended particulate filter (TSP). Particulate samples are evaluated via gravimetric analysis and subsequently subjected to comprehensive particulate matter characterization that includes: 1) scanning electron microscopy (SEM) imaging; 2) energy dispersive spectroscopy (EDS); 3) electron backscattered diffraction (EBSD); 4) proton induced x-ray emission (PIXE); 5) the Minnesota Department of Health's 852 Method Transmission Electron Microscopy (TEM) Analysis for Mineral Fibers in Air; and 6) the International Standard Organization's Method 10312 Ambient air – Determination of Asbestos Fibers – Direct-Transfer TEM Method (ISO 10312, 1995).

Over the past year, the NRRI has completed particulate sampling within MIR taconite operations, MIR communities, and non- MIR communities. This includes 14 sampling events at taconite operations and 67 sampling events at locations within communities in northeastern Minnesota, as summarized in Table 1. As well, continued analysis of lake sediment samples from “North of Snort Lake” indicates collection of sediment dating back to ~1840, which pre-dates iron mining on the MIR. At Silver Lake, logging activities in the early part of the 20th century disrupted the sediments; however, we believe we will have good post-1915 lake sediment data, which will mark the period where the transition from natural ore to taconite mining took place. Continued analysis, interpretation and reporting will take place in 2011.

In-Plant Sampling Events			
<i>Taconite Facility</i>	<i>Sampling Events</i>	<i>Taconite Facility</i>	<i>Sampling Events</i>
United Taconite	2 events while active	Keetac	1 event while active, 1 event while inactive
Hibbing Taconite	1event while active, 1 event while inactive	Northshore	1 event while active, 3 events while active
Minntac	1 event while active	Minorca	3 events while active
Community Sampling Events			
<i>Community Sampling Location</i>		<i>Sampling Events and Number per Season</i>	
Silver Bay High School		11 Events (4 Winter / 7 Summer)	
Virginia Court House		9 Events (4 Winter / 5 Summer)	
Hibbing High School		9 Events (4 Winter / 5 Summer)	
Keewatin Elementary School		6 Events (3 Winter / 3 Summer)	
Babbitt Municipal Building		15 Events (7 Winter / 8 Summer)	
Duluth NRRI Rooftop		10 Events (4 Winter / 6 Summer)	
Ely Fernberg Site		7 Events (4 Winter / 3 Summer)	

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

REFERENCES

- ISO 10312, 1995, Ambient air – determination of asbestos fibers – direct transfer transmission electron microscopy method, 51p.
- Marple, V. A., Rubow, K. L., and Behm, S. M., 1991, A microorifice uniform deposit impactor (MOUDI): description, calibration, and use: Aerosol Science and Technology, v. 14, p. 434-446.
- Oreskovich, J. A., and Patelke, M. M., 2006, Historical use of taconite byproducts as construction aggregate materials in Minnesota: A Progress Report: Natural Resources Research Institute Report of Investigation NRRI-RI-2006-02, 10 p.

Bedrock geologic map of Minnesota—Precambrian geology

Mark A. Jirsa, Terrence J. Boerboom, and Val W. Chandler

Minnesota Geological Survey (MGS), 2642 University Ave., St. Paul, MN, (www.mnngs.umn.edu)

Digital products associated with the new bedrock geologic map of Minnesota (*MGS State Map Series S-21*) allow removal of Cretaceous, Paleozoic, and some parts of Mesoproterozoic strata to reveal an interpretation of the underlying Precambrian bedrock (simplified on Figure 1). Corresponding GIS data tables permit attribute searches based on age, terrane, and lithologic and nomenclatural subdivisions; which allow users to create attribute-based thematic maps. Companion data containing an outcrop database and all known geochronologic analyses linked to sample locations were published in 2010 as *MGS Open-File Report OF10-02*. Collectively, these products provide a new interpretation of Minnesota's Precambrian terranes, summarized here. Much of the Precambrian geology on *S-21* is depicted in the context of major orogenic, rifting, and meteorite impact events. The understanding of these events in the Lake Superior region has evolved considerably in recent years by the works of many authors.

The Archean rocks are subdivided approximately by their apparent temporal relationship to three major periods of deformation; the first (D_1) at about 2695 Ma, which may be equated with the Shebandowan orogeny in adjacent Ontario; the second (D_2) at about 2680 Ma occurred during the Minnesotan orogeny and produced regional transpressive fabrics, folds, and metamorphism to greenschist-amphibolite grade (orogenic nomenclature via Percival and others, 2006). The former may represent collision of the Wawa subprovince with the composite Superior superterrane to the north. The latter can be attributed to oblique collision of the Minnesota River Valley subprovince with the Superior superterrane along a north-dipping suture known as the Great Lakes Tectonic Zone. A D_3 event is manifest in the Quetico subprovince as broad folds involving D_2 fabrics, and elsewhere by faulting. Structures bounding major components of the Superior Province are locally inferred to be thrust faults that initially formed during terrane assembly. Although little is known in detail about their vergence and offset history, the interpretation here builds on seismic surveys in Minnesota, and extrapolation from results of the Western Superior Lithoprobe and NATMAP Transects in adjacent areas of Canada (Percival and Helmstaedt, 2006).

The Proterozoic rocks are the products of 4 orogenic and rifting events. The Paleoproterozoic rocks contain evidence for a cycle of rifting and continental collision during the Geon 18 Penokean orogeny. An ejecta blanket resulting from the 1850 Ma Sudbury meteorite impact forms a definitive time-line within the Animikie Group at the stratigraphic top of Gunflint and Biwabik Iron Formations. Crust in the southern half of the state was deformed, metamorphosed, and plutonized to varying degrees during Geon 17 Yavapai orogenesis. The Yavapai Province in extreme southeastern Minnesota contains older continental crust deformed during Geon 17 and intruded by granitic rocks. Although deposition of strata assigned to the Animikie Basin began during the late stages of Penokean orogenesis, it is likely that sedimentation continued during the Yavapai event. The effects of later orogenic events in Minnesota are unclear. The Geon 16 Mazatzal orogeny is well delineated in adjacent Wisconsin; however, only scant evidence of metamorphic overprint is documented in the McGrath Gneiss in Minnesota, and alteration of the Sioux Quartzite is assigned to a Geon 14 hydrothermal event. Mesoproterozoic rocks result from Geon 11 continental rifting, producing volcanic and sedimentary rocks of the Keweenaw Supergroup and plutonic rocks of the Midcontinent Rift Intrusive Supersuite. Mafic dike swarms of inferred Paleoproterozoic and Mesoproterozoic age represent significant episodes of crustal extension.

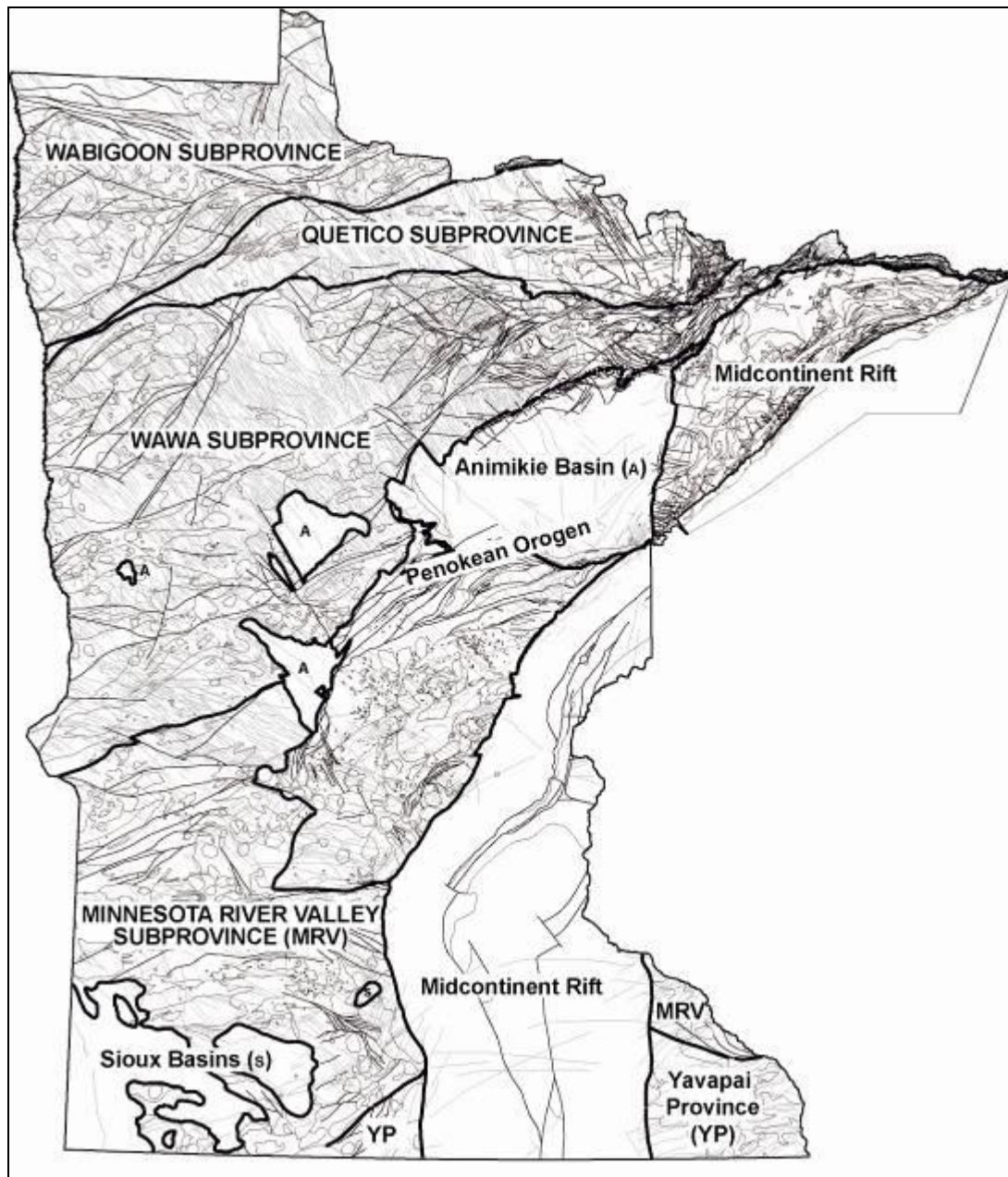


Figure 1. Terrane map of Precambrian bedrock showing subprovinces of the Archean Superior Province (caps), significant components of Paleoproterozoic bedrock, the Mesoproterozoic Midcontinent rift, and mafic dikes (gray) of Paleoproterozoic and Mesoproterozoic age.

REFERENCES

- Percival, J.A., and Helmstaedt, H., 2006, The Western Superior Lithoprobe and NATMAP transects: Introduction and summary: *Can. Jour. Earth Sci.* 43:743-747 and articles therein.
- Percival, J.A., Sandborn-Barrie, M., Skulski, T., Stott, G.M., Helmstaedt, H., and White, D.J., 2006, Tectonic evolution of the western Superior Province from NATMAP and Lithoprobe studies: *Can. Jour. Earth Sci.* 43:1085-1117.

Highlights of the new bedrock geologic map of Minnesota

Mark A. Jirsa, Terrence J. Boerboom, Val W. Chandler, John H. Mossler, Anthony C. Runkel, and Dale R. Setterholm

*Minnesota Geological Survey (MGS), 2642 University Ave., St. Paul, MN,
(www.mnngs.umn.edu)*

The latest bedrock geologic map of Minnesota—*MGS State Map Series S-21**—is a new construct that incorporates existing geologic maps where prior mappers had adequate ground control, and new interpretations based on drill hole, geophysical, and unpublished data where they did not. The interpretation differs significantly from previous maps to reflect the new data and accommodate scale. It portrays our current geologic understanding of the temporal and geographic distribution of units within major Precambrian terranes (Jirsa and others, this volume) and of Phanerozoic strata.

The previous state-wide compilation of bedrock geology, S-20, was created in 2000, modified in 2003, and produced at a scale of 1:1,000,000. Although S-20 was a suitable image for its time, the new map shows considerably more detail at twice the scale; it incorporates recent detailed mapping and previously unpublished data; and its interpretations are reconciled with reprocessed, high-resolution geophysical data. Digital files associated with this map allow removal of Cretaceous, Paleozoic, and some parts of Mesoproterozoic strata to reveal an interpretation of the underlying Precambrian bedrock. Corresponding GIS data tables permit attribute searches based on age, terrane, and lithologic and nomenclatural subdivisions. Ancillary files, published in 2010 as *MGS Open-File Report OF10-02**, include new state-wide maps of outcrops, bedrock topography, depth to bedrock, and geochronologic data. Major areas of improvement include the depiction of Precambrian rocks beneath Phanerozoic strata, and the subdivision of Archean units in a broad area of subdued magnetic character north of the Great Lakes Tectonic Zone that was formerly referred to as “the Quiet Zone.” Mafic dike swarms are the remnants of significant crustal extension events during the Paleoproterozoic and Mesoproterozoic. Despite this significance, and the prominent magnetic fabric created by dike anomalies, this map is the first attempt at state-wide depiction. Improvements in Phanerozoic geology include a much more accurate western erosional edge of Paleozoic bedrock, subdivision of Cambrian strata into two units, and the use of modern stratigraphic nomenclature that is more broadly correlative with adjacent jurisdictions. The Phanerozoic geology was compiled from mapping that required contouring of bedrock surfaces using test hole and water well data. Much of the Cretaceous depiction, for example, is taken from grid-subtraction of contoured elevations of top and bottom of units.

The new map provides a jumping-off point for future scientific and exploration endeavors. It should be noted that the geologic depiction is based solely on geophysical maps and scant drill hole information in many areas. In addition, the creation of S-21 did not involve logging of all drill core and MGS well-cuttings sets, targeted geophysical modeling, and test drilling, as would be conducted for larger-scale mapping. The lack of ground-truth in much of central and western Minnesota is a call to new drilling. Recent studies in other regions have shown that both temporal and tectonic considerations are needed to identify greenstone belts with enhanced base and precious metal prospectivity. In light of this, the dearth of high-precision geochronologic and lithogeochemical data for Precambrian supracrustal rocks in Minnesota clearly needs to be addressed. Work on the topography of major bounding surfaces, and the depiction of geology beneath them, is on-going.

****MGS Open-File Report OF10-02 and State Map Series S-21 were prepared and published with the support of the Minnesota Legislature, as administered by the Minerals Coordinating Committee.***

Paleomagnetism and Paleointensity as recorded by 1.08 GA Lake Shore Traps (Keweenaw Peninsula, Upper Michigan)

Evgeniy V. Kulakov¹, A.V. Smirnov¹, J.F Diehl¹

¹*Department of Geological and Mining Engineering and Sciences, Michigan Technological University, 1400, Townsend Drive, Houghton, Michigan, 49931, USA.*

Here we report new results of paleomagnetic and paleointensity investigations carried out on samples collected from a sequence of lava flows (12 lava flows) interbedded within the Copper Harbor Conglomerate on the Keweenaw Peninsula of Michigan. This sequence, known as the Lake Shore Traps (LST), represents the latest stage of volcanic activity associated with North American Mid-Continent Rift (MCR). Our sampling localities were on Silver Island (10 lava flows) situated along the western shore of Keweenaw Peninsula north of Eagle Harbor, MI and on the mainland (two lava flows) directly east of Silver Island. The Silver Island lava flows are equivalent to the upper lava flows of the Middle LST at the tip of the Peninsula while the mainland lava flow are equivalent to lower lava flows of the middle LST (Diehl and Haig, 1994; Diehl et al., 2009). At the tip of the Peninsula, the upper and lower sections of the middle LST are separated by a 27 m thick conglomerate layer. The LST flows exposed along the western coast of Keweenaw Peninsula and at its northern tip are characterized by different strike and dip angles. That allows us to use the paleomagnetic directional data to test the conclusion by Hnat et al. (2006) that the curvature of MCR in the Keweenaw Peninsula, where structural trends vary from NE/SW to E/W to NW/SE, is a primary rift structure (as opposed to a secondary feature caused by oroclinal bending of the rift related rocks).

Characteristic remanent magnetizations (ChRM) were isolated by thermal or alternating field demagnetization, or by combination of both techniques. ChRM was interpreted as primary magnetization, acquired during the original cooling of these lavas. Mean paleomagnetic directions were combined with the results from the previous study (Diehl and Haig, 1994) of the Lower and Upper Middle LST, sampled at northern tip of Keweenaw Peninsula. The group means (N=2) for Upper and Lower Middle LST from the western sites coincide at 95 per cent confidence with those reported for same flows exposed on the northern tip of the peninsula. This provides further support to the conclusion that the curvature of MCR is primary in its origin.

We also performed determinations of the strength of Earth magnetic field (paleointensity) recorded by the Lake Shore Traps. The paleointensity database for the Precambrian is very limited and needs to be significantly extended. Determinations of absolute paleointensity were conducted using Thellier method (Thellier and Thellier, 1957) on 107 samples from nine lower lava flows and ten upper flows. 43 per cent (46 samples) of determinations passed our reliability criteria and have been accepted. Paleointensity (36 μ T) recorded by the oldest lower flows is relatively high and comparable with the modern field strength. Paleointensity decreases to ~ 13.2 μ T toward in the younger lower flows. All upper flows are characterized by low values of paleofield with mean of ~ 13.1 μ T. Our paleointensity values are less than 50% the values reported by Pesonen and Halls (1983). We suggest that their values are biased because of the use of low-temperature demagnetization data for calculating paleointensity.

REFERNECES

- Diehl, J.F., T.D. Haig, 1994, A paleomagnetic study of the lava flows within the Copper Harbor Conglomerate, Michigan: new results and implications, *Canadian Journal Sciences*, 31, 369-380.
- Diehl, J. F., A.J. Durant, C. Schepke, 2009, Paleomagnetism of Silver Island, Keweenaw Peninsula, Michigan: Additional Support (?) for the Primary Curvature of the MCR, *Eos Trans. AGU*, 90(22), Jt. Assem. Suppl., Abstract GP11E-01.
- Hnat, J.S., B.A. van der Pluijm, R. van der Voo, 2006, Primary curvature of the Mid-Continent Rift: Paleomagnetism of the Portage Lake Volcanics (northern Michigan, USA), *Tectonophysics*, 425
- Pesonen, L. J., H.C. Halls, 1983, Geomagnetic field intensity and reversal asymmetry in late Precambrian Keweenawan rocks. *Geophysical Journal. Royal Astronomical Society*, 73, 241-270.
- Thellier, E., and O. Thellier, 1959, Sur l'intensité du champ magnétique terrestre dans le passé historique et géologique: *Annales Géophysique*, v. 15, p. 285–378.

Testing models of late Paleoproterozoic Penokean orogenesis in the Great Lakes Region, U.S.A. using sedimentary provenance: planning the investigation

Todd A. LaMaskin

Department of Environmental Science, University of Wisconsin -Extension & Wisconsin Geological and Natural History Survey, 3817 Mineral Point Road, Madison, Wisconsin 53705, lamaskin@wisc.edu

Aspects of the overall plate-tectonic setting and regional controls on crustal deformation during late Paleoproterozoic time in the Lake Superior region of the U.S. midcontinent remain debated. Synthesis of the geology and tectonic history of the region suggests that both marginal-basin regime and Cordilleran-style plate-margin tectonic processes were well established in late Paleoproterozoic time; however, the driving forces that produced crustal deformation and coeval subsidence are not fully understood.

During Paleoproterozoic time, the southern periphery of Laurentia was a convergent margin that experienced episodic southward continental growth through accretion of both arc and micro-continent lithosphere (Fig. 1). Tectonic "events" during the Penokean orogenic interval (ca. 1.9–1.75 Ga) represent the initiation of this long-lived stage of accretionary southward growth of the North American craton. The Penokean Orogenic Province (POP; Fig. 1) of the Lake Superior region provides an excellent testing ground for evaluating the style and timing of lithospheric accretion in the Proterozoic growth of Laurentia. The POP contains Archean and Paleoproterozoic rocks that represent two distinct magmatic arcs and their associated sedimentary basins (Marshfield and Pembine-Wasau terranes, respectively), as well as two temporally distinct, spatially overlapping sedimentary successions: (1) turbidite iron-formation basins of the Menominee Group, and (2) a collision-related foreland fold-thrust complex (Baraga-Animikie Groups).

The original composition of weathered source rocks is a dominant control on the makeup of terrigenous sediments, therefore, geographic and stratigraphic variations in sediment provenance in both successions can provide important constraints on the tectonic evolution of the region. Investigation of sedimentary successions in the POP is planned using U-Pb and Hf detrital zircon analysis, mudrock trace-element and Sm-Nd geochemistry, and (U-Th)/He thermochronology. The sampling program is designed to test specific predictions of proposed and new models for the tectonic setting of individual basins, and for the tectonic evolution of the region as a whole.

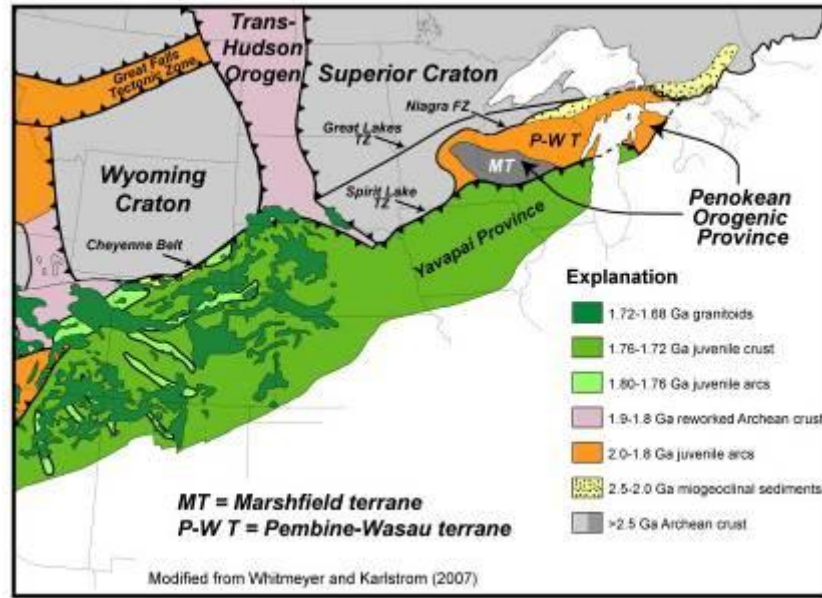


Figure 1. Map showing major Precambrian crustal provinces in the United States prior to accretion of the Mazatzal Province and formation of Mesoproterozoic igneous and tectonic provinces.

The Biwabik Iron Formation: geochemical and textural evidence for deposition of iron-formation in a Paleoproterozoic epeiric sea

Phillip Larson¹, John Swenson², and Marsha Patelke³

¹Duluth Metals Limited, 306 W Superior Street #610, Duluth MN 55802, USA

²Department of Geological Sciences, 1114 Kirby Drive, University of Minnesota Duluth, Duluth MN 55812, USA

³Natural Resources Research Institute, 5013 Miller Trunk Highway, Duluth MN 55811, USA

The Paleoproterozoic Biwabik Iron Formation of northeastern Minnesota, USA, consists of interbedded ‘cherty’ granular iron-formation (GIF) and ‘slaty’ banded iron-formation (BIF) lithofacies. Advances in geochronology have demonstrated that the 1.85 Ga Biwabik IF is the chronostratigraphic correlative of other Paleoproterozoic iron-formations preserved along the margins of the 2.7 Ga Superior craton, including the Gunflint, Ironwood, Vulcan, Negaunee, Temiscamie, Sokomon, and Kipalu iron formations. The Biwabik and Gunflint IFs are essentially undeformed flat-lying platform sequences, at present extending several 100 km inboard of the craton margin. However, in contrast the majority of the circum-Superior iron-formations are preserved as deformed rocks in orogenic belts at the craton margin. In common, all these iron-formations, ranging in thickness from 10s to several 100 m, are sandwiched within clastic sequences. In the case of the Biwabik IF, chemically precipitated Fe occurs in both the footwall and hangingwall clastic sequences, indicating that the trigger for iron-formation accumulation was not the commencement of Fe precipitation, but rather the cessation of clastic input into the basin.

While the origin of GIF is contested (shallow-water oolite vs. reworked BIF), the association with high energy environments is clear. The preponderance of GIF in the Biwabik IF, as well as the occurrence of Mn-rich bioherms interbedded with GIF, suggests a predominantly shallow-water depositional environment.

Mineralogy of the Biwabik IF is dominated by Fe-oxides, silica, and a variety of Fe-bearing silicate and carbonate species. Lithofacies are characterized by distinct mineralogical assemblages, suggesting a strong control imposed on mineralogy by the depositional environment. Textural evidence indicates essentially all mineral species present are the product of diagenetic reactions, chiefly silica addition, recrystallization of primary precipitates into oxide, carbonate, and silicate species, and conversion of ferric Fe-bearing precipitates to ferrous Fe-bearing minerals. Magnetite strongly correlates with carbonate-bearing iron-formation, and magnetite enrichment suggests significant ferrous Fe mobility during late diagenesis. Wrapping of bedding around early chert concretions in BIF indicates significant volume and mass loss subsequent to deposition. Stylolites are a common feature in both silicate-carbonate BIF and GIF; they too indicate significant mass loss during early diagenesis, likely from carbonate-rich iron-formation precursor sediments. A significant fraction of the precipitates deposited on the seafloor seem to have remobilized soon after deposition. This evidence indicates that iron-formation *accumulation* is strongly controlled by physical and chemical processes in the benthic zone, and is largely independent of the processes controlling Fe precipitation in the water column.

The most abundant elements in iron-formation – Fe, Si, Mg, Mn, Ca, and P – were deposited as chemical precipitates. In contrast, Al, Ti, and to a lesser extent K, were deposited as terrigenous sediment. In the Biwabik IF, Al and Ti strongly correlate, suggesting

they are ultimately sourced from a long-lived, homogeneous reservoir. We suggest this reservoir was ultimately either windblown or suspended clay and silt.

Al₂O₃ concentration in the Biwabik IF averages 0.44%. Concentrations are lowest in GIF, and highest in BIF, ranging from 0.10% in the coarsest GIF to 1.84% in the Intermediate Slate. Assuming PAAS-like compositions, these translate into terrigenous input contributions of 0.4% to 9.5%, averaging 2.5%. In comparison, the insoluble residue of modern Bahamian periplatform carbonates is 1-2% (Boardman et al. 1986). We infer that the bulk of Biwabik IF sedimentation therefore occurred in an environment similarly isolated from terrigenous input as the modern Bahamas platform.

These lines of evidence suggest that the Biwabik IF and its correlative iron-formations were deposited in a single continental-scale depositional system. The bulk of the iron-formation accumulated in shallow-water depositional environments in conjunction with carbonate, likely at very low rates. Indeed, a lack of any significant terrigenous input may have been the key factor responsible for accumulation of significant thicknesses of iron-formation. The clear textural, geochemical, and mineralogical evidence for co-precipitation of ferric iron and carbonate suggests a depositional environment essentially analogous to Paleozoic epeiric sea carbonates, if not modern platform carbonates. We suggest that deposition of the Biwabik IF and its correlative iron-formations occurred in an epeiric sea (and adjacent continental margins) that nearly, if not completely, inundated the Superior craton through much of Biwabik IF time. Iron-formation was a ubiquitous feature of the Paleoproterozoic sea, and accumulation on the Superior craton only ceased when renewed orogenic activity along the craton margin (e.g. Penokean orogeny) significantly increased the flux of terrigenous sediment onto the craton, with consequent dilution of iron-formation accumulation.

REFERENCES

- Boardman, M.R., Neumann, A.C., Baker, P.A., Dulin, L.A., Kenter, R.J., Hunter, G.E., and Kiefer, K.B. 1986. Banktop responses to Quaternary fluctuations in sea level recorded in periplatform sediments. *Geology* 14: 28-31.

Platinum-Palladium-Copper-Nickel mineralization at the Thunder Bay North Deposit, Ontario

A.D. MacTavish¹, G.J. Heggie¹, V.R. Goodgame², J.R. Johnson¹, A.E. Beswick³, W.E. Stone⁴, and K.P. Watkins⁵

¹*Magma Metals (Canada) Limited, 1004 Alloy Drive, Thunder Bay, Ontario, Canada P7B 6V1*

²*Excelsior Mining Corp., Suite 1240, 1140 West Pender Street, Vancouver, British Columbia, Canada V6E 4G1*

³*Consulting Geoscientist, 11 Little Panache Road, Whitefish, Ontario, Canada P0M 3E0*

⁴*Magma Metals Limited, Suite 2700, Brookfield Place, 161 Bay Street, Toronto, Ontario, Canada M5J 2S1*

⁵*Magma Metals Limited, Level 3, 18 Richardson Street, West Perth, Western Australia WA6005*

The drill discovery of the Thunder Bay North (TBN) Pt-Pd-Cu-Ni deposit by Magma Metals (Canada) Limited (Magma) in late 2006 was the result of the initial 2001 discovery of glacially transported mineralized peridotite boulders on the west shore of Current Lake. The TBN deposit is located ~50 km northeast of the city of Thunder Bay, Ontario. Since December 2006 Magma has drilled 630 holes (120,000 m) that have defined 9.5 million tonnes (Mt) indicated at 2.3 gpt Pt Equivalent (Pt-Eq) and 0.27 Mt inferred at 2.8 gpt Pt-Eq. Conceptually, 90% of the defined deposit can be mined by an open pit. Recoverable metals include Pt, Pd, Cu, Ni, Ag, Au, Rh and Co.

The TBN deposit occurs within the 1120±23 Ma Current Lake Intrusive Complex ('CLIC') which crosscuts Archean rocks of the Quetico Sub-province. The CLIC is one of three mafic-ultramafic intrusive complexes which are part of a network of magma conduits associated with the Keweenawan age Mid-Continent Rift. The conduits comprise narrow, nearly flat-lying, sinuous tubes and small tabular bodies that are classified as chonoliths, rather than sills or dykes. The emplacement of these conduits is controlled by pre-existing sub-horizontal and sub-vertical structures. Local conduit morphology is controlled by the rheology of the enclosing country rocks. The Archean country rocks consist of variably deformed fine wackes and siltstones metamorphosed to lower amphibolite-grade, and granitoid rocks typified by foliated granodiorite and tonalite. Conduits occurring within the metasedimentary rocks form tabular bodies, whereas those within granitoid rocks form tubes. The CLIC is undeformed, only weakly altered, and has been preserved in almost the same orientation as it formed.

The earliest CLIC intrusive phases are a complex series of variably inclusion-rich, hybridized gabbro to diorite rocks that exhibit a wide variety of textures. The hybrids intrude along preexisting sub-horizontal and sub-vertical structures, are hematized, and contain carbonate ocellae. The mineralized mafic-ultramafic rocks are emplaced through these earlier hybrid rocks, and comprise two or more pulses of sulphide-bearing peridotite and olivine melagabbro. The mafic-ultramafic rocks exhibit chemical differentiation, but lack layering, and all internal contacts are gradational. The upper portions of the conduits contain diffuse zones of varitextured (taxitic) gabbro. Serpentinization of olivine is observed near the conduit margins and is attributed to late magmatic (deuteric) processes, rather than post-magmatic hydrothermal activity and metamorphism. The host rocks immediately adjacent to

the CLIC are hematized for 5 to 10m. Metasedimentary hanging-wall rocks exhibit strong in-situ brecciation, carbonatization, epidotization and sericitization, and contain up to 5% finely disseminated pyrite. This brecciation and alteration is less prominent in metagranitoid hanging-wall rocks.

Mineralization within the TBN deposit is dominated by thick zones of disseminated pyrrhotite, chalcopyrite, pentlandite, and minor cubanite. Disseminated mineralization commonly fills the entire conduit within the Current Lake and Bridge zones of the deposit. Small, lenticular, very high-grade zones of net-textured and massive sulphides occur within troughs and depressions at the base of the conduit within the western Beaver Lake Zone. Most of the mineralization within the central and eastern Beaver Lake Zone is disseminated to blebby and is also confined to basal troughs and depressions. In addition to the basal mineralization, the 'Cloud Zone' forms a diffuse zone containing <2% very finely disseminated chalcopyrite that occupies the upper third of the conduit in the northern Beaver Lake area. Sub-horizontal and sub-vertical sulphide veins and veinlets, up to 3 cm thick, are common within the Current Lake and Bridge zones, but rare within the Beaver Lake Zone. Composite sulphide blebs, up to 2 cm in diameter, are common throughout the well-mineralized portions of the deposit. Angular to sub-angular, fractured or broken sulphide fragments, up to 3 cm in length, are minor, but observed throughout the deposit.

There is a strong positive correlation of sulphide abundance to base and precious metal grades. A very strong positive correlation of Pt, Pd, Cu and Ni indicates a pristine magmatic system with little re-distribution of metals. The Pt:Pd ratio value is 1.07; the Ni:Cu ratio value is approximately 0.5:1.0; the PGE and base metals tenor is relatively consistent throughout most of the deposit; and the chalcophile metal pattern is fractionated.

The magmatic conduit system presently defined within the TBN area is comparable in size to other sulphide-rich magma conduits elsewhere. The CLIC shares a number of common features with the conduits observed at Noril'sk-Talnakh (Russia): 1) the mineralized intrusive rocks form chonoliths; 2) both systems exhibit sill-like marginal mafic rocks; 3) taxitic (varitextured) phases are observed in both; 4) both systems contain both basal and internal mineralization; 5) both magmatic systems were dynamic, 6) both are closely associated with large igneous provinces, and 7) both show evidence of marked wall rock alteration.

The CLIC is part of a much larger magmatic system which formed from a deep sourced magma, focused magma flux, and considerable wall-rock assimilation. The sulphides within the TBN deposit are strongly fractionated (PGE and Cu-rich), which reflects entrained sulphides being transported to their present location from a crystallizing and fractionating Ni-rich sulphide trap located deeper within the system. This scenario strongly suggests there may be one or more Ni-rich, massive sulphide deposits located magmatically upstream from the TBN Deposit.

Magma continues to explore along strike from the defined TBN deposit and has identified low-grade mineralization at 1040 m depth, 2 km to the southeast, within the down-plunge extension of the CLIC. Exploration also continues on the two other conduit systems identified within The Thunder Bay North land package. The most advanced work is at the Steepledge Lake Intrusive Complex (SLIC), located 3 km west of the CLIC, where drilling has intersected rocks and disseminated Pt-Pd-Cu-Ni mineralization similar to that present within the CLIC.

Using Credit-by-Exam to connect advanced high school geology courses to university geology programs: Lessons learned from a state-wide pilot study in Michigan

Stephen Mattox¹ and Sandra Rutherford²

¹*Department of Geology, Grand Valley State University, Allendale, MI 49401-9403, mattox@gvsu.edu*

²*Geography and Geology Department, Eastern Michigan University, Ypsilanti, Michigan 48197, srutherford@emich.edu*

To address the national shortage of geologists and to diversify the geoscience workforce we are constructing a seamless path from rigorous high school geology classes taught by well-trained teachers to geoscience programs at state universities and colleges. This program is modeled on an existing high school – university collaboration that has added a significant number of students to the career pipeline. We have obtained Memorandums of Understanding (MOU) from school districts with high populations of diverse students that have administrators and teachers ready to join the program. Discussions and visits with department chairs and faculty at numerous state universities and colleges resulted in a second set of Memorandums of Understanding to award college credit to students that successfully pass a rigorous credit by exam.

Although geologists have vigorously lobbied for an AP course and exam in geology, the College Board has resisted because they perceive that demand will be low. The lack of an AP course has made it difficult for those high schools nationwide that offer advanced (i.e., college-level content) geology courses to obtain appropriate recognition for their students' accomplishments.

Mattox designed a test, with input from my GVSU peers, that includes 60 multiple choice, 10 essay questions, a map test with skills and landforms, and a rock and mineral exam (essentially what we use in our physical geology introductory course). We give the exam over 5-6 hours on two different days. About 70-80% of students from a local high school pass. With the same exam at a different high school no students passed, although several were close. This exam is prepared, reviewed, and administered by geology department faculty.

The authors received a NSF planning grant titled “Collaborative Project: Collaborations for Building Michigan Geology Talent” and significant accomplishments include:

Mattox visited eight state universities and colleges and discussed credit-by-exam and the high school advanced geology exam with geology department faculty and university administrators.

A template MOU was drafted for high schools and for universities.

To date, seven signed MOUs to award credit-by-exam and be involved with the high school advanced geology exam have been received from EMU, GVSU, Lake Superior State University, MTU, Wayne State University, Western Michigan University, and Hope College (a private college). Geology faculty at two other universities (Central Michigan University and University of Michigan-Dearborn) are guiding MOUs through administrative review at their institutions. Michigan State University is interested but currently focused on curriculum restructuring of their geology program. Mattox is currently in dialogue with

faculty at the University of Michigan and Northern Michigan University to establish site visits and visits with administrators. **By the end date of this planning grant at least 7 of 10 state universities with B.S. geology degree programs will have signed agreements to award credits to students that pass an approved high school advanced geology exam.**

Recruiting targeted high schools with underrepresented groups throughout Michigan has been initiated in our planning grant. Rutherford received MOUs from school districts, including the Detroit school district with 30 high schools and diverse student populations. Administrators and teachers are interested in adding the geology course. If funding continues, we plan to support existing highly trained teachers that are ready to offer the course. Teachers that need additional training will be supported to earn a M.S. in geoscience education from EMU. Our proposal also includes funds for teaching materials. The MOU asks the high school to return the materials they were provided and releases the obligation to pay for the teachers' Masters if the high school does not teach the advanced geology class. Additional insights from this project include:

We have developed a poster to be displayed in high school classrooms where the advanced geology course and exam are being offered.

Administrators were surprising receptive to and supportive of a rigorous high school geology credit by exam course.

Numerous teachers are excited at the prospect of earning a M.S. degree to be better prepared to teach the geology credit by exam course.

Many university faculty were unaware that credit by exam was already available at their university. This mechanism made establishing a high school credit by exam easier.

After reviewing the existing exam most faculty immediately embraced the idea of credits that pass the exam.

We have demonstrated the feasibility of establishing a statewide network of universities to award college credit for passing a credit by exam during a high school geology course.

This material is based upon work supported by the National Science Foundation under OEDG Grant No. NSF 08-605 1006652.

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

2010 Precambrian field camp mapping in the Jack Lake area, Cook County, Northeastern Minnesota

Jim Miller, Ben Brooker, Max Hadley, Levi Markwood, Jeff Olson, and Alex Tomlinson

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

As part of the 2010 Precambrian field camp, a crew of five students and an instructor (Miller) conducted five days of field mapping bedrock geology in the Jack Lake area of northeast Minnesota. This area is composed of intrusive and volcanic rocks formed during the 1.1 Ga Midcontinent Rift (MCR) in northeastern Minnesota. This year's mapping project expanded on capstone mapping projects conducted in 2007 (Frost et al., 2007) and 2009 (Blakely et al., 2009). These mapping projects have focused on an as yet unnamed, well differentiated layered mafic intrusion that forms the western part of the Brule Lake –Hovland gabbro of Miller et al. (2001). A 1:12,000-scale bedrock geologic map was generated of a 4 mile by 1 mile area that profiles the igneous stratigraphy of the intrusion. A pdf version of this and other Precambrian field camp capstone geologic maps can be downloaded from the PRC website: www.d.umn.edu/prc/fieldcamp/capstone.

Prior to the detailed mapping conducted by the PRC field camp students, the general geology of this area was poorly known. Township-scale outcrop mapping by Grout et al. (1959) showed the area to be dominantly composed of gabbroic to felsic intrusive rocks, mafic volcanic rocks and minor volcanogenic sedimentary rocks. They noted that the gabbroic rocks are well layered and portions are particularly rich in Fe-Ti oxide. Reconnaissance mapping by Davidson (1972) designated the mafic intrusion as an olivine gabbro unit that he interpreted as an early intrusion relative to granophyric and anorthositic rocks in the area (Davidson, 1977; Davidson and Burnell, 1977). The regional geologic map of northeastern Minnesota, which focused on the geology of the Duluth Complex (Miller et al., 2001), incorporated Davidson's (1972) mapping of the area, but his olivine gabbroic unit is now interpreted to be a relatively late intrusion that is roughly equivalent to the Beaver Bay Complex to the south.

2010 capstone mapping was conducted along a north-south-trending chain of lakes and rivers that included Kelly Lake, Jack Lake, Weird Lake, Mama Bear Lake, and the Temperance River. Exposures along the shorelines of these waterways provided a nearly complete profile across the moderately south-dipping internal structure of the unnamed mafic intrusion and the overlying Eagle Mountain granophyre. The igneous stratigraphy of the approximately 2 km-thick intrusion generally defines a progressively differentiated sequence. However, it is not clear whether this differentiation took place entirely by *in situ* fractional crystallization.

The lowest unit exposed in the north of the map area, along the Temperance River, is a complex mixture of medium-grained, augite troctolite to olivine gabbro and fine-grained, intergranular gabbroic rocks of uncertain origin – diabase intrusions or hornfels basalt inclusions? Overlying this mixed rock unit, the small Mama Bear Lake area, is an augite troctolite (Pl+Ol cumulate) unit that is ophitic to subophitic, poorly to moderately foliated, and medium- to coarse-grained. The augite troctolite grades into an interval that contains abundant hornfels inclusions of basalt and volcanogenic sandstone. The rock hosting the inclusions ranges from augite troctolite to olivine gabbro. This inclusion-rich unit, which is exposed at the north end of Weird Lake, is overlain by a very thick sequence of foliated, intergranular oxide gabbro to olivine oxide gabbro (Pl+Cpx+Ox±Ol cumulate). This unit locally contains cm- to m-thick layers rich in Fe-Ti oxides and occasional inclusions of gabbroic anorthosite. The lower section of this oxide gabbro unit is intruded by a complex network of intermingled diabase, ferromonzondiorite, and quartz monzonite that mostly appear to be sill-like. These mixed intrusion also occur higher in the sequence where they appear to be more dike-like. In the northern part of Jack Lake, the oxide gabbro abruptly grades into an apatite oxide gabbro with the appearance of 3-5% apatite prisms (Pl+Cpx+Ox+Ap cumulate). The apatite

oxide gabbro unit is homogeneous, medium-grained, and well foliated. The oxide gabbro and the apatite oxide gabbro units are each about 800 m thick and comprise about 80% of the intrusion stratigraphy. At the south end of Jack Lake, the apatite oxide gabbro grades into a prismatic ferromonzodiorite, which grades into a ferromonzonite, and which in turn grades into micrographic leucogranite of the Eagle Mountain granophyre. The transition from apatite oxide gabbro to leucogranite occurs over a 200 m-thick interval and appears to represent a zone of mixing and assimilation between the younger mafic intrusion and the older granophyre body.

The Jack Lake sequence generally correlates with the igneous stratigraphy mapped to the east during 2007 and 2009 capstone projects. The main correlation horizon that links the Jack Lake sequence with areas to the east is the interval rich in hornfels inclusions of basalt and volcanogenic sandstone. This interval can be traced for over six miles from the north end of Weird Lake, to the north end of Vern Lake, and along the north shore of Homer Lake. This volcanic screen was actually identified by Grout et al. (1959), but curiously is not shown on Davidson's maps (Davidson, 1977; Davidson and Burnell, 1972). Below the hornfels-rich horizon, the troctolite-dominant lithologies of the Temperance River /Mama Bear Lake area generally correlate with what Frost et al. (2007) and Blakely et al. (2009) termed the Axe Lake sequence to the east. The oxide gabbros and apatite oxide gabbros of the Jack Lake area generally correlate with what is called the Homer Lake sequence to the east. One notable difference is that the 800m-thick apatite oxide gabbro unit in the Jack Lake area dramatically thins by an order of magnitude to the east.

Plans are to return to the area for the 2011 capstone and continue mapping to the west. In addition, Ben Brooker will be conducting more mapping throughout the area next summer, as well as petrographic and mineral chemical studies, to better understand the emplacement and crystallization history of this intrusion for his MS thesis at UMD. A major objective of Ben's study is to evaluate the genetic relationship between the lower troctolitic cumulates and the upper oxide gabbroic cumulates. Although these rock types could represent the progressive differentiation of a mafic magma, their separation by a screen of volcanic and interflow sedimentary rocks suggests that they may represent two discreet intrusions formed by different parental magmas. Ben also promises to name the intrusion.

REFERENCES

- Blakely, S., Brown, A., Foley, D., Rowland, A., Stifter, E., and Miller, J., 2009, Bedrock Geology Map of Homer Lake and Adjacent Areas; Cook County, Northeastern Minnesota: University of Minnesota Duluth, Precambrian Research Center, PRC/MAP-2009-01, 1: 12,000.
- Davidson, D.M., Jr., 1972. Eastern part of Duluth Complex. In: Sims, P.K. & Morey, G.B. (eds.) *Geology of Minnesota - A Centennial Volume*. Minnesota Geological Survey, p. 354-360
- Davidson, D.M., Jr., 1977, Cherokee Lake Quadrangle, Cook County, Minnesota: Minnesota Geological Survey, Miscellaneous Map Series, M-30, 1:24,000.
- Davidson, D.M., Jr., and Burnell, J.R., 1977, Brule Lake Quadrangle, Cook County, Minnesota: Minnesota Geological Survey, Miscellaneous Map Series, M-29, 1:24,000.
- Frost, S.J., Juda, N.A., and Miller, J., 2007, Bedrock Geology Map of Homer Lake and Adjacent Areas; Cook County, Northeastern Minnesota: University of Minnesota Duluth, Precambrian Research Center, PRC/MAP-2007-02, 1: 12,000.
- Grout, F.F., Sharp, R.P., and Schwartz, G.M., 1959, The Geology of Cook County Minnesota: Minnesota Geological Survey Bulletin 39, 163p.
- 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

The Mineral Exploration Trifecta

Dean Peterson, Phil Larson, Gabriel Sweet, and Jack Gibbons

Duluth Metals Limited, 306 West Superior Street, Suite 610, Duluth, MN 55802

Mineral exploration is the research activity of the mining industry. At its foundation are ideas, visions, or intuitive geologic thoughts that are evaluated through repeated phases of data gathering (geological, geochemical, and geophysical studies), interpretation, and drilling. Mineral deposit models have arisen as mental paradigms that act as guidebooks to help geologists process information. Effective mineral deposit models increase discovery rates and decrease exploration and mining costs. However, it is becoming increasingly apparent that analog deposit targeting models are decreasing in their effectiveness. Adherence to these decreasingly effective analog deposit targeting models has created a misalignment between future societal mineral resource needs and the ability of the mineral exploration industry to meet those needs.

Over the last several decades, companies have focused on brownfields exploration around existing mines with a trend toward lower grade open-pit resources at the expense of greenfields exploration for the next generation of high-quality deposits. In addition, we have moved into an energy-constrained and environmentally-concerned world and global society's demands that the mining industry reduce its physical, social and environmental footprint are translating into legislation. Duluth Metals recognizes these challenges and has implemented a three-part fundamental philosophical shift in our mineral exploration programs to support the discovery of new, high-quality ore deposits. We at Duluth Metals have coined this shift the “**Mineral Exploration Trifecta**”, which utilizes (1) the mineral system approach, (2) innovative technology, and (3) trained people.

Mineral System Approach

A mineral system approach to exploration attempts to understand ore deposits as expressions of multi-scale systems encompassing the Earth that focus mass and energy transfer to ultimately form ore deposits. This approach to mineral exploration leads to systematic, scale-dependent targeting models and allows for the recognition of the largest-scale footprints of ore-forming systems.

Of particular importance to us at Duluth Metals is the recognition of the physical magmatic processes in the Duluth Complex intrusions we are exploring. We view all these processes from the perspective of the initial conditions of the intrusion in general (and the target area in detail) and attempt to understand the chemical processes that are intimately paired with these physical processes. We ask each other simple questions like: (1) Where did magmas in intrusion X behave in a manner that was conducive for the concentration of ore minerals? (2) Where are their changes in the geometry of intrusions Y, i.e., areas of flow expansion, and areas of flow focusing?

Technology

The quantity and quality of data available to exploration geologists increases greatly with each passing year. Great innovations in geophysical techniques, geochemical analyses, and geospatial data management occur seemingly every month and a sound mineral exploration program must create and utilize these data in inventive ways into their ore

deposit targeting models. Duluth Metals is fully engaged in the innovations being developed for the minerals exploration industry and have: (1) acquired state-of-the-art airborne geophysical data over a 160,000 acre survey area and have seemingly innumerable 2D and 3D datasets of magnetics, gravity, and conductivity; (2) set in motion a large geochemical survey that will utilize QEMSCAN & MLA technologies as well as in-the-field geochemical analyses via a hand-held XRF; and (3) have built an impressive computer system with state-of-the-art software (ArcMap GIS, Oasis Montaj, Encom PA) to integrate all of these data into a single exploration platform.

People

Duluth Metals recognizes that the science of mineral exploration is more than just applied economic geology. It is a distinct discipline in its own right that embraces aspects from many other fields including; probability theory, risk-management, economics, and decision science. Most importantly, mineral exploration depends on well trained people who know geology and know how to think big, utilize technology, and protect the environment. Duluth Metals is a proud sponsor of the Precambrian Research Center and has other research ties to the University of Minnesota to help answer focused earth system questions (e.g. AMS to understand magmatic flow directions

Paleomagnetism of Midcontinent Rift rocks from the northern shore of Lake Superior (Ontario, Canada): Preliminary results

Elisa Piispa¹, Aleksey Smirnov¹, Lauri Pesonen²

¹*Department of Geological and Mining Engineering and Sciences, Michigan Technological University, 630 Dow, ESE Building, 1400 Townsend Drive, Houghton, MI 49931, USA*

²*Department of Physics, University of Helsinki, P.O. Box 64, FIN-00014 Helsinki, Finland*

We report the preliminary results of our paleomagnetic and rock magnetic investigations of a suite of extrusive and intrusive rocks representing the Mesoproterozoic Midcontinent Rift system along the northern shore of Lake Superior in Ontario, Canada. Specifically we investigated: (1) The abundant ~1144 Ma lamprophyre dykes near Marathon. These dykes, coeval with the Abitibi diabase dyke swarm, possibly represent the first magmatic stage of the Midcontinent Rift; (2) The ~1100 Ma copper-nickel-PGE-mineralized layered intrusion named Crystal Lake Gabbro South of Thunder Bay; (3) The ~1115 Ma Logan Sills predominating in the Southern Thunder Bay; (4) At least three different dyke sets: the NE –trending Pigeon River dykes with two potential magmatic episodes at ~1079 and ~1141 Ma, the ~1109 Ma NW-trending Cloud River dykes, and the ~1109 Ma Mount Mollie dyke; (5) The rocks of ~1108 Ma Coldwell Complex which represents the largest alkaline intrusion related to the Midcontinent Rift; and (6) Newly discovered Devon Township basaltic outcrops NE of Thunder Bay with an unknown age. A preliminary set of 220 independently oriented samples of these rocks were subjected to a detailed paleomagnetic study using both alternating field and thermal demagnetization, baked contact tests, and the measurements of magnetic hysteresis and other rock magnetic properties. In combination with the recently published high precision ages, we plan to use these paleomagnetic data to test the models of the apparent geomagnetic reversal asymmetry during the Precambrian as well as to further refine both the Apparent Polar Wander Path between 1144 and 1079 Ma and the evolution of the Midcontinent rifting sequence.

The use of S/Se ratios in magmatic Ni-Cu-PGE sulfide deposits and its implications for exploration: Example of the Duluth Complex, Minnesota, USA

Matthias Queffurus and Sarah J. Barnes

Université du Québec à Chicoutimi, DSA, matthias.queffurus@uqac.ca

S/Se ratios have been used in the study of magmatic Ni-Cu-PGE sulfide deposits as petrogenetic indicator of ore forming processes (e.g., Eckstrand et al., 1989). Despite the utility of S/Se ratios, no study has been dedicated specifically to the characteristics of the processes that could modify these ratios. We have compiled S, Se, $\delta^{34}\text{S}$ and metals data from more than fifty magmatic Ni-Cu and PGE deposits and added some new Se data for the country rocks from the Duluth Complex with the aims of: a) characterizing the deposits, b) better constrain the application of S/Se and, c) considering a wider range of processes than have been discussed in the past. Se concentrations were determined by TCF-INAA technique (Thiol Cotton Fiber - Instrumental Neutron Activation Analysis), developed by Savard et al. (2006).

Our results indicate that some processes, other than those mentioned in the past, i.e. the assimilation of country rocks and the remobilization of S post-cumulate, could modify the S/Se ratios and these include: a) changes in silicate to sulfide liquid ratio, R-factor (Thériault and Barnes, 1998); b) the segregation of the sulfide liquid (Barnes et al., 2009); c) a fractionation between MSS and ISS. These processes influence the concentrations of S and Se in mineralized rocks, i.e. S/Se ratio, and may overprint the original source of S and the interpretation of the genesis of the deposit. At the Duluth Complex, where country rocks assimilation is believed to play a key role in the genesis of the mineralization, the preliminary results of our work show that most of the Virginia Formation samples have S/Se ratios lower than the ore. Only the samples close to the contact of a particularly S-rich layer, known as the Bedded Pyrrhotite Unit (BPU) and the xenoliths, have S/Se ratios higher to than sulfide-bearing igneous rocks. The concentration of S, high S/Se ratio and sulfur isotopic values of rocks samples from the BPU strongly indicate that this layer would be the main source of S assimilated by the mafic magma.

REFERENCES

- Eckstrand, O.R., Grinenko, L.N., Krouse, H.R., Paktunc, A.D., Schwann, P.L., and Scoates, R.F., 1989, Preliminary data on sulphur isotopes and Se/S ratios, and the source of sulphur in magmatic sulphur in magmatic sulphides from the Fox River Sill, Molson Dykes and Thompson nickel deposits, northern Manitoba. *In: Current Research, Part C. Geological Survey of Canada v. 89-1C*, p. 235-242.
- Barnes, S.-J., Savard, D., Bédard, L.P., and Maier, W.D., 2009, Selenium and sulfur concentrations in the Bushveld Complex of South Africa and implications for formation of the platinum-group element deposits. *Mineralium Deposita*, v. 44, p. 647-663.
- Savard, D., Bédard, L.P., and Barnes, S.-J., 2006, TCF selenium preconcentration in geological materials for determination at sub- $\mu\text{g.g}^{-1}$ with INAA (Se/TCF-INAA): *Talanta* v. 70, p. 566-571.
- Thériault, R.M., and Barnes, S.-J., 1998, Compositional variations in Cu-Ni-PGE sulfides of the Dunka Road deposit, Duluth Complex, Minnesota: the importance of combined assimilation and magmatic processes: *Canadian Mineralogist* v. 36, p. 869-886.

Reconnaissance Bedrock Geological map of the northern part of Sudan Underground Mine State Park and the northwestern part of Lake Vermilion State Park, St. Louis County, Minnesota

Amy L. Radakovich, Charlie T. Parent, Molly E. Partridge, Andrew D. Ritts, Rita Pierce, and George J. Hudak

Precambrian Research Center, Natural Resources Research Institute, University of Minnesota Duluth, 5013 Miller Trunk Highway, Duluth, MN 55811

The “capstone” project for the Precambrian Research Center (PRC) summer field camp encompasses detailed field mapping and map production in small groups with faculty from the field camp. During the fifth and sixth weeks of the 2010 field camp, five PRC field camp students, under the direction of PRC Faculty member George Hudak, mapped Neoproterozoic rocks in the northeastern part of Sudan Underground Mine State Park and the northwestern part of Minnesota’s newest state park, Lake Vermilion State Park (Radakovich et al., 2010). This capstone mapping project sought to: 1) identify the lithologies and stratigraphy of the Neoproterozoic supracrustal strata in this area; 2) define and characterize the nature of the contact between various units of the Neoproterozoic supracrustal strata and intrusive rocks; 3) obtain a better understanding of geological structures and their orientations within the area; and 4) to make a comprehensive bedrock geological map for future use by the new Lake Vermilion State Park.

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

Neoproterozoic supracrustal rocks consist of a NE/SW striking, NW facing homoclinal sequence comprising three distinctive rock sequences. Up-section, these sequences are:

- (1) the Central Basalt Sequence of the Lower Member of the Ely Greenstone Formation, which is composed of medium green to dark green, aphyric to sparsely plagioclase-phyric, sparsely amygdaloidal sheet flow- and pillowed facies basalt lava flows which are locally strongly quartz-epidote altered;
- (2) the Sudan Member of the Ely Greenstone Formation, an interbedded sequence comprising: a) laminated to medium-bedded, planar-bedded, locally chaotically folded, dark gray to red-brown, Algoma-type oxide facies iron formation; b) medium- to dark green, aphyric to locally sparsely plagioclase-phyric, massive to moderately amygdaloidal andesite to basalt sheet flow facies lava flows; and c) localized gray to gray green, quartz $\pm$ plagioclase-phyric rhyodacite tuffs and polymict lapilli tuffs which are generally less than 10m in stratigraphic thickness.
- (3) the Gafvert Lake Member of the Lake Vermilion Formation, which is dominantly composed of intermediate to felsic volcanoclastic rocks comprising: a) a basal unit composed of massive, light gray, quartz- and plagioclase-phyric polymict dacite to

rhyodacite tuff; b) interbedded light gray, massive, quartz- and plagioclase-phyric dacite to rhyodacite tuff and pumiceous lapilli tuff; c) epiclastic deposits comprising light gray to brownish-gray, polymict volcanoclastic conglomerates and sandstones derived primarily from felsic rocks; and d) white to gray, thinly-bedded to massive, fine- to locally coarse-grained dacite to rhyodacite tuff breccias which locally exhibit graded bedding. Chemical sedimentary rocks composed of: a) light gray to black, laminated to very thickly bedded chert deposits; and b) light gray to dark gray, laminated to medium-bedded Algoma-type iron formation, occur in two distinctive stratigraphic horizons up to 300 meters thick in the central and northeastern parts of the field area.

Intrusions into the supracrustal assemblages include feldspar $\pm$ quartz porphyritic dacite to rhyodacite dikes and sills, medium-grained granodiorite dikes, and medium-grained gabbro sills. An east-west striking shear zone in the northeastern part of the field area is composed of highly foliated basalt or chlorite schist.

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

REFERENCES

- Hudak, G. J., Hoffman, A. T., Peterson, D. M., and Heine, J., 2007, Recent developments understanding the volcanic, magmatic, tectonic and metallogenic evolution of the Ely Greenstone Formation, Vermilion District, NE Minnesota. Institute on Lake Superior Geology, Proceedings Volume 53, Part 1 – Programs and Abstracts, p. 42-43
- Peter, J. M., 2003, Ancient iron formations: their genesis and use in the exploration for stratiform base metal sulphide deposits, with examples from the Bathurst Mining Camp: in Lentz, D. R., ed., *Geochemistry of Sediments and Sedimentary Rocks: Evolutionary Considerations to Mineral Deposit-Forming Environments*: Geological Association of Canada, GeoText 4, p. 145-176.
- 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-2003/29, 88 p.
- Radakovich, A. L., Parent, C. T., Partridge, M. E., Ritts, A. D., Pierce, R., and Hudak, G. J., 2010, Reconnaissance Bedrock Geological Map of the northern part of Soudan Underground Mine State Park and the northwestern part of Lake Vermilion State Park, St. Louis County, Minnesota: Precambrian Research Center Map Series, PRC/MAP-2010/04, 1:5000 scale.

Fluid flow events in the Biwabik Iron Formation, Minnesota

Ryan Rague and Steven Losh

Dept. of Chemistry and Geology, FH 241, Minnesota State University, Mankato MN 56001

Fluids have interacted with banded iron formation rocks of the Paleoproterozoic (~1.85 Ga) Biwabik Fm, exposed in the Mesabi range, during diagenesis and dissolution/oxidation. Burial diagenesis likely took place shortly after deposition at temperatures of around 150° – 200° C based on mineral assemblages and published oxygen isotope thermometry (Perry et al., *Econ. Geol.* 68, 1110-1125), whereas dissolution of silicates and carbonates and oxidation of iron to hematite (forming ‘natural ore’) has long been interpreted as a much younger supergene phenomenon associated with intense chemical weathering, perhaps during the Cretaceous. However, fluid inclusion and bulk geochemical analysis (specifically rare earths) of veins and whole-rock samples, respectively, from the Hibbtac, Thunderbird, Thunderbird South, Fayal, and LTV#6 pits, shows that oxidation may have taken place over a range of burial depths and temperatures, hence over a protracted period of time. Quartz vein samples from a variety of paragenetic settings (mainly from unoxidized low-angle faults, high-angle veins (+/- calcite +/- minnesotaite) without oxidation, and veins in high-angle faults (+/- Fe oxides) associated with oxidation) show considerable overlap of fluid inclusion homogenization temperatures (mean = 154° +/- 74° C, n= 467) and salinity (9.5 +/- 5.3 wt % NaCl equivalent, n=166) in the sample set. These temperatures are at the low end of those inferred for diagenesis; addition of a temperature correction due to fluid pressure, estimated at ~ 50° C corresponding to ~ 3-4 km burial depth, improves the correlation. Notably, fault breccia samples associated with oxidized (red hematitic) iron formation in the Hibbtac and Thunderbird South pits show elevated temperature and salinity, not consistent with supergene alteration.

Rare earth element analysis of samples of unoxidized and oxidized iron formation and veins from nearby faults indicate that fluids that precipitated quartz in the fault zones had locally interacted with a large amount of iron formation, acquiring its rare earth element ‘fingerprint’ in terms of positive europium, thulium, and/or cerium anomalies (relative to NASC). In the Fayal pit, ‘natural ore’ and associated quartz / calcite + hematite fault breccia are both characterized by strong cerium anomalies consistent with near-surface oxidation. In the Hibbtac pit, both oxidized iron formation and quartz + hematite fault breccia associated with oxidized ore show no cerium anomaly. Instead, both rock types show pronounced Tm anomalies (as does unoxidized iron formation at that location), indicating local control on the chemistry of fluids associated with oxidation and absence of large volumes of externally-derived supergene fluids during oxidation of iron formation adjacent to the sampled fault. Thus an early oxidation event, separate from late supergene ‘natural ore’ formation, may have tapped a mixture of diagenetic and oxidizing meteoric waters during uplift shortly after burial.

Preliminary stratigraphy and physical volcanology associated with the Paleoproterozoic Back Forty VMS deposit, Menominee County, Michigan

Cabin Ross¹, George Hudak², Ron Morton¹, Tom Quigley³, and Bob Mahin³

¹*Department of Geological Sciences, University of Minnesota Duluth, Duluth, MN 55812*

²*Precambrian Research Center, NRRI, University of Minnesota Duluth, Duluth, MN 55811*

³*Aquila Resources Inc., E807 Gerue Street, Stephenson, MI 49887*

Aquila Resources' Back Forty volcanogenic massive sulfide (VMS) deposit is the most recent VMS discovery within the Wisconsin Magmatic Terrane. The deposit is located approximately 200 meters east of the Menominee River, approximately 25 kilometers west of Stephenson in Michigan's Upper Peninsula. This research, which represents the first detailed volcano logical and hydrothermal alteration studies of the Back Forty VMS deposit, aims to: 1) establish the physical, chemical, and spatial attributes of the lithologies associated with the Back Forty deposit; 2) establish the stratigraphy in the vicinity of the Back Forty deposit and its relationship with VMS mineralization; 3) establish the physical, chemical, and spatial attributes of metamorphosed hydrothermal alteration mineral assemblages associated with the Back Forty deposit; 4) evaluate the spatial relationships of the alteration mineral assemblages to the Back Forty deposit mineralization; 5) identify chemical variations associated with alteration mineral phases at the Back Forty deposit, and evaluate the spatial relationships of these mineral compositional variations with the Back Forty mineralization; and 6) develop a coherent geological model of the volcanic setting and mineralizing environment associated with the genesis of the Back Forty VMS deposit.

Our study involved a multi-faceted approach including geological mapping, diamond drill core logging, petrographic, lithogeochemical, and mineral chemistry analyses. Geological mapping of the Back Forty deposit and surrounding area was completed at a 1:100 or 1:500 scale. Information mapped at each outcrop included descriptions of lithology, alteration minerals present, alteration intensity, mineralization, structural features and measurements, and other unique features (i.e. weathering patterns, magnetism, etc.). Regional mapping was limited to outcrop sampling with reference to previous work by Greenberg and Brown (1984). The drill cores investigated were selected based on location within mineralized zones, and previously defined stratigraphy and alteration types (Quigley et al., 2008). Twenty-three diamond drill core were selected throughout the mineralized zone with an additional 22 cores evaluated for regional lithology and alteration zone characteristics (a total of approximately 10,000 meters of drill core). 170 samples were selected for petrographic analysis based on lithological distribution, alteration mineral representation, variable spatial relationships to massive sulfides zones (i.e. above, below, or away from), and volcanic textures. Seventy-seven samples were submitted to Activation Laboratories Ltd. (ACTLABS, Ancaster, Ontario) for whole rock lithogeochemical major and trace element analysis.

Preliminary stratigraphy of the Back Forty deposit includes four main tuff units: A) massive, coarse-grained, quartz-phyric, rhyolitic lapilli tuff with 7-10%, <1-5mm euhedral to subhedral quartz crystals and angular quartz crystal fragments in a coarse, inequigranular quartz-rich matrix containing possible pumice and glass fragments; B) massive, quartz-feldspar-phyric, rhyolitic-rhyodacitic tuff with 5-7%, <1-5mm, subhedral quartz crystals and angular quartz crystal fragments and 1-3%, <1-2mm subhedral feldspar crystals and feldspar

crystal fragments in a variably coarse- to fine-grained, quartz-rich matrix; C) massive, fine-grained, quartz-phyric, rhyolitic-rhyodacitic tuff breccia with 5-7%, <1-4mm quartz crystal fragments and quartz shards in a fine-grained, quartz-rich matrix that contains fragments of unit A; D) massive, coarse-grained, aphyric, rhyolitic-rhyodacitic tuff to tuff breccia containing quartz-phyric tuff fragments in an aphyric, coarse-grained, quartz-rich matrix. Units A-C are interbedded with laminated ash and tuffaceous sedimentary rocks. Compositional classification (Winchester and Floyd, 1977) and tectonic affinity (Pearce et al., 1984) based on immobile trace elements indicate that host rocks for the Back Forty mineralization are arc-associated FII-type rhyodacites and rhyolites.

Alteration mineral assemblages and alteration zoning are still under review. Initial studies indicate the presence of four primary alteration minerals of various abundances: sericite, Mg-chlorite, iron-rich chlorite and quartz.

Mineralization at the Back Forty is generally bounded by laminated tuffaceous sedimentary rocks within the massive tuff units and could indicate conformable massive sulfide zones. However, remnant textures in massive sulfide zones suggest replacement-style mineralization (Doyle and Allen, 2003). To date, drilling at the Back Forty deposit has outlined a combined NI 43-101 compliant measured and indicated resource (open pit and underground development potential) of 18.1 million tonnes grading 0.19% copper, 2.48% zinc, 1.63 grams/tonne gold, and 20.04 grams/tonne silver (Aquila Resources' Press Release, October 15, 2010; www.aquilaresources.com).

Preliminary stratigraphic interpretations place tuff units A-D from oldest to youngest, respectively. Further analysis is needed to more completely define these relationships. Detailed physical volcanological environment is under investigation. Thick sequences of felsic volcanic rocks may be consistent with a caldera setting; however, more widespread regional stratigraphic studies will be needed to further test this interpretation.

REFERENCES

- Doyle, M.G. and Allen, R.L., 2003, Subsea-floor replacement in volcanic-hosted massive sulfide deposits: *Ore Geology Reviews*, 23, 183-222.
- Greenberg, J.K. and Brown, B.A., 1984, Bedrock Geology of Wisconsin, Northeast Sheet: Wisconsin Geological and Natural History Survey Map 84-2, Scale 1:250,000.
- Pearce, J.A., Harris, N.B.W. and Tindle, A.G., 1984, Trace element discrimination diagrams for the tectonic interpretation of granitic rocks: *Journal of Petrology*, 25, 956-983.
- Quigley, T., Mahin, B., and Aquila Field Office Geologic Staff, 2008, Back Forty Geology and Mineralization: 54th Annual Institute on Lake Superior Geology, Field Trip #3.
- Winchester, J.A. and Floyd, P.A., 1977, Geochemical discrimination of different magma series and their differentiation products using immobile elements: *Chemical Geology*, 20, 325-343.

Whole rock geochemical analyses of sheared granitic rocks from Mountain, Wisconsin

Brittany J. Saylor, Jonathan C. Stencil, Michael A. DeVasto, and Prajukti Bhattacharyya

University of Wisconsin – Whitewater, 800 W. Main St., Whitewater, WI 53190

Ductile deformation deep within the earth's crust and mantle are localized within narrow bands called shear zones. The purpose of our research is to gain a better understanding of how chemistry and mineral alignment patterns change across shear zones. We conducted our research on samples collected from around the Mountain Shear Zone exposed near the town of Mountain, Oconto County, Northern Wisconsin (Figure 1a-b: Sims et al. (1989a, b, 1991)) concluded that rocks in the study area belong to the eastern part of the Pembine-Wausau Terrane, which was accreted to the Superior craton during the Penokean Orogeny approximately 1.8 billion years ago. The study region was affected by ductile shearing about 25-35 million years after the main continent-arc collision event of the Penokean Orogeny (Sims et al., 1990, 1991). Most of the shear zones of comparable age in Wisconsin are buried under glacial deposits, so the exposed Mountain Shear Zone provides an excellent opportunity to study rock deformation processes that have taken place deep within the earth. Here, we present our preliminary observations on whole rock geochemistry, variation of magnetic susceptibility values along and across deformed samples collected from the study area.

In order to see whether whole rock chemistry changes with shear deformation we collected both deformed and undeformed granitic rock samples from the study area (Figure 1b), and recorded their locations using a hand-held GPS unit. We analyzed the whole rock geochemistry of selected samples using X-Ray Fluorescence (XRF) at the UW Milwaukee Campus to see how the whole rock chemistry differs in deformed and undeformed rocks. We also used the Magnetic Susceptibility Meter SM 30 to measure how the magnetic susceptibility values change within the same deformed samples.

The major minerals in the studied samples are quartz, potassium feldspar, plagioclase, biotite, and hornblende, with normative magnetite. Based on the QAP diagram, the analyzed samples can be classified as grandodiorite. The studied samples can be classified as peraluminous S-type granite common in orogenic belts.

We used samples M0513-O, M0513-Q, and M1003 as examples of undeformed rocks, and M1002-1 and M1002-A was taken from different parts of a sample showing a shear zone. The results of the chemical analysis show that the chemical compositions of even undeformed samples are different from each other. One explanation for this might be that there was more than one episode of minor granitic intrusion after the shearing event. Observations of rock texture in sample M1002-AB seems to support this hypothesis.

The magnetic susceptibility values per unit area of rock surface changes with distance in deformed samples, but seems to show no correlation with mineral alignment patterns. This variation could be due to higher concentration of magnetic minerals like magnetite in some parts of the analyzed samples as indicated by normative mineralogy.

We need to conduct detailed geochemical analyses including REE and trace element analyses to see if we can identify different generations of granite in the study area. We also

need to conduct detailed mineralogical and textural analyses using an optical microscope to study the effects of shearing on our samples.

Figures

Figure 1a



Figure 1b

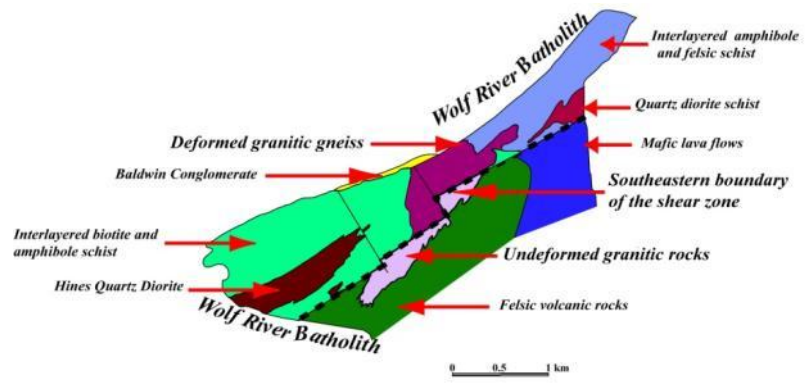


Figure 1. (a). A simplified regional geologic map modified after Sims, (1990) showing the study area outlined in red. (b). Detailed geologic map of the area around Mountain Shear Zone, modified after Sims, (1989a).

REFERENCES

- Sims, P.K. 1989a. Geologic map of Proterozoic rocks near Mountain, Oconto County, Wisconsin: U.S. Geological Survey Miscellaneous Investigations Series map I-1903, scale 1:24,000
- Sims, P.K., Van Schmus, W.R., Schulz, K.J., and Peterman, Z.E., 1989b, Tectonostratigraphic evolution of the Early Proterozoic Wisconsin magmatic terranes of the Penokean Orogen. *Canadian Journal of Earth Sciences*, 26, 2145-2158.
- Sims, P.K., Klasner, J.S., and Peterman, Z.E. 1990. The Mountain shear zone, northeastern Wisconsin – a discrete ductile deformation zone within the early Proterozoic Penokean Orogen. U.S. Geological Survey bulletin, 1904, Contributions to Precambrian geology of Lake Superior region
- Sims, P.K., Klasner, J.S., Day, W.C., and Peterman, Z.E. 1991. Mountain shear zone, Oconto County, Wisconsin – A post-Penokean discrete ductile deformation zone. Field trip guide, 37th Annual Meeting of Institute on Lake Superior Geology, Eau Claire, Wisconsin.

Comparison of microscale and regional scale structural control on gold mineralization in the North Caribou Greenstone Belt, Superior Province, Northwestern Ontario

Robert Scott¹, Maura Kolb¹, and Mary Louise Hill¹

¹*Dept. of Geology, Lakehead University, 955 Oliver Road, Thunder Bay, Ontario, P7B 5E1, Canada; rjscott@lakeheadu.ca*

The North Caribou greenstone belt is bounded on the north and east by the North Caribou-Totagan Lake shear zone that divides the North Caribou terrane from the Island Lake domain. The greenstone belt is host to the gold deposit at Musselwhite Mine, where gold is found in banded iron formation metamorphosed to the lower amphibolite facies. Microstructural analysis shows that gold is commonly found in the strain shadows of garnet where strain is lower. Strain shadows at the regional scale may also provide an area of lower strain that serves as a preferential location for gold mineralization. Understanding regional structural control on gold mineralization will provide an important tool in the exploration for gold.

On the microscopic scale, less competent matrix minerals (including quartz, biotite and grunerite) deform in a ductile manner while more competent minerals (including garnet and arsenopyrite) are more rigid and deform in a brittle manner. The competency contrast between garnet and the matrix creates strain shadows around the garnet; these areas of low strain are favourable locations for gold mineralization. Similarly, the lithological competency contrast between rigid granitic plutons and the more ductile metasedimentary and metavolcanic greenstone belt creates areas of low strain on the regional scale. The North Caribou batholith shows microstructural evidence of solid state deformation by dislocation creep along its eastern margin, indicating that it was crystallized and solid before being deformed by the North Caribou-Totagan Lake shear zone system. Although the batholith is more competent and therefore strain is localized in the more ductile greenstone belt, the edge of the batholith is affected by the deformation. At Libert Lake, a splay off the main North Caribou-Totagan Lake shear zone appears to anastomose around the Southern pluton. In this area there is evidence for recovery through grain boundary area reduction (GBAR) in addition to evidence for dislocation creep. GBAR suggests a significant decrease in strain to allow for recovery at the elevated temperatures of metamorphism.

There is a common spatial relationship between gold deposits and strain shadows on the regional scale, some of which are major gold camps including Hemlo, Red Lake and Musselwhite Mine, where the gold deposits are situated in greenstone belts proximal to several granitic plutons. The low strain (strain shadow) areas are produced by competency contrast between plutons and greenstone belts and in these cases host significant gold mineralization. Regional structural control of gold mineralization is similar in geometry to the microstructural control, and lithological competency contrast may be a useful tool for predicting the occurrence of other economic orogenic gold deposits.

The Pillar Lake Volcanics: new insights into an enigmatic mesoproterozoic volcanic suite near Armstrong, Ontario

Mark Smyk¹, Peter Hollings², and Robert Cundari²

¹*Ontario Geological Survey, Ministry of Northern Development, Mines and Forestry, Suite B002, 435 James St. South Thunder Bay, ON P7E 6S7 Canada*

²*Department of Geology, Lakehead University 955 Oliver Road Thunder Bay, ON P7B 5E1 Canada*

The Pillar Lake volcanic suite was first recognized and mapped by Macdonald (2004) and is the subject of an ongoing study by Magee (in progress). Initial observations suggested that it largely consisted of a sequence of flat-lying pillowed and massive flows and autoclastic and hyaloclastic breccias. The volcanic rocks unconformably overlie the Badwater gabbro (~1599 Ma) and Badwater syenite (~1590 Ma) and are capped by Keweenawan Inspiration diabase sills (1159 ± 33 Ma), yielding an apparent thickness of 20 to 40 m (Hart and Macdonald 2007; Heaman et al. 2007). Titanite in an andesitic unit yielded a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1129.0 ± 4.6 Ma; no zircon nor baddeleyite was recovered in the sample (Heaman et al. 2007).

Reinvestigation of these volcanic rocks in 2010 was prompted by a new exposure south of Armstrong that had been created during ballast quarry development. The quarry face exposes a ~15 m section of thin (0.5 to 2 m), flat-lying, variably altered, columnar-jointed, basaltic andesite flows, capped by a diabase sill. Individual flows may persist over the 130 m length of the exposure while others bifurcate and terminate as thin tendrils in flow breccia. Autobrecciated zones are rubbly weathering and occupy the spaces between thin, pinching flows. Thin flow top breccias separate flows. Massive flows contain zones of pipe amygdules at their bases and tops. The morphology and disposition of these flows is suggestive of an intercalated, subaerial pahoehoe and a'a flow succession. Ropy flow tops were noted at a nearby location for the first time during this investigation. Ellipsoidal features seen in some sections that were initially considered to be pillow forms may now be reinterpreted as pahoehoe toes.

These volcanic rocks are variably altered along fractures, flow contacts and within brecciated zones. This hydrothermal alteration is typically manifested as a beige to pink discolouration of the dark grey-black flows resulting from the destruction of primary ferromagnesian minerals and the introduction of alkali feldspar, sericite and quartz. Void spaces along joints and fractures and in vesicles has been occupied by large (≤ 3 cm), black, euhedral actinolite crystals. Small acicular asbestiform crystals of edenite were also identified by x-ray diffraction analysis. Alteration is characterized by increases in Al_2O_3 , K_2O , Na_2O , and SiO_2 and decreases in CaO , Fe_2O_3 , MgO , P_2O_5 and TiO_2 .

The trace element geochemistry of the sill that caps the quarry face is identical to that of the Inspiration sill identified by Hart and Macdonald (2007) and we propose that this sill is part of that intrusive suite. Samples of the volcanic rocks display REE enrichment and negative Nb anomalies comparable to the range of samples of the Pillar Lake volcanic suite reported by Magee (personal communication, 2011). Samples of the Inspiration sills are geochemically indistinguishable from the Pillar Lake volcanic rocks and to least-altered pillowed samples with the lowest LOI values. The similarity between these two enigmatic

suites suggests that they may be derived from the same source.

MacDonald and Tremblay (2005) distinguished the Inspiration sill, which exclusively overlies the Pillar Lake rocks, on the basis of its normal polarity and distinct geochemistry. Primary clinopyroxene in the Inspiration sill was commonly replaced by actinolite (Schandl, 2004). MacDonald et al. (2005) also noted a remarkable lack of chilled margins on the Inspiration sill and suggested that it was older than the Nipigon sills. Later work by Heaman et al. (2007) determined an age of 1159 ± 33 Ma for the Inspiration sill, which is consistent with the early period of normal polarity.

We propose that the Pillar Lake basalts may in fact be may be coeval with the Inspiration sill which, in turn, may represent either a subvolcanic intrusion or possibly a massive, ponded flow / lava lake. This may account for the extensive alteration in the Pillar Lake basalts with the sill acting as an impermeable cap to hydrothermal fluids, which were concentrated in the underlying volcanic flows. The similarity of the Pillar Lake and Inspiration sill magmatism to other magmas of the MCR, including the Nipigon sills and Osler volcanic rocks (Hollings et al., 2007), suggests that these rocks may represent a very early extrusive to subvolcanic phase of rift activity. The location of these rocks close to the ~1599 Ma Badwater gabbro, the ~1590 Ma Badwater syenite and the ~1540 Ma English Bay anorogenic granite, which have been interpreted as evidence for a long-lived crustal weakness (Hollings et al. 2004), may offer an explanation for how these magmas were erupted so early in the rift history.

REFERENCES

- Hart, T.R., MacDonald, C.A., 2007. Proterozoic and Archean geology of the Nipigon Embayment: Implications for emplacement of the Mesoproterozoic Nipigon diabase sills and mafic to ultramafic intrusions. *Canadian Journal of Earth Sciences* 44, 1021–1040.
- Heaman, L.M., Easton, R.M., Hart, T.R., Hollings, P., MacDonald, C.A., 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., MacDonald, C.A., 2007a. Geochemistry of the Mesoproterozoic intrusive rocks of the Nipigon Embayment, northwestern Ontario: evaluating the earliest phases of rift development. *Canadian Journal of Earth Sciences* 44, 1087–1110.
- Hollings, P., Fralick, P., Kissin, S., 2004. Geochemistry and geodynamic implications of the Mesoproterozoic English Bay Granite-Rhyolite complex, northwestern Ontario. *Canadian Journal of Earth Sciences* 41, 1329–1338.
- MacDonald, C.A. 2004. Precambrian geology of the south Armstrong-Gull Bay area, Nipigon Embayment, northwestern Ontario; Ontario Geological Survey, Open File Report 6136, 42p.
- MacDonald, C.A. and Tremblay, E. 2005. Lake Nipigon Region Geoscience Initiative, Bedrock Mapping Project: Geology of the northwest Nipigon Embayment; unpublished poster, Ontario Geological Survey.
- MacDonald, C.A., Tremblay, E. and Easton, R.M. 2005. Precambrian geology of the west-central map area, Nipigon Embayment, northwestern Ontario, Lake Nipigon Region Geoscience Initiative; Ontario Geological Survey, Open File Report 6164, 49p.
- Magee, A. (in progress). Geology and geochemistry of the Pillar Lake volcanic sequence, northwestern Ontario; unpublished M.Sc. thesis, Carleton University, Ottawa ON.
- Schandl, E.S. 2004. Petrographic data from the northwest Nipigon Embayment, Lake Nipigon Region Geoscience Initiative (LNRGI); Ontario Geological Survey, Miscellaneous Release-Data 141.

Microstructural control on gold mineralization in greenschist to amphibolite facies metamorphism, Greenstone, Ontario

Victoria R. Stinson and Mary Louise Hill

Dept. of Geology, Lakehead University, 955 Oliver Road, Thunder Bay, Ontario, P7B 5E1 Canada; vrstinso@lakeheadu.ca

In Greenstone, Ontario, north of Lake Superior in the Superior Province, gold mineralization is associated with regional shear zones within the Beardmore-Geraldton and Onaman-Toshota greenstone belts. Metamorphic grade increases from greenschist facies near Jellicoe, Ontario to amphibolite facies in Longlac, Ontario. Gold is hosted within various lithologies, including iron formation, mafic volcanics, and granodiorite, typically in association with ductile and brittle-ductile structures such as deformed quartz veins. On the microscopic scale, gold is found along quartz-quartz and quartz-muscovite grain boundaries, as inclusions in porphyroblasts of pyrite and albite, and in pressure shadows around competent porphyroblasts. Gold is present in association with similar microstructures regardless of lithology and metamorphic grade.

Mafic volcanics at the Prodigy Gold Incorporated Hercules and Castlewood properties north of Jellicoe have been metamorphosed to the greenschist facies with stable metamorphic mineral assemblages that include chlorite and albite. Gabbro at the Prodigy Gold Inc. Milestone property in Longlac has been metamorphosed to amphibolite facies with a stable metamorphic mineral assemblage of hornblende and plagioclase. Within shear zones at Milestone, epidote and chlorite replace hornblende indicating retrograde greenschist facies metamorphism during deformation after peak amphibolite facies metamorphism.

All samples with gold mineralization from both Jellicoe and Longlac have microstructures characteristic of ductile deformation at temperatures of greenschist facies metamorphism or higher including quartz grains with irregular grain boundaries, undulose extinction in quartz, and subgrains in quartz. In samples from Longlac with gold mineralization, plagioclase has undulose extinction consistent with ductile deformation at temperatures of amphibolite facies metamorphism or higher. In all samples, gold is found along subgrain boundaries in quartz and along grain boundaries, commonly within muscovite. Pyrite commonly has strain fringes of quartz that have been rotated, indicating non-coaxial strain. Inclusions of gold are within porphyroblasts of pyrite and albite, and also within pressure shadows around the porphyroblasts. Gold is present in similar microstructures regardless of metamorphic grade.

A deformation history of the Ivanhoe Lake Fault

Brittney Swoffer and Mary Louise Hill

Lakehead University, Department of Geology, 955 Oliver Road, P7B 5E1, Thunder Bay, Ontario, Canada. bswoffer@lakeheadu.ca

Ivanhoe Lake is located 220km east of Wawa, Ontario, Canada. The Ivanhoe Lake Fault runs northeast to southwest and is the boundary between the high grade metamorphism of the Kapuskasing Structural Zone and the low grade metamorphism of the Abitibi Subprovince. This difference in grade of metamorphism is what makes the Ivanhoe Lake Fault so interesting to study. Through analysis of the microstructures seen in thin section a long deformation history was revealed. Ductile deformation characteristic of deep burial as well as deformation at or near the brittle-ductile transition zone were evident. This affects a wide area that extends to either side of the fault. This was followed by brittle fracturing at a shallower depth of burial. The brittle deformation is confined to a narrow zone found along Ivanhoe Lake. Examples of ductile deformation within the thin sections include: undulatory extinction in quartz, subgrains in quartz and feldspars, deformation twins in plagioclase and microcline, as well as irregular grain boundaries for all grains. The brittle-ductile transition zone is documented by the existence of pseudotachylites. These glassy rocks are characteristic of large faults. The brittle history is documented by quartz or calcite filled fractures found at both the outcrop and microscopic scale. These brittle structures commonly cross cut the ductile features. This cross-cutting relationship suggests that the fault has had a long history which began with ductile deformation and progressed into brittle deformation.

Geology and mineralization of the Serpentine Cu-Ni deposit, Duluth Complex Minnesota

Erik R. Tharalson and Thomas Monecke

Department of Geology and Geological Engineering, Colorado School of Mines, 1516 Illinois Street, Golden, Colorado 80401, USA, etharals@mines.edu

The Serpentine Cu-Ni deposit is located approximately 7km southeast of Babbitt, MN and is hosted within the South Kawishiwi intrusion, in the 1.1 Ga Duluth Complex (Fig. 1). The footwall rocks to the deposit are comprised of metagreywacke and banded iron ores of the Paleoproterozoic Virginia and Biwabik Iron Formations.

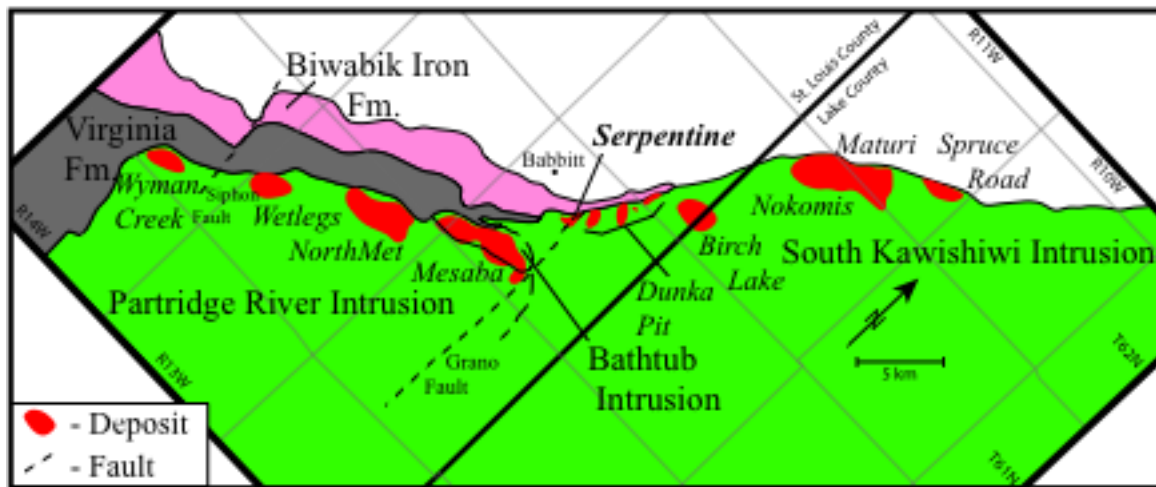


Figure 1: Generalized geologic map showing the locations of deposits within the Duluth Complex (modified from Severson and Hauck, 2008).

The South Kawishiwi intrusion has been studied in detail and an igneous stratigraphy has been established by Severson (1994). However, the identified igneous stratigraphy is not recognizable in the area of the Serpentine deposit, possibly due to the occurrence of a local magmatic feeder intruding the stratigraphy or even the occurrence of separate intrusion. The Serpentine deposit is located immediately adjacent to the Grano fault (Fig. 1), which is believed to have been instrumental in controlling the location of a feeder for the Bathhtub intrusion (Severson & Hauck, 2008) and the Local Boy massive sulfide deposit (Severson, 1994). Drill core logging in the Serpentine area has identified a heterogeneous mix of troctolitic rocks with minor norites. Igneous textures are characterized by subhedral to euhedral plagioclase with intergranular olivine, augite, and oxides. Plagioclase is locally enclosed in subophitic to ophitic augite.

The Serpentine deposit was discovered in 1958 by AMAX following up an EM survey (Kulas, 1979). The deposit consists of two resources: (1) a disseminated sulfide resource yielding 430 million tons of 0.41% Cu and 0.14% Ni, and (2) a semi-massive sulfide resource of 7 million tons of 0.88% Cu and 0.30% Ni (Kulas, 1979). Disseminated mineralization occurs as thick intervals (>50 feet) of interstitial sulfides making up <5% by volume. Pyrrhotite is the dominant sulfide, but chalcopyrite and cubanite locally occur in

equal amounts. The semi-massive and massive sulfides are pyrrhotite-rich with up to 7% copper sulfides and minor pentlandite. The massive sulfide intervals display sharp and gradational contacts and can be up to 19 feet thick. They often display variable textures; including rounded pyrrhotite with interstitial copper sulfides and pegmatitic pyrrhotite with wormy, crosscutting copper sulfides. Most of the semi-massive to massive sulfide occurs within the footwall Virginia Formation or at the basal contact of the Virginia Formation with the South Kawishiwi intrusion. Sulfur isotope values for the Virginia Formation were analyzed by Arcuri and others (1998) and found to range from 8.1 to 29.1 per mil, with most values above 15 per mil. New sulfur isotope values for massive sulfides ranging from 13.1 to 16.3 per mil are consistent with the Virginia Formation representing the principal sulfur source.

Understanding the deposit geology and reasons for the accumulation of massive sulfide at Serpentine will help to better focus exploration in developing this deposit. Continued research will establish whether the deposit occurs in proximity to a local magmatic feeder.

REFERENCES

- Arcuri, T., Ripley, E.M., and Hauck, S.A., 1998, Sulfur and oxygen isotope studies of the interaction between pelitic xenoliths and basaltic magma at the Babbitt and Serpentine Cu-Ni deposits, Duluth Complex, Minnesota.
- Kulas, J.E., 1979, Serpentine reserve; MINNAMAX Project Babbitt, Minnesota: Internal AMAX Company Report, 17p.
- Severson, M.J., 1994, Igneous stratigraphy of the South Kawishiwi intrusion, Duluth Complex, northeastern Minnesota: Natural Resources Research Institute, Technical Report NRRI/TR-93/34, 210 p., 15 pls.
- Severson, M.J., and Hauck, S.A., 2008, Finish logging of Duluth Complex drill core (and a reinterpretation of the geology at the Mesaba (Babbitt) deposit): Natural Resources Research Institute, Technical Report NRRI/TR-2008/17, 68 p., 94 pls.

The mineralogy, spatial distribution, and isotope geochemistry of sulfide minerals in the Biwabik Iron Formation

Steph Theriault¹, Jim Miller¹, Mike Berndt², and Ed Ripley³

¹*Department of Geological Sciences, University of Minnesota-Duluth, Duluth, MN 55812*

²*Division of Lands and Minerals, MN Department of Natural Resources, St. Paul, MN 55155*

³*Department of Geological Sciences, Indiana University, Bloomington, IN 47405*

Sulfate cycling in the St. Louis River Watershed (SLRW) requires knowledge of the distribution of sulfide minerals undergoing oxidation in the region, including those from the Biwabik Iron Formation (BIF). The BIF occurs along the Mesabi Range in northeastern Minnesota and continues to be extensively mined for taconite. Associated tailings basins and waste rock piles containing BIF and the overlying Virginia Formation are located along the northern portions of the SLRW. Although the BIF is not considered a sulfide-bearing formation, it contains measurable amounts of sulfide minerals, primarily in the form of pyrite and pyrrhotite (Gundersen and Schwartz, 1962).

Three notable previous studies have been conducted on the geochemistry of primary sulfide minerals in the Animikie Basin sediments. The sulfur isotope ($\delta^{34}\text{S}$) values cited in each of the studies suggest that primary sulfide minerals of the Animikie Group sediments are the result of bacterial reduction of late Paleoproterozoic seawater sulfate (Poulton et al., 2010; Johnston et al., 2006; Carrigan and Cameron, 1991). However, these studies principally focused on primary sulfide minerals which formed during or soon after the deposition of the BIF. This study, which is being conducted in conjunction with the Minnesota Department of Natural Resources sulfate cycling study of the SLRW, seeks to delineate the mineralogy, distribution, and sulfur isotope geochemistry of sulfide minerals in the BIF. This includes minerals formed by secondary processes, such as the thermal metamorphism of the 1.1 Ga Duluth Complex and the formation of natural ores. These data can be used to better define the major source components of sulfate to the SLRW and to help determine how sulfate, once released, behaves in the environment.

Samples containing visible sulfide minerals were collected from five well-spaced drill cores across the Mesabi Range (Fig. 1). Each sulfide-bearing stratigraphic subunit of the BIF (upper slaty, upper cherty, lower slaty, intermediate slate, lower cherty) was sampled in each drill core. Commonly multiple samples were collected when various sulfide mineral habits were encountered in a given unit. In all, 123 samples were collected; 63 were prepared for sulfur isotope analysis and 26 were made into polished thin sections for petrographic study of mineral paragenesis and mineral identification. Results were compared to sulfur isotope data for dissolved sulfate in streams leading from the mining operations.

Preliminary results show a complex relationship between geographic location, stratigraphic position, and type of sulfide occurrence. A large range of $\delta^{34}\text{S}$ values were obtained from samples collected for this study, spanning from +80.37‰ to -36.11‰ (see Fig. 1). Also, four different sulfide mineral habits were noted in the BIF: euhedral cubes, euhedral framboids or spheroids, anhedral “blebs,” and veins. Primary sulfides, in this study, appear mainly as anhedral “blebs” but also occurred as euhedral cubes. They are characterized by a limited range of slightly heavy $\delta^{34}\text{S}$ values, from +2‰ to +13‰, similar to those cited in the studies mentioned above. In this study, for example, the primary sulfide isotope values were observed throughout the intermediate slate layer and in the eastern-most, metamorphosed portion of the Mesabi Range. Metamorphism, including the transition from pyrite to pyrrhotite, does not appear to have affected sulfur isotopic composition of the sulfide minerals. However, it is possible that the $\delta^{34}\text{S}$ values were homogenized during metamorphism and now artificially appear primary. Sulfide minerals formed through secondary processes occur in veins or as euhedral framboids, spheroids, or cubes. They correspond to the more extreme $\delta^{34}\text{S}$ values, which presumably formed through processes such as weathering and hydrothermal alteration.

In conclusion, both primary and secondary processes are evident in the formation of sulfide minerals throughout the BIF, with secondary sulfide values spanning a broader range than the limited, +2‰ to +13‰, values associated with primary sulfides. Sulfur isotope values for sulfates in stream water samples collected close to mining operations have a relatively narrow range of +4‰ to +9‰, as well. This suggests that primary sulfides within the BIF may contribute most of the sulfate found in the streams. The veins and other noted sparse occurrences sampled in this study may also contribute to the sulfate in area streams, but it is possible their contribution is negligible compared to that of the primary sulfides or there is a balance where the average values from secondary sulfides are, coincidentally, isotopically similar to that of the primary sulfides. However, because sampling was conducted only for visible sulfide minerals in this study, it is possible this correlation is only coincidental. Additional sulfur isotope analyses in the region will help to further delineate all possible sources of sulfate to the SLRW.

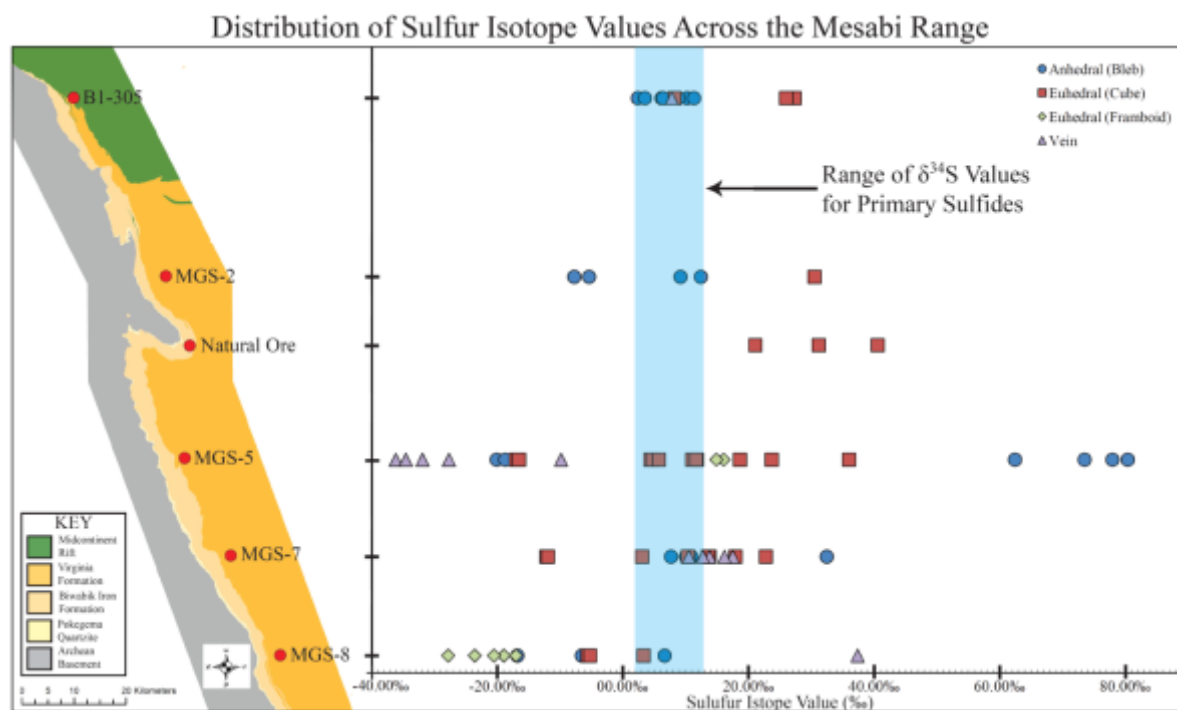


Figure 1. Distribution of sulfur isotope ($\delta^{34}\text{S}$) values at each core location across the Mesabi Range in northeastern Minnesota. Values are reported in per mil (‰) from sulfide mineral occurrences taken throughout the Biwabik Iron Formation and lower most portions of the Virginia Formation.

REFERENCES

- Carrigan, W.J. and Cameron, E.M., 1991, Petrological and stable isotope studies of carbonate and sulfide minerals from the Gunflint Formation, Ontario: evidence for the origin of early Proterozoic iron-formation, *Precambrian Research*, v. 52, p. 347-380.
- Gunderson, J.N. and Schwartz, G.M., 1962, *The Geology of the Metamorphosed Biwabik Iron-Formation, Eastern Mesabi District, Minnesota*.
- Johnston, D.T., Poulton, S.W., Fralick, P.W., Wing, B.A., Canfield, D.E., and Farquhar, J., 2006, Evolution of the oceanic sulfur cycle at the end of the Paleoproterozoic, *Geochimica et Cosmochimica Acta*, v. 70, p. 5723-5739.
- Poulton, S.W., Fralick, P.W., and Canfield, D.E., 2010, Spatial variability in oceanic redox structure 1.8 billion years ago, *Nature Geoscience*, v.3, p. 486-490.

Characterization of gangue minerals in lower cherty ores of the Biwabik Iron Formation at United Taconite LLC

Michael Totenhagen¹, Penny Morton², and Phil Larson³

¹*M.S. Candidate Department of Geological Sciences, University of Minnesota Duluth, 229 Heller Hall 1114 Kirby Drive, Duluth, MN 55812*

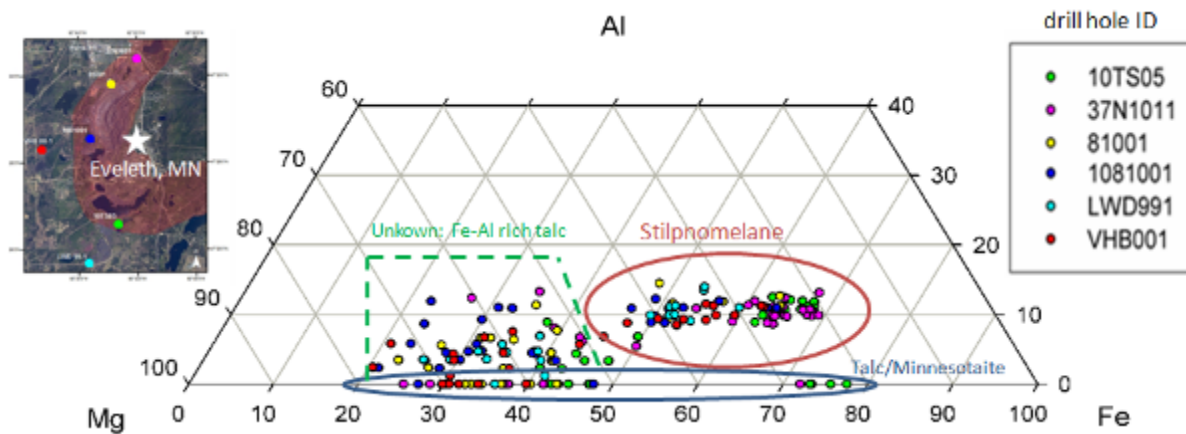
²*Associate Dean Swenson College of Science and Engineering, Associate Professor Department of Geological Sciences, University of Minnesota Duluth, 229 Heller Hall 1114 Kirby Drive, Duluth, MN 55812*

³*Senior Geologist Duluth Metals, 306 West Superior Street, Suite 60, Duluth, MN 55802*

Gangue minerals in lower cherty ores of the Biwabik Iron Formation at United Taconite's Thunderbird mine in Eveleth Minnesota cause an observed decrease in plant water quality during processing. Cliffs Natural Resources (CNR) thinks this problem may be related to a particular gangue mineral staying suspended in plant water. CNR has identified this mineral as a Fe-rich talc occurring in the LC4 ore unit, a cherty thick to thin bedded ore as defined by United Taconite. This project focuses on the gangue minerals in lower cherty ore at United Taconite's Thunderbird mine through petrography, X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM) and microprobe analysis, to describe both the mineral abundance and composition in diamond drill core. Fe-rich talc, minnesotaite, stilpnomelane and Fe-Al rich talc display the most intense variations in abundance, occurrence and composition in comparison with carbonates, oxides and quartz. The total abundance of these minerals varies between 10-70%, with the highest abundance occurring in the LC4 and LC2 ore units. There is no apparent spatial variation along strike (Fig 1. A). However, the LC4 and LC2 ore units contain the majority of Fe-Al rich talc and the LC5 ore unit contains a high concentration of Mg-rich stilpnomelane (Fig 1. B).

Some of the Fe-rich talc contains elevated amounts of Al as shown by both SEM and microprobe analysis (Figure 1. A & B). This suggests that there might be an unknown mineral (Fe-Al rich talc) occurring with Fe-rich talc, minnesotaite and stilpnomelane. This Fe-Al rich talc appears to be an early stage mineral as it is commonly overprinted by minnesotaite and stilpnomelane but overprints early quartz and carbonate.

A.



B.

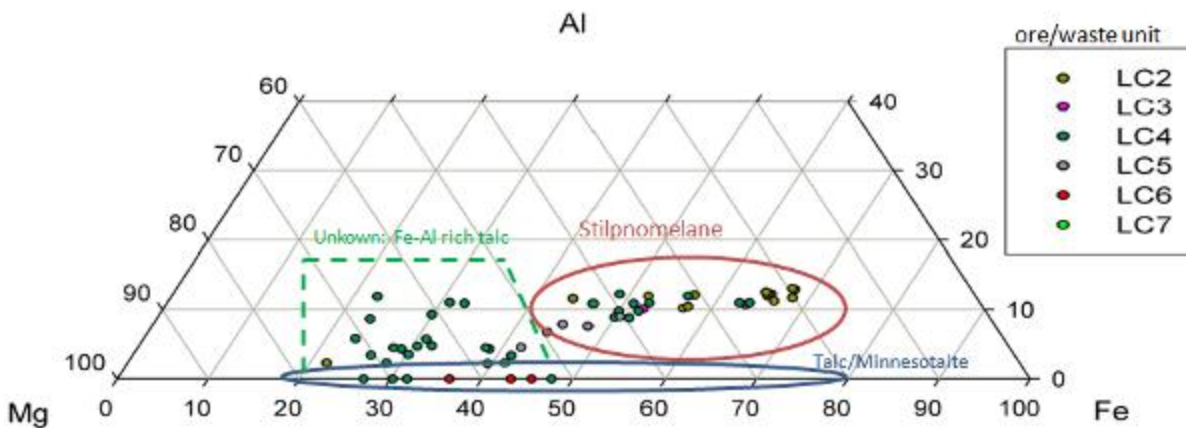


Figure 1. A. Compositional variation by drillhole of talc-minnesotaite, Al rich talc, and stilpnomelane in the LC4 ore unit. **B.** Stratigraphic compositional variation in drill hole 1081001.

These results are consistent with CNR observations of stratigraphic variation in Fe-rich talc, however we have identified a Fe-Al-rich talc which has not been previously reported. Both of these minerals might be responsible for the decrease in water quality during processing of some LC4 ore. Further research is needed to follow the character of these minerals through the concentrating process to confirm if the observed variation in abundance, composition, and distribution are responsible for variable results during processing.

Using cleavage refraction and microstructural evidence to determine the relative rheology of naturally deformed quartzites and phyllites from Baraboo, Wisconsin

Jolene T. Traut and Dyanna M. Czeck

Department of Geosciences, University of Wisconsin–Milwaukee, P.O. Box 413, Milwaukee, WI 53201

Understanding the rheology of rocks is a first-order question in tectonic studies where we aim to understand how rocks flow in response to stress. Rock rheology is largely studied through experimental work, but cannot be easily applied to natural deformation because of the long time-scales involved and the complications derived from rocks containing multiple minerals, all with different strengths. The Baraboo syncline near Baraboo, WI is an ideal test case to compare natural deformation to rheologic experimental results conducted on quartz because the main lithology at Baraboo is a quartzite derived from a clean quartz arenite. Within the Baraboo syncline, the variation in lithology (quartzite and phyllite) results in a difference in how these rocks responded to deformation and metamorphism during the regional contraction from the Mazatzal orogeny.

We conducted a detailed analysis of the cleavage refraction through a graded contact between the quartzite and phyllite layers in several areas around the syncline (Figure 1) and combined those results with mineralogy determined by X-ray diffraction (XRD). The angle between bedding and cleavage varies between approximately 89° in the most competent quartzite layers (approximately 99% quartz and 1% pyrophyllite) and 15° in the least competent phyllite layers (approximately 82% quartz and 13% pyrophyllite). Due to the increase in pyrophyllite, cleavage readily forms in the phyllite causing a smaller cleavage/bedding angle than what can be seen in the more competent quartzite. Where possible, we determined effective viscosity ratios using the Treagus (1999) cleavage refraction method. Preliminary cleavage/bedding angle data suggest that the effective viscosity ratios range between 1.0 – 3.7, which are values comparable to other studies.

Microstructural evidence indicates that varying degrees of recrystallization of quartz occurred during deformation, and it is possible that the amount of smaller, recrystallized grains respond differently than the original depositional grains. By combining point counting methods and the total quartz abundance determined through XRD, we will be able to extract whether these recrystallized grains impact the overall rheology.



Figure 1: Field photos of cleavage refraction in a graded contact between quartzite and phyllite located in the Williams Quarry near Baraboo, WI on the north limb of the syncline. The black lines represent the orientation of bedding, and the white lines represent the orientation of cleavage as it refracts through the two lithologies.

REFERENCES

- Treagus, S., 1999. Are viscosity ratios of rocks measurable from cleavage refraction?
Journal of Structural Geology, 21, 895-901.

Surface and subsurface geologic maps of the Soudan Underground Mine State Park, St. Louis County, Northeastern Minnesota

Alexandra M. Vallowe¹, Ernest J. Thalhamer², Damon L. Rhoades³, and Dean M. Peterson⁴

University of Minnesota Duluth, Precambrian Research Center

¹*Virginia Polytechnic Institute and State University 4044 Derring Hall (0420) Blacksburg, VA 24061, USA*

²*SUNY College: University at Buffalo, Buffalo, NY 14260-1608*

³*University of Central Missouri, Warrensburg, MO 64093*

⁴*University of Minnesota Duluth, University of Minnesota Duluth, Duluth, MN 55812*

Three Precambrian Research Center field camp students, under the guidance of Dean M. Peterson, completed an underground and surface mapping project at the Soudan Mine, northeastern Minnesota. The purpose of the mapping was to provide the Soudan Underground Mine State Park an updated geological map of the surface and subsurface geology of the Soudan Mine for use in geologic tours and scientific research. In addition, the underground geologic map of the 27th level has been, and continues to be used extensively in numerous geobiology studies. These maps are the result of five days field mapping by the authors in August 2010.

The surface geology (Map 1) was mapped for several hours in the afternoon over a period of five days. The authors worked as individuals to cover the mapping area. The authors recorded notes and observations, collected samples, took structural measurements (bedding orientations, lineation, foliation), and plotted data on a 1:5,000 scale field map. Location was determined using a handheld GPS unit, and structural measurements were taken using a Brunton Pocket Transit. Surface outcrops were exposed by peeling back moss layers and sweeping up remaining soils with whisk brooms. Open pits and other “man-made” exposures were also available within the mapping area, but with limited access. The surface bedrock map displays sheared rocks composed of chlorite (5c) and sericitic schists (5s), intrusive rocks such as granite (Gr) and quartz feldspar porphyry (Qfp), and the Upper Sequence rocks which include oxide facies iron formation (4a), lapilli tuff (2e), and greywacke (3a). The surface map also shows two major shear zones which are truncated by the Soudan fault to the east, as well as a minor shear zone. Our assumptions and interpretations of the surface field data were influenced by previously existing map data. Information from Peterson and Patelke’s 2003 surface map, as well as historical drill core data (circa 1954) from the Oliver Mining Division of US Steel Corporation was incorporated into building the final map.

The geology of the 27th level west drift was mapped by the authors over a period of five nights (5:00 PM – Midnight). The authors worked as a team to locate contacts, collect samples, take structural measurements (cleavage, lineation, fault orientations, etc.), record notes and observations, and plot important features on a field map. Geologic information from horizontal drill holes were used to interpret the geology adjacent to the drift. Locations in the mine were determined by measuring tape. Structural data were measured using a Brunton Pocket Transit; there was no deviation of local magnetic field observed. In contrast to the surface mapping, the drift provided complete outcrop exposure with rare exceptions where the drift walls and ceilings were obscured by pipes and other man-made structures.

The drift map (Map 2) includes rock units that correlate to units on Map 1, however, there are two below ground units, gabbro (Gb) and fragmented schist (5f), that do not show a surface expression. Map 2 includes the geology of the 27th level east drift which was previously mapped by Peterson and Patelke (2003). Map 2 also includes annotations by the authors which indicate the locations of significant drift features that may be relevant for mine employees, visitors, and scientists.

REFERENCES

- Oliver Iron Mining Company., 1953-1954. Soudan Mine Area Worksheet.
- Peterson, D. M. and Patelke, R.L., 2003. Bedrock Geologic Map of the Soudan Mine Area, St. Louis County, Northeastern Minnesota: Natural Resources Research Institute Technical Report NRRI/TR-2003/29. Scale 1:5,000.
- Peterson, D.M. and Patelke, R.L., 2003. Geologic Map of the 27th Level East Drift, Soudan Mine.
- Peterson, D.M. and Patelke, R.L., 2003. National Underground Science and Engineering Laboratory (NUSEL) Geological Site Investigation for the Soudan Mine, Northeastern Minnesota. Economic Geology Group, Natural Resources Research Institute, University of Minnesota Duluth.

Neoarchean magmatism in the NW Superior Craton: Granitoids of the North Caribou Terrane

Amanda Van Lankvelt¹, David Schneider¹, Keiko Hattori¹, and John Biczok²

¹Department of Earth Sciences, University of Ottawa, Ottawa, ON K1N 6N5 Canada

²Goldcorp Canada Ltd., Musselwhite Mine, P.O. Box 7500, Thunder Bay, ON, P7B 6S8 Canada

The North Caribou Terrane (NCT), located in northwestern Ontario and eastern Manitoba, is the core of the Archean Superior Province. Like many Archean terranes, the NCT is characterized by central greenstone belts of strongly deformed metavolcanics and metasediments surrounded by variably deformed granitoids. We are investigating these external granitoids that comprise the larger batholiths surrounding the North Caribou Greenstone belt in the NCT in an attempt to understand the magmatic history and processes involved in batholith formation. Mapping and petrologic work identified two distinct groups of granitoids in the region: voluminous, massive to gneissic tonalite, trondhjemite, granodiorite (TTG) batholiths and massive pegmatitic to aplitic K-feldspar-rich granites, which intrude the margins of the greenstone belt and are also ubiquitous throughout the TTG suites. These rocks cross-cut all rock types and occur mostly as convoluted, brittle-ductile dykes (Figure 1). There are two types of pegmatitic rocks: an undated suite consisting primarily of K-feldspar and quartz with minor oxides, including magnetite, and S-type intrusions, containing muscovite, biotite, garnet, and less K-feldspar. Notably, zircon and titanite are absent from pegmatites.

The TTG batholiths have a wider variety of compositions, ranging from tonalite to granite (*sensu stricto*). Important accessory minerals include titanite, zircon, epidote, and hornblende. Epidote tends to occur in cross-cutting quartz veins, which suggests a late- to post-magmatic metasomatic event. This thermal episode was accompanied by moderate-temperature strain as evidenced by undulose extinction and bulging recrystallization in quartz and planar alignment of biotite and amphibole. Migmatitic textures in discrete parts of the batholiths indicate that partial melting of, or melt segregation within, the TTG batholiths could be the source for the K-feldspar-rich pegmatites. We performed Al-in-hornblende geobarometry on several batholith samples spanning granitic, granodioritic and tonalitic compositions; emplacement depths are variable across the batholith, ranging from pressures of 3.0 ± 0.5 kbar (~ 13 km) to the southeast (tonalite) and 6.5 ± 0.5 kbar (~ 20 km, granodiorite) to the north of the belt. To complement our geobarometric data, we also carried out U-Pb geochronology on igneous titanites and zircons using LA-ICP-MS methods to determine crystallization ages. The oldest zircons have a ca. 3.0 Ga inherited core, but the majority of grains have well-defined concordant ages of ca. 2850 Ma or ca. 2730 Ma. The former age signature is more prominent in the north of the belt, in contrast to the ca. 2730 Ma age that is more localized in the south-centre margin of the belt. In one sample, zircons have 2850 Ma cores and 2730 Ma rims. Titanite ages are similar to those from zircon. These new U-Pb ages are in accord with the few previously reported ages from the NCT (e.g. Breaks et al. 2001, Klipfel 2002, Wyman et al. 2010).

The original core of the Superior Province, recorded in the inherited zircons in this study and detrital and volcanic zircons from elsewhere in the NCT (Percival 2007, Lin et al. 2006) had formed by 3.0 Ga. This crust was subsequently deformed and intruded by, or incorporated into, 2850 Ma granitoids, which form the large batholiths that comprise much of

the NCT. At this stage, the granitoids of tonalitic composition were emplaced at midcrustal levels. Later magmatism, at 2730 Ma, was more evolved with granodioritic to granitic composition. This stage of magmatic activity took place at shallower, mid- to uppercrustal depths. The most recent magmatic activity (granitic pegmatites) was post-deformation, occurred near the brittle-ductile transition, and has a highly evolved composition. The discrete magmatic events recognized in the NCT shows a long history of magmatism, over 300 m.y., and re-working of existing crust in the interior of the craton.

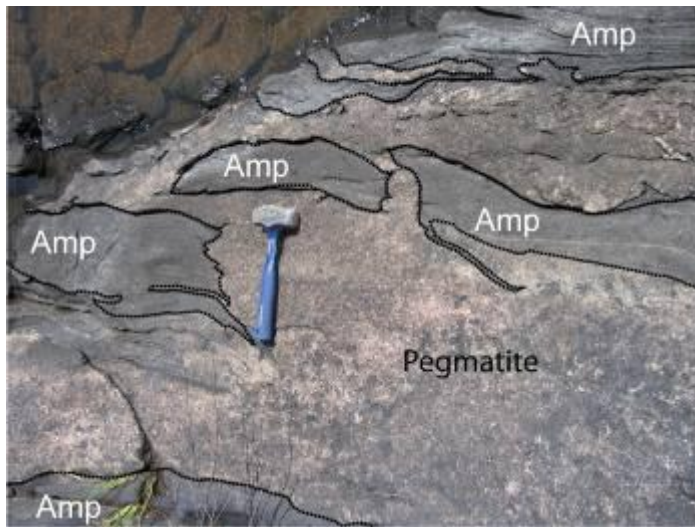


Figure 1: Pegmatite intruding strongly lineated amphibolite (Amp). Notice brittle and ductile structures (cracks parallel to lineation and pinched-out amphibolite rafts), suggesting pegmatites were intruded near the brittle-ductile transition.

REFERENCES

- Breaks, F., Osmani, L., DeKemp, E. 2001. Geology of the North Caribou Lake Area, Northwestern Ontario, Ontario Geological Survey, Open File Report 6023. 80 pp.
- Klipfel, P. 2002. Musselwhite U-Pb zircon and Ar-Ar dates: synthesis and interpretation. Internal report. 23 pp.
- Lin, S., Corkery, M., Bailes, A., and Davis, D. 2006. Geological evolution of the northwestern Superior Province: Clues from geology, kinematics, and geochronology in the Gods Lake Narrows area, Oxford-Stull terrane, Manitoba. *Canadian Journal of Earth Sciences*. v. 43. pp. 749-765.
- Percival, J. 2007. Geology and Metallogeny of the Superior Province, Canada. *in* Goodfellow, w., ed., *Mineral Deposits of Canada: A Synthesis of Major Deposit Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods: Geological Association of Canada, Mineral Deposits Division, Special Publication No. 5*, pp. 903-928.
- Wyman, D.A., Hollings, P., Biczok, J. 2011. Crustal evolution in a cratonic nucleus: Granitoids and felsic volcanic rocks of the North Caribou Terrane, Superior Province Canada. *Lithos*. in press.

Towards a geochemical characterization of native copper ores of the Keweenaw Peninsula, Michigan

Jillian E. Votava and Theodore J. Bornhorst

A. E. Seaman Mineral Museum, Michigan Technological University, Houghton, MI 49931

The Keweenaw Peninsula is well known for its world-class native copper deposits. These deposits have been subject to many geologic studies yet the native copper ores are poorly characterized in terms of bulk geochemical composition. This study represents a first step towards a geochemical characterization of the native copper ore. The samples for this study came from the Caledonia native copper mine near Mass, MI since there is underground access. The Caledonia is part of the southern extension of the main native copper district where native copper is hosted in several different mineralized basalt lava flow tops, collectively known as the Evergreen Series. At Caledonia the native copper is hosted by two brecciated flow tops and is accompanied by secondary minerals filling amygdulites and spaces between fragments. The secondary minerals include: quartz, feldspar, pumpellyite, chlorite, calcite, and epidote. The Caledonia mine has yielded ~3.1 million kg of refined copper with an average grade of 1.24%. Native copper mineralization is typical of that found elsewhere in the district.

For this study, 16 underground grab samples were taken at thirteen locations and 1 background sample of massive, visually unaltered basalt from the surface rock pile. Underground mineralized samples were focused on areas with high and variable degrees of alteration. The goal was to obtain a sufficient number of samples with different amounts of copper that bracketed the average copper in the ore. Thereby, the median abundance of constituents in the suite of mineralized samples will be used to represent the geochemical composition of the native ore. Representative subsets of each grab sample were prepared and analyzed for 64 elements by Actlabs using 4-Acid digestion with ICP or ICP-MS finish, INAA, and Hg by cold vapor FIMS.

The Caledonia background sample was compared to fresh tholeiitic basalt (BCR-1) to insure Caledonia background values were reasonable and if not, BCR-1 was used for the background value. Ratios of enrichment for each element were calculated using the median of the mineralized samples. Using these ratios each element was placed into one of 6 categories: enriched, depleted, potentially enriched or depleted, same as background, and indeterminate. Ratios greater than 1.0 were considered to be enriched while ratios less than 1.0 were considered depleted. Ratios around 1.0 were generally considered same as the background (no change). Elements with moderate variance or with some (less than half) of the samples less than the detection limit were placed into the appropriate potentially depleted or potentially enriched category. Those with high variance or with more than half the samples below the lower detection limit were considered indeterminate.

The native copper ore is enriched in Cu, Ag, Hg, As, Te, Sr, Ca, Cd, and Se while depleted in Ba, Rb, Na, Nb, K, and V. Each of these elements was plotted against copper and the highest correlations are with Hg and Ag ($\rho = 0.597$ and 0.635 , respectively). Strikingly, when rank correlations between all of these are calculated, Hg and Ag had a rank correlation coefficient of 0.966 and a log-log plot illustrates this high correlation (Fig. 1).

Heretofore, the native copper ores were well known for the association of Ag and As with Cu. The abundance of calcite as an alteration mineral is consistent with the enrichment of Ca and Sr. The enrichment of Cd, Te, and Se and potential enrichment of Au is previously

not documented. The strong enrichment of Hg is also previously not documented although geochemical studies of stamp sands suggested this enrichment (Kerfoot, personal communication). That Hg so strongly correlates with Ag suggests a synchronous timing of deposition. The combination of Hg, Se, Te, and Au are often found associated with gold deposits elsewhere and their genetic connection to the native copper deposits is unknown at this time. This study highlights the value in characterizing the geochemical composition of the native copper ores. Additional sampling is needed to validate the results presented here since they only represent one mine.

Table 1: Chemical characterization of native copper ore from Caledonia Mine, MI. Values represent amount of element at the median Cu level (1.6%). Categories described in text.

Composition of Native Copper Ore with 1.6% Cu at Caledonia Mine									
Enriched		Depleted		Same as Background		Same as Background		Indeterminate	
Ag	9.68 ppm	Ba	14 ppm	Al	7.79 %	Nd	18 ppm	Co	Re
Hg	65 ppb	Rb	2.70 ppm	Be	0.6 ppm	P	0.045 %	Li	Sn
As	4.5 ppm	Na	0.1 %	Ce	36 ppm	Pr	4.5 ppm	Mg	W
Te	0.4 ppm	Nb	0.6 ppm	Dy	4 ppm	Sb	0.2 ppm	Ti	Ta
Sr	837 ppm	K	0.38 %	Er	2.3 ppm	Sc	21 ppm	Tl	S
Ca	12.8 %	V	120 ppm	Eu	1.57 ppm	Sm	4.4 ppm	In	Mo
Cd	0.9 ppm			Fe	7.35 %	Tb	0.7 ppm	Ir	Bi
Se	0.7 ppm			Ge	0.3 ppm	Th	1.5 ppm	Ga	Br
Potentially Enriched		Potentially Depleted		Gd	4.6 ppm	Tm	0.3 ppm	Ni	Cs
Pb	25 ppm	Zn	52 ppm	Hf	1.9 ppm	U	0.3 ppm		
Au	1 ppb	Cr	140 ppm	Ho	0.8 ppm	Y	23 ppm		
				La	18 ppm	Yb	2 ppm		
				Lu	0.3 ppm	Zr	65 ppm		
				Mn	1040 ppm				

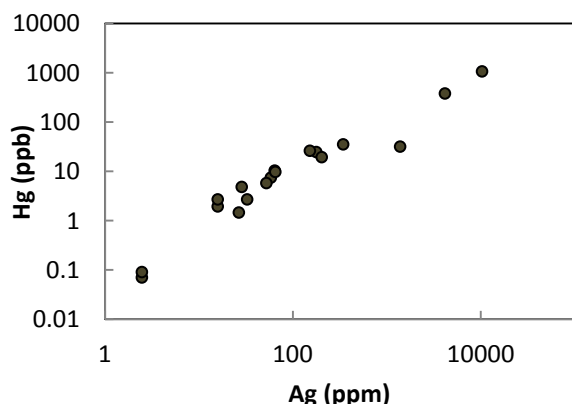


Figure 3: Plot of Ag versus Hg and the apparent relationship between silver and mercury in the samples from Caledonia Mine.

Pyroclastic Magnetite Bombs in the Hemlock Formation Iron County, Michigan

Thomas Waggoner^{1*}, Doug Duskin², Musa Karakus³ and John Gartner⁴

¹141 Chippewa Negaunee, MI 49866 thomaswaggonergeo@hotmail.com

²210 Union St. Camden, SC 29020

³Cliffs NR 550 E. Division Ishpeming, MI 49849

⁴PMR 723 Riverside Plaza Iron River, MI 48935

The Mt. Hemlock Stratovolcano has a footprint of at least 2000 square miles and reaches a height of 30,000 feet without inclusion of the two Kiernan Sills. Recent age dating (Schneider, 2002) places a single rhyolite unit age at 1874 $\pm$ 7 Ma. The volcanic pile includes massive/vesicular/pillowed basalts, agglomerates/hyaloclastites, rhyolite flows/tuffs, basic volcanoclastics, ash beds, slates and at least two bands of carbonate chert iron formation. Limited outcrop exposure and drilling has prevented better definition of the detail lithology so each new drill hole offers additional useful information.

Basalt outcrops on the west side of Mt. Hemlock (Johnson, 1975; Dann, 1978; Foose, 1981) indicate a high magnetite content and samples from the southwest flank show the iron content doubles in the top 6,000 feet of the Hemlock volcanics. The increase in iron oxide content is associated with two banded iron formations of limited areal extent that formed on the inclined flank of the volcano.

In 2007 Prime Meridian Resources drill tested a 2,000 nT total field magnetic anomaly over outcrops that showed traces of chalcopyrite. Located in the NE ¼ NE ¼ Sec. 32 T. 43N. R. 31 W., inclined NQ diamond core hole KS-102-2 was drilled on an angle to the east designed to intercept the volcanics and test the metal content. The hole penetrated thin cherty zones alternating with thin amygdaloidal basalts near the top followed by a tuff unit, amygdaloidal basalt and ending in pyroclastics consisting of rounded and flattened vesicular bombs of basalt and magnetite resting in fine volcanoclastic sediments. SEM-EDS, XRF and XRD were employed to identify the rock constituents. Iron values ranged from 8 to 25%, mostly as magnetite, while titanium oxide values ranged from 2-6.5%. Both metals are present in unusually high amounts. The TiO₂/FeO ratio plotted against FeO illustrates the Hemlock is quite different from other basalts. Even though titanium is elevated, it does not match the larger increase in iron oxide.

Basaltic units of the Hemlock Formation have already been reported to contain high percentages of titanium free magnetite (Johnson, 1974, Dann, 1978). Magnetite in some bombs account for up to 80% of the groundmass. The magnetite is confined to the ground mass and does not fill the vesicles indicating primary crystallization.

The drill hole is located between the basal pyroxenite and the lower gabbro zone of the differentiated West Kiernan sill. Some metasomatism of the proximal Hemlock occurred during emplacement of the sill. Both the Hemlock and West Kiernan sills have undergone sodium and potassium metasomatism. Original minerals including pyroxene, calcium feldspars and ilmenite were replaced by epidote, albite, titanite, Fe-chlorite, biotite, quartz, potassium minerals, calcite, ilmenite, chalcopyrite, pyrite and calcium REE fluorocarbonate + barite in biotite. Many of these minerals can be found as amygdaloidal fillings.

The sodium, silica and potassium alteration has converted the pyroxenes, feldspar and ilmenite to albite, chlorite, biotite and titanite leaving the original magnetite and apatite

unaltered. The subhedral and euhedral magnetite quickly crystallized from the magma and migrated toward the vesicle openings that formed quickly by rapid de-gassing. The fine magnetite crystals range from 3-50 microns in size and are generally devoid of any inclusions, including titanium minerals.

It is postulated the gravity separation took place in a quiescent magma chamber where iron oxide rich segregations pooled. The subsequent violent eruption of a gas laden magma allowed for creation of vesicular magnetite pyroclastic bombs that varied in size from pebbles up to more than 8 inches that quickly solidified and deposited in water on the slope of the volcano in a random pattern.

High magnetite tholeiitic basalts and magnetite rich bombs are very rare in extrusive volcanic rocks of any age. One example is the high grade magnetite bombs preserved in the 2 Ma El Laco deposit located in Chile (Henriquez, 1998) where they are part of magnetite flows.

We can speculate that near cessation of active volcanism an iron oxide rich magma was tapped by sea water and formed a large hydrothermal plume that vented distal to the central vent on the sea bottom instantly forming fine crystals of magnetite or specularite depending on piping, distance or chemistry at the instant of entry into a reduced temperature/pressure gradient. The Fence River iron formation on the east flank of the Amasa uplift exhibits both magnetite and specularite lithologies.

Drilling, mapping and analytical examination have shown that parts of the Hemlock Formation originated from unusually rich iron oxide magma that resulted in the creation of vesicular magnetite rich pyroclastics.

REFERENCES

- Dann, J.C., 1978, Major-Element Variation within the Emperor Igneous Complex and the Hemlock and Badwater Volcanic Formations, MTU MS Thesis, 198 pages. Foote, M.P., 1978, Geologic Map of the Ned Lake Quadrangle, Iron and Baraga Counties, Michigan, USGS Map I-1284, Scale: 1:62,500.
- Henriquez, F., Nstrom, J.O., 1998, Magnetite Bombs at El Laco Volcano, Chile, GFF V. 120 p. 269-271.
- Johnson, D.J., 1975, Petrology of a Portion of the Hemlock Formation, Iron County, Michigan. MTU MS Thesis, 55p.
- Schneider, D.A., et al, 2002, Age of Volcanic Rocks and Syndepositional Iron Formation, Marquette Range Supergroup; Implications for the Tectonic Setting of Paleoproterozoic Iron Formations of the Lake Superior Region, Canadian Journal of Earth Sciences, V. 39, p. 999-1012.

Physical volcanology and hydrothermal alteration of the Rainy River Gold Project, Northwestern Ontario

Jakob Wartman¹, Ron Morton¹, George Hudak² and Cory Hercun³

¹*Dept. of Geol. Sciences, Univ. of Minnesota Duluth, Duluth, Minnesota 55812*

²*Precambrian Research Center / NRRI, Duluth, Minnesota 55811*

³*Rainy River Resources Ltd., P.O. Box 3, Emo, Ontario P0W 1E0*

The Rainy River Gold Project (RRGP) is located 75km northwest of Fort Frances, Ontario, within the Rainy River greenstone belt. This advanced stage exploration project has a NI43-101 compliant gold resource of 3.42 Moz indicated and 3.17Moz inferred (from Rainy River Resources Press Release, February 2011) represented by low grade (<2g/t), low-moderate grade (2-10g/t), and high grade (>10g/t) gold mineralization. The nature of the gold mineralization in this deposit has been the subject of controversy, and several competing models have been proposed to explain its genesis. Initial exploration in 1967 suggested that the deposit was a shear zone-hosted resource. However, recently completed exploration drilling has now defined large, diffuse zones of gold mineralization in dacitic volcanic and volcanoclastic rocks, suggesting, in part, a syn-genetic genesis for the gold mineralization. While previous studies have examined structural regimes and timing of gold mineralization, this research focuses on the physical volcanology and hydrothermal alteration associated with the deposit.

Field mapping is difficult due to a paucity of outcrop, and geological correlations are complicated by polyphase deformation, hydrothermal alteration, and both regional, and locally contact, metamorphism. This study included comprehensive fieldwork involving mapping of all available outcrops at a 1:24,000 scale and exploration drill core logging along three sections totaling ~7,400 m of core. Fieldwork, supplemented with 210 thin sections and 73 geochemical samples, has enabled distinction of stratigraphy, volcanic facies, and hydrothermal alteration assemblages.

Drill core is locally intensely altered and deformed, resulting in many of the units having a false pyroclastic appearance. Despite this, strata associated with the RRGP contain some well-preserved primary textures. These primary textures indicate that the volcanic facies in the deposit include coherent dacitic flows and associated syn-volcanic intrusions with autoclastic breccias, hyaloclastites, peperites, and syn- to post-depositional resedimented volcanoclastic deposits. The coherent dacitic flows are massive, range in thickness up to 150 m, and in lateral extent for 2500 meters. Coherent dacite flows grade into a heterogeneous facies, characterized by pods and lobes of coherent dacite, enveloped by autoclastic breccia and hyaloclastite. Flows are interspersed with strongly altered volcanoclastic sediments that are locally punctuated by peperites. Volcanic facies reconstruction indicates the presence of lobe-hyaloclastite dome/flow complex fed, and locally intruded by, synvolcanic dacite hypabyssal intrusions. An apparent feeding fissure is centered to the west of the main area of mineralization.

Hydrothermal alteration is widespread throughout the deposit and is marked by silicification, chloritization, sericitization, and carbonitization (as well as minor epidote and local biotite). Quartz, sericite and chlorite are ubiquitous in the deposit. Grant's (1986) isocon method and Large et al.'s (2001) box plot were applied to the rocks at the RRGP and quantify the chemical alteration resulting from the hydrothermal alteration. Alteration

assemblages are dominantly stratabound, and related to original rock permeability, with flow tops, autoclastic breccias, and volcanoclastic sediments being most strongly altered. Shear-zones also preserve stronger alteration intensities.

Gold mineralization appears to have occurred within a synvolcanic, low-sulfidation (Simmons et al., 2005) epithermal system. Elevated gold values are strongly correlated with highly permeable units and increased alteration intensity, suggesting enhanced mineralization in areas that experienced higher water: rock ratios. Post-volcanic remobilization of the gold appears to have occurred, as the highest gold values in the deposit are spatially related to shear-zones and associated quartz-carbonate-epidote veins.

REFERENCES

- Grant, J. A., 1986, The Isocon diagram—A simple solution to Gresen's equation for metasomatic alteration: *Economic Geology*, v. 81, p. 1976–1982.
- Large, R.R., Gemmell, J.B., Paulick, H., and Huston, D., 2001, The alteration box plot: A simple approach to understanding the relationship between alteration mineralogy and lithogeochemistry associated with VHMS deposits: *Economic Geology*, v. 96, p. 957–972.
- Simmons, S.F., White, N.C., and John, D.A., 2005, Geological characteristics of epithermal precious and base metal deposits: *Economic Geology*, 100th Anniversary Volume, p. 485–522.

AUTHOR INDEX

PROCEEDINGS VOLUME 57 PART 1— PROGRAM AND ABSTRACTS

Amisse, L. and Barnes, S.J	1
Bajjali W., Holstrom C., and Fuller, D.	2
Beh, B. and Fralick, P	3
Birkmeier, R., Boley, T., Brannan, B., Doucette, R., Jirsa, M., and Lee, A.	5
Boerboom, T.J. and Green, J.C.	7
Brown B.A. and Schoepfoester, P.	9
Buchholz, T.W., Falster A., and Simmons, W. B.	10
Carl, C., Hollings, P., and Smyk, M.	12
Carlson E.J., Boerboom T.J., Holton C.J., Kubitza, K.W., Mulvey, L., and Scheurer, E.	14
Cervin, D., Morton, P., Miller J., and Patelke, R.	16
Chandler, V.W. and Lively, R.S.	18
Chandler, V.W. and Lively, R.S.	20
Cummings, K. and Bjørnerud, M.	22
Cundari, R., Hollings, P., and Smyk, M.	24
Dayton, R.N., Miller, J.D., and Vervoort, J.D.	26
Deschamp, M. and McGuire, J.	28
DeVasto, M.A., Czeck D.M., Bhattacharyya, P.	29
Easton, R.M. and Heaman, L.M.	31
Esch, J.M.	33
Floyd, C.T., Syverson, K.M., and Hupy, C.M.	35
Foley, D.J., and Miller, J. D.	37
Fralick, P. and Zaniewski, K.	39
Geller, P., Fralick, P., Hill, M.L., and Gillies, P.	41
Gilbert, H.P.	42
Goldner B.D. and Miller J.D.	44
Hudak, G., Monson Geerts, S., Zanko, L., Severson A., Severson, A., and Bandli, B.	46
Jirsa, M.A., Boerboom, T.J., and Chandler, V.W.	48
Jirsa, M.A., Boerboom, T.J., Chandler, V.W., Mossler, J.H., Runkel, A.C., and Setterholm., D.R.	50
Kulakov, E.V., Smirnov, A.V., and Diehl, J.F.	51
LaMaskin, T.A.	53
Larson, Phillip, Swenson, J., and Patelke, M.	55
MacTavish, A.D., Heggie, G.J., Goodgame, V.R., Johnson, J.R., Beswick, A.E., Stone, W.E., and Watkins, K.P.	57
Mattox, S.	59
Miller, J., Brooker, B., Hadley, M., Markwood, L., Olson, J., and Tomlinson, A.	61
Peterson, D., Larson, P., Sweet, G., and Gibbons, J.	63
Piispa, E.J., Smirnov, A.V., Pesonen, L.J.	65

Queffurus, M. and Barnes, S.J.	66
Radakovich, A.L., Parent, C.T., Partridge, M.E., Ritts, A.D., Pierce, R., & Hudak G.J.	67
Rague, R. and Losh, S.	69
Ross, C., Hudak, G., Morton, R., Quigley, T., Mahin, B.	70
Saylor, B.J., Stencil J.C., DeVasto, M.A., and Bhattacharyya, P.	72
Scott, R. J., Kolb, M.J., and Hill, M.L.	74
Smyk, M., Hollings, P., and Cundari, R.	75
Stinson, V. and Hill, M.L.	77
Swoffer, B., and Hill, M.L.	78
Tharalson, E.R., and Monecke, T.	79
Theriault, S., Miller, J., Berndt, M., and Ripley, E.	81
Totenhagen, M., Morton, P., and Larson, P.	83
Traut, J.T. and Czeck, D.M.	85
Vallowe, A.M., Thalhamer, E.J., Rhoades, D. L., and Peterson, D.M.	87
Van Lankvelt, A., Schneider, D., Hattori, K., and Biczok, J.	89
Votava, J.E. and Bornhorst, T.J.	91
Waggoner, T., Duskin, D., Karakus, M., and Gartner, J.	93
Wartman, J., Morton, R., Hudak, G., and Hercun, C.	95