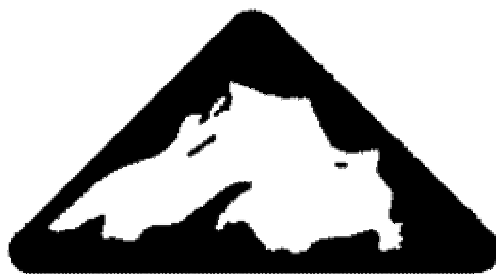


50TH ANNUAL



INSTITUTE ON LAKE SUPERIOR GEOLOGY
DULUTH, MINNESOTA, MAY 4-9, 2004





INSTITUTE ON LAKE SUPERIOR GEOLOGY

50TH ANNUAL MEETING

MAY 4-9, 2004

DULUTH, MINNESOTA

HOSTED BY:

STEVEN A. HAUCK AND MARK J. SEVERSON

Co-Chairs

NATURAL RESOURCES RESEARCH INSTITUTE, UNIVERSITY OF MINNESOTA DULUTH

WITH ASSISTANCE FROM

**THE NRRI ECONOMIC GEOLOGY GROUP, MINNESOTA GEOLOGICAL SURVEY, AND
THE DEPARTMENT OF GEOLOGICAL SCIENCES, UMD**

Volume 50

Part 1 – Proceedings and Abstracts

Compiled and edited by Steven A. Hauck, Dean Peterson, and Julie Oreskovich

Cover Photos: Upper Left – Soudan Iron Formation, 25th Level West, Soudan Underground Mine State Park, Soudan, MN; Center – ILSG 2003 Quinnesec Mine, WI, Menominee Iron District Field Trip; Lower Left – Natural Ore Auburn Mine, Eveleth MN, Looking Northwest Along the Auburn Fault.

50TH INSTITUTE ON LAKE SUPERIOR GEOLOGY

VOLUME 50 CONSISTS OF:

PART 1: PROGRAM AND ABSTRACTS

PART 2: FIELD TRIP GUIDEBOOK

TRIP 1: Volcanic Stratigraphy, Hydrothermal Alteration, and VMS Potential of the Lower Ely Greenstone, Fivemile Lake to Sixmile Lake area.

TRIP 2: Geologic Highlights of New Mapping in the Southwestern Sequence of the North Shore Volcanic Group and Beaver Bay Complex.

TRIP 3: Late Wisconsinan Superior-lobe Deposits in the Lake Superior Basin Northeast of Duluth.

TRIP 4: Geology of the Eastern Mesabi Iron Range, Northeastern Minnesota.

TRIP 5: Classic Outcrops of Northeastern Minnesota.

TRIP 6: Glacial and Postglacial Landscape Evolution in the Glacial Lake Aitkin and Upham Basin, Northern Minnesota.

TRIP 7: Economic Geology of Archean Gold Occurrences in the Vermilion District, Northeast of Soudan, Minnesota.

TRIP 8: Geology of the Western Contact of the Duluth Complex, Partridge River and South Kawishiwi Intrusions, Northeastern Minnesota.

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

Holm, D.K., Van Schmus, R.W., and Schneider, D.A., 2004, The Influence of Radiometric Dating for Unraveling the Precambrian Geologic History of the Lake Superior Region [abstract]; Institute on Lake Superior Geology Proceedings, 50th Annual Meeting, Duluth, MN, v. 50, part 1, p. 80-84.

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

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

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INSTITUTES ON LAKE SUPERIOR GEOLOGY

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

29	1983	Houghton, Michigan	T.J. Bornhorst
30	1984	Wausau, Wisconsin	G.L. LaBerge
31	1985	Kenora, Ontario	C.E. Blackburn
32	1986	Wisconsin Rapids, Wisconsin	J.K. Greenberg
33	1987	Wawa, Ontario	E.D. Frey & R.P. Sage
34	1988	Marquette, Michigan	J. S. Klasner
35	1989	Duluth, Minnesota	J.C. Green
36	1990	Thunder Bay, Ontario	M.M. Kehlenbeck
37	1991	Eau Claire, Wisconsin	P.E. Myers
38	1992	Hurley, Wisconsin	A.B. Dickas
39	1993	Eveleth, Minnesota	D.L. Southwick
40	1994	Houghton, Michigan	T.J. Bornhorst
41	1995	Marathon, Ontario	M.C. Smyk
42	1996	Cable, Wisconsin	L.G. Woodruff
43	1997	Sudbury, Ontario	R.P. Sage & W. Meyer
44	1998	Minneapolis, Minnesota	J.D. Miller & M.A. Jirsa
45	1999	Marquette, Michigan	T.J. Bornhorst & R.S. Regis
46	2000	Thunder Bay, Ontario	S.A. Kissin & P. Fralick
47	2001	Madison, Wisconsin	M.G. Mudrey, Jr. & B.A. Brown
48	2002	Kenora, Ontario	P. Hinz & R.C. Beard
49	2003	Iron Mountain, Michigan	L.G. Woodruff & W.F. Cannon
50	2004	Duluth, Minnesota	S.A. Hauck & M.J. Severson

CONSTITUTION OF THE INSTITUTE ON LAKE SUPERIOR GEOLOGY

(Last amended by the Board—May 8, 1997)

Article I **Name**

The name of the organization shall be the "Institute on Lake Superior Geology".

Article II **Objectives**

The objectives of this organization are:

- A. To provide a means whereby geologists in the Great Lakes region may exchange ideas and scientific data.
- B. To promote better understanding of the geology of the Lake Superior region.
- C. To plan and conduct geological field trips.

Article III **Status**

No part of the income of the organization shall insure to the benefit of any member or individual. In the event of dissolution, the assets of the organization shall be distributed to _____(some tax free organization).

(To avoid Federal and State income taxes, the organization should be not only "scientific" or "educational, but also "non-profit")

Minn. Stat. Anno. 290.01, subd. 4

Minn. Stat. Anno. 290.05(9)

1954 Internal Revenue Code s.501(c)(3)

Article IV **Membership**

The membership of the organization shall consist of persons who have registered for an annual meeting within the past three years, and those who indicate interest in being a member according to guidelines approved by the Board of Directors.

Article V **Meetings**

The organization shall meet once a year. The place and exact date of each meeting will be designated by the Board of Directors.

Article VI **Directors**

The Board of Directors shall consist of the Chair, Secretary-Treasurer, and the last three past Chairs; but if the board should at any time consist of fewer than five persons, by reason of unwillingness or inability of any of the above persons to serve as directors, the vacancies on the board may be filled by the Chair so as to bring the membership of the board to five members.

Article VII **Officers**

The officers of this organization shall be a Chair and Secretary-Treasurer.

A. The Chair shall be elected each year by the Board of Directors, who shall give due consideration to the wishes of any group that may be promoting the next annual meeting. His/her term of office as Chair will terminate at the close of the annual meeting over which he/she presides, or when his/her successor shall have been appointed. He/she will then serve for a period of three years as a member of the Board of Directors.

B. The Secretary-Treasurer shall be elected at the annual meeting. His/her term of office shall be four years, or until his/her successor shall have been appointed.

Article VIII **Amendments**

This constitution may be amended by a majority vote (majority of those voting) of the membership of the organization.

BY-LAWS OF THE INSTITUTE ON LAKE SUPERIOR GEOLOGY

I. Duties of the Officers and Directors

- A. It shall be the duty of the Annual Chairman to:
 - 1. Preside at the annual meeting.
 - 2. Appoint all committees needed for the organization of the annual meeting.
 - 3. Assume complete responsibility for the organization and financing of the annual meeting over which he/she presides.
- B. It shall be the duty of the Secretary-Treasurer to:
 - 1. Keep accurate attendance records of all annual meetings.
 - 2. Keep accurate records of all meetings of, and correspondence between, the Board of Directors.
 - 3. Hold all funds that may accrue as profits from annual meetings or field trips and to make these funds available for the organization and operation of future meetings as required.
- C. It shall be the duty of the Board of Directors to plan locations of annual meetings and to advise on the organization and financing of all meetings.

II. Duties and Expenses

- A. Regular membership dues of \$5.00 or less on an annual basis shall be assessed each member as determined by the Board of Directors..
- B. Registration fees for the annual meetings shall be determined by the Chair in consultation with the Board of Directors. The registration fees can include expenses to cover operations outside of the annual meeting as determined by the Board of Directors. It is strongly recommended that registration fees be kept at a minimum to encourage attendance of students.

III. Rules of Order

The rules contained in Robert's Rules of Order shall govern this organization in all cases to which they are applicable.

IV. Amendments

These by-laws may be amended by a majority vote (majority of those voting) of the membership of the organization; provided that such modifications shall not conflict with the constitution as presently adopted or subsequently amended.

Last Amended – May, 1996

MEMBERSHIP CRITERIA FOR THE INSTITUTE ON LAKE SUPERIOR GEOLOGY

Approved May 8, 1997

A. Membership in the Institute on Lake Superior Geology requires either participation in Institute activities, or an indication on a regular basis of interest in the Institute. Those individuals registering for an annual meeting will remain as members for 4 years unless: 1) they indicate no further interest in the Institute by responding negatively to the statement on meeting circulars "Remove my name from the mailing list"; or 2) two successive mailings in different years are returned by the postal service as address unknown.

B. Those individuals who have not registered for an annual meeting in the past 4 years must indicate an interest in the Institute by postal, electronic, or verbal correspondence with the Secretary-Treasurer at least once every two years. Such individuals will be removed from the membership if they indicate no further interest in the Institute or two successive mailing in different years are returned by the postal service as address unknown.

C. The Secretary-Treasurer will maintain a list of current members. The list will include the date of the beginning of continuous membership, dates of returned mail, dates of last contact (expression of interest), and the date membership expires, barring a change of status initiated by the member. Those individuals who have become members of ILSG by Section B will have an expiration date listed at 2 years from the upcoming meeting. For example, a member who expresses interest in September of 1997 (the next annual meeting is May, 1998) will have an expiration date of May, 2000, unless the member contacts the Secretary-Treasurer or attends an annual meeting.

D. "Member for Life" status is granted to individuals who have been (nearly) continuous participants of the ILSG meetings for 15 years, Goldich Medal recipients, or those who have served as meeting chairs. This status will be further maintained unless the individuals indicate no further interest in the Institute, or 4 mailings in different years are returned by the postal service as address unknown, or they are deceased.

E. All members will be mailed the First Circular for the Annual Meeting and the ILSG Newsletter. The Chair of the annual meeting may opt to send the first circular to additional individuals. All returned mail should be reported to the Secretary-Treasurer.

F. The Secretary-Treasurer can designate any individual who is on the ILSG membership list (mailing list) as of January 1, 1997 as a member for life based on participation in ILSG activities.

G. Members are strongly encouraged to send address corrections to the Secretary-Treasurer to avoid unintentional lapse of membership.

GOLDICH MEDAL GUIDELINES

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

Preamble

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

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

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

Award Guidelines

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

Nominating Procedures

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

Selection Guidelines

- 1) Nominees are to be evaluated on the basis of their contributions to Lake Superior geology (sensu lato) including:

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

GOLDICH MEDAL COMMITTEE

Serving through the meeting year shown in parentheses

George Hudak (2006)

University of Wisconsin, Oshkosh

Ron Sage (2004)

Ontario Geological Survey (retired)

David Meineke (2005)

Meriden Engineering, Hibbing, Minnesota

Steve Kissin, as out-going senior member of Institute Board of Directors, is liaison between Goldich Medal Committee and the Board through the 2004 meeting

2004 GOLDICH MEDAL RECIPIENT

Paul W. Weiblen

Department of Geology & Geophysics
University of Minnesota, Minneapolis

GOLDICH MEDALISTS

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

Citation

Paul W. Weiblen 2004 Goldich Medal Recipient

Paul W. Weiblen, or P.W., has been a friend and professional colleague for more than 40 years. We have worked together on more projects than I can remember since P.K. Sims selected us to help implement his programs at the Minnesota Geological Survey in the early 1960s. Therefore, it is my distinct honor and privilege to serve as P.W.'s citationist for the 2004 Goldich Medal.

P.W. was born and raised in Miller, South Dakota, and after graduation from high school in 1945, he entered the U.S. Army. In the summer of 1945, World War II had ended in Europe, but we were still in combat with Japan. Luckily, before P.W. finished training, the war ended, and he was sent to Germany. After military service P.W. returned to college and earned a B.A. degree at Wartburg College in Waverly, Iowa (1950), and an M.A. in History at the University of Minnesota (1952).

P.W. came into geology in sort of a roundabout way. Apparently, he was in Istanbul working as an agent for American Express when he met a geologist who exposed him to the wonders of the profession. Consequently, he returned to the University of Minnesota in 1959, received an M.S. degree (1962) and Ph.D. degree (1965). He stayed at the University in the Geology and Geophysics Department as an Assistant Professor (1965), Associate Professor (1969), Professor (1980), and Professor Emeritus (1997). He was hired specifically to organize and supervise the Department's Electron Microprobe Laboratory (1965-1980). In the 1960s, electron microprobes were at the cutting edge of modern research, and this facility was one of the first in the country. Along the way he served as Curator of the petrology collection (1970-1997) and supervisor of the scanning electron microscope facility (1970-1997). He took a year off from the University to work at NASA Headquarters in Washington, D.C., and served as Director of the University's Space Science Center (1985-1990).

As an academic, P.W. served on an array of academic, professional, and service committees. That service included the Board of Directors of the Campus Club (1994-1996) and its President (1996-1997). He regularly taught courses in physical geology, igneous and metamorphic petrology, optical mineralogy/electron microprobe techniques, and numerous seminars covering all kinds of geologic topics. He served as mentor for 10 Ph.D. theses—by students including M.G. Mudrey, Jr., K.J. Schulz, R.W. Copper, R. Bauer, W. Day, J.D. Miller, Jr., S.W. Nicholson, and B. Saini-Eidukat—and 13 master's theses.

P.W. was first and foremost an igneous petrologist with eclectic interests, and he could generate ideas faster than anyone I know, which he was always willing to share. Much of the research that I have received credit over the years started out in P.W.'s brain as a throwaway. Unlike many research geologists today who focus on one narrow topic, P.W. concentrated on five separate research topics over much of his career. One subject included activities that focused primarily on the petrogenesis of the Midcontinent Rift System, especially the Duluth Complex. A second subject focused on the origin of copper- and nickel-sulfide mineralization in the Duluth Complex, especially as it relates to metal

recovery from these possible ores. A third topic revolved around the origin of Archean greenstones in northern Minnesota and the high-grade gneisses in the Minnesota River Valley. A fourth subject, which he researched with Ed Roedder of the U.S. Geological Survey, focused on petrologic and geochemical attributes of melt inclusions in lunar samples obtained on various Apollo missions. Lastly, P.W. has been active in research to improve quantitative chemical analyses using electron beam techniques. Lately P.W. has delved into high-voltage electrical pulse methods for disaggregating rocks to produce clean mineral separates.

All of these activities produced well over 100 publications including many presented here at the Institute. All are marked by the careful use of data, acquired both in the field and in the laboratory, and a strong intellectual component. Some of his contributions have been controversial, but they have always made us think. That thinking has led us to a better understanding of geologic processes, and for us in the Institute, a better understanding of early earth history in the Lake Superior region.

Before I close, I would like to say a few words about P.W. the man. You never really know a person until you have to live with them in a tent camp after five days of rain. P.W. was always an easy-going, personable, considerate guy who was a pleasure to be around. I would go into the bush with him any day. It is my distinct honor to present to the Institute, Paul W. Weiblen as its 2004 recipient of the Goldich Medal for “Outstanding contributions to the geology of the Lake Superior region”.

Submitted by G. B. Morey
April 2004

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 annual Chair, who is responsible for the selection, will consider the following general criteria:

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

<u>INSTITUTE ON LAKE SUPERIOR GEOLOGY</u>	
	
Eisenbrey Student Travel Award Application	
Student Name: _____	Date: _____
Address: _____	
email: _____	
_____ Department Head-Typed	
Educational Status: _____	_____ Department Head-Signature
Are you the senior author of an oral or poster paper? YES _____ NO _____	
Will any other students be traveling with you?	Who? _____
Statement of need (use additional page if necessary)	

Please return to:	

STUDENT PAPER AWARDS

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

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

Student papers will be noted on the Program.

2004 Student Paper Awards Committee

Glenn Adams (Chair) – Doe Run Company, Viburnum, MO
Angelique Magee – Ontario geological Survey, Thunder Bay, ONT
Jim Small – Edward Kraemer and Sons, Burnsville, MN

2004 Session Chairs

David Dahl – MN Dept. of Natural Res., Lands & Minerals Div., Hibbing, MN
Jayne Englebert – MSA Professional Services, Baraboo, WI
Sidney Hemming – Lamont-Doherty Earth Observatory, Palisade, NY
Douglas Hunter – Wallbridge Mining Company, Lively, Ont.
Jill Peterman – Wisconsin Department of Transportation, Superior, WI
Mark Smyk – Ontario Geological Survey, Thunder Bay, Ont.
Wanda Taylor – University of Nevada at Las Vegas, Las Vegas, NV
Scott Wolter – American Petrographics Service Company, St. Paul, MN

2003 BOARD OF DIRECTORS

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

Steven A. Hauck Co-Chair 2004 Meeting (2007)

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

Laurel Woodruff (2006)

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

Peter Hinz (2005)

Ontario Geological Survey, Kenora, ONT

Michael G. Mudrey, Jr. (2004)

Wisconsin Geological and Natural History Survey, Madison, WI

Peter Hollings-Secretary-Treasurer (2006)

Lakehead University, Thunder Bay, ONT

2004 LOCAL COMMITTEES

General Co-Chairs

Steven A. Hauck – Natural Resources Research Institute, Univ. Minn. Duluth

Mark J. Severson – Natural Resources Research Institute, Univ. Minn. Duluth

Program and Abstracts Editors

Steven A. Hauck -- Natural Resources Research Institute, Univ. Minn. Duluth

Dean Peterson -- Natural Resources Research Institute, Univ. Minn. Duluth

Julie Oreskovich -- Natural Resources Research Institute, Univ. Minn. Duluth

Field Trip Guidebook Editor

Mark J. Severson – Natural Resources Research Institute, Univ. Minn. Duluth

Acting Local Committee, Duluth, MN

Barbara Hauck – Duluth, MN

John Heine – Natural Resources Research Institute, University of Minnesota Duluth

Julie Heinz – Natural Resources Research Institute, University of Minnesota Duluth

Charles Matsch - Department of Geological Sciences, University of Minnesota Duluth

James D. Miller, Jr. – Minnesota Geological Survey, Duluth, MN

Penny Morton – Department of Geological Sciences, University of Minnesota Duluth

Julie Oreskovich - Natural Resources Research Institute, University of Minnesota Duluth

Richard Patelke - Natural Resources Research Institute, University of Minnesota Duluth

Dean M. Peterson - Natural Resources Research Institute, University of Minnesota Duluth

Lawrence M. Zanko - Natural Resources Research Institute, University of Minnesota Duluth

2004 BANQUET SPEAKER

R. H. Dott, Jr.

**Department of Geology & Geophysics
University of Wisconsin, Madison, WI 53706**

**THE VAN HISE ARMY AND OTHER PIONEERS
OF LAKE SUPERIOR GEOLOGY**

Report of the Chair of the 49th Annual Meeting

REPORT OF THE 49TH ANNUAL MEETING OF THE INSTITUTE ON LAKE SUPERIOR GEOLOGY Iron Mountain, Michigan

The U.S. Geological Survey, with assistance from Michigan Technological University, hosted the 49th Annual Institute on Lake Superior Geology on May 7 – 11, 2003 at the Pine Mountain Resort in Iron Mountain, Michigan. The meeting consisted of two days of technical sessions with two pre- and two post-technical session field trips. John Gartner and Ted Bornhorst provided pre-meeting assistance. Sally LaBerge, Gretchen Klasner, and Suzanne Nicholson provided valuable logistical assistance on-site at Pine Mountain. Connie Dicken was media czar for the technical sessions, keeping all presentations on track while ignoring all needless advice. Pre-meeting registration was 104 students and professionals with an additional 61 on-site registrations, for a total of 165 registrants.

Proceedings Volume 49 was published in two parts. Part I – Program and Abstracts, edited by Laurel Woodruff and Ted Bornhorst – the volume contains 45 published abstracts, for 33 oral and 12 poster presentations; and Part 2 – Field Trip Guidebook, edited by William Cannon, with assistance from Connie Dicken and Stacy Saari.

The 49th meeting marked the first time in its history that an ILSG meeting was held in this part of Michigan. Field trips visited areas new to the ILSG, which may have resulted in the excellent subscription for all the trips. On Wednesday, May 7, Bill Cannon and staff from Cleveland Cliffs Mining lead a field trip to the Republic Mine, where the life cycle of the deposit, from ore genesis to mining and restoration, was covered. Three other field trips were developed to examine exposures along and on both sides of the Niagara suture zone, a major structural and geologic feature that marks the boundary between the Superior craton and the Wisconsin magmatic terranes. Klaus Schulz and Gene LaBerge lead the Wednesday field trip to the Wisconsin magmatic terrane on the southern side of the suture zone. On Saturday and Sunday, May 10 and 11, Bill Cannon, Gene LaBerge, John Klasner, and Dick Ojakangas were co-leaders for successive field trips through the Menominee Iron District (Saturday) and the Iron River – Crystal Falls area (Sunday). The Field Trip Guidebook for these three trips drew on previous studies in the area and the more than 100 cumulative years of Lake Superior geology expertise of the field trip leaders to provide a comprehensive and definitive compilation of the Paleoproterozoic stratigraphy and structure of the Niagara suture zone in this part of Michigan and Wisconsin.

One hundred and twenty participants attended the banquet on Thursday night. This year's banquet speaker was Susan Martin of Michigan Technological University. Dr. Martin is a professor of industrial archeology at Michigan Technological University and the author of the book *Wonderful Power: The Story of Ancient Copper Working in the Lake Superior Basin*. The title of Dr. Martin's post-banquet talk was: *The indigenous people of the Lake Superior Basin: understanding the links among environment, geology, and religious belief*. As always, a highlight of the banquet was the presentation of the 2003 Goldich medal to Klaus Schulz of the U.S. Geological Survey, recognizing his long and productive career as a geologist in the Lake Superior region.

The technical session began with three invited presentations. The first was by Harold Bernhardt of the Menominee Range Historical Foundation Museum on the mining history of the Menominee Iron Range. The following two talks, by Bill Cannon and Klaus Schulz, were on the Paleoproterozoic rocks of the Niagara suture zone, established the context for the three field trips on that topic. The student paper committee had a difficult job this year. Twenty of the presentations in the technical sessions were from students – 15 oral and 5 posters. In the end, three awards were given: Best Student Paper (\$300) went to Karoun Charkoudian (University of Wisconsin-Madison) for her talk titled: *Strike-slip separation of the Burntside trondhjemite and the Wakemup Bay tonalite, Northern Minnesota*. In recognition of the large number of excellent student presentations, two additional students were chosen for Honorable Mention (\$100 each) - Amy Garbowicz (Lawrence University) and Stephanie Hocker (University of Wisconsin – Oshkosh). The Student Paper Award fund was supplemented by silent auction of an original volume of the classic Butler and Burbank USGS Professional Paper 144 on Copper Deposits of Michigan. Eisenbrey Student Travel Grants were given to 15 students: Greg Joslin and Phillip Larson – University of Minnesota, Duluth; Merida Keatts and Mary McKenzie – Kent State; John Marma and Karoun Charkoudian, – University of Wisconsin, Madison; Amy Garbowicz – Lawrence University; Daniela Vallini – University of Western Australia; Stephanie Hocker – University of Wisconsin-Oshkosh; and Becky Rogola, Geoff Heggie, Justin Johnson, Riku Metsaranta, Eric Potter and Adam Richardson, all from Lakehead University. All awards were presented at the conclusion of the technical sessions.

The Institute's Board of Directors met on May 8, 2003 and a brief overview of the meeting is provided below:

1. Accepted the Report of the Chair for the 48th ILSG from Peter Hinz and minutes of last Board meeting, May 14, 2002 from ILSG secretary-treasurer, Mark Jirsa.
2. Accepted the 2002-2003 ILSG Financial Summary from Mark Jirsa.
3. Approved one co-chair from the 49th meeting, Laurel Woodruff, as on-going board member.
4. Nominated George Hudak of the University of Wisconsin, Oshkosh to replace Frank Luther on the Goldich Committee, a position that George later graciously accepted.
5. Approved Duluth, Minnesota as the location for the 2004 (50th annual) ILSG and co-chairs Steve Hauck and Mark Severson.
6. Discussed the transition of the Secretary Treasurer position from Mark Jirsa to Peter Hollings and accepted a proposal that both be appointed co-treasurers during the transition period.
7. Discussed the transition and evolution of the ILSG webpage and procedures required to move the ILSG into the electronic era.
8. Discussed possible activities related to 50th meeting to commemorate the longevity and impact of the ILSG.

The 49th ILSG meeting was a great success and we wish to thank all the people who contributed to that success. The staff of Pine Mountain was professional and responsive to the needs of a large group. Kleiman Pump and Well Drilling, Iron Mountain, MI, Prime Meridian Resources, Ltd., Fond du Lac, WI, and Coleman Engineering Co., Iron Mountain, MI provided generous monetary contributions. The field trips this year had a large number of participants, and thanks are due to field trip leaders, van drivers, and everyone else who stepped up when needed to drive, hand out lunches, unlock gates, or keep the crowds

moving. As always, everyone who attended the 49th ILSG was willing to help as necessary or adapt to any situation that developed. The meeting this year was well attended and we are heartened by the excellent student participation and attendance, a trend we hope continues. Because of the outstanding response to the meeting and field trips, the 49th ILSG generated several thousand dollars for the ILSG general fund.

We both are very happy with the outcome of the 49th meeting and hope that others think it was a success. An ILSG meeting requires a lot of work and time for all involved, but the assistance of the larger ILSG community makes the job of the co-chairs almost bearable, and we encourage others to take on the task.

Laurel Woodruff and Bill Cannon
Co-Chairs, 49



INSTITUTE ON LAKE SUPERIOR GEOLOGY

BOARD OF DIRECTORS MEETING

49th Annual Institute Meeting

Thursday, May 8, 2003

Iron Mountain, Michigan

Board of Directors

Laurel Woodruff (2003 General Chair)
William Cannon (2003 Co-chair)
Peter Hinz (2002 Co-chair)
Michael Mudrey (2001 Co-chair)
Steve Kissin (2000 Co-chair)
Peter Hollings (Institute Secretary-Treasurer)

Guests

Mark Jirsa (Emeritus Institute Secretary-Treasurer)
Steve Hauck (proposed 2004 Co-chair)
Mark Severson (proposed 2004 Co-chair)
Ted Bornhorst (Communications Coordinator)
Ron Sage (Goldich Committee)
Frank Luther (Goldich Committee-outgoing member)

The following is based on the secretaries' notes and recollection; any omissions or misstatements are unintentional. Motions by the Board of Directors are generally paraphrased—"approved" or "accepted" implying that a motion was made, seconded, and passed unanimously. The expression "generally agreed" carries less formality, but indicates a directive that will be pursued. Some issues that were resolved after the Board meeting, but during the conference are included here for closure.

MINUTES

1. Peter Hinz presented his report on the 48th meeting and stressed the importance of ensuring that the audiovisual component of the sessions runs smoothly. Hinz remarked that the folder of advice to meeting chairs has been replaced by an electronic version, which Woodruff agreed to forward to the next Chairs. Jirsa noted that the full minutes of the Board of Directors Meeting is not normally published in the Proceeding Volume. Accepted report of the Chairs for the 48th ILSG, Kenora, Ontario; as printed in the Proceeding Volume (Hinz), and minutes of last Board meeting, May 14, 2002 (Jirsa).
9. Received, discussed, and accepted 2002-2003 ILSG Financial Summary (Jirsa). Bornhorst agreed to close the ILSG Michigan accounts this year.
10. Approved Laurel Woodruff as on-going board member
11. Discussed replacing Frank Luther as "academic member" on Goldich Committee (end of term 2003). George Hudak of the University of Wisconsin, Oshkosh was proposed and accepted by the Board. George later accepted the position and was welcomed.
12. Discussed and approved 2004 (50th annual) meeting location—Duluth, Minnesota, and co-chairs Steve Hauck and Mark Severson. Hauck and Severson presented a list of seven potential field trips proposed for the meeting. Bornhorst advised the co-chairs to keep field trips close to home in order to avoid impacting upon future meetings.
13. Discussed the transition of the Secretary Treasurer position from Jirsa to Hollings. Distribution of publications to be transferred to Hollings this year with transfer of the Archives and funds at the 50th Annual Meeting. Hollings to open Canadian bank accounts and arrange non-profit status for ILSG in Canada. Accepted a proposal that Jirsa and Hollings be appointed co-treasurers during the transition period.

14. Discussed the transition of Webmaster from Bornhorst to Mudrey. It was agreed that the website would be moved from Michigan Tech to a commercial ISP with Mudrey and Bornhorst to coordinate the transition
15. Discussed and accepted transition from a paper to an electronic newsletter. Mudrey suggested establishing an Email list and agreed to moderate this. Woodruff, Jirsa, Mudrey and Hollings to form a committee to investigate the possibility of making the proceedings volumes available on-line. Committee to report to the board at the 50th annual meeting.
16. Discussed and agreed that long service pins are created for members who have been involved with the Institute for more than 15 years. Woodruff has the attendance lists and will pursue for presentation at the 50th annual meeting.
17. Other business
 - a. Bill Cannon proposed a compilation of 50 years of ILSG photos. This would be prepared as a CD to coincide with the 50th annual meeting. Cannon will be assisted by Gene LaBarge. A request for photographs was presented to the membership at the banquet.
 - b. It was requested by Luther that GPS locations of outcrops be included in future field guides
 - c. Mark Smyk and Pete Hollings offered to organize 51st Annual meeting in Nipigon, Ontario in 2005, to coincide with the culmination of new geoscience initiatives in the region.

Adjournment

Respectfully submitted on May 13, 2003 to Laurel Woodruff, Co-chair of the 49th annual meeting, for incorporation into the Report of the Chair to appear in Proceedings Volume 50.

Pete Hollings and Mark Jirsa
Secretary-Treasurer, Institute on Lake Superior Geology

2003 Best Student Paper Awards

Best Student Paper (\$300):

Karoun Charkoudian, University of Wisconsin, Madison; for her presentation co-authored with Basil Tikoff; Strike-slip separation of the Burntside trondhjemite and the Wakemup Bay tonalite, northern Minnesota.

Honorable Mentions (\$150 each):

Amy Garbowicz, Lawrence University, Appleton, Wisconsin; for her presentation co-authored with Marcia Bjornerud; Paleostress inferences from fault slip vectors in the eastern part of the Wisconsin segment of the Midcontinent Rift.

Stephanie Hocker, University of Wisconsin, Oshkosh; for her poster co-authored with G. Hudak, J. Odette, and T. Newkirk; Chemistry of alteration mineral phases at the Fivemile Lake volcanic-hosted massive sulfide prospect, northeastern Minnesota.

2003 Eisenbrey Student Travel Awards

- 1) Geoff Heggie, Lakehead University (\$100)
- 2) Adam Richardson, Lakehead University (\$100)
- 3) Justin Johnson, Lakehead University (\$100)
- 4) Becky Rogala, Lakehead University (\$100)
- 5) Eric Potter, Lakehead University (\$100)
- 6) Riku Metsaranta, Lakehead University (\$100)
- 7) Greg Joslin, University of Minnesota, Duluth (\$100)
- 8) Phillip Larson, University of Minnesota, Duluth (\$100)
- 9) Merida Keatts, Kent State, Ohio (\$100)
- 10) Mary McKenzie, Kent State, Ohio (\$100)
- 11) John Marma, University of Wisconsin, Madison (\$100)
- 12) Karoun Charkoudian, University of Wisconsin, Madison (\$100)

- 13) Amy Garbowicz, Lawrence University, Appleton, Wisconsin (\$100)
- 14) Stephanie Hocker, University of Wisconsin, Oshkosh (\$100)
- 15) Daniela Vallini, University of Western Australia (\$200)

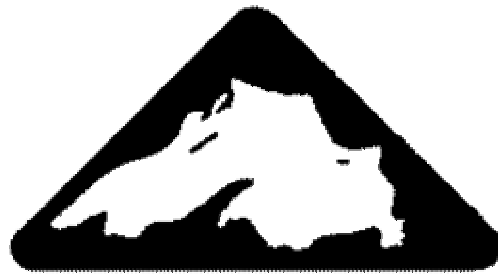
2004 Goldich Medal Recipient

Paul W. Weiblen, Department of Geology & Geophysics, University of Minnesota

MTU Archives Donation

Proceedings including Part 1 (Programs and Abstracts) and Part 2 (Field Trip Guidebook) are available from the Institute:

Institute on Lake Superior Geology
c/o Mark Jirsa, Secretary - Treasurer
Minnesota Geological Survey
2642 University Avenue
St. Paul MN 55114-1057
Phone: 612.627.4539 Fax: 612.627.4778
e-mail: jirsa001@tc.umn.edu



PROGRAM



The following companies made generous contributions to the 50th Annual Meeting. We thank them for their commitment to the Institute on Lake Superior Geology. For 50 years this organization has thrived through the sustained interests of individuals, corporations, universities, and government agencies in the international geologic community. This dedication to an exchange of scientific ideas and a passion for field trips (even in driving rain or snow) has enabled the ILSG to fulfill one of its primary objectives: to promote better understanding of the geology in the Lake Superior region.

Franconia Minerals Corporation, Spokane, WA
Idea Drilling Incorporated, Virginia, MN
Iron Mining Association, Duluth, MN
Lehmann Exploration Management, Minneapolis, MN
Meriden Engineering, LLC, Hibbing, MN
Minerals Processing Corporation, Duluth, MN
Minnesota Exploration Association (MExA), Minneapolis, MN
Minnesota Minerals Coordinating Committee, St. Paul, MN
Teck Cominco American Incorporated, Spokane, WA
Wallbridge Mining Company, Lively, ONT

Tuesday May 4, 2004

7:30 a.m. **Field Trip 1:** Volcanic stratigraphy, hydrothermal alteration, and VMS potential of the lower Ely Greenstone, Fivemile Lake to Sixmile Lake area.

Field Trip Leaders: George Hudak (UWO), John Heine (NRRI), Mark Jirsa (MGS), Dean Peterson (NRRI).

6:00 p.m. Overnight in Tower, MN at Fortune Bay Casino.

8:00 a.m. **Field Trip 2:** Geologic Highlights of New Mapping in the Southwestern Sequence of the North Shore Volcanic Group and Beaver Bay Complex.

Field Trip Leaders: Terry Boerboom (MGS), Jim Miller (MGS), and John Green (UMD – Dept. of Geol. Sci.).

6:00 p.m. Overnight in Duluth on your own.

Wednesday May 5, 2004

8:00 a.m. **Field Trip 2:** Geologic Highlights of New Mapping in the Southwestern Sequence of the North Shore Volcanic Group and Beaver Bay Complex.

Field Trip Leaders: Terry Boerboom (MGS), Jim Miller (MGS), and John Green (UMD – Dept. of Geol. Sci.).

8:00 a.m. **Field Trip 3:** Late Wisconsinan Superior-lobe Deposits in the Lake Superior Basin Northeast of Duluth.

Field Trip Leader: H. Hobbs (MGS).

8:00 a.m. **Field Trip 4:** Geology of the Eastern Mesabi Iron Range, Northeastern Minnesota.

Field Trip Leaders: R. Ojakangas (UMD – Dept. of Geol. Sci.), M. Severson (NRRI), P. Jongewaard (United Taconite), D. Halverson (Northshore mining), J. Arola (Inland), J. Evers (Cliffs-Services).

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

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

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

Thursday May 6, 2004

7:00 a.m. – 4:00 p.m. **REGISTRATION**

8:00 a.m. – 8:05 a.m. **INTRODUCTORY REMARKS**
Steven A. Hauck and Mark J. Severson, Co-Chairs

SPECIAL TECHNICAL SESSION I

The History of Geologic Investigations in the Lake Superior Region

Session Chairs: **Mark Smyk**, Ontario Geological Survey, Thunder Bay, ONT
Sidney Hemming, Lamont-Doherty Lab., Columbia Univ., NY

- 8:05 a.m. – **Old Prospector**
“Gold is Where You Find It! So Is Ag and Cu and Fe!”
The OLD PROSPECTOR: Gold Rushes and Mineral Prospecting, 1848 to 1900 in Western North America and The Lake Superior Region
- 8:35 a.m. – **Johnson, A.M.**
Douglass Houghton’s 1840 Field Excursion to Lake Superior
- 8:55 a.m. – **Miller, J.D., Jr.**
N.H. Winchell's Study of the Keweenawan Supergroup Rocks of Northeastern Minnesota, 1872-1900
- 9:15 a.m. – **Smyk, M.C., and Magee, A.**
Silver Threads and Golden Needles: Geological Milestones in Northwestern Ontario
- 9:35 a.m. – **Holm, D.K., Van Schmus, R.W., and Schneider, D.A.**
The Influence of Radiometric Dating for Unraveling the Precambrian Geologic History of the Lake Superior Region

9:55 a.m. - 10:20 a.m. **COFFEE BREAK AND POSTER SESSION**

- 10:20 a.m. – **Chandler, V.W., Boerboom, T.J., and Jirsa, M.A.**
Promontory Tectonics of the Penokean Orogen in Minnesota: A Gravity and Magnetic Perspective
- 10:40 a.m. – **Medaris, G., Jr., and Singer, B.**
Geochronology of Precambrian Rocks in Central Wisconsin: A Review and New $^{40}\text{Ar}/^{39}\text{Ar}$ Analyses
- 11:00 a.m. – **Southwick, D.L.**
Late Paleoproterozoic Rhyolite-Quartzite Sequences in the Southwestern U.S.: Speculative Relationship to Rocks of the Baraboo Interval
- 11:20 a.m. – **Ormand, C.J., and Czeck, D.M.**
Three-Dimensional Geometry and Strain of the Baraboo Syncline: Kinematic Implications

11:40 a.m. – **Fralick, P., and Pufahl, P.K.**

Oxygenation of the Archean Hydrosphere: Evidence from the Eagle Island Deltaic Complex

12:00 p.m. – 1:10 p.m. – **LUNCH BREAK – POSTER SESSION and ILSG BOARD MEETING**
(by invitation)

TECHNICAL SESSION II

Session Chairs: **Jill Peterman**, Wisconsin Department of Transportation, Superior, WI
Dave Dahl, MN Dept. Natural Resources, Lands & Minerals Div., Hibbing, MN

1:10 p.m. – **Metsaranta, R.T.*, and Fralick, P.W.**

Geochemistry and Petrography of Altered Basement Rocks Underlying the Middle Proterozoic Sibley Group

1:30 p.m. – **Heggie, G.*, and Hollings, P.**

Multiple Intrusive Stages Associated with Keweenawan Rifting: The Leckie Stock, Seagull Intrusion, and Nipigon Sill.

1:50 p.m. – **Richardson, A.*, and Hollings, P.**

A Geochemical Study of the Sills of the Nipigon Basin, Ontario

2:10 p.m. – **Boerboom, T.J.**

Newly Recognized Diatreme Breccia Dikes on Lake Superior Near Two Harbors, Minnesota

2:30 p.m. – 2:55 p.m. **COFFEE BREAK AND POSTER SESSION**

2:55 p.m. – **Hollings, P.**

Trace Element Geochemistry of the Osler Group Volcanics – Implications for Mid-Continent Rifting

3:15 p.m. – **Hart, T.R.**

Geochemistry of the Proterozoic Intrusive Rocks of the Nipigon Embayment

3:35 p.m. – **MacDonald, C.A. and Tremblay, E.**

Lake Nipigon Region Geoscience Initiative: Results of Bedrock Mapping in the Northern Part of the Western Nipigon Embayment, Northwestern Ontario, Canada

3:55 p.m. – **Schneider, R.V.**

Depth Migration of Seismic Reflection Data: An Example for Lake Superior Studies

Ballroom Must Be Empty by 4:30 p.m. for Banquet Setup.

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

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

- **Announcement of 51st Annual Meeting Location**
- **2004 Goldich Award Presentation to Paul Weiblen**
- **2004 Banquet Address**

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

Friday May 7, 2004

8:00 a.m. – 8:05 a.m.

INTRODUCTORY REMARKS **Steven A. Hauck and Mark J. Severson, Co-Chairs**

TECHNICAL SESSION III

Session Chairs: **Jayne Englebert**, MSA Professional Services, Baraboo, WI
Douglas Hunter, Wallbridge Mining Company, Lively, Ontario, Canada

8:05 a.m. – **Johnson, J.R.,* Hollings, P., and Kissin, S.**

Regional Geochemistry Surrounding the Norton Lake Cu-Ni-PGE Deposit, Uchi Subprovince, Ontario

8:25 a.m. – **Rossell, D.M., and Coombes, S.**

The Geology of the Eagle Nickel-Copper Deposit: Marquette County, Michigan

8:45 a.m. – **Mahin, R.A., Quigley, T.O., and Lynott, J.S.**

The Discovery and Geology of the L-K Massive Sulfide Deposit, Menominee County, MI

9:05 a.m. – **Bornhorst, T.J., and Robinson, G.W.**

Precambrian Aged Supergene Alteration of Native Copper Deposits in the Keweenaw Peninsula, Michigan

9:25 a.m. – **Severson, M.J., and Hauck, S.A.**

Whatever Happened to Those Cu-Ni Deposits?

9:45 a.m. – **Shafer, P.L.,* and Ripley, E.M.**

Hydrogen Stable Isotopic Evidence for Hydrothermal Alteration and PGE Concentration Involving Meteoric Water in the Birch Lake Area, Duluth Complex, MN

10:05 a.m. - 10:30 a.m.

COFFEE BREAK AND POSTER SESSION

10:30 a.m. – **Hudak, G.J., Newkirk, T.T., Drexler, H., Odette, J.D., and Hocker, S.M.**

Neoproterozoic Peperites in the Vicinity of Fivemile Lake, Vermilion District, NE Minnesota

10:50 a.m. – **Han, T.-M.**

Effect of Mineralogy on Processing of Low Grade Iron Ores From the Negaunee Iron-Formation on Marquette Range of the Lake Superior District

11:10 a.m. – **Fosnacht, D., Iwasaki, I., and Bleifuss, R.**

Iron Nodule Research at the Natural Resources Research Institute, UMD

11:30 a.m. – **Zanko, L.M., Oreskovich, J.A., and Niles, H.B.**

Taconite Aggregate Potential of Coarse Tailings from the Biwabik Iron Formation, With an Emphasis on Geology, Mineralogy, and Microscopy

11:50 a.m. – **Larson, P.C.,**

Regional Till Sampling in the Vermilion Greenstone Belt, Minnesota: Preliminary Results and Interpretations

12:10 p.m. - 1:00 p.m. **LUNCH BREAK – POSTERS REMOVED AFTER LUNCH**

SPECIAL TECHNICAL SESSION IV

***Department of Geological Sciences, University of Minnesota Duluth
Fifty Years of Geological Contributions to Lake Superior Geology and Other Geological
Areas***

1:00 p.m. – **Introductory Remarks on 50 years of Geology at University of Minnesota, Duluth:**
Penny Morton

Session Chairs: **Scott Wolter**, American Petrographics Service Company, St. Paul, MN
Wanda Taylor, University of Nevada at Las Vegas, Las Vegas, NV

1:05 p.m. – **Ojakangas, R.W., and Ojakangas, G.W.**
*Deposition of Paleoproterozoic Siliciclastics and Iron-Formation in a Tidally Influenced
Shelf Environment, Animikie Basin, Lake Superior Region*

1:25 p.m. – **Breckenridge, A.***
*The Lake Superior Varve Stratigraphy and Implications for Eastern Lake Agassiz
Outflow From 10,700 to 8,900 YBP (9.5-8.0 ¹⁴C KA)*

1:45 p.m. – **Syverson, K.M.**
*Origin of Pre-Wisconsinan Glacial Units in Northern Wisconsin Based on Lithologic
Characteristics*

2:05 p.m. – **Jirsa, M.A.**
*Mapping by the Minnesota Geological Survey in Support of Land-use and Water
Planning on the Mesabi Iron Range*

2:25 p.m. – **Brown, T.R.**
*Recent Geophysical and Geochemical Applications to Exploration Activities in the
Cripple Creek Mining District, Colorado*

2:45 p.m. – 3:10 p.m. **COFFEE BREAK AND POSTER SESSION**

3:10 p.m. **Student Paper and Travel Awards**

3:20 p.m. – **Vervoort, J.D., and Wirth, K.R.**
Origin of the Rhyolites and Granophyres of the Midcontinent Rift, Northeast Minnesota

3:40 p.m. – **Schmidt, S.Th., and Seifert, K.**
Ocean-Floor-Type-Alteration of Drilled MRS Volcanic Rocks in Iowa

4:00 p.m. – **Davidson, D.M., Jr.**
Heller, Sims and Marsden: Mentors Extraordinaire

4:20 p.m. – **Grant, J.A.**
Isocon Analysis: How to Make It Work for You

4:40 p.m. – **Morton, R.**
Twenty-One Years in a Caldera: UMD Geology Students and Sturgeon Lake, Ontario

5:30-7:30 p.m. **Buffet at the Depot Sponsored by the UMD Dept. of Geological Sciences (All ILSG Registrants are invited)**

Saturday May 8, 2004

8:00 a.m. **Field Trip 5:** Classic Outcrops of Northeastern Minnesota.

Field Trip Leaders: M. Jirsa (MGS), T. Boerboom (MGS), R. Ojakangas (UMD-Dept. Geol. Sci.), J. Miller (MGS), J. Green (UMD-Dept. Geol. Sci.), G.B. Morey (MGS), D. Peterson (NRRI), M. Severson (NRRI), R. Patelke (NRRI).

6:00 p.m. Overnight in Tower, MN at Fortune Bay Casino.

8:00 a.m. **Field Trip 6:** Glacial and Postglacial Landscape Evolution in the Glacial Lake Aitkin and Upham Basin, Northern Minnesota.

Field Trip Leaders: L. Marlow, P. Larson, H. Mooers (UMD-Dept. Geol. Sci.).

6:00 p.m. Return of Trip to Radisson Hotel, Duluth Minnesota.

7:00 a.m. **Field Trip 7:** Economic Geology of Archean Gold Occurrences in the Vermilion District, Northeast of Soudan, Minnesota.

Field Trip Leaders: D. Peterson (NRRI), R. Patelke (NRRI).

6:00 p.m. Return of Trip to Radisson Hotel, Duluth Minnesota.

8:00 a.m. **Field Trip 8:** Geology of the Western Contact of the Duluth Complex, Partridge River and South Kawishiwi Intrusions, Northeastern Minnesota.

Field Trip Leaders: M. Severson (NRRI), J. Miller, Jr. (MGS).

6:00 p.m. Return of Trip to Radisson Hotel, Duluth Minnesota.

Sunday May 9, 2004

8:00 a.m. **Field Trip 5:** Classic Outcrops of Northeastern Minnesota.

Field Trip Leaders: M. Jirsa (MGS), T. Boerboom (MGS), R. Ojakangas (UMD-Dept. Geol. Sci.), J. Miller (MGS), J. Green (UMD-Dept. Geol. Sci.), G.B. Morey (MGS), D. Peterson (NRRI), M. Severson (NRRI), R. Patelke (NRRI).

6:00 p.m. Return of Trip to Radisson Hotel, Duluth Minnesota.

POSTER PRESENTATIONS

Boerboom, T.J.

Bedrock Geologic Maps of the Two Harbors and Castle Danger 7.5-Minute Quadrangles, North Shore of Lake Superior, Minnesota

Buchholz, T.W., Falster, A.U., and Simmons, Wm.B.

A Greisen-like Mineral Assemblage from the Nine Mile Pluton, Marathon County, Wisconsin

Cordua, W.S.

Enigmatic 1300 – 1400 Ma Mafic Pluton from the Koss Pit, Marathon County, WI

Drexler, H.L.*, Hudak, G.J., and Peterson, D.M.

A Field and Laboratory Study to Evaluate the Genetic Relationships Between the Purvis Pluton and Volcanic Rocks and Volcanic-Associated Mineralization in the Vermilion District of NE Minnesota

Erickson, M.L.*, and Barnes, R.J.

Late Wisconsin Till and Arsenic Contamination in Upper Midwest Groundwater

Fitzpatrick, F.A.

Influence of Geologic Setting on Hydrogeomorphic Characteristics of Southern Lake Superior Tributaries

Green, J.C., and Miller, J.D., Jr.

The Geology of the Duluth Complex and the North Shore Volcanic Group Portrayed in New 7.5' Quadrangle Maps of the Duluth Metropolitan Area

Hart, T.R., and Magyarosi, Z.

Precambrian Geology and Mineralization of the Northern Black Sturgeon River area, Nipigon Embayment

Hemming, S.R., and Roy, M.

⁴⁰Ar/³⁹Ar Hornblende Evidence for Provenance of Ice Rafted Detritus in the North Atlantic: Implications for Tracking Past Changes in the Extent and Dynamics of Northern Hemisphere Ice Sheets

Hoffman, A.T.*, Peterson, D.M., Patelke, R.L., and Hudak, G.J.

Preliminary Petrography and Hydrothermal Alteration of the Soudan Mine Area, Vermilion District, Northeastern Minnesota

Jirsa, M.A.

Regional Compilations of Bedrock Geology in Northern Minnesota: The Vermilion, Ely, and Basswood Lake Quadrangles

Kaukonen, R.J., and Alapieti, T.T.

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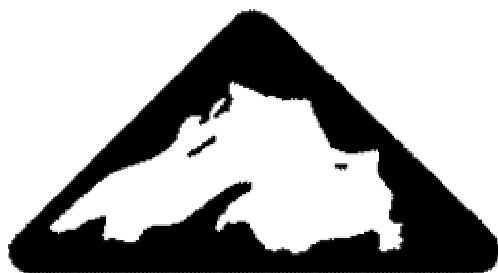
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NOTE: Asterisk * denotes a student eligible for a Best Student Paper Award.



ABSTRACTS

BEDROCK GEOLOGIC MAPS OF THE TWO HARBORS AND CASTLE DANGER 7.5-MINUTE QUADRANGLES, NORTH SHORE OF LAKE SUPERIOR, MINNESOTA

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

Two recent quadrangle-scale geologic maps of an area adjacent to Lake Superior have been published by the Minnesota Geological Survey as part of the U.S. Geological Survey STATEMAP program. This ongoing mapping effort has resulted in five published quadrangle geologic maps in an area stretching from Duluth to Castle Danger (Boerboom and others, 2002a, b, 2003a, b; Fig. 1a). Work is currently in progress on a sixth geologic map (Split Rock Point); and another (Two Harbors NE) will be mapped in the coming year. Field mapping for all these maps was or will be conducted at a scale of 1:12,000, and map compilations are at 1:24,000.

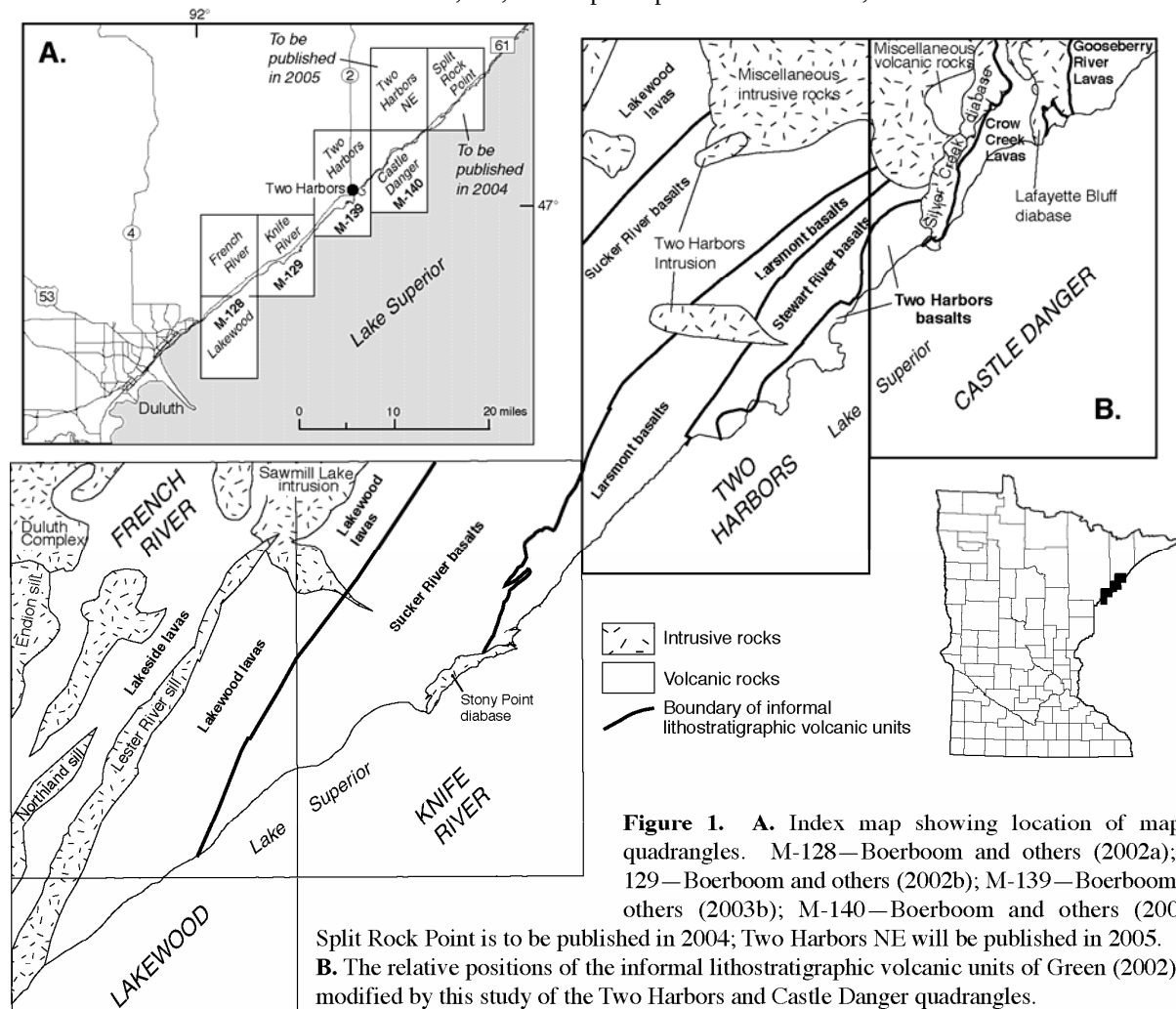


Figure 1. A. Index map showing location of mapped quadrangles. M-128—Boerboom and others (2002a); M-129—Boerboom and others (2002b); M-139—Boerboom and others (2003b); M-140—Boerboom and others (2003a). Split Rock Point is to be published in 2004; Two Harbors NE will be published in 2005.

B. The relative positions of the informal lithostratigraphic volcanic units of Green (2002) and modified by this study of the Two Harbors and Castle Danger quadrangles.

The North Shore is experiencing ever-increasing development of both commercial property and private residences, creating a concomitant demand on ground-water resources, which near Lake Superior come mainly from bedrock reservoirs, particularly layered volcanic flows and interflow sedimentary rocks. Development also brings an increased need for quality aggregate materials for both construction and shoreline preservation projects. Although some volcanic flows may be suitable for crushed-rock aggregate, the intrusive rocks are likely to provide the best source of this material. Thus, the goal of this mapping is to refine the stratigraphy of volcanic rocks in the southwest limb of the North Shore Volcanic Group, and to identify the extent, mineralogy, and relationships of intrusive rocks emplaced into the volcanic pile. This mapping will not only lay the groundwork for present and future resource demands, but also further our understanding of the geologic aspects of these rocks.

Green (2002) subdivided volcanic rocks of the Keweenaw North Shore Volcanic Group into a series of informal lithostratigraphic units based on the relative thickness and composition of the volcanic flows or by areas separated by intervening intrusions. Several of these units were extended into the Two Harbors and Castle Danger quadrangles from the southwest (Fig. 1b). Two new lithostratigraphic units were added to those of Green (2002) based on this mapping—the Stewart River basalts and the Crow Creek lavas (Fig. 1b). The Stewart River basalts include several flows of diabasic-textured basaltic lavas and an ambiguous unit that has attributes of both a lava flow and an intrusion, interpreted as a shallow-level subvolcanic intrusion that breached the surface to form flows along its upper margin. The Crow Creek lavas are named for olivine tholeiitic and andesitic flows that outcrop mainly along Crow Creek. These lavas contrast with flows east of the Lafayette Bluff diabase and west of the Silver Creek diabase, implying that the intrusions have created a major disruption of the volcanic stratigraphy.

Mapping has refined the shape and intrusive relationships of known intrusions, and has identified several new intrusions. Most noteworthy among these is the previously known but poorly understood Two Harbors intrusion, which has been shown to form a small, zoned, east-plunging, synform-shaped body. This intrusion grades from troctolitic diabase through poikilitic olivine gabbro to well-foliated intergranular gabbro, from the lowest exposed to the highest exposed portions of the body. Another smaller body of more massive olivine-rich ophitic olivine diabase may be related to the Two Harbors intrusion, but does not exhibit any consistent modal or textural layering.

Of particular interest is the recognition of a diatreme-like breccia that cuts volcanic rocks near the mouth of Crow Creek (Boerboom, 2004). This diatreme contains clasts from less than 1 millimeter to 5 meters in size, in a matrix of zeolite- and chlorite-cemented rock flour. The clasts include a heterogeneous mixture of fine-grained porphyritic basalt, amygdaloidal to ophitic to intergranular basalt, and interflow sedimentary rocks. Fine-grained felty-textured prismatic ferromonzodiorite also occurs as intrusions into basalt adjacent to the diatreme, and as clasts in the diatreme, indicating a possible cogenetic relationship between the two.

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NEWLY RECOGNIZED DIATREME BRECCIA DIKES ON LAKE SUPERIOR NEAR TWO HARBORS, MINNESOTA

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

Recent mapping by the Minnesota Geological Survey during the 2002 and 2003 field seasons (see Boerboom, 2004) has identified two nearly identical diatreme-like breccias located about 15 kilometers apart, both of which intrude volcanic rocks of the North Shore Volcanic Group. One is located near the mouth of Crow Creek, 3 kilometers southwest of Castle Danger, and the other is located near the mouth of the Split Rock River.

The diatremes contain clasts that range up to four meters in diameter. The clasts are composed of typical North Shore volcanic group rocks, including intergranular to ophitic basalt, porphyritic basalt, and minor interflow sedimentary rocks, as well as felty-textured prismatic monzodiorite that also occurs as intrusions into basalts adjacent to the diatremes. At both places the clasts are heavily replaced by zeolites (mainly laumontite) and chlorite, and are surrounded by a matrix of zeolites and chlorite mixed with rock flour. Irregularly distributed brown gossans that probably represent zones of pyritic matrix have also been identified at Crow Creek.

The Crow Creek diatreme is the best exposed of the two diatremes, but outcrops are mainly accessed by water. Exposures on a shore-parallel high cliff wall and in cliffs of basalt that are cut by the breccia and protrude into the lake show the dike to be approximately 10 meters wide and vertical in orientation, with clasts up to 4 meters in size. At the shore the dike is oriented approximately east-west, but other scattered, low outcrops inland imply that the dike may have an overall 0.25 mile diameter ring-like structure or a very irregular strike direction. Monzodiorite associated with this diatreme is poorly exposed, and where visible contains abundant angular basalt clasts and small amygdules of chlorite and calcite. The same monzodiorite also occurs as clasts in the diatreme, thus it must have preceded the diatreme in timing but may have been closely associated with it.

The Split Rock River diatreme is exposed just southeast of the river mouth as a 6-meter wide, north-striking, subvertical dike that truncates amygdule-layered tholeiitic basalts. This dike contains clasts of both intergranular and ophitic basalt up to 20 centimeters in diameter, and small clasts of interflow sedimentary rocks and ferromonzodiorite petrographically identical to that at Crow Creek. The latter also occurs alone in an outcrop near the diatreme. Narrow, dike-parallel, anastomosing zones of brecciation cut both basalt and ferromonzodiorite in the vicinity of the diatreme dike. In both cases, the brecciated texture, multiple clast varieties of North Shore volcanic group-related rocks and sharp cross-cutting contacts with adjacent volcanic rocks imply that the diatremes were emplaced as an explosive, gas-charged intrusion that cut across the volcanic strata. The amygdaloidal and deuterically-altered Lafayette Bluff diabase occurs in close proximity to the Crow Creek diatreme (Boerboom and others, 2003), which may have provided a source of volatiles as it cooled.

These diatremes are soft and easily eroded and thus unlikely to form significant outcrops inland, and they could easily be misidentified as a volcanic flow breccia. Careful examination of isolated or seemingly out of sequence flow breccias for disparate clast lithologies may reveal more of these diatreme dikes.

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Precambrian Aged Supergene Alteration of Native Copper Deposits in the Keweenaw Peninsula, Michigan

BORNHORST, Theodore J., and ROBINSON, George W., A.E. Seaman Mineral Museum, Michigan Technological University, Houghton, MI 49931

The Keweenaw Peninsula within the Midcontinent Rift System is host to a world-class native copper mining district from which about 6 billion kg of refined copper was mined from 1845 to 1968. By far the principal economic minerals mined were native copper and native silver. Supergene alteration minerals occur irregularly throughout the district. The most abundant of these are cuprite, tenorite, malachite, and chrysocolla in close association with native copper. Less common are azurite and paramelaconite, though about fifty additional species are known (Table 1). These minerals typically occur as thin coatings on or replacing native copper, irregular thin coatings along fractures, and euhedral crystals in small pockets filling remaining pore space. For the most part supergene minerals are found near the surface (< 300 m) and are well below the current water table.

As might be expected, sulfates are conspicuously uncommon, owing to the general absence of sulfide ores in the district. Likewise, the arsenates (e.g., annabergite, tyrolite, erythrite, etc.) are associated with the copper arsenide minerals domeykite and algodonite. One group, however, the chlorides (e.g., paratacamite, calumetite, etc.), may have formed by reaction with fossil brines, rather than strictly supergene means, as these minerals have been found in isolated areas 1375 m below surface with no visible means of connection to downward-moving meteoric waters.

The rocks of the Midcontinent Rift System were deposited between roughly 1.1 and 1.0 Ga, and late in the evolution of the rift (about 1.05 Ga) the rift was subjected to regional compression resulting in reverse faulting, uplift, and sediment deposition. During this compression event, native copper was deposited from a large-scale hydrothermal system along with numerous other hydrothermal minerals. Uplift related to reverse faulting likely continued for some time after the formation of the native copper deposits, likely ending about 1.0 Ga. The rift rocks of the Keweenaw Peninsula were subjected to erosion. If enough cover was removed, the native copper could have been sufficiently near the surface to be exposed to oxygenated groundwater, which would form supergene minerals. Erosion ended by the end of Precambrian time, when the rift rocks were unconformably overlain by Paleozoic sediments, which still cover major portions of the rift. These sediments sheltered the rift rocks of the Keweenaw Peninsula from weathering and erosion. The Paleozoic sediments were removed by Pleistocene glaciers, again making supergene alteration possible. Since the last glacial retreat it is probable that the water table has not been significantly lower than it is today. In turn, Pleistocene supergene alteration should be more or less restricted to above the current water table. Because most observed supergene alteration is below the water table, it is unlikely that it formed since the glaciers removed the Paleozoic cover. Thus, supergene alteration must have occurred during/near the end of the protracted period of erosion in late Precambrian time. The copper deposits had to be reasonably near the surface at that time for supergene alteration to occur. While the Pleistocene glaciers removed significant thickness of Paleozoic cover they could not have removed any significant thickness of rift rocks, else the supergene altered zones would have been removed too. Therefore, the current surface of the Keweenaw Peninsula is likely near the same stratigraphic/erosional level that was present when the Keweenawan rocks were buried by Paleozoic sediments.

acanthite	lavendulan
annabergite	likasite
anthonyite	malachite
ardennite ?	manganite
atacamite	mirabilite
azurite	montmorillonite
brochantite	moolooite ?
buttgenbachite	nantokite
calcite	olivenite
calumetite	paramelaconite
carbonate-cyanotrichite	paratacamite
chalconatronite	pharmacolite
chrysocolla	picropharmacolite
connellite	plancheite
covellite	posnjakite
crednerite	pseudomalachite
cuprite	rauenthalite
diopase	spertiniite
erythrite	tenorite
gerhardtite	tyrolite
goethite	vaterite
guerinite	veszelyite
gypsum	vladimirite
halite	whewellite ?
humboldtine ?	unknown Ca-Cl mineral
hydromagnesite	unknown Cu-Cl minerals
kaolinite	unknown Cu-Ca-Cl mineral
langite	

Table 1. Supergene minerals found or reported from the Keweenaw native copper deposits.

THE LAKE SUPERIOR VARVE STRATIGRAPHY AND IMPLICATIONS FOR EASTERN LAKE AGASSIZ OUTFLOW FROM 10,700 TO 8,900 CAL YBP (9.5 - 8.0 ¹⁴C KA)

BRECKENRIDGE, Andy, Large Lakes Observatory, University of Minnesota Duluth, 10 University Drive, 109 RLB, Duluth, MN 55812-2496, brec0027@d.umn.edu

Glaciolacustrine rhythmites from Lake Superior record the regional recession of the Laurentide Ice Sheet (LIS) from 10,700 to 8,900 cal ybp (ca. 9.5-8.0 ¹⁴C ka). LIS retreat from Superior opened eastern Lake Agassiz outlets so that the rhythmites reflect the combined impacts of sediment-laden meltwater and Lake Agassiz discharge. Using sediment cores retrieved from Lake Superior, I present rhythmite stratigraphies, a time series analysis of the thickness measurements, and high-resolution inorganic carbonate data to demonstrate that this is an annual record (varved). The varve thickness records primarily document regional ice margin dynamics: thick varve sequences at 9,100 cal ybp (~8.1 ¹⁴C ka) and 10,400-10,200 cal ybp (~9.2-9.0 ¹⁴C ka) record two periods of moraine formation (the Nakina and Nipigon). General varve cessation is associated with the circumvention of Lake Agassiz and glacial meltwater into Lake Ojibway at 9,040 cal ybp (~8.1 ¹⁴C ka), although adjacent to meltwater inlets, rhythmic sedimentation persisted for another 200 years.

Positively identifying Lake Agassiz catastrophic discharge events remains speculative but seems feasible. The initial influx of Lake Agassiz water is expected at around 10,600 cal ybp (~9.4 ¹⁴C ka), but at this time, most of eastern and northern Lake Superior was covered by ice. Three sets of thick-thin varves in western Lake Superior perhaps record influxes of Lake Agassiz at around 10,630, 10,600, and 10,570 cal ybp (~9.4 ¹⁴C ka). Varve formation in Superior coincides with high lake levels in Lake Huron, suggesting that high lake levels in Huron correspond to periods of high Agassiz and/or meltwater flow into Lake Superior.

Recent Geophysical and Geochemical Applications to Exploration Activities in the Cripple Creek Mining District, Colorado

BROWN, Timothy R., Cripple Creek and Victor Gold Mining Company, P.O. Box 191, Victor, CO 80863, tbrown@anglogoldna.com

Approximately 23 million ounces of gold have been produced from underground and surface operations since gold was discovered in the Cripple Creek Mining District in 1891. This total includes nearly 2 million ounces produced by Cripple Creek and Victor Gold Mining Company (CC&V) over the past 10 years. Gold has been produced from numerous veins in a 30 MA alkaline diatreme complex and is strongly associated with intense potassic alteration. Current production is mining low-grade disseminated haloes around the major historic producers from two open pits and the gold is recovered from a heap leach facility. This rate of production, and future production, in a mature mining district could not take place without an aggressive, ongoing exploration program that utilizes every available tool.

Airborne geophysical surveys conducted in 1999 included magnetics, resistivity, and radiometrics. The magnetic survey clearly outlines the diatreme and shows numerous geological, structural, and cultural features inside the diatreme while contributing to the understanding of the alteration. Resistivity has given a better understanding of the zones of clay, potassic alteration, and possibly water. All of these suggest the location of structural features. The radiometric survey, and especially K, outlines large zones of alteration, however this is strongly influenced by historical and recent disturbances as well as the leach pad.

IP and CSAMT surveys were initiated in 2001 and the results were encouraging enough to launch a much larger survey in 2002 that covered 37 line miles. The density of data allowed us to model and display the information in several different ways that include plans, sections, and 3D shells.

CC&V utilizes a survey tool that captures oriented joint and fracture information with a down-hole camera. This tool captures important geotechnical data as well as structural orientations that can be cross-referenced to assay data.

The geochemical relationships between Au and Te and the potassic alteration have long been known in the district. Recent studies have shown a consistent relationship between gold and other elements (As, Hg, Sb, and V) and have suggested high-grade gold always occurs with strong potassic alteration although strong potassic alteration does not always indicate zones of high-grade gold.

Application of the knowledge gained from a better understanding of the district's geology, alteration, and structure has led to focused, efficient drilling programs. The results of the exploration programs have continued to add to the operations as mid-year 2003 reserves stand at 4.2 million ounces and production is scheduled to continue through 2013.

A GREISEN-LIKE MINERAL ASSEMBLAGE FROM THE NINE MILE PLUTON, MARATHON COUNTY, WISCONSIN

BUCHHOLZ, Thomas W., 1140 12th Street North, Wisconsin Rapids, Wisconsin 54494,
FALSTER, Alexander U., and SIMMONS, Wm.B., Department of Geology and Geophysics,
University of New Orleans, New Orleans, Louisiana 70148.

The Nine Mile pluton is the youngest and most silicic of the four known intrusive centers of the approximately 1.5 Ga Wausau complex, exposed in Marathon County, Wisconsin. Mineralization in this epizonal pluton is often varied and complex, though frequently restricted to small localized environments in pegmatitic veins, aplites, and miarolitic granite. Recently a greisen-like mineral assemblage was identified in the Maguire weathered granite quarry, located approximately ¼ mile west of the Ladick East (or Charneski) quarry in the south central portion of the pluton.

Quarrying here has intersected several small aplite-pegmatite dikes ranging in thickness from approximately 2" (5 cm) to about 15" (40 cm). These consist of layered banded aplite, commonly with thin 1-3" thick pegmatitic cores, and locally exhibit a highly peraluminous composition that is unusual in the predominantly alkalic Nine Mile granite.

Due to the rapid progress of pit operations and ongoing reclamation work, most dikes could not be studied in their original position, but one briefly exposed gently dipping subhorizontal dike was observed in situ. Piles of discarded aplite-pegmatite boulders indicate the probable locations of additional dikes, possibly as many as three based upon varying characteristics. Most dikes were probably roughly vertically oriented, as adjacent pit walls show no signs of the dikes. Much material was recovered from piles of mingled boulders; sample characteristics generally allow attribution to one of the surmised four dikes.

Exotic mineralization is often present in both the aplite and pegmatitic portions, but is concentrated along and adjacent to aplite-pegmatite contacts and along thin discordant mica-rich veinlets cutting across visible banding or layering. Late-stage mineralization in these dikes, generally confined to the vicinity of the pegmatitic cores, shows mineralization indicative of a greisen-like environment.

Minerals identified to date include topaz (19-20% F content) as masses intergrown with albite and other minerals and as tiny clear crystals to 0.4 mm. Ferberite/hübnerite is found as well-formed dark red-brown to black crystals to 1.5 mm on and in albite and quartz. Most crystals have a high Mn content, but some portions of crystals are Mn dominant and are therefore hübnerite. Cassiterite, though less common than ferberite/hübnerite, has been found as dark red-brown crystals and masses to 3 mm. It appears that these represent the first reports of topaz, ferberite and hübnerite from in-situ occurrences in the Wausau complex, and indeed from the state of Wisconsin. Cassiterite has been observed in trace amounts from several other sites within the Nine Mile Pluton, but its relative abundance at this site is highly unusual.

Monazite- (Ce) is common as clear to translucent yellow-orange crystals up to 4.5 mm in size. Columbite-group minerals are common as well-formed crystals to approximately 4 mm, and are ferrocolumbite with significant Mn and Ta. Some crystals have W-contents of over 12%, making them tungstenian columbite-tantalite. Zircon is locally very abundant, and is Hf-rich. Xenotime is sparse, and appears to show significant enrichment in HREE. Other minerals

noted include pyrite, chalcopyrite, barite (excellent clear platelets), an unidentified bright blue Cu sulfide, ilmenite, quartz, microcline, albite, siderophyllite, muscovite and possibly zinnwaldite. Rare phases include tiny inclusions of stolzite/raspite in ferberite, microlite, a Bi mineral forming minute tabular crystals, a beam-sensitive W mineral, an ilmenorutile like mineral, a grayite-like Th phosphate and silvery black crystals of a Nb-dominant ixiolite-like mineral with octahedral morphology.

Interestingly, considering the abundance of fluorite at other Nine Mile Pluton sites, fluorite is much less common here. Nonetheless, the high F content of topaz and associated micas indicates that these were very F-rich systems.

The association of topaz, cassiterite and ferberite, and the highly peraluminous nature of the mineralization indicate that a greisen-like environment prevailed in the latter stages of crystallization of these dikes. To the knowledge of the authors this is the first observation of such an environment in the Nine Mile pluton, in the Wausau Complex, and probably in the state of Wisconsin.

Promontory Tectonics of the Penokean Orogen in Minnesota: A Gravity and Magnetic Perspective

CHANDLER, V.W., BOERBOOM, Terrence J., and JIRSA, Mark A., Minnesota Geological Survey, chand004@umn.edu

The sharp southward bend of the Penokean orogen in central Minnesota and possible continuation southwest into Iowa along the Spirit Lake trend (Anderson and Black, 1983; Van Schmus and others, 1993) have been cited as evidence for a promontory in the pre-collisional margin of the Superior Province craton (Schulz and Sims, 1993). Recent geologic investigations in this area have clarified the structure of both the orogen and the proposed promontory. Owing to a lack of bedrock exposure and drill holes, these investigations have relied to varying degrees on geophysical data. Of particular importance have been the high quality gravity and aeromagnetic databases in Minnesota (Chandler, 1991; Chandler and Schaap, 1991) and Wisconsin (Daniels and Snyder, 2002).

Gravity and magnetic data have guided recent re-interpretations of the high-grade gneissic rocks in the Minnesota River Valley subprovince, which forms the core of the proposed promontory. On the basis of distinctive anomaly signatures, Southwick and Chandler (1996) divided the subprovince into 4 blocks bounded by three major east- to northeast-striking shear zones, which most likely formed during late Archean accretion of the Minnesota River Valley rocks onto the Superior craton. These shear zones, which are inferred from geophysical models and seismic data to have a moderately steep north dip (Southwick and Chandler, 1996), were likely reactivated during the roughly north-south convergence of the Penokean orogen. On a broad scale, the gravity and magnetic signatures of the Minnesota River Valley subprovince differ significantly from those associated with the Archean gneissic rocks of the Marshfield terrane in Wisconsin. This supports the view that the two Archean gneiss terranes are unrelated, and were most likely brought together during events related to the Penokean orogeny (Schulz and others, 1993).

Geologic mapping supported by geophysical data reveals that significant changes in the structure of the Penokean orogen occur near the proposed promontory. Derivative enhanced gravity and magnetic data indicate that the structural grain of the orogen changes from northeast-southwest to nearly north-south (Boerboom and others, 1995; Jirsa and Chandler, 1997), and neither external zone fold-and-thrust belts nor foreland basin deposits appear to extend appreciably south of lat 45°15'N. Part of the internal zone of the orogen includes syntectonic granitic and metavolcanic rocks that are similar to those of the Penokean magmatic terranes of northwestern Wisconsin, but a large proportion of the internal zone is comprised of post-orogenic granitic rocks (Jirsa and Chandler, 1997). In fact, these post-orogenic granites, which are collectively referred to as the east-central Minnesota batholith (Holm and others, in press) are interpreted to constitute the dominant part of the orogen south of lat 45°15'N. In that area, the orogen is characterized by a broad magnetic low, the source of which is tentatively interpreted by geophysical modeling to represent non-magnetic, metasedimentary rocks that occur at a depth of 5 to 15 kilometers beneath Paleoproterozoic granitic rocks.

Gravity and magnetic signatures indicate a somewhat complicated structure for the orogen in southern Minnesota. The orogen is truncated near lat 44°45'N. along a fault bounded block of Minnesota River Valley subprovince rocks. Both the orogen and Minnesota River Valley rocks are covered to the east by rocks of the Mesoproterozoic Midcontinent Rift System, but south of lat 44°15'N., rocks of the orogen are interpreted to re-emerge from the Midcontinent Rift System and extend southwest along the Spirit Lake trend. A broad magnetic low, combined with the drilling data from Minnesota (Southwick, 1994) and Iowa (Van Schmus and others, 1993), indicate that the geology along this part of the Spirit Lake trend may be similar to the internal zone of the orogen in east-central Minnesota.

In conclusion, recent geologic interpretations in central and south-central Minnesota have helped refine our understanding of the effects of the large continental promontory with the western margin of the

Penokean orogen. In fact, some of the changes in orogen structure may be explainable by the promontory. For example, pre-existing crustal weaknesses within the promontory may have enhanced thrusting, sedimentation, igneous activity, and crustal thickening during Penokean convergence. Increased crustal thickening near the promontory, in the area now occupied by the east-central Minnesota batholith, could have led to the removal of foreland fold-and-thrust belts and foreland basin deposits, and to increased melt generation of the lower crust to produce the post-orogenic granites.

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Enigmatic 1300 – 1400 Ma Mafic Pluton from the Koss Pit, Marathon County, WI

CORDUA, William S., Dept. Plant and Earth Science, University of Wisconsin - River Falls, 10 South Third Street, River Falls, WI 54022, william.s.cordua@uwrf.edu

In late Fall, 2002, an unusual body of mela-diorite cutting granite was found by mineral collector Tom Buchholz in a newly excavated area of the Red Rock quarry #510 (A.K.A. Koss Pit), on the east side of County O, SW 1/4 sec 2 T27N R6E, SW of Wausau, Marathon County, WI. The quarry is dominantly in the 1520 – 1480 Ma Nine Mile granite (Buchholz, et. al., 2000). The unusual rock is exposed as rubble in a teardrop shaped area approximately 2 meters wide by 15 meters long, trending N55°E. This rock contains spectacular euhedral twinned crystals of plagioclase up to 20 cm. long. It has chilled margins against the granite and contains granite xenoliths. It is cross-cut by thin pinkish diorite dikes less than a centimeter wide. Samples were collected for thin section work, major and minor trace element analysis and radiometric dating.

Study of 8 thin sections revealed the pluton is a mela-diorite consisting of 7 – 20 % plagioclase phenocrysts in a matrix of medium to fine -grained hornblende (20- 24%), biotite (27 - 37%), titanite (3-4%) and felsic material (22 -28%). The felsic material is an equigranular mosaic consisting mostly of oligoclase (about An 14). The hornblende and biotite occasionally form clots of coarser crystals. No feldspathoids, olivine or pyroxenes were found. The plagioclase phenocrysts were rounded and embayed, suggestions partial resorption. Their compositions were andesine (about An 43) but showed zoning on the rims and along cleavages to oligoclase. The phenocrysts had numerous inclusions of biotite and hornblende identical to that found in the groundmass. This suggests that the plagioclase crystals are not xenocrysts.

Chemical analyses were done of 2 samples: WSC-03-01 was from near the contact with the granite. WSC-03-02 is from the center of the body. Both samples are nepheline normative (WSC-03-01 ne = 0.63; WSC-03-02 ne = 3.41) and olivine normative (WSC-03-01 ol = 9.16 WSC-03-02 ol = 10.46). The less undersaturated nature of WSC-03-01 may be due to contamination by the granite country rock. These rocks are similar chemically to lamprophyres. Some of their major element trends fall within the shoshonite fields (Joplin, 1968). Mineralogically, however, the rocks are distinct from typical lamprophyres in the conspicuous plagioclase phenocrysts and lack of modal pyroxene or olivine (Rock, 1991).

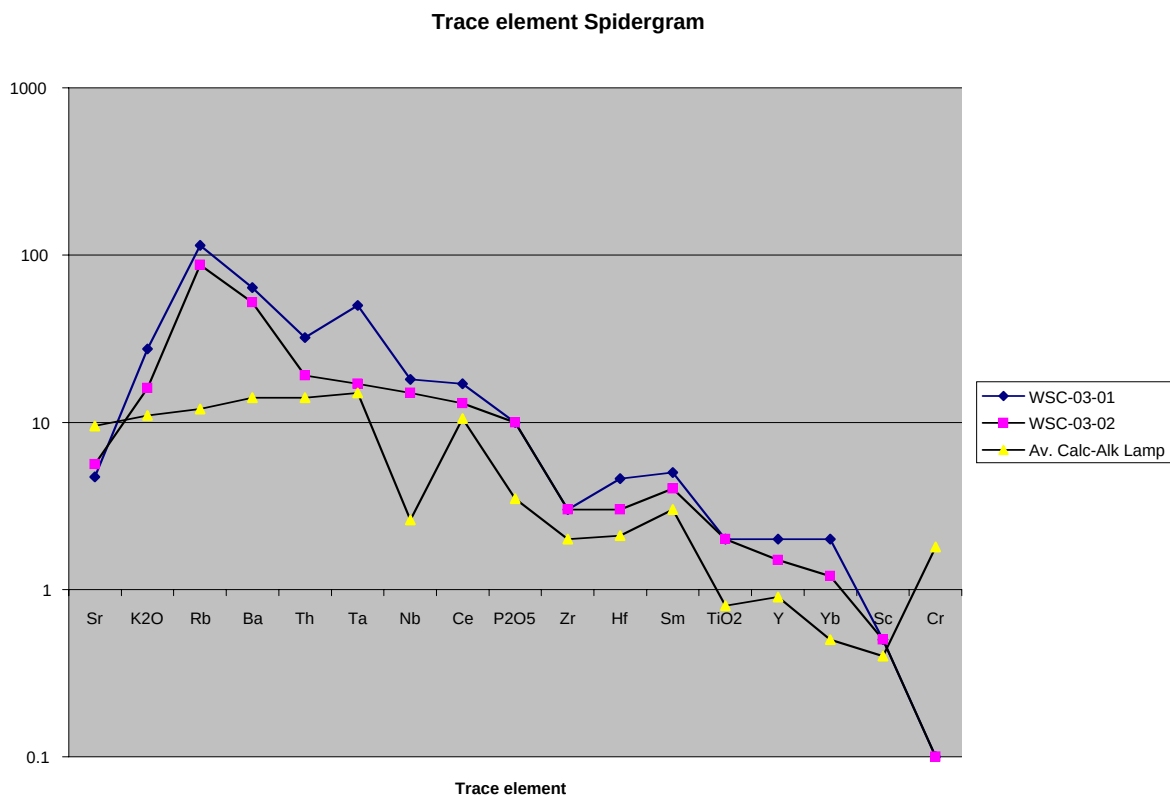
Trace element chemistry of these two samples is consistent with trends from shoshonitic and alkalic rocks formed in mid-plate regions (Pierce, 1982). Spider gram plots show the Koss Pit mela-diorite is enriched in both compatible and incompatible lithophile elements relative to MORB (figure 1). Its pattern resembles that of lamprophyres, such as the calc-alkaline lamprophyre series (Pierce, 1982, Rock, 1991). REE distribution shows a negative slope and enrichment in all REEs relative to Chengwatana volcanic rocks (Wirth, et al., 1997) and local Penokean granites. They are inconsistent with a Keweenaw body contaminated with granitic basement. They are consistent with the partial melting of a metasomatically enriched lithospheric mantle. A possible source of enrichment could be volatile- rich material subducted during the Penokean orogeny.

K-Ar ages were determined by Activation Labs Ltd. Argon was determined by isotope dilution procedure on noble gas mass spectrometry. K concentrations were determined by ICP. The whole age measured was 1307.2 +/- 41 Ma. A biotite separate was determined to have an age of 1410.8 +/- 47 Ma.

These ages are unique for central Wisconsin, which had shown a gap in igneous activity between the Nine-Mile granite at 1520 - 1480 Ma, and Keweenaw events at 1100 Ma. The ages are consistent with the field data, in that the mela-diorite clearly cross-cuts the Nine-Mile

Granite but is chemically and mineralogically dissimilar to younger Keweenaw bodies. Unless its radiometric age has been reset due to uplift, the Koss Pit mela-diorite pluton represents a newly discovered igneous event in central Wisconsin.

Fieldwork by the author has found other thin, highly altered dikes of mafic to lamprophyric character cutting older granites elsewhere in central Wisconsin. Their altered character make petrographic and radiometric work difficult. One may speculate that these are related in age to the Koss Pit mela-diorite. The small size, easily eroded character, and extensive glacial cover make the extent and relationships of such mafic igneous rocks difficult to determine.



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Heller, Sims and Marsden: Mentors Extraordinaire

DAVIDSON, Donald M., Jr., P.O. Box 2571, Tubac, AZ 85646

In considering the measure of my “contributions to the science”, particularly as related to UMD, it became apparent that three men played essential roles in this pilgrim’s progress.

Robert L. Heller was instrumental in building an outstanding geoscience department at UMD. Basically he hired people, including myself, who were committed to effective teaching as well as research. But above all, he set the pattern for hiring people largely based on “how well we got along” and then “what they did”. This premise served me well in building departments at both UTEP and NIU.

Bob was also highly committed to teaching himself and thus was not afraid to ask considerable of his department. I distinctly remember a 27 contact hour quarter my first year in harness! However, he was equally quick to encourage educational innovation and that led to what I consider an outstanding series of team taught courses and course sequences: Earth Materials (integrated mineralogy-petrology); Earth Structure (integrated sedimentation-tectonics); Geology of North America; and Precambrian Geology to name a few. Although more difficult to set in place under the semester system, I tended to encourage such thinking at other schools and the team-teaching process served me well at Exxon Research. Finally, through his activities at AGI Bob helped me truly realize that “the whole was indeed bigger than the sum of the parts” and thus I worked diligently at getting AGU back under the AGI umbrella during my tenure at GSA, I believe for the betterment of the science.

Paul K Sims is well known to this Institute. His professional work represents to me the essence of doing “good science”. He was a patient reviewer, particularly for neophytes, and thus influenced my approach to graduate student thesis supervision as well as “in-house” publications at Exxon.

It was a real pleasure to work for him summers under the sponsorship of the Minnesota Geological Survey mapping in the Boundary Waters with outstanding assistants and colleagues such as Paul Weiblen. While he demonstrated considerable administrative skill as Survey Head, I was fortunate to see such talent in action again during his tenure as SEG President and President of the Economic Geology Publishing Company. This outstanding role model of organization stood me in good stead both serving as director of graduate studies at UMD, but in preparing for and carrying out the first graduate program review.

Ralph W. Marsden, as well as helping found the ILSG, was the consummate Department Chair. He was infinitely patient and delegated frequently and well. More importantly, once he gave you a responsibility, he left you alone to work on it, although always available for advice. He also gave young faculty license to develop and grow - in my case organizing informal departmental sessions in 1969 on a new paradigm for how the earth works: Plate Tectonics.

Yet I believe Ralph will best be remembered for his service to the science through society work. He was extremely active both in SEG and AIME and encouraged young faculty to join and participate in societies of their interest. Under his tutelage I became the Business Manager for *Economic Geology*, and later Treasurer of SEG. I am truly pleased SEG named its distinguished service medal after him. None could be more deserving.

Happy Fiftieth Birthday UMD Geology and ILSG!

THE VAN HISE ARMY AND OTHER PIONEERS OF LAKE SUPERIOR GEOLOGY

DOTT, R.H., Jr., Department of Geology & Geophysics, University of Wisconsin, Madison, WI 53706

Sir William Logan, first Director of the Canadian Geological Survey (1842-1869), initiated investigations of Precambrian rocks. He coined Laurentian for the complex granitic and gneissic rocks of southern Ontario and adjacent Quebec and he assumed that these represented the original continental crust. The Algoman granite and overlying Huronian sedimentary series were soon named north of Lake Huron. These three names were thought to represent universal Precambrian subdivisions for many years. The first comprehensive surveys south of Lake Superior were initiated by Congress to investigate mineral deposits. The first two were led by David Dale Owen in 1839-40 to the lead mining district of the upper Mississippi Valley and in 1848-49 farther north to Lake Superior. In 1850-51 J.W. Foster and J.D. Whitney surveyed northern Michigan and adjacent Wisconsin, where copper and iron deposits were known.

Minnesota, Wisconsin, and Michigan funded state surveys during the 1860s and 1870s, but these were parochial and uneven in quality. Most important were surveys under N.H. Winchell in Minnesota, T.C. Chamberlin in Wisconsin, and T.B. Brooks and R.J. Pumpelly in northern Michigan. For the Tenth National Census of the United States, Congress mandated that the U.S. Geological Survey catalogue the nation's mineral resources. In 1880 several university geologists, including T.C. Chamberlin and Roland D. Irving of Wisconsin, were recruited to help accomplish this formidable task. At the conclusion of the census, Wisconsin's Irving suggested that an integrated geological investigation of the Precambrian of the Lake Superior region was needed to facilitate the understanding and exploitation of the iron ranges. U.S. Geological Survey Director J.W. Powell agreed, and in 1882 created a Lake Superior Division to be located at Madison with Irving in charge. The first of nine large USGS Monographs to be published by the Division was Irving's *Copper-Bearing Rocks of Lake Superior* (1883). In this he recognized the Lake Superior syncline and presented petrographic analyses of varied Keweenawan rocks, an early application of that important, new technique. In 1888 Irving died suddenly, so his young assistant, Charles R. Van Hise, immediately became both Director of the Division and Professor of Geology. The program went forward at a fast pace with a small army of young geologists fanning out across the different iron ranges. Four more Monographs and two Bulletins appeared during the 1890s. In 1903, Van Hise was chosen President of the University of Wisconsin, so his protégée, Charles K. Leith, took over both of his mentor's former offices. Leith's own Mesabi Range Monograph (1903) and four others plus one Bulletin were published under his direction.

Besides an overarching synthesis of all of the work of the army, which was published in 1911 (Monograph 52), Van Hise and Leith devoted much attention to the development of universal principles for deciphering complex structures and metamorphism in terms of fundamental mechanics and chemistry. To cope with the scattered nature of rock exposures in a recently glaciated region of complex geology, the USGS group honed techniques for determining the relations between visible outcrop-scale (mesoscopic) and very obscure larger-scale (macroscopic) structures. Slaty cleavage and drag folds were employed early as valuable tools for such analysis, and in 1910 William O. Hotchkiss, a student of the Van Hise-Leith school (and about-to-be Wisconsin State Geologist), recognized the value of cross bedding and graded bedding for determining 'way up.' These fundamental insights gained by the Van Hise army and ground-breaking textbooks by Leith of structural geology (1913), metamorphic geology (1915;

with his protégée Warren J. Mead), and economic geology (1921) thrust the University of Wisconsin's Department of Geology into international prominence. Soon many students came from Canada, China, Japan, and Britain for postgraduate work in the 'Wisconsin School of Precambrian Geology.' The largest contingent was from Canada after 1910 when Director R.W. Brock of the Geological Survey of Canada adopted the policy that survey geologists henceforth must have the Ph.D. degree. The flow from the north to Wisconsin and other U.S. universities continued until the 1960s when more Canadian institutions began granting the Ph.D.

By 1900 there was a need to reconcile some Canadian and U.S. interpretations of the major divisions of the Precambrian rocks of the Lake Superior region. Of particular note was a discrepancy in the Rainey Lake area along the Minnesota-Ontario border, where Andrew C. Lawson had inferred in 1887 that the oldest rocks were sediments of the Coutchiching formation, but U.S. geologists believed that the Keewatin volcanic complex was older and that the Coutchiching was equivalent to the younger Knife Lake series in Minnesota. In 1905 an international committee of survey geologists from both countries reviewed the evidence and favored the U.S. interpretation. In response, Lawson restudied the area in 1911, but stubbornly reaffirmed his original belief in spite of the fact that his field assistant, J.D. Trueman, a PhD student of Leith's, showed him the value of cross bedding for determining 'way up,' which should have led recalcitrant Lawson to see his error. It was not until 1925 that Frank F. Grout of Minnesota disproved Lawson definitively using both graded bedding and cross bedding. The Minnesota-Ontario border region also became the burial ground of the long-standing dogma that Laurentian granites and gneisses represented the original crust of North America, for here the Keewatin volcanic complex now claimed that title. By this time the commonly accepted divisions of the Lake Superior Precambrian record had become Archean (including Keewatin, Algoman and Huronian) and Proterozoic (including Animikie and Keweenaw).

By the mid-twentieth Century, the major stratigraphic divisions of the region were established and isotopic dating was beginning at last to provide a sound basis for long-range correlations. A.O. Nier and S.S. Goldich at the University of Minnesota were especially important in applying the new techniques to the Precambrian of this region, which allowed the recognition and dating of several additional tectonic and metamorphic events. Meanwhile, Francis J. Pettijohn had pioneered the study of Precambrian sedimentary rocks with his classic *Archean Sedimentation* (1943) and many subsequent studies with his University of Chicago graduate students. Stanley A. Tyler's discovery in 1953 of the Gunflint fossils on the north shore of Lake Superior and Preston Cloud investigations while at the University of Minnesota in the 1960s revolutionized thinking about Precambrian life. Meanwhile the study of the region was greatly enhanced by the widespread application of geophysical techniques such as aeromagnetic surveys and geochemical studies. Finally, since 1970 plate tectonics has revolutionized our understanding of the evolution of the Lake Superior region.

A Field and Laboratory Study to Evaluate the Genetic Relationships Between the Purvis Pluton and Volcanic Rocks and Volcanic-Associated Mineralization in the Vermilion District of NE Minnesota

DREXLER, H.L.*, **HUDAK, G.J.**, Geology Department, University of Wisconsin Oshkosh,
800 Algoma Blvd., Oshkosh, WI 54901; drexlh92@uwosh.edu

PETERSON, D.M., Natural Resources Research Institute, 5013 Miller Trunk Highway, Duluth,
MN 55811

The Purvis Pluton is an east-west trending, moderate- sized ($\sim 3\text{km}^3$), sill-like multiphase dioritic to tonalitic intrusion with a strike length of 5.7 km and a thickness, which ranges from 100-1200 meters (Peterson, 2001). This intrusion occurs near the base of the eastern part of the Ely Greenstone – Lower Member (Peterson and Jirsa, 1999; Jirsa et al., 2001). Peterson (2001) has suggested that the Purvis Pluton represents a felsic, synvolcanic sill-like subvolcanic intrusion that may have been the heat engine, which drove subseafloor hydrothermal activity, which produced VMS-like Cu-Zn mineralization at the Eagles Nest and Purvis Road prospects. The evidence for this interpretation is based on the local presence of an east-west oriented D_2 foliation within the Purvis Pluton, the lack of a significant contact aureole adjacent to the intrusion, and the intimate relationship between the uppermost margins of the pluton and intense, semi-conformable quartz + epidote alteration zones. Volcanic rocks in the Ely Greenstone – Lower Member consistently contain the D_2 foliation, which is constrained by age dates to have occurred during regional deformation between 2674 and 2683 Ma (Boerboom and Zartman, 1993; Peterson et al., 2001).

We have conducted detailed field mapping, petrographic and lithogeochemical studies to further evaluate the spatial, mineralogical, and chemical characteristics of the Purvis Pluton. Field mapping, supported by subsequent petrographic studies, indicates that the Purvis Pluton contains several distinct phases. These include: 1) xenolithic hornblende diorite; 2) xenolithic hornblende tonalite; 3) xenolithic leucotonalite; 4) leucotonalite and trondhjemite; and 5) leucotonalite dikes. Paragenetic relationships between these phases have been determined in the field based and by petrography based on cross-cutting relationships and the xenolith contents of the various phases. Angular, coarse-grained gabbro/diorite lapilli, which have rare earth element characteristics similar to the other phases of the pluton (Figure 1a), are common in the xenolithic hornblende tonalite and xenolithic leucotonalite phases, and appear to represent an early product of Purvis Pluton crystallization. The xenolithic hornblende diorite, xenolithic hornblende tonalite, and xenolithic leucotonalite commonly contain basalt-andesite lapilli, epidote + quartz-altered basalt-andesite lapilli, and lapilli and blocks of oxide facies iron formation. These three xenolithic phases are intruded by the main phase of the intrusion, leucotonalite/trondhjemite. Leucotonalite dikes are a minor phase of the intrusion, and when present, consistently cut through the other plutonic phases. A sample of the hornblende tonalite has been submitted for geochronological analysis, and we are anxiously awaiting the results.

Preliminary lithogeochemical evaluations indicate that the Purvis Pluton is calc-alkalic (Figure 1b). The various phases of the intrusion are classified as tonalite and trondhjemite using O'Connors normative-based granitic rock classification scheme (Figure 1c). Based on trace element characteristics, all phases of the Purvis Pluton were formed in a volcanic arc setting (Figure 1d), which is consistent with the geochemical affinity of the volcanic strata in the Ely Greenstone – Lower Member (Hudak et al., 2002).

Recent studies by Galley (2003) have evaluated the physical and chemical characteristics of synvolcanic intrusions spatially and temporally associated with VMS deposits in Canada and Scandinavia. We are currently completing our evaluation of the lithogeochemical features of the Purvis Pluton, and our comparison of these features to VMS-associated synvolcanic intrusions associated with VMS deposits.

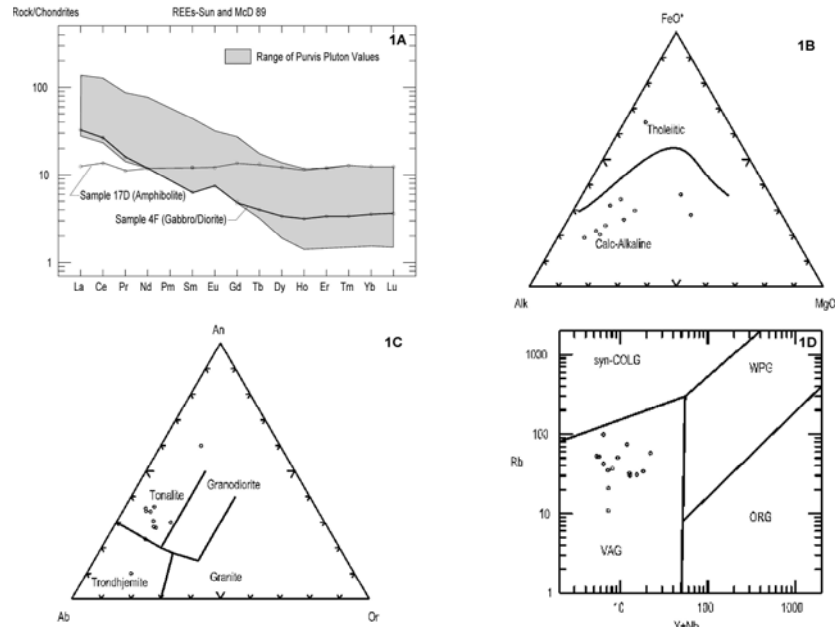


Figure 1. a) REE diagram illustrating trends associated with Purvis Pluton phases, gabbro/diorite xenoliths, and amphibolite xenoliths; b) normative alkali - total iron – magnesium ternary plot (after Irvine and Baragar, 1971); c) normative feldspar ternary plot for the Purvis Pluton (after O'Connor, 1965); d) Rb – (Y + Nb) discriminant diagram for the Purvis Pluton (after Pearce et al., 1984).

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Late Wisconsin Till and Arsenic Contamination in Upper Midwest Groundwater

ERICKSON, Melinda L.*(Water Resources Sciences), and **BARNES, Randal J.**, (Civil Engineering), University of Minnesota, 500 Pillsbury Dr. SE, Minneapolis, MN 55455, eric0984@umn.edu

Exposure to arsenic, a recognized human carcinogen, is a widespread public health problem, with more than 150 million people worldwide estimated to be exposed to unsafe levels of arsenic from their drinking water. To reduce arsenic exposure from drinking water, the US Environmental Protection Agency recently adopted a new, more protective arsenic drinking water standard, 10 µg/l. All public water systems must comply with the new arsenic standard by January 2006.

In the upper Midwest, arsenic in ground water is a widespread, naturally occurring contamination problem regionally impacting both public and private drinking water wells. Hundreds of upper Midwest public water systems serving over a million people are affected by the change in the arsenic standard. Additionally, in Minnesota alone, 150,000 – 250,000 people are estimated to obtain drinking water from private wells with arsenic concentrations exceeding 10 µg/l. Private well owners are not forced to comply with federal drinking water standards. Figure 1 illustrates that groundwater arsenic concentrations in excess of 10 µg/l are associated with the lateral extent of northwest-sourced late Wisconsin sediment. Statistical analysis supports the visual observation: 10.7% of public water systems located within the footprint of the Late Wisconsin till exceed 10 µg/l, and only 2% of public water systems outside the footprint exceed 10 µg/l.

Our research results indicate that the elevated arsenic concentrations in upper Midwest groundwater are *not* primarily due to high arsenic concentrations in Late Wisconsin till. Sediment analyses indicate that Late Wisconsin sediment in western Minnesota does not have particularly high arsenic concentrations, and water arsenic and sediment arsenic concentrations measured in our research are not correlated (Figure 2).

We hypothesize that the specific physical characteristics of the Late Wisconsin till, such as its fine-grained matrix, entrained organic carbon, and active anaerobic biological activity, create the geochemical environment favorable to a regional-scale mobilization of arsenic via desorption. In western Minnesota aquifer sediments, we measured that 0.5 – 0.7 mg/Kg of the total arsenic is adsorbed arsenic. Adsorbed arsenic is labile and can be readily desorbed, especially in suboxic and reduced aquifers.

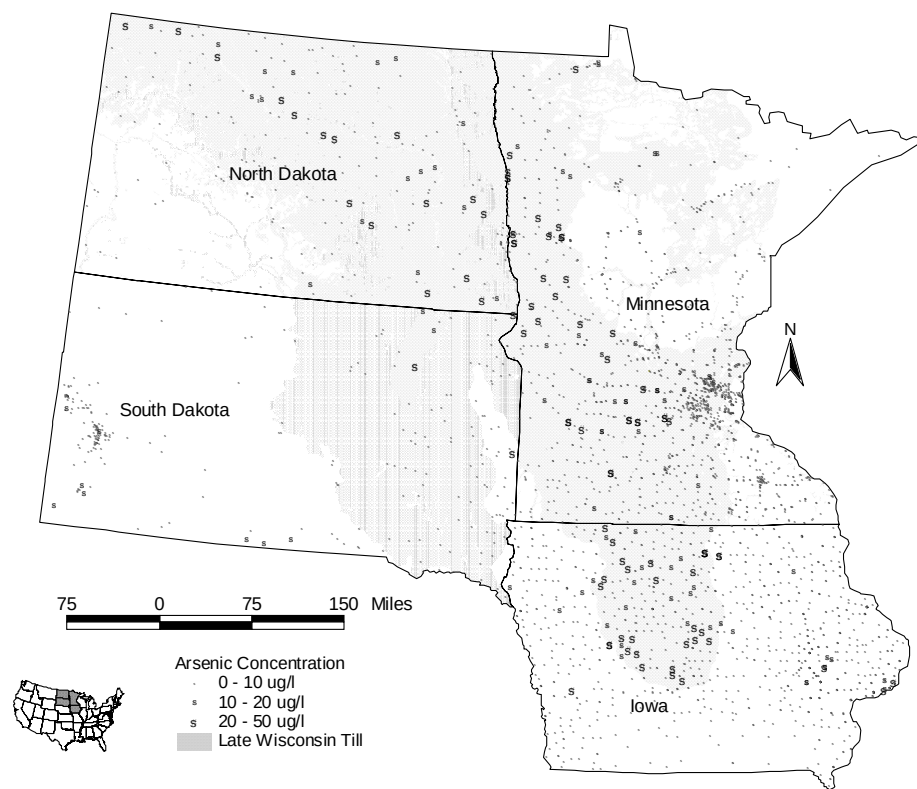


Figure 1 – Arsenic concentrations in upper Midwest public water systems

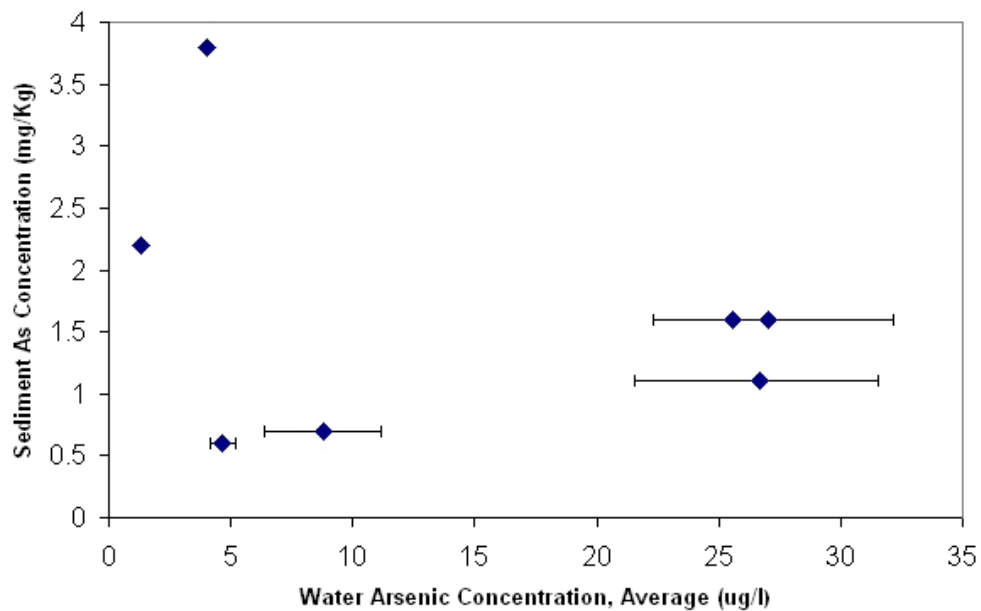


Figure 2 – Measured arsenic concentrations in water and sediment collected from western Minnesota.

INFLUENCE OF GEOLOGIC SETTING ON HYDROGEOMORPHIC CHARACTERISTICS OF SOUTHERN LAKE SUPERIOR TRIBUTARIES

FITZPATRICK, Faith A., U.S. Geological Survey, 8505 Research Way, Middleton, WI 53562,
fafitzpa@usgs.gov

The U.S. Geological Survey has conducted assessments of historical and current geomorphic, sediment, and flooding characteristics for several Lake Superior tributaries in the Duluth, Minnesota and Bayfield County, Wisconsin areas. These assessments were done to determine historical natural and human-caused alterations in aquatic habitat and to provide base line data for stream restoration activities. For streams with little or no bedrock control, such as those in the Bayfield County area, historical geomorphic responses to clear-cut logging and burning in the late 1800s and subsequent agriculture in the early 1900s included channel incision and lateral migration in upstream reaches and aggradation, widening, and lateral migration in downstream reaches (Fitzpatrick et al., 1999). However, these geomorphic responses to changes in land cover were dependent on composition of glacial deposits, type of glacial or glacio-lacustrine landforms, spatial position within the watershed, and relative timing of large floods. Geomorphic responses to increased runoff and sediment inputs were manifested during extreme floods that occurred one to two decades after maximum agricultural activity (Fitzpatrick and Knox, 2000). For streams with bedrock control, such as those in the Duluth area, the main geomorphic response to land clearing, such as urban sprawl, is channel widening. The major source of sediment in most of the southern Lake Superior tributaries has been and continues to be from channels down-cutting through relict glacial lake shorelines. Longitudinal profiles of the tributaries are a reflection of a combination of glacial and glacio-lacustrine landforms and bedrock topography (fig. 1). Slopes are steep where streams intersect glacial lake shorelines and (or) bedrock near the surface. Longitudinal profiles are a useful reconnaissance tool for identifying stream reaches prone to erosion or sedimentation. Inflection points on the longitudinal profiles represent reaches with slope transitions. These transitional reaches tend to be the most sensitive to changes in water and sediment inputs.

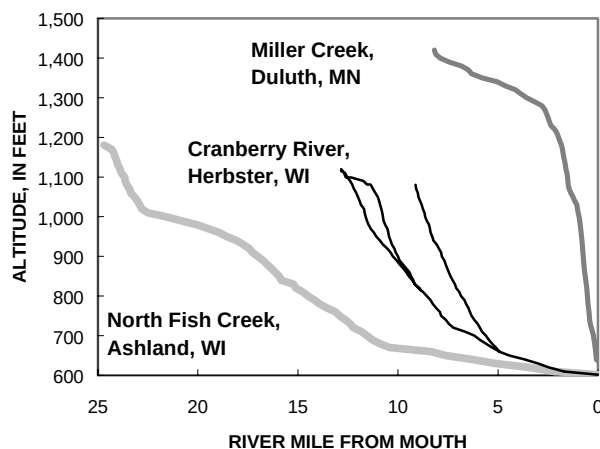


Figure 1. Longitudinal profiles for three Lake Superior tributaries.

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IRON NODULE RESEARCH AT THE NATURAL RESOURCES RESEARCH INSTITUTE, UMD

FOSNACHT, Donald R., Center for Applied Research and Technology Development, Natural Resources Research Institute, University of Minnesota Duluth, Duluth, MN

IWASAKI, Iwao, and **BLEIFUSS, Rodney**, Coleraine Minerals Research Laboratory, Natural Resources Research Institute, University of Minnesota Duluth, Coleraine, MN

Synopsis

A program jointly funded by the Economic Development Administration and the University of Minnesota Permanent University Trust Fund has been underway at the Coleraine Minerals Research Laboratory over the last two years. During this period, significant research and development has taken place using a variety of new furnace capabilities to test the responsiveness of iron ore taconite concentrates to reduction and smelting under a variety of test conditions. During the course of the investigation, over 1150 tests were undertaken using a laboratory tube furnace, these were supplemented by over 200 tests from a 2-stage laboratory box furnace, and finally by dozens of tests from a 3-stage pilot-scale linear hearth furnace. During the program, the conditions for producing satisfactory iron nodules with low sulfur, gangue, and tramp impurity levels were elucidated. A variety of reductants, slag fluidizers, and iron ore mixtures were employed during the test program.

Laboratory Tube Furnace Tests

The test program was initiated using a tube furnace (see Figure 1) with a 2" dia. x 48" long mullite tube, which takes 1" wide x 4" long and 1" high graphite boat, to screen the test conditions for use in laboratory box and pilot plant linear hearth furnaces. Major parameters investigated included such raw materials as:

- (1) taconite concentrates with different levels of silica content as well as pellet plant wastes and screened pellet fines,
- (2) different carbonaceous reductants including Eastern anthracite, low-, medium- and high-volatile bituminous and Western sub-bituminous coals as well as their carbonized char and coke, and
- (3) different types of additives, such as balling binders and some specific additives for slag fusion temperature reduction and iron nugget sulfur control.

Furnace operating conditions included temperature and time at temperature, furnace atmosphere, hearth layer materials, iron nugget and slag chemistries as well as iron nugget size. Environmental issues of concern are slag disposal and/or utilization and effluent emission of mercury, NO_x, SO_x and particulate matter.



Figure 1: Laboratory Tube Furnace

In the tube furnace, over 1150 different conditions have been tested. Test results demonstrated that larger-sized iron nuggets can be routinely produced by feeding dry raw material mixtures without prior agglomeration. Taconite concentrates with different levels of silica indicated that magnetic concentrates with 6% SiO₂ produced metallic iron nuggets more readily than a more expensively produced super-concentrate of 2% SiO₂. Pellet plant wastes and screened pellet fines produced satisfactory iron nuggets, but consisting mainly of hematite, these raw materials appeared to require somewhat different conditions.

Laboratory Box Furnace Tests

A laboratory, electrically-heated box furnace (see Figure 2), having two 12"x12"x12" heating chambers with the two chambers capable of controlling temperatures up to 1450°C (2642°F) independently, and which accepts a 5" wide x 6" long x 1-1/2" high graphite tray was designed and constructed during the project. Over 220 different conditions have been tested in the box furnace, confirming the results obtained in the tube furnace for both dry balled feed and a feed without prior agglomeration. In the box furnace, a major emphasis was placed in developing

methods to produce larger-sized iron nuggets by feeding dry raw material mixtures in an attempt to circumvent costly balling and drying steps. A series of different size iron nuggets were produced, ranging from 5/15" to 2-1/2" (7 to 65 mm) in size.



Figure 2: Laboratory Box Furnace
Pilot-plant Linear Hearth Furnace Tests (Rotary Hearth Simulator)

The natural gas-fired pilot-scale linear hearth furnace simulator has been installed and commissioned. The furnace is a forty-foot long iron reduction furnace (see Figure 3), consisting of three individual heating zones and a final cooling section. Sample trays are conveyed through the furnace by a hydraulically driven walking beam system. Zones are controlled individually according to temperature, pressure and feed rate, making this furnace capable of simulating several reduced iron processes and operating conditions. An Allen Bradley PLC micro logic controller coupled to an Automation-Direct PLC for the walking beam mechanism controls the furnace through a user-friendly PC interface.

The PLC control system regulates individual zone burners to manage zone temperatures. A pair of 450,000 BTU/hr natural gas fired burners heats zones one and two. Zone one is rated for a continuous operating temperature of 2000 °F, while zone two can be continuously operated up to 2400 °F. Zone three is fired by a pair of 1 Million BTU/hr burners that were required to achieve the operating temperatures of 2600 °F in reasonable time to complete testing. Each zone has an individual exhaust duct and control damper to regulate pressure in that zone. A manually controlled exhaust fan damper is also installed to reduce the capacity of the exhaust fan, and allow the individual duct control dampers to manipulate pressures to desired set-points. Reducing the burner air, to operate the burners sub-stoichiometric, and operating zone pressures positive is required to reduce oxygen levels to 0.0% and provide acceptable furnace atmospheres for iron reduction.



Figure 3: Pilot Scale Linear Hearth Furnace (Rotary Hearth Simulator)

Major differences in the test conditions from laboratory electric furnaces were the low CO/CO₂ ratio and high turbulence of the furnace gas and the sample pallets acting as an unexpectedly large heat sink. Research work focused on careful adjustment in the amount of coal addition, and on the type and amount of additives in order to minimize the generation of micro nuggets.

The Linear Hearth Furnace has routinely been used to test a variety of the test variables shown to be important from the box furnace and tube furnace tests. It is possible to make various size iron nuggets at this scale that have low amounts of micro-nuggets and which have low levels of undesirable tramp elements. The furnace is extremely useful for testing a multiplicity of test parameters in a very short period of time.

OXYGENATION OF THE ARCHEAN HYDROSPHERE: EVIDENCE FROM THE EAGLE ISLAND DELTAIC COMPLEX

FRALICK, Philip, Department of Geology, Lakehead University, Thunder Bay, ON, Canada, P7B 5E1, philip.fralick@lakeheadu.ca

PUFAHL, Peir K., Department of Geological Sciences and Geological Engineering, Queens University, Kingston, ON, Canada, K7L 3N6, pufahl@geol.queensu.ca

The Eagle Island Group is located in southern Uchi Subprovince, Canadian Shield, at the west end of Lake St. Joseph. It overlies 2713 Ma volcanic rocks and is deformed by an event, which probably occurred prior to 2702 Ma (Stott and Corfu 1991). Outcrop along the shores of Eagle Island is excellent and provides a rare opportunity to document an Early Precambrian depositional system including abundant iron formation.

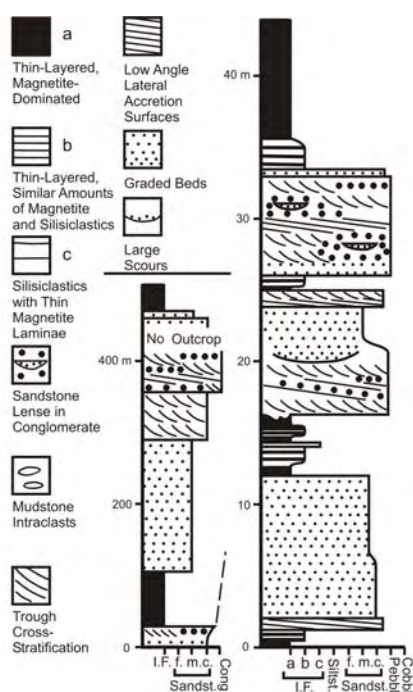


Fig.1. Stratigraphic sections of the Eagle Island Group.

The lowermost 35 m of section contains three coarse-grained parasequences separated by assemblages of graded sandstone beds and iron formation (IF) (Fig. 1). The IF consists of three types: (a) dominantly magnetite-rich sediment with mm- to cm-scale, graded or ungraded siltstone interbeds: (b) cm-scale graded to sharply bounded siltstone layers either contiguous or separated by mm-thick laminae of magnetite-rich sediment: (c) sandstone beds in places separated by magnetite-rich intervals. The lowermost coarse-grained parasequence consists of graded sandstones and conglomerates separated by a-type IF units. The second parasequence contains: graded sandstones and conglomerates separated by magnetite; graded sandstone lenses surrounded by magnetite; cross-stratified sandstones with magnetite drapes on reactivation surfaces; low angle, laterally accreting sandstone and conglomerate packages with internal magnetite laminae; multistory conglomerates with internal magnetite drapes; and ripple laminated sandstones in a-type IF with mm-thick magnetite laminae draping avalanche surfaces in ripple trains.

The upper parasequence is composed of cross-stratified, coarse-grained sandstones interlayered with conglomeratic lenses. This is sharply overlain by 73 m of b-type, gradational to a-type, IF. A 182 m thick succession of graded, medium-grained sandstone beds overly the IF and these are succeeded upwards by 67 m of trough cross-stratified, coarse-grained sandstones. Next is a 60 m thick sandstone-conglomerate assemblage consisting of sharp-sided, nongraded laterally extensive, thin conglomerate lenses interlayered with well-sorted medium-grained sandstones with internal, shallowly inclined pebble stringers. Approximately 50% of the clasts are IF. This assemblage is overlain by a thin package of turbidites capped by a-type IF.

The Eagle Island Group was previously considered a deep-water submarine fan deposit (Meyn and Palonen 1980, Berger 1981). The lithofacies associations present and their architectural organization make this unlikely. The thick succession of graded beds is interpreted as shallow-water storm deposits and the trough cross-stratified sandstones represent either nearshore sands, a distributary mouth bar

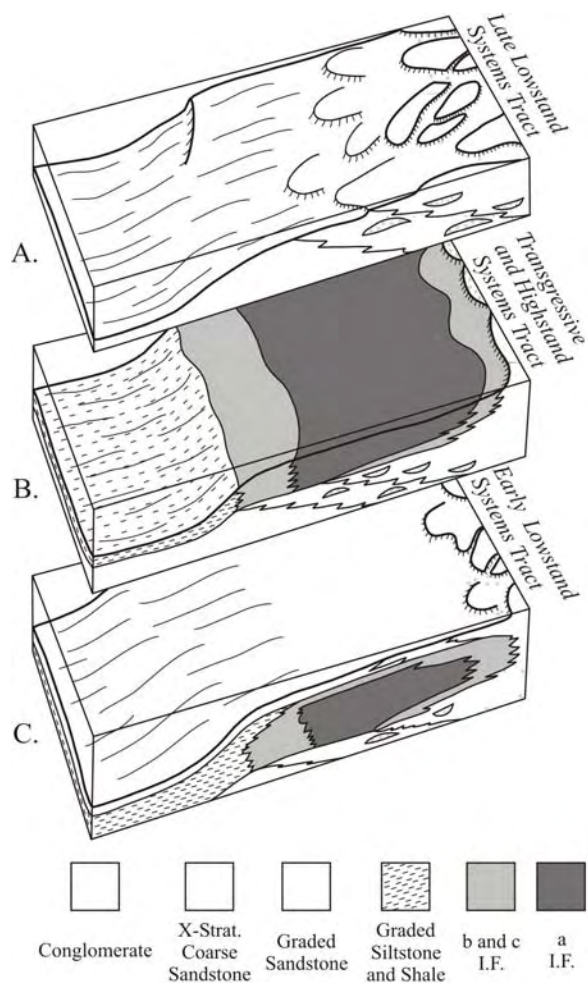


Fig.2. Deltaic systems tract developed in the Eagle Island Group.

complex or braided fluvial channels. The overlying conglomerate-sandstone unit consists of layers characteristic of foreshore beach deposits interlayered with fluvial mouth gravel bars. The 400 m thick, coarsening upwards sequence represents a wave modified delta. Thirty-five meters of strata underlying the coarsening-upwards delta is also progradational with three parasequences building from subaqueous (lower) to strandline (middle) to braided fluvial (upper). The parasequences are separated by IF developed on flooding surfaces. The most interesting features exist in the middle (strandline) parasequence. Here, IF was deposited at periods of low stream discharge in the very proximal distributary mouth environment. Magnetite laminae drape all scales of reactivation surfaces developed in this proximal nearshore setting. In contrast the 73 m thick IF was deposited on the delta top during a major flooding event and represents a portion of the transgressive and highstand systems tract (Fig. 2) where chemical sedimentation kept pace with relative sealevel rise.

The accumulation of IF only in the nearshore of this depositional system limits possible precipitation mechanisms. IF accumulation models relying on relatively constant Fe precipitation in the world ocean combined with siliciclastic starvation are not compatible with data presented here. Freshwater influx into the nearshore, and resultant increase in pH, may have been responsible for iron precipitation but accompanying fresh water dilution of marine waters makes this unlikely. Photo-synthetically induced oxygenation of the shallow nearshore is the probable cause of iron precipitation.

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Isocon Analysis: How To Make It Work For You.

GRANT, James A., Department of Geological Sciences, University of Minnesota Duluth, MN 55812

Isocon analysis (Grant, 1986) is a simple and effective means of quantitatively estimating changes in mass or volume or concentrations in mass transfer. The method has been applied to such diverse phenomena as hydrothermal alteration, replacement, migmatites, shear zones, paleosols, silcretes, sedimentary exhalative deposits and fumarolic deposits. It may be accomplished graphically by plotting an altered composition (C_i^A) against an original composition (C_i^O) with no significant manipulation of the data. Species that have remained immobile in the process define the isocon, which is a straight line through the origin. Data points falling above the isocon represent gain, and those below represent loss, of the corresponding chemical species, and the slope of the isocon gives the mass change in the process.

It is critical to obtain as close an approximation to the original rock composition as possible, since that rock no longer exists. Sampling the altered rock is generally less problematic, even if the alteration is zoned. Given zonation or general heterogeneity of the rocks, judicious sampling and averaging of samples is necessary. Fortunately it is painless to try different combinations and arrive at a reasonable compromise.

Scaling should be important only in producing a satisfactory isocon diagram to portray the model in question. If the slope of the isocon is based on C_i^A/C_i^O values, scaling cannot affect the results because the scale factor cancels out. Scaling can however affect the perception of the results especially if points are crowded close to the origin.

The choice of immobile species can be determined by inspection of a well-constructed isocon diagram, by inspection of C_i^A/C_i^O values, by statistical methods like that of Baumgartner and Olsen (1995), or by plotting pairs of species like Cail and Cline (2001). In any case the geochemical characteristics of the species and of the process involved need to be considered thoughtfully.

Characterization of an isocon based on immobile species (as opposed to constant mass, volume or predetermined species) devolves to defining a slope for the isocon. This may be done graphically, by a least squares method of linear regression, or by averaging the slopes for the immobile species. Commonly there is some range within which reasonable isocons could be chosen. Data points that lie close to a chosen isocon within such ranges would correspond to small gains and losses, and not much significance should be placed on them. Data points far from the range of possible isocons will not be affected significantly by the minutiae of the choice of isocon.

Log-log plots do not add anything to the analysis, except the possibility of confusion, and should be avoided.

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THE GEOLOGY OF THE DULUTH COMPLEX AND THE NORTH SHORE VOLCANIC GROUP PORTRAYED IN NEW 7.5' QUADRANGLE MAPS OF THE DULUTH METROPOLITAN AREA

GREEN, J.C., Department of Geological Sciences, University of Minnesota Duluth, Duluth, MN 55812
(jgreen@d.umn.edu)

MILLER, J.D., Jr., Minnesota Geological Survey, c/o Dept. of Geological Sciences, University of Minnesota, Duluth, MN 55812

The most current bedrock geologic map of the Duluth area is the 40 year old map by R.B. Taylor (1964), which was the first detailed-scale (1:24,000), full color map of Precambrian bedrock geology published by the Minnesota Geological Survey. This map, which built on the earlier field studies of Grout (1918) and Schwartz (1949), served as a companion to MGS Bulletin 44 and focussed mainly on the geology and petrology of the Duluth Complex. Taylor's map divided the complex into two major series, the layered series and the anorthositic series, and several subordinate units. The volcanic rocks of the North Shore Volcanic Group (NSVG), which compose the hanging wall and part of the footwall of the Duluth Complex, were not subdivided, but the major mafic sills that intrude the hanging wall volcanic rocks were delineated.

The first author (Green) has conducted reconnaissance mapping in the Duluth area since 1960, focussing mostly on the volcanic rocks of the Duluth Quadrangle. In 1992, the Minnesota Geological Survey received funding from the Minnesota Minerals Coordinating Committee to conduct detailed mapping in nine quadrangles encompassing the Duluth metropolitan area. Approximately five months of intense field mapping resulted in the production of a 1:48,000-scale open-file map (Miller, Green and Chandler, 1993). We have conducted intermittent mapping over the past 11 years, which has continued to improve our understanding of the Duluth area. These field data are currently being digitally compiled into new 1:24,000-scale maps for the Duluth, Duluth Heights, and West Duluth quadrangles and parts of the Esko and Adolph quadrangles. Preliminary versions of these maps will be displayed as a poster presentation.

One of the most important contributions of these new maps is their detailed delineation of the igneous stratigraphy of the layered series. As Taylor (1964) recognized, the layered series at Duluth (DLS) is a well-differentiated, 3- to 4.5-km-thick, moderately east-dipping, sheet-like mafic layered intrusion. Our mapping has subdivided the DLS into six major zones and various subzones on the basis of dominant cumulate rock types. A 150-300m-thick basal contact zone is composed of coarse-grained, taxitic olivine gabbro and augite troctolite. This is overlain by a 300-600m thick zone of complexly layered cumulate rocks including feldspathic dunite, oxide peridotite, melatroctolite, augite troctolite and olivine gabbro that comprise the melanocratic zone. These rock types commonly define several macrocyclic subzones grading from dunite/melatroctolite upward to augite troctolite/olivine gabbro. However, in many areas, melatroctolite transgresses augite troctolite. The structural complexities of this zone are interpreted to represent the effects of multiple intrusions during the early inflation stage of the DLS magma chamber. The next zone up is the troctolite zone. It is 700-1200m thick, consists mostly of homogeneous foliated troctolitic cumulates. The cyclic zone forms the medial section of the DLS and is characterized by cyclical variations in cumulus mineralogy between troctolitic and gabbroic cumulates. At least four major troctolite-gabbro macrocycle subzones are delineated within the well-exposed southern extent of the cyclic zone. Miller and Ripley (1996) suggested that the cyclicity formed by pressure fluctuations attending magma venting episodes. The persistent occurrence of gabbroic cumulates defines the next unit, the 600m- to 1700m-thick gabbro zone. Gabbroic cumulates, in turn, grade upward into nonfoliated (noncumulate) apatitic quartz ferromonzodiorite, which composes most of the 50m- to 200m-thick upper contact zone. This quartz ferromonzodiorite complexly mixes with a fine-grained biotitic ilmenite ferrodiorite, which forms the "chilled" DLS contact with anorthositic series rocks. A couple of small bodies of melanogranophyre, which irregularly cut through the anorthositic series, probably represent the uppermost differentiate of the DLS. This igneous stratigraphy, which is complimented by cryptic

layering of cumulus mineral compositions, implies that the DLS formed by bottom-up, open-system fractional crystallization of a moderately evolved, olivine tholeiitic magma.

The structurally and lithologically complex anorthositic series (AS), which caps the layered series, is subdivided into four units: 1) a troctolitic anorthosite unit that fringes the lower part of the series; 2) an ophitic olivine leucogabbro unit that occurs mainly as inclusions in the upper part of the layered series; 3) a plagioclase-phyric gabbro unit that occurs along the upper contact; and 4) a main unit of undifferentiated gabbroic anorthosite that comprises 90% of the AS. Although their physical relations clearly indicate that the DLS intruded the AS, precise U/Pb zircon dating (Paces and Miller, 1993) shows essentially identical ages of 1099 Ma for both series.

A more complete picture of geologic structure in the Duluth area is also portrayed by these new maps. Much of the area is cut by ENE to ESE-trending faults. With the exception of the fault zone exposed in Stewart Creek, these faults are speculative and inferred from topography, aeromagnetic data, and geologic offset. One of the more enigmatic structural features of the area is an antiform-synform duplex defined by foliation and layering in the Spirit Mountain area (West Duluth quadrangle). The limb between these fold structures is near vertical and their N-S fold axes are doubly plunging. By their orientation, they do not appear to be related to faulting. Perhaps the folds developed by collapse of the cumulate pile overlying a feeder zone.

Another major improvement on the geologic picture of the Duluth area is in the subdivision of the North Shore Volcanic Group and related hypabyssal intrusions, which form the Duluth Complex hanging wall. The AS intruded normal-polarity lavas of the NSVG, of which approximately 2445 m form the section within the Duluth quadrangle. These volcanic rocks are intruded by the 600m thick Endion sill near the middle, the lensing Northland sheet in the upper part, and the Lester River sill at the top, plus two minor diabasic intrusions along with several late basaltic dikes. Several distinctive and mappable volcanic and sedimentary units within this section include five large felsic flows that constitute 37% of the sequence (Green and Fitz, 1993). From lowest to highest, these are the City Hall icelandite, the Congdon Park rhyolite, the 40th Ave. East icelandite (dated at 1098.4 $\pm$ 1.9Ma, Davis and Green, 1997), the 42nd Ave. East rhyolite, and the Lester Park icelandite.

The lowermost lavas are contact-metamorphosed by the Duluth Complex to pyroxene-hornfels to hornblende-hornfels facies; the remainder show greenschist and laumontite-prehnite-pumpellyite assemblages due to burial metamorphism (Schmidt, 1993).

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EFFECT OF MINERALOGY ON PROCESSING OF LOW GRADE IRON ORES FROM THE NEGAUNEE IRON-FORMATION ON MARQUETTE RANGE OF THE LAKE SUPERIOR DISTRICT

HAN, Tsu-Ming, Senior Research Scientist (Retired), Cleveland-Cliffs Inc., Ishpeming, Michigan, USA

During the past half-century, Cleveland-Cliffs has investigated and processed three types of low-grade iron ores from the Negaunee Iron-Formation on the Marquette Range of the Lake Superior District. The three ore types are:

- (1) Specular hematite ore of medium metamorphic grade with the principal gangue of chert and locally some sericite, garnet, epidote and grunerite.
- (2) Magnetite ore of low metamorphic grade with the principal gangue of chert, siderite, ankerite, stilpnomelane, minnesotaite and some clastics.
- (3) Oxidized magnetite ore in which martite is the principal ore mineral. Ultrafine-grained hematite, microplaty hematite, goethite and earthy hematite are locally present in substantial quantities. Chert and clastic quartz are the principal gangue with local distribution of some gypsum and clay minerals (kaolin, dickite, and montmorillonite).

Some minor minerals in the above ores have caused problems in the concentration process and concentrate grade control either in plant practice or from the laboratory testing. Others have caused the physical and chemical quality of the final pellet product. This paper reports the mode of occurrence of these minerals and their negative effects affecting the plant operation and the quality of the pellet product.

I – Mineralogy affecting the process of concentration

A – Laboratory data showed that gypsum causes total flocculation during desliming due to the release of calcium ions into solution. It prevents the rejection of slimes from flotation feed. This minimizes the selectivity of amine flotation resulting in lower the weight and iron unit recoveries as a result.

B– Montmorillonite absorbs amine killing froth leading the catastrophic failure in separating ore minerals from gangue. It can easily be detected by a simple procedure referred to as “Shake Test”, or by analyzing MgO content of the crude ore before processing, i.e., in most cases, the concentrate grade is determined by the MgO content of the crude ore.

II – Ore mineralogy that can affect concentrate grade

A – Ultrafine-grained magnetite is typically present in the iron-formation adjacent to chloritized basic dikes and sills. The magnetite may represent as much as 40% of the iron-formation. However, its grain size is generally finer than 5 microns and it is practically impossible to produce a magnetic concentrate with an acceptable grade by any feasible mechanical means from this type of material.

B – Ultrafine-grained hematite occurs as irregular grains and microplates of a few microns or less finely disseminated in chert. Such a hematite and chert relationship has been referred to as

“Hematitic Chert”. It is the host of martite and is considered as waste, which cannot be rejected by the magnetic oxide conversion process (MOC) but can be partially removed by the amine flotation.

III – Mineralogy that can affect pellet physical quality

Graphite can be rejected during desliming and flotation. However, some of it is entrapped in the magnetic concentrate for palletizing. It causes internal fusion of pellets due to the differential rate of heat transfer and oxygen diffusion toward center of the pellets. This leads to the development of concentric cracking in the pellets and consequently lowers the physical quality of the pellets during transfer. The resulting structural weakness in the pellets can be minimized by the addition of hematite to the balling feed to enhance oxygen availability

IV – Mineralogy that can affect pellet chemical quality

A – Phosphorus in the oxidized ore occurs as apatite, which has been designated as P1, and as an impurity in goethite and dove-tailed hematite, as P2. Most of the P1 can be rejected during the desliming and flotation stages, whereas the P2 increases with the increase of iron in the concentrate. In order to produce an acceptable final product containing less than 0.03% P from some of the highly oxidized ore, a substantial amount of these ore minerals has to be rejected by high intensity magnetic separation.

B – Titanium is present as rutile in some specular hematite. It is practically impossible to separate from its specular hematite host by any known mechanical means. Consequently, it reports with the iron in the concentrate from the specular hematite.

C – Stilpnomelane and minnesotaite contain the potassium and sodium. These constituents are a detriment to blast furnace refractory. Most of these minerals are rejected during magnetic separation and flotation. Some of them are entrapped in the magnetite fines as a result of magnetic flocculation. Generally, the alkaline content in the pellets has not been a major problem.

Specular hematite concentrate is no longer produced. Oxide ore containing montmorillonite or gypsum remain to be successfully processed. Magnetite iron-formation adjacent to the intrusives has been considered as “waste” and removed by selective mining.

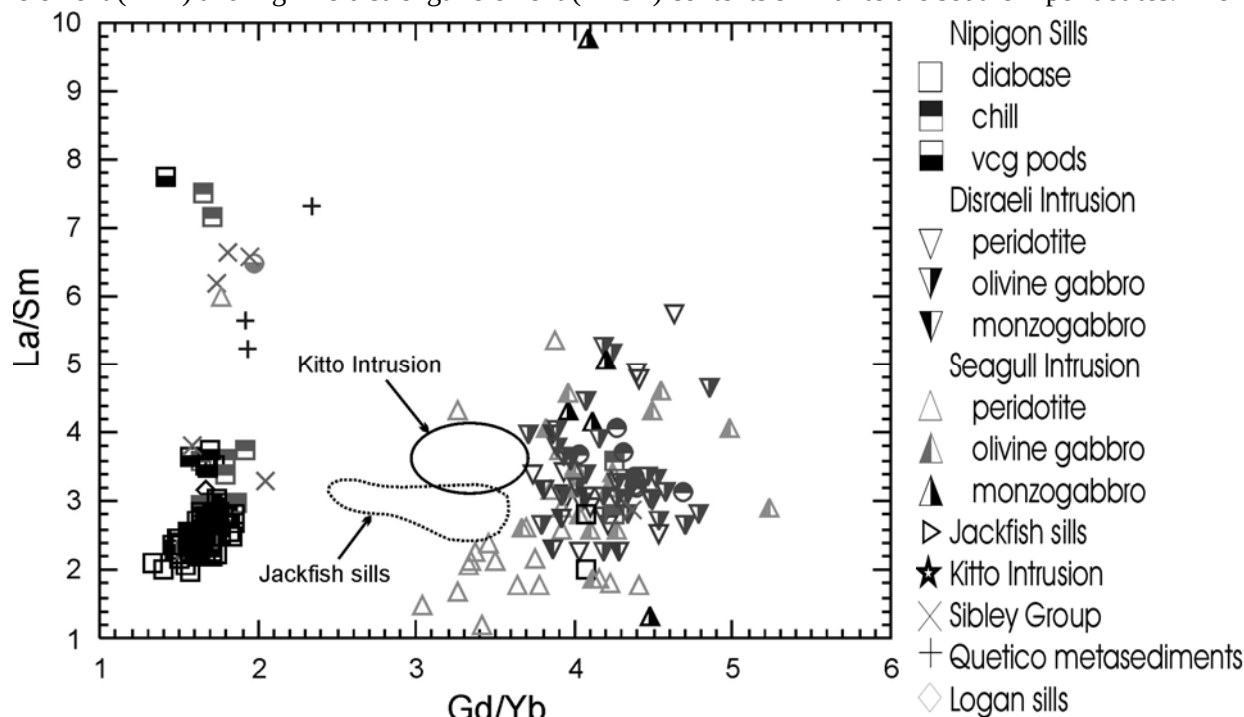
Geochemistry of the Proterozoic Intrusive Rocks of the Nipigon Embayment

HART, T.R., Precambrian Geoscience Section, Ontario Geological Survey, 933 Ramsey Lake Road, Sudbury, Ontario P3E 6B5 (tom.hart@ndm.gov.on.ca)

The Nipigon Embayment is an approximately 19 000 km² area of Proterozoic igneous and sedimentary rocks centred on Lake Nipigon, north of Lake Superior and approximately 110 km northeast of Thunder Bay. There are three geochemically distinct Proterozoic intrusive rock types in the Nipigon Embayment, the southern ultramafic intrusions, the Kitto-Jackfish intrusions and the Nipigon Sill Complex (Hart, 2003).

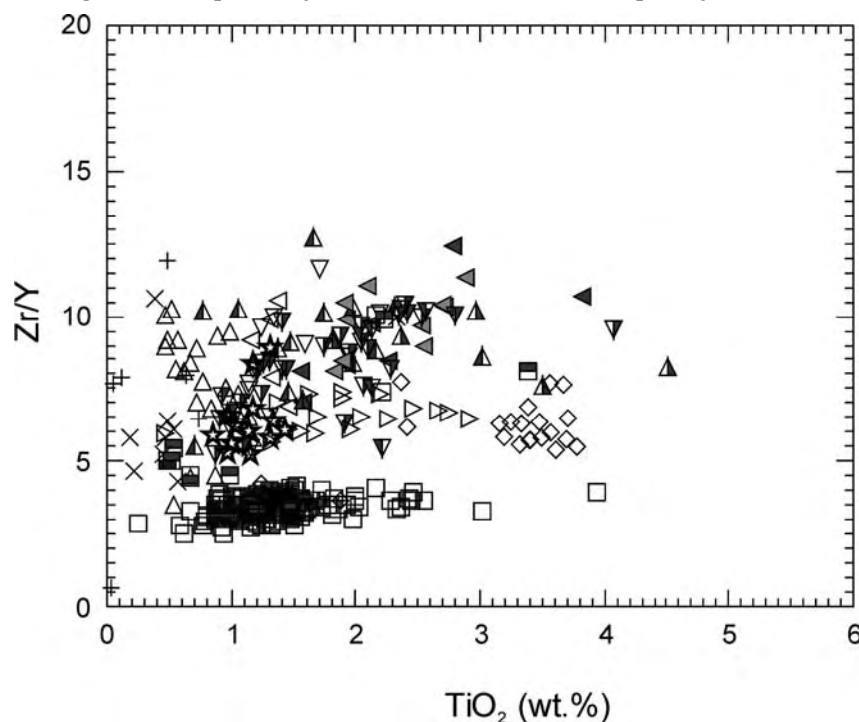
The southern ultramafic intrusions consist of the Disraeli, Seagull-Leckie, and Hele intrusions located in the area between Lake Nipigon and Lake Superior. These intrusions are composed of a pyroxene peridotite core with irregular olivine gabbro zones along their margins, and intrude the rocks of the Archean Quetico Subprovince and the Proterozoic Sibley Group. Their present geometry is sill-like, but all three intrusions are composed predominantly of cumulate wehrlite and lherzolite and may represent the remnants of large bodies. The intrusions have calc-alkaline affinities with $[La/Yb]_{mn}$ (mantle normalized) ratios of 5.3 to 18.53 and have weakly depleted Th and little to no Nb anomalies ($[Th/Yb]_{mn}$ ratios of 0.78 to 1.1). The broad range in composition is probably a result of a combination of igneous processes within the magma chambers and assimilation of country rock. Evidence of assimilation is most evident in small, irregular monzogabbro pods that are geochemically similar to the surrounding olivine gabbro but have higher K₂O contents. All three intrusions have REE and HFSE ratios that are comparable to ocean island basalts as has been noted for the Seagull Intrusion by Heggie and Hollings (2004).

The Kitto-Jackfish intrusions range from an approximately 750 m thick sill-like body at Kitto to an approximately 50 m thick sill at Jackfish Island, English Bay area (MacDonald, 2004), and sills up to a few metres thick at Kama Hill, Nipigon Bay of Lake Superior. The Kitto Intrusion is composed of a pyroxene peridotite core with an irregular olivine gabbro border zone comparable to the southern peridotites (Hart et al., 2002). These sills intrude the rocks of the Quetico and Wabigoon subprovinces and the Sibley Group. The Kitto-Jackfish sills have calc-alkaline affinities with $[La/Yb]_{mn}$ ratios of 6.3 to 10.7, weak Th depletion and weak negative Nb anomalies ($[Th/Nb]_{mn}$ ratios of 1.1 to 1.8) and rare earth element (REE) and high field strength element (HFSE) contents similar to the southern peridotites. The



trend of these intrusions on a La/Sm - Gd/Yb diagram could be a result of either a higher degree of assimilation than the southern peridotites or an indication of a different magma source. The presence of platinum group element (PGE) mineralization in the Seagull and Kitto intrusions suggests that differences in geochemistry are not a useful tool in area selection during exploration.

A series of generally flat-lying to shallow-dipping diabase sills of the Nipigon Sill Complex ranging from a few metres to greater than 100 m in thickness intrude both the southern ultramafic intrusions and the Kitto intrusion. The 1109 Ma sills (Davis and Sutcliffe, 1985) have tholeiitic affinities with $[La/Yb]_{mn}$ ratios of 1.61 to 3.29 and moderate negative Nb anomalies ($[Th/Nb]_{mn}$ ratios of 1.8-3.1). Although the sills probably formed as a result of multiple injections of magma, geochemistry suggests



that many of the sills are single cooling units. There is geochemical evidence of assimilation of the country rock, which is supported by field relationships. The effects of assimilation are most evident in the chilled margins, although sills of similar thickness appear to display variability in composition suggesting that the degree of assimilation depends on the composition of the country rock. The Nipigon diabase sills have lower TiO_2 (0.87 to 2.0 wt.%), Zr/Y (4.2 to 2.7) and $[La/Yb]_{mn}$ ratios than the Logan sills (TiO_2 : 3.45 to 3.79 wt.%; Zr/Y: 5.5 to 7.7; $[La/Yb]_{mn}$: 6.5 to 7.8) located south of Thunder Bay. The

$[La/Yb]_{mn}$ ratios of the Logan sills are comparable to the ultramafic intrusions of the Nipigon Embayment, but their REE and HFSE contents are about 3 times higher than the intrusions. Similar geographic related geochemical variations have been observed in some flood basalt provinces (e.g., Mantovani et al. 1985).

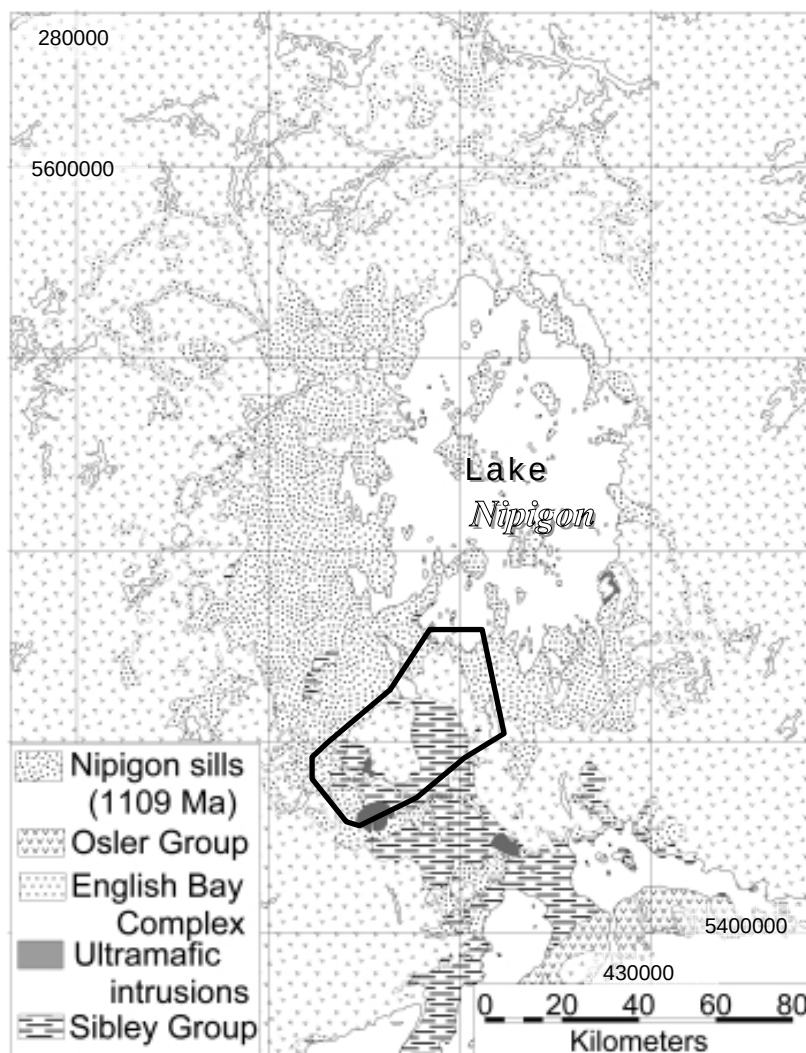
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Precambrian Geology and Mineralization of the Northern Black Sturgeon River area, Nipigon Embayment

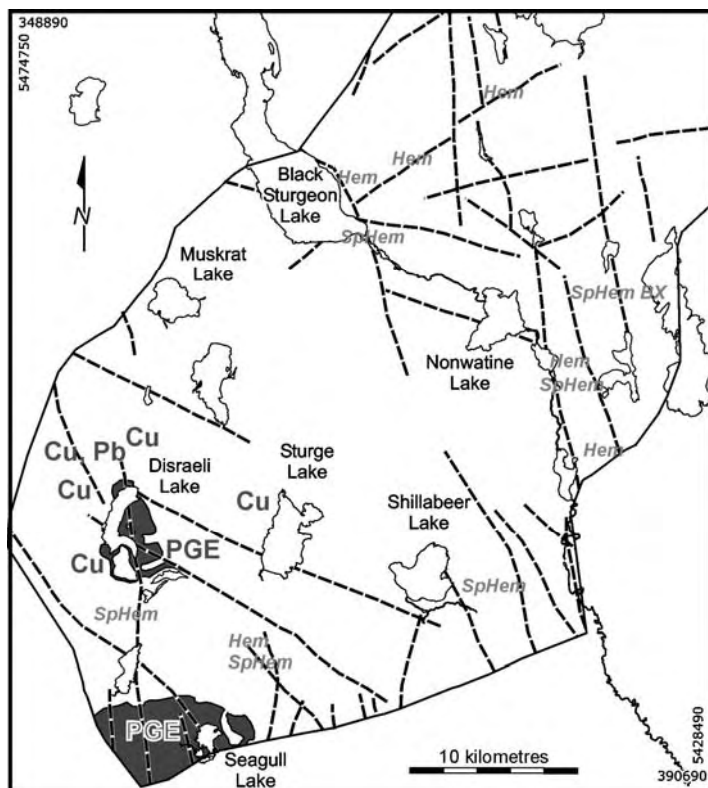
HART, T.R., and MAGYAROSI, Z., Precambrian Geoscience Section, Ontario Geological Survey, 933 Ramsey Lake Road, Sudbury, Ontario P3E 6B5 (tom.hart@ndm.gov.on.ca)

A 1:50 000 scale bedrock mapping project in the northern Black Sturgeon River area was conducted to investigate the regional geological setting of the platinum group element (PGE) bearing mafic to ultramafic intrusion in the Seagull Lake area, in the southern portion of the Nipigon Embayment (Hart and Magyarosi, 2004). The Nipigon Embayment is an approximately 19 000 km² area of Proterozoic igneous and sedimentary rocks centred on Lake Nipigon, north of Lake Superior. This mapping was completed by the Ontario Geological Survey as part of its commitment of in-kind support to the Lake Nipigon Region Geoscience Initiative (LNRGI). The LNRGI is a geoscience-based geological data acquisition and compilation program operated by the Ontario Prospectors Association (OPA) and funded through an agreement with the Northern Ontario Heritage Fund Corporation (NOHFC). The LNRGI also includes partnerships with the private sector, Lakehead University and communities in the Lake Nipigon area. The initiative also includes airborne magnetic and radiometric surveys, ground gravity surveys, and targeted surficial geochemical and geochronological studies.



The north Black Sturgeon River map area is located approximately 110 km northeast of Thunder Bay and south of Lake Nipigon, and is underlain by metamorphosed and deformed Archean volcanic and sedimentary rocks of the southern Wabigoon Subprovince and metamorphosed feldspathic wackes and siltstones of the Quetico Subprovince. Sedimentary rocks of the relatively flat-lying 1340 Ma Sibley Group (Franklin, 1978), consisting of conglomerates, sandstones, mudstones, siltstones, limestone, unconformably overlie the Archean rocks. Proterozoic mafic to ultramafic intrusions in the Disraeli Lake and the Seagull–Leckie lakes areas intrude the Quetico Subprovince and Sibley Group. Both intrusions are composed of a pyroxene peridotite core with an irregular olivine gabbro zones along the margin. A series of undulating, generally flat-lying to shallow-dipping 1109 Ma diabase sills of the Nipigon Sill Complex (Davis and Sutcliffe, 1985) intrude all other rock units in the map area. The Black Sturgeon fault zone consists of a series of north and

northwest-trending faults which form an asymmetric basin or half-graben. Less prominent northeast-trending faults probably represent reactivation of structures in the Archean basement rocks.



The location of alteration and the ultramafic intrusions appear to be controlled by the distribution of faults within the Black Sturgeon fault zone. The Disraeli and Seagull ultramafic intrusions occur along the same series of north trending faults that appear to correlate with north-trending structures in the northern Gull Bay area about 80 km to the north. A parallel series of north-trending faults about 25 km to the east hosts the Hele ultramafic intrusion. The most significant PGE mineralization in the Seagull Intrusion was intersected at or near the basal contact of the peridotite with metasedimentary rocks of the Quetico Subprovince. The mineralization is interpreted by Heggie and Hollings (2004) to be magmatic, and formed as a result of sulphur saturation of the magma during initial stages of emplacement. Biotite is ubiquitous in the ultramafic intrusions, but textural evidence is unclear as to whether the biotite is a primary igneous mineral. Preliminary microprobe analyses from the Disraeli

Intrusion indicates that biotite may contain up to 5 wt.% Cl, which is similar to the high Cl and F contents reported in biotite associated with PGE minerals in the Coldwell Complex (Watkinson and Ohnenstetter, 1992). The ultramafic intrusions are also cut by the faults suggesting a later reactivation. Metre to tens of metre wide zones of intense hematization occur in along these faults in the Seagull intrusion, and a 40 m thick interval in one drill hole is reported to contain a sylvite rich brine. One sample from the brine rich interval has 3.4 ppm Pt and 1.2 ppm Pd along with elevated Cu and K₂O contents suggesting that late fluids could remobilize, and possibly concentrate, the PGEs. Further work is required to understand the timing of this late alteration and the metallogenic significance.

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Multiple Intrusive Stages Associated with Keweenaw Rifting: The Leckie Stock, Seagull Intrusion, and Nipigon Sill

HEGGIE*, G., and HOLLINGS, P., Department of Geology, Lakehead University, 955 Oliver Rd., Thunder Bay, Ontario, P7B 5E1, Canada; gheggie@lakeheadu.ca

Igneous activity related to Keweenaw Rifting (ca. 1108 Ma, Davis and Green, 1997) has produced a wide spectrum of lithologies and numerous igneous suites (Osler Volcanics, North Shore Volcanics, Mamainse Point Volcanics, Duluth Complex, Logan Sills, Nipigon Sills, Coldwell Complex, English Bay Complex, Eva Kitto Intrusion, Seagull Intrusion, Leckie Stock). Found on the periphery of Lake Superior and Lake Nipigon these igneous bodies have been studied for 95 years (first mapped in Canada by Wilson 1910), as work further expands our understanding of the magmatic history, the more complex igneous relationships become.

Rift related intrusive rocks outcrop extensively around Lake Nipigon (Figure 1). The most abundant intrusions in this region are the Nipigon Sills (Sutcliffe 1986, Hart and McDonald 2003). Other igneous bodies have been identified in the process of PGE, Cu and Ni exploration. These intrusive bodies, including the Seagull Intrusion and Leckie Stock, although not as expansive as the Nipigon Sills still play an integral part in the development of a unified petrogenetic model.

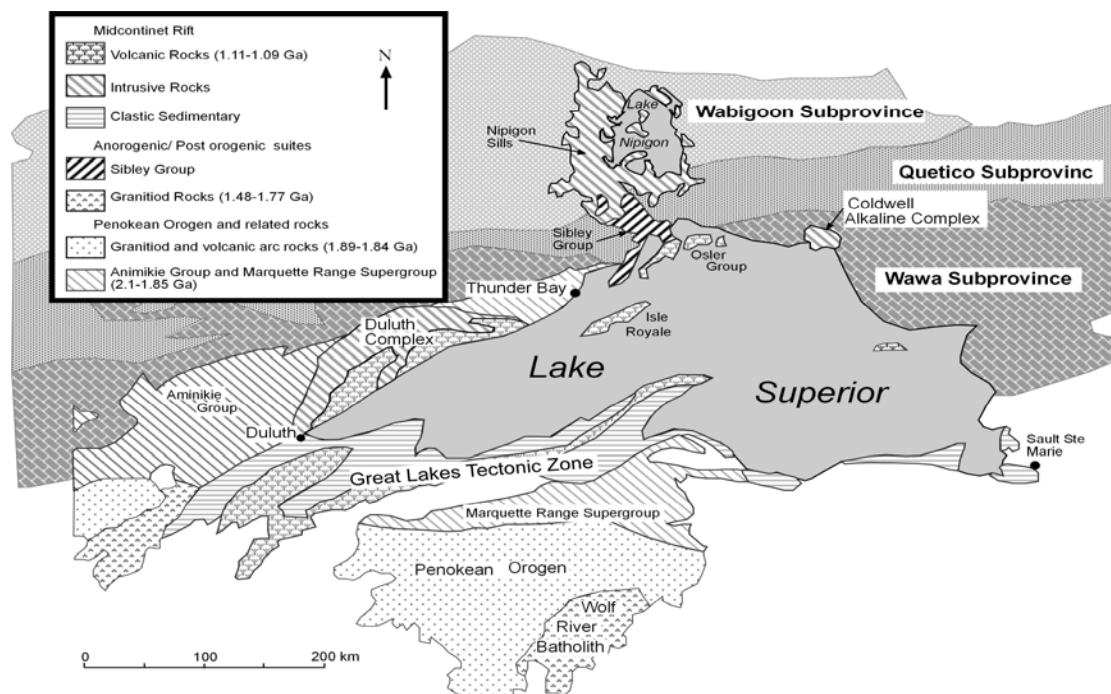


Figure 1. Location of intrusive, extrusive, and sedimentary rocks associated with the Keweenaw Rifting event. Modified after Sutcliffe, 1991.

Contact relationships between the three intrusive suites (Leckie Stock, Seagull Intrusion, and Nipigon Sill) are not yet fully understood. Chill margins on a Nipigon Sill crosscutting the Leckie Stock have been identified in drill core, establishing that the Nipigon Sill post dates the

Leckie Stock. Age relationships between the Seagull Intrusion and Nipigon Sill are still unknown, as is the relationship between Seagull Intrusion and Leckie Stock.

Lithologically, geochemically, and mineralogically it is possible to distinguish between the three bodies. The Leckie Stock is characterized by ultramafic lithologies, with rare earth element plots similar to ocean island basalt with $(\text{La}/\text{Sm})_n$ values of 1.01-5.21 and $(\text{Gd}/\text{Yb})_n$ of 1.82-3.73. Mineralogically the Leckie Stock is dominated by olivine with an average composition of Fo_{82} . This compares to the mafic lithologies (olivine gabbro - gabbro norites) of the Nipigon Sills with $(\text{La}/\text{Sm})_n$ of 1.51-1.61 and $(\text{Gd}/\text{Yb})_n$ values of 1.46-1.49. Olivine mineralogy in the Nipigon Sill varies more than in the Leckie Stock, and has an average olivine composition of Fo_{50} . Lithologically the Seagull Intrusion, displays the greatest variation, varying from olivine gabbros, - gabbros to granophyres. Olivine analysed from this body has an average composition of Fo_{67} .

Mineralogical and geochemical data suggest that the Leckie Stock is the most primitive magma of the three intrusive suites. The Seagull Intrusion and Nipigon Sills are similar in terms of mineralogy and petrology in that they display overlapping olivine compositions, but REE data (Hart 2002) suggests that the Seagull Intrusion is more closely related to the ultramafic Leckie Stock, if a cross cutting relationship exists between the two (Seagull Intrusion crossing Leckie Stock). The Leckie Stock could not be a feeder zone for either the Seagull Intrusion or the Nipigon Sill, but a feeder for some yet unidentified igneous body higher up in stratigraphy.

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$^{40}\text{Ar}/^{39}\text{Ar}$ Hornblende Evidence for Provenance of Ice Rafted Detritus in the North Atlantic: Implications for Tracking Past Changes in the Extent and Dynamics of Northern Hemisphere Ice Sheets

HEMMING, Sidney R., and ROY, Martin, Lamont-Doherty Earth Observatory of Columbia University, Rt. 9W, Palisades, NY 10964

The concentration and provenance of terrigenous sand grains from North Atlantic sediment cores from pelagic environments provide important constraints on the dynamics of former Northern Hemisphere ice sheets. The association of this ice rafted detritus (IRD) signal with proxy records for climate conditions in the North Atlantic, brings additional constraints on ice sheet dynamics in a paleoclimate context. Studies at proximal locations identify configuration changes in specific ice sheets, while studies of cores in the open ocean can yield a history of variation where relative timing of iceberg discharges from different source regions as constrained by simple stratigraphic principles.

An example is the case of the Laurentide ice sheet (LIS) where the distinctive variations in age provinces underlying the LIS from south to north can be used to constrain its extent and ice stream activity during the last glacial cycle. $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende data from IRD indicate the ice reached Grenville and Appalachian provinces along the margin after about 30 kyr (e.g., and the Last Glacial Maximum, LGM). The increase in flux of IRD at the LGM is coincident with the increase in southeastern LIS provenance components. The last glacial cycle was punctuated by Heinrich events, massive discharges of icebergs from the Hudson Strait ice stream. The general trend in LIS development and identification of major ice stream events that are captured by the marine sediment record show the potential power of this approach for understanding the evolution of ice sheets in general. This approach can be applied throughout the Pleistocene to understand the temporal and spatial development of large volume ice sheets and the transition to the 100-ky cycle that dominated the past 700 kyrs. We seek to expand the studies both geographically and through the Pleistocene.

PRELIMINARY PETROGRAPHY AND HYDROTHERMAL ALTERATION OF THE SOUDAN MINE AREA, VERMILION DISTRICT, NORTHEASTERN MINNESOTA

HOFFMAN, A.T.*, Dept. of Geosciences, University of Minnesota, Duluth,
hoff0578@d.umn.edu

PETERSON, D.M., PATELKE, R.L., Economic Geology Group, Natural Resources Research
Institute, University of Minnesota Duluth, 5013 Miller Trunk Highway, Duluth MN
55811

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

The Ely Greenstone of the western Vermilion District is a lithologic and structurally diverse setting located in the southern extension of the Wawa Subprovince of the Superior Province of the Canadian Shield. The Wawa Subprovince is the host for a significant number of mineral deposits and showings, most notably lode gold and volcanogenic massive sulfides (VMS) (Williams et al., 1991). In the last decade, there has been a significant effort put forth to document areas in the Vermilion district that seem geologically and mineralogically compatible for hosting these deposits. This work includes reconnaissance mapping in the eastern Murray shear zone for mesothermal gold mineralization (Peterson, 2001; Peterson and Patelke, in prep.) and the re-evaluation of the Fivemile Lake, Purvis Lake, Eagles Nest, Skeleton Lake, and Needleboy Lake VMS prospects (Peterson, 2001; Hudak et al., 2002a; Hudak et al., 2002b).

In the summer of 2003 mapping for a National Underground Science and Engineering Laboratory (NUSEL) was completed near the Soudan Mine in northeastern Minnesota (Peterson and Patelke, 2003). This work revealed localized lode gold and volcanogenic massive sulfide type alteration. This alteration may correlate with alteration located in the adjacent Fivemile Lake Prospect (Hudak et al., 2002b) and Murray Gold Prospect (Peterson, 2001). The goal of this project is to better understand the volcanic stratigraphy, and syn- and post hydrothermal alteration near the Soudan Mine.

Eighty thin sections were analyzed to defined primary syn-volcanic alteration assemblages in the Soudan Mine area. Classification of mineral assemblages followed Hudak et al. (2002b) in effort to establish consistent hydrothermal mineral alteration nomenclature across the Vermilion District. Four mineral assemblages dominate the area: 1) Epidote + Quartz + Actinolite $\pm$ Chlorite; 2) Epidote + Quartz $\pm$ Chlorite; 3) Mottled Epidote + Quartz $\pm$ Actinolite $\pm$ Chlorite $\pm$ Albite (Epidosites); and 4) localized and lesser amounts of Garnet + Magnetite. Alteration assemblages 1 (Epidote + Quartz + Actinolite $\pm$ Chlorite) and 2 (Epidote + Quartz $\pm$ Chlorite) likely represent early-formed, semi-conformable zones associated with down welling seawater. Alteration assemblages 3 (Mottled Epidote + Quartz $\pm$ Actinolite $\pm$ Chlorite $\pm$ Albite (Epidosites)) and 4 (localized Garnet + Magnetite) appear to represent hydrothermal fluid up-flow zones that may be proximal to syn-volcanic structures (Harper, 1999; Gibson et al., 1999). These results suggest that volcanogenic massive sulfide targets may be present near the Soudan Mine. Petrographic analysis is ongoing and a detailed field analysis during summer 2004 will better constrain these relationships.

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Trace Element Geochemistry of the Osler Group Volcanics – Implications for Mid-Continent Rifting

HOLLINGS, Pete, Department of Geology, Lakehead University, 955 Oliver Rd., Thunder Bay, Ontario, P7B 5E1, Canada; peter.hollings@lakeheadu.ca

To date three major Proterozoic events have been recognized on the northern margins of Lake Superior (Sutcliffe, 1991); 1) the Paleoproterozoic Animikie Group sediments (~1.86 Ga), 2) ~1.54 Ga Mesoproterozoic anorogenic granites and Sibley Group sediments, 3) Mesoproterozoic rifting at ~1.11 to 1.09 Ga during which the Keweenaw Supergroup was deposited. The Osler Group volcanics are found towards the base of the Keweenaw Supergroup.

The Osler Group volcanics comprise a bimodal sequence of basalts and less abundant rhyolites that are well exposed on a series of islands off Rosport on the northern shore of Lake Superior and also as sparse outcrop on the Slate Islands off Terrace Bay (Fig. 1). The Osler Group has been described as a thick sequence of tholeiitic flood basalts with up to 2800m exposed on the Black Bay Peninsula (Sutcliffe, 1991). The majority of the sequence comprises magnetically reversed Lower Keweenaw flows with a small section of magnetically normal flows at the top of the sequence (Halls, 1974). Davis and Sutcliffe (1985) have reported U-Pb ages of 1107.5 $\pm$ 4/-2 Ma for a rhyolite from the base of the sequence and 1097.6 $\pm$ 3.7 Ma for a rhyolite towards the top.

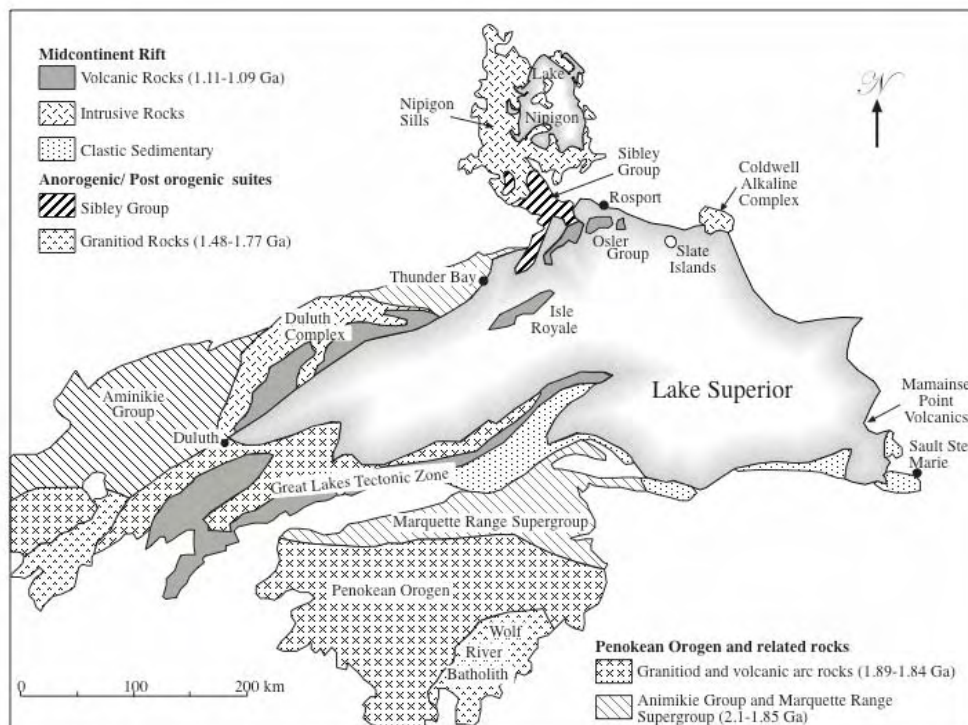


Figure 1. Location of the intrusive, extrusive and sedimentary rocks associated with Keweenaw Rifting. Modified after Sutcliffe (1991).

Detailed sampling traverses were undertaken on Wilson and Vein islands in the summer of 2002, in order to investigate geochemical variations within the Osler Group. Exposure on the two islands is excellent, beginning at the northern end of the islands with a basal conglomerate that includes abundant clasts of Sibley sediments. The conglomerate is strongly heterolithic and indicates an approximately northward flow direction. The volcanic units comprise numerous flows ranging from a few centimeters to a few metres in thickness. Individual flows are frequently marked by rubbly flow tops or ropey, pahoehoe textures, while thicker flows may show well developed columnar jointing (Fig. 2).

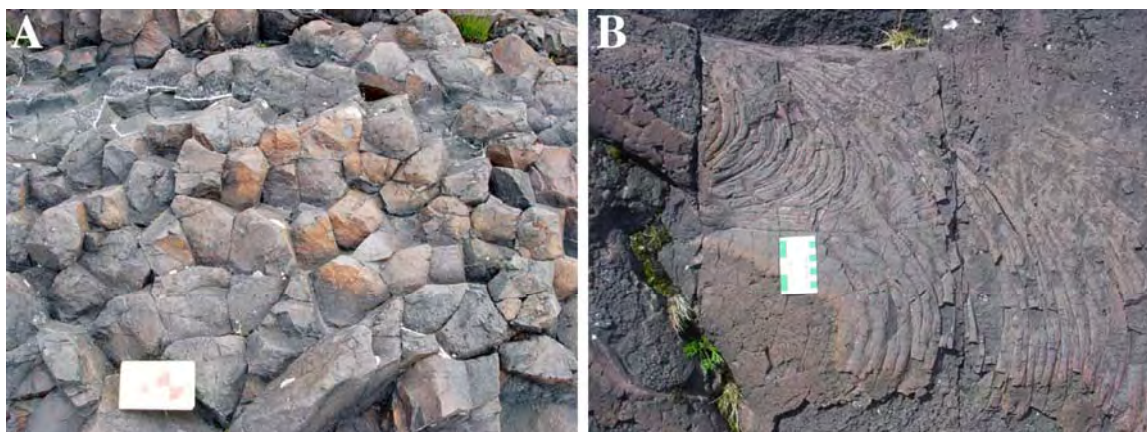


Figure 2. A) Columnar basalts within the Osler Group on Simpson Island. B) Pahoehoe texture in thin basalt flow on Wilson Island.

SiO₂ and MgO contents of the Osler Group volcanics on Wilson and Vein Islands range from 47-54 wt. % and 5-15% respectively, consistent with data from earlier studies. Basalts are characterized by weak to moderate LREE enrichment ($\text{La}/\text{Sm}_n = 1-5$), weakly fractionated HREE ($\text{Gd}/\text{Yb}_n = 2-4$) and display primitive mantle normalised patterns comparable to modern Ocean Island Basalts. Preliminary examination of REE data for the Group suggests that the La/Sm_n ratio, a good indicator of crustal contamination, increases towards the top of the sequence (ranging from ~ 1.5 near the base to ~ 5 near the top).

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The Influence of Radiometric Dating for Unraveling the Precambrian Geologic History of the Lake Superior Region

HOLM, Daniel K., Dept. of Geology, Kent State University, Kent, OH 44242,

dhholm@kent.edu

VAN SCHMUS, R.W., Dept. of Geology, Univ. of Kansas, Lawrence, KS 66045

SCHNEIDER, D.A., Dept. of Geological Sciences, Ohio University, Athens, OH 44701

The paucity of biostratigraphic controls in Precambrian rocks has long made radiometric dating of primary importance for unraveling the complex geologic history in the Lake Superior region (Goldich, 1968). The first ILSG meeting in 1955 occurred very close to the time of initiation of a radiometric dating program by S.S. Goldich and A.O. Nier in 1956. Subsequent geochronologic investigations laid the theoretical and practical foundation upon which current radiometric studies are expanding. Thus the tremendous influence of geochronologic studies in this region, only briefly summarized here, has been well chronicled at ILSG meetings over the past 50 years.

Pioneering studies in K-Ar, Rb-Sr, and U-Pb dating. Early studies by Goldich et al. (1961, 1970), Aldrich et al. (1965), and Peterman (1966) were pioneering applications of radiometric dating which provided a broad-brush means of correlation (based on age rather than on degree of metamorphism and deformation) and contributed to the formation of a world-wide time scale for the Precambrian (Goldich, 1968), flatteringly referred to by some as “Goldich’s time scale”. The early results represented a significant breakthrough in Precambrian geology, yet proved difficult to interpret as co-existing minerals gave different ages for the same decay scheme. Comparative mineral studies by Aldrich et al. (1965) and Hanson and Gast (1967) led to the recognition of metamorphic effects on various isotopic systems (especially K-Ar and Rb-Sr). For instance, Van Schmus et al. (1975a) used Rb/Sr age data to document the existence of a widespread but poorly understood low-grade 1650 Ma metamorphic event in Wisconsin. The 2700 Ma age of the greenstone-granite belts in Minnesota and southern Ontario was documented early on by whole-rock Rb-Sr ages (Jahn and Murthy, 1975), K-Ar, and U-Pb ages (Peterman et al., 1972). The large analytical uncertainty in these data, however, precluded their use for resolving the time of important, short-lived, geological events (plutonism, deformations) that occurred during their formation and accretion. Likewise, the errors on initial U-Pb zircon ages on Mid-continent Rift rocks would not allow for differentiation of magmatic pulses, but simply suggested “a sharp pulse of igneous activity” at 1115 ± 15 Ma (Silver and Green, 1963). Early U-Pb zircon work in the Minnesota River Valley temporarily produced some of the world’s oldest dated rocks (Catanzaro, 1963; Goldich et al., 1970; Goldich and Hedge, 1974), and clearly demonstrated that K-Ar and Rb-Sr mineral ages reflect younger metamorphic events. For instance, using K-Ar and Rb-Sr ages, Goldich et al. (1961) first bracketed the Penokean orogeny as having occurred between 1800 and 1600 Ma. Similarly young K-Ar biotite ages (compared to U-Pb zircon ages from the same rock) from Precambrian shields and orogenic belts worldwide led to the concept of a ‘metamorphic veil’ (Armstrong, 1966) which reflects younger overprinting events (common in Precambrian terranes) and obscures the age of older rock forming events.

Modern U-Pb dating (bulk aliquot to single crystal to spot dating). In the 1970’s and 1980’s, advances in conventional U-Pb zircon analyses (Krogh, 1973, 1982) allowed geochronologists to see through the ‘metamorphic veil’ and firmly established the age spectrum of igneous activity in the region (Silver and Green, 1972; Van Schmus et al., 1975b; Van Schmus, 1976; 1980). For instance, the age of the Penokean orogeny was definitively bracketed between 1870-1830 Ma by Van Schmus (1976, 1980), who first invoked the plate tectonic concept of a southern magmatic arc colliding with a northern passive margin. Archean age gneisses (Marshfield terrane) were dated south of the Penokean magmatic arc rocks (Van Schmus and Anderson, 1977) and Early Archean ages were obtained from gneiss dome rocks north of the Niagara fault zone (Peterman et al., 1980).

The greatly improved accuracy in U-Pb zircon dating has allowed researchers (Boerboom and Zartman, 1993; Corfu and Stott, 1986, 1998; Davis et al., 1989; Zaleski et al., 1999; Ayers et al., 2002) to document the time of short-lived magmatic and deformational events commonly involved in the

formation of late Archean granite–greenstone belts. Enough high precision data has been obtained (i.e., Shebandowan, Vermillion, and Manitouwadge) to suggest correlation of volcanic assemblages and their subsequent deformation along 600 km of strike (Peterson et al., 2001).

New U-Pb single-crystal zircon studies continue to refine the earlier plutonic ages, which were obtained on mg-size fractions. Post-Penokean “1760 Ma” plutonism (Sims et al., 1989) is now known to have actually occurred in southeast younging pulses at ca. 1800, 1775, and 1750 Ma, possibly reflecting flip in subduction polarity and slab-rollback of Yavapai-age oceanic lithosphere (Holm et al., 2004). The Penokean orogenic belt twice formed the source region for generation of crustal-melt batholiths; first at ca. 1775 Ma with intrusion of the East-central Minnesota batholith (Holm et al., 2004) and again at 1470 Ma in central Wisconsin (Van Schmus et al., 1975). The new single crystal results show that the East-central Minnesota batholith was emplaced over a ca. 20 m.y. duration (Holm et al., 2004; Keatts et al., 2004), whereas Wolf River magmatism was relatively short-lived (with nine different phases intruded over a <5 m.y. interval; Dewane and Van Schmus, 2003).

New important U-Pb zircon results have also been obtained from volcanic rocks over the last decade or so (see Van Schmus and Hinze, 1985 for a summary of earlier age data). High precision U-Pb geochronology on the volcanics of the Midcontinent Rift system indicate rapid eruption over a relatively short duration (1108–1094 Ma; Davis and Paces, 1990; Paces and Miller, 1993; Davis and Green, 1997; Zartman et al., 1997). The great volume of magma generated over this short time span and the limited degree of extension strongly favor a mantle plume origin. New geochronology on interlayered volcanics within the Marquette Range Supergroup yield essentially identical ages of 1875 Ma for the Hemlock (Schneider et al., 2002) and Gunflint (Fralick et al., 2002) Formations. The revised age constraining the timing of deposition of the Supergroup across the Animikie basin suggests these sediments were laid down coeval with arc formation to the south and supports the hypothesis of Hoffman (1987), who first proposed that the iron formations are syn-Penokean foredeep deposits.

Conventional single crystal and SHRIMP U-Pb dating of detrital zircons (Van Wyck, 1995; Holm et al., 1998; Medaris et al., 2003) finally resolved the controversy over the maximum age of the Baraboo Quartzite and similar red quartzites in northern Wisconsin and Minnesota (<1750 Ma). A completely different geochronologic database described next provided firm constraints on the minimum age of quartzite deposition (>1650 Ma).

Ar-Ar thermochronology. Thermochronology (the study of the time-temperature evolution of rocks) was born from the realization that many mineral-isotopic systems could be used to determine the time of cooling of a terrain through a series of predictable temperatures. Because an intimate relationship exists between the thermal and tectonic processes operating during orogenesis and subsequent events, reconstructing the thermal history of a region ultimately aids in constraining its tectonic evolution. Thermochronologic data from the region was initially dominated by the Rb/Sr method on biotite (Peterman and Sims, 1988). In the 1990’s, application of the Ar-Ar incremental heating technique on hornblende, muscovite, and biotite yielded considerable information bearing on the Proterozoic thermal history of the southern Lake Superior region (Holm and Lux, 1996, 1998; Schneider et al., 1996; Holm et al., 1998a; Romano et al., 2000). Especially important was the proposal that a separate, perhaps widespread, geon 17 amphibolite facies metamorphic event occurred after the Penokean orogeny, followed by an episode of rapid crustal exhumation (Holm et al., 1998a). Additionally, the widespread geographic distribution of basement Ar/Ar biotite ages serendipitously provided a key minimum age constraint (ca. 1630 Ma) on the overlying Proterozoic red quartzites and led to a greater appreciation of the role of younger tectonism (i.e. Mazatzal deformation) in the region (Holm et al., 1998b).

New minerals, new techniques, and new directions. Rapid advances in technology (allowing higher precision, increased mass and spatial resolution, and *in situ* capabilities) and the application of new chronometers (monazite and xenotime) are now verifying earlier hypotheses for widespread tectonothermal events following Penokean orogenesis. Recent results of U-Pb monazite dating using both ion and electron microprobe techniques now recognize distinct metamorphic pulses at 1835, 1800, and 1770 Ma – thermal pulses which can be directly tied to known magmatic events (Schneider et al., 2004). New U-Pb xenotime ages (Vanelli et al., 2003, and in progress) from coarse sandstone/conglomerate beds

of the Marquette Range Supergroup identify a widespread 1790-1760 Ma fluid flow event – an event that may have been ultimately responsible for forming the high-grade iron ore deposits in this region (Morey, 1999). Recent single crystal Ar-Ar dating of fine-grained, low-temperature minerals within the Baraboo Interval Quartzites (Medaris et al., 2003) has documented a much younger, but apparently even more vast hydrothermal fluid system generated by Mesoproterozoic plutonism. Finally, Ar-ion laser dating results reveal significant age gradients (~200 to 500 m.y.) in coarse muscovite from basement samples interpreted to signify partial resetting by fluids during both Mazatzal orogenesis and Mesoproterozoic magmatism (McKenzie, 2004; Rose, 2004).

In addition to direct dating of metamorphism and fluid flow, geochronology is now being used to put absolute time (not simply time constraints) on important deformation features in the Lake Superior region. The age of the Mazatzal tectonic front in northwest Wisconsin is dated by the age of reset biotite in basement beneath the deformed quartzites. The Malmo Structural discontinuity in Minnesota and the Flambeau Flow fault in Wisconsin are now thought to be geon 17 exhumation structures (formed during orogenic collapse) on the basis of differing metamorphic ages across these faults (McKenzie et al., 2003; Schneider et al., 2004). Current monazite work on tectonite samples of the Niagara fault zone (Rose, 2004) and the Eau Claire shear zone (Loofboro, 2005) should provide direct time constraints on their formation (Williams and Jercinovic, 2002).

Beginning this month we anticipate the publication of a large number of new ages in just the next few years – in terms of raw numbers, perhaps more than has been published in the Lake Superior region in the entire past 50 years! For instance, Van Wyck and Martin (2004) exploit the relatively fast LA-ICP-MS technique to report over 200 U-Pb detrital zircon ages from the Baraboo and Hamilton Mounds quartzites. Geochronologic work accepted and in progress (Schneider et al., 2004, 2005; Holm et al., 2004, 2005; Vanelli et al., in progress; Bickford et al., in progress; McKenzie, 2004; Rose, 2004; Keatts, 2004; Loofboro, 2005; Schmitz and Bowring, in progress; Medaris et al., in progress; et al. that we may be unaware of) will certainly continue to refine our knowledge of the Precambrian geologic history of this region and very likely yield surprises which can not be anticipated.

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NEOARCHEAN PEPERITES IN THE VICINITY OF FIVEMILE LAKE, VERMILION DISTRICT, NE MINNESOTA

HUDAK, G. J., NEWKIRK, T. T., DREXLER, H., ODETTE, J. D., and HOCKER, S. M.,
Department of Geology, University of Wisconsin Oshkosh, 800 Algoma Blvd., Oshkosh,
WI 54901, hudak@uwosh.edu

The Ely Greenstone – Lower Member in the vicinity of Fivemile Lake contains a well-studied sequence of ~2722 Ma, more or less east-west striking, steeply north-dipping and north-facing, arc-associated submarine basalt-andesite pillow lavas, tuffs and lapilli tuffs, rhyodacite to rhyolite tuffs, lapilli tuffs, and lavas, and synvolcanic diabase and diorite sills and dikes (Peterson et al., 2001; Hudak et al., 2002). Volcanic facies mapping at 1:5000 scale, supported by grants from the Natural Resources Research Institute (University of Minnesota Duluth), the University of Wisconsin Oshkosh, and the Minerals Diversification Plan of the Minnesota State Legislature, identified a northeast-trending zone of basalt - andesite tuffs, lapilli tuffs, and tuff-breccias which contain zones of northeast-trending coherent facies andesite-dacite that display pillowed, amoeboid, and commonly, jigsaw-puzzle fit morphologies. The southern extent of this zone occurs along a peninsula on the southwestern shoreline of Fivemile Lake. The northern extent of this zone extends approximately 150 meters north of the north-central shoreline of Fivemile Lake. Over the past year, extremely detailed volcanic facies mapping (1:50-1:100 scale), as well as petrographic and lithogeochemical studies, have been performed in an attempt to determine the genesis of these apparently genetically related coherent- and volcanoclastic facies-bearing, northeast-trending zones.

On the south shoreline of Fivemile Lake, the volcanoclastic facies is typically matrix-supported. The matrix consists of non-bedded basalt-andesite tuff, and locally contains amoeboid-shaped zones that contain up to 60% <1 mm quartz amygdulites. Localized zones adjacent to northeast-striking coherent facies andesite-dacite comprise lapilli tuffs and tuff-breccias. Clasts in these deposits are commonly curvilinear to angular and jigsaw puzzle-fit in shape (Figure 1a), are moderately to highly vesicular (10-50%), have extremely fine-grained margins, and locally contain <1-2 cm wide, apparently contact metamorphosed zones adjacent to their margins. These blocks and lapilli are compositionally similar to, more common adjacent to, and have their long axes aligned with, northeast-trending, sheet-like to pillow-shaped coherent facies andesite-dacite. The deposits on the north-central shoreline of Fivemile Lake have slightly different morphologies. A sharp, north-south contact occurs between east-west striking, steeply north-dipping, bun- to mattress-shaped pillowed basalt-andesite and basalt-andesite tuffs and lapilli tuffs that comprise the base of a 700 meter wide, 200 meter thick, shallow submarine tuff cone (Hudak et al., in prep.). The tuffs and lapilli tuffs at this location are intruded by northeast-trending, synvolcanic, amoeboid (Figure 1b), pillow-like, and lobe-like zones of coherent-facies andesite-dacite which appear to have locally undergone in-situ fragmentation to produce localized lapilli tuffs and tuff-breccias that contain moderately to highly vesicular curvilinear, amoeboid, and blocky jigsaw puzzle-fit lapilli and blocks. These fragments have very fine-grained margins that are also rimmed by fine-grained, apparently contact metamorphosed zones. Locally, numerous thin (up to 1cm wide), parallel, highly vesicular zones occur within the volcanoclastic deposits that more or less mimic the orientations the margins of amoeboid coherent facies andesite-dacite or the margins of andesite-dacite blocks.

The northeast-trending zones containing coherent and volcanoclastic facies are interpreted to comprise peperites with associated synvolcanic dikes. Peperites are fragmental rocks that form from the intimate mixing of hot magma with unconsolidated, typically wet sediments (Batiza and White, 2000; Schmidt and Schminke, 2000). They are common in submarine arc-related volcano-sedimentary sequences (Skilling et al., 2002), and commonly occur in proximity to synvolcanic fault zones. The interpretation that the volcanoclastic deposits represent peperites is based on the morphology of the lapilli and blocks which comprise the deposits, the consistent grain size variations from the margins to the centers of the lapilli and blocks, their spatial relationships adjacent to, and orientations parallel to, synvolcanic sheet-like to pillowed coherent facies andesite-dacite, and the presence of amygdulites within the fine-grained tuffaceous matrix. The interpretation that the sheet-like to pillowed, coherent facies andesite-dacite represents dikes rather than lava flows is based on the northeast strike of the pillowed dikes (which is parallel to synvolcanic structures mapped in the Fivemile Lake region (Hudak et al., 2002)), the lack of consistent facing directions in the pillowed coherent

facies, and the similarity in the chemical compositions of the coherent domains and the lapilli and blocks within the lapilli tuffs and tuff-breccias. The differences in the morphologies of the peperites on the southwestern and north-central shorelines of Fivemile Lake may represent their different levels of formation in the shallow sub-seafloor. Blocky peperites south of Fivemile Lake appear to have formed in lava flow-confined submarine aquifers located several hundred meters below the paleoseafloor, whereas more amoeboid peperites found north of Fivemile Lake appear to have formed near the seafloor within water-saturated submarine vent-fill deposits associated with a shallow submarine tuff cone volcano. Discordant zones of peperites can be used to identify synvolcanic fault zones that may be important in the exploration for volcanic-hosted massive sulfide deposits.

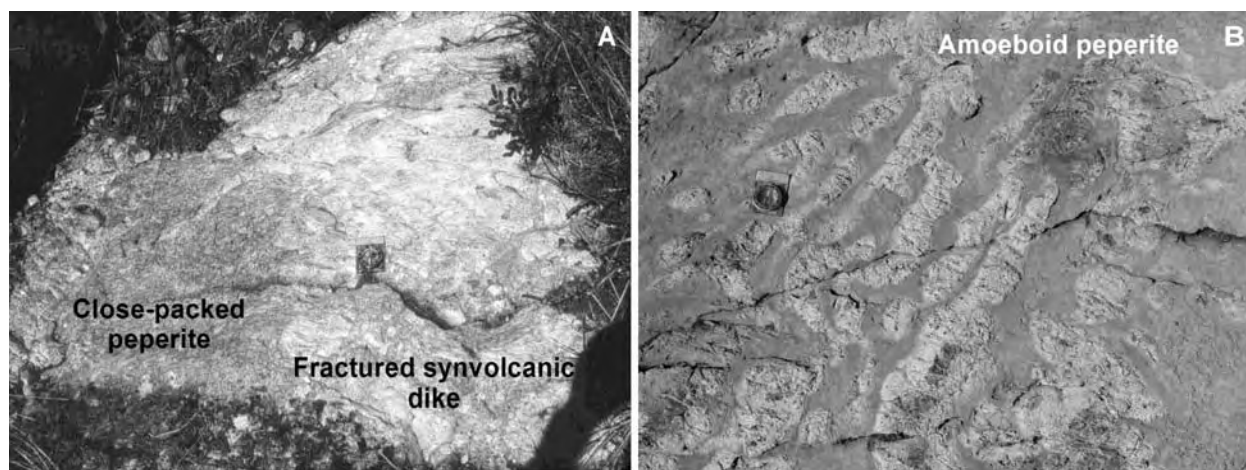


Figure 1. Photographs of peperites deposits south (A) and north (B) of Fivemile Lake.

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MAPPING BY THE MINNESOTA GEOLOGICAL SURVEY IN SUPPORT OF LAND-USE AND WATER PLANNING ON THE MESABI IRON RANGE

JIRSA, Mark A., Minnesota Geological Survey, jirsa001@umn.edu

This presentation describes two mapping projects on the Mesabi Iron Range underway by the Minnesota Geological Survey:

- 1) Hydrogeologic base maps of the Mesabi Iron Range—Funded by the Legislative Commission on Minnesota Resources; and
- 2) Bedrock and Quaternary geologic maps of the Mesabi Iron Range—Funded by the Minnesota Minerals Coordinating Committee.

In recent years, a number of mining companies have been working with the University of Minnesota's Department of Landscape Architecture on development concepts for the Mesabi Iron Range. Although not directly a part of those efforts, the Minnesota Geological Survey's mapping projects are designed to provide technical data to address issues—primarily related to water—that require consideration *prior* to development. When mining and associated pumping ceases in any particular locality, water enters the mine from a variety of sources: rain and runoff, percolation through porous unconsolidated sediment layers, and flow through fractures and weathered zones in bedrock. The movement of ground water through these diverse materials is complex and poorly understood; however, it is clear that the boundary between the bedrock and overlying unconsolidated sediments is the single most important interface in the movement of ground water. Project 1, the hydrogeologic maps, addresses the location and shape of this hydrologically important interface. Some of this information for the western half of the Mesabi Range has already been published (Fig. 1; Jirsa and others, 2002; Lively and others, 2002). Project 2 will provide details about the lithologic content, structure, and water-bearing characteristics of the materials above and below that interface. Among other objectives, the bedrock geologic mapping is designed to identify other structures that may be important hydrologic interfaces, such as fractures, faults, and bedding surfaces. The bedrock mapping will modify and digitize the most recent existing map of the Mesabi Range compiled by a large group of scientists (Meineke and others, 1999). This will be compiled with other archived maps and new fieldwork. These efforts are reconnaissance in scope, and considerably more detail could be extracted from mine exposures, mining company records, and surface geologic mapping. Nevertheless, these projects will produce framework geologic maps and site-specific data in digital format that will be useful in resolving issues related to ground and surface waters, aggregate resource management, and land-use planning. They are intended to lay the groundwork for more detailed investigations into specific areas of future concern.

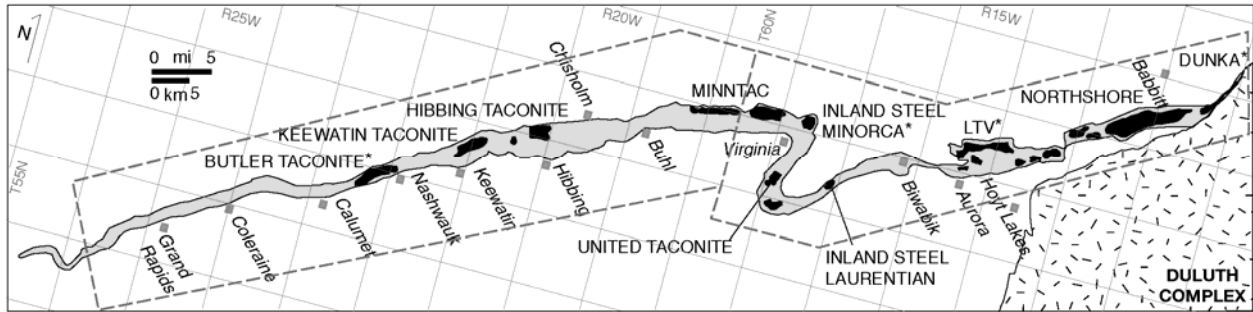


Figure 1. Generalized geologic map of the Mesabi Iron Range showing the subcrop location of Paleoproterozoic Biwabik Iron Formation (gray) and Mesoproterozoic Duluth Complex, and various taconite mining operations (black; asterisk indicates inactive mine). Dashed polygons outline western and eastern map areas.

None of these projects would be possible without the contributions of drill hole and geologic data and insight from members of the Minnesota Department of Natural Resources, the Natural Resources Research Institute, and most particularly, the mining companies.

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REGIONAL COMPILATIONS OF BEDROCK GEOLOGY IN NORTHEASTERN MINNESOTA: THE VERMILION, ELY, AND BASSWOOD LAKE QUADRANGLES

JIRSA, Mark A., Minnesota Geological Survey, jirsa001@umn.edu

Compilations of geologic mapping, although not typically portraying new field information in great detail, serve the important functions of providing regional mapping consistency, framework for various lithologic and geochemical surveys, and regional guidance for exploration and environmental issues. With this in mind, several regional bedrock geologic compilations at scale 1:100,000 have recently been completed and are underway for areas in northeastern Minnesota (Fig. 1), funded in large part by the STATEMAP program of the U.S. Geological Survey. The Vermilion Lake 30' x 60' quadrangle was completed in 2003 (Jirsa and Boerboom, 2003), and is displayed and described here. The adjacent Ely and U.S. portion of Basswood Lake 30' x 60' quadrangles are slated for completion in 2004. Perhaps as important as the functions listed above, the new compilations integrate disparate analog mapping, including some from the late 1800s and early 1900s, into a lithostratigraphically consistent, digital (GIS) format.

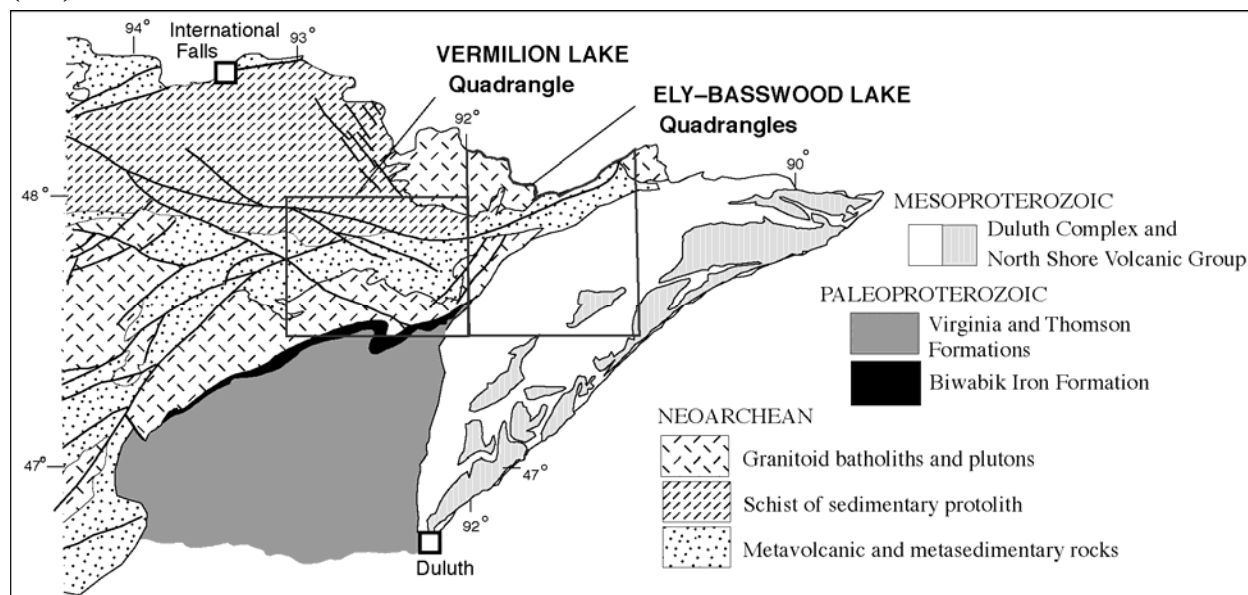


Figure 1. Generalized geologic map of northeastern Minnesota showing the location of 30' x 60' quadrangles.

The Vermilion Lake quadrangle covers most of the exposed area of the Vermilion district of northeastern Minnesota that lies outside of the Boundary Waters Canoe Area Wilderness (BWCAW), and is thus open in the broad sense to mineral exploration and mining. The Vermilion district is a local designation applied to the portion of the Neoproterozoic Vermilion greenstone belt in which there has been mining activity in the past, primarily of high-grade iron ore. The quadrangle also covers the east end of the Mesabi Iron Range, a world-class mining district in Paleoproterozoic strata that for decades has been the principal economic force in this part of Minnesota. Nevertheless, there is interest in finding alternative industries for cities along the iron range and alternative commodities for a diversified mining industry. At the present time there are encouraging indications that one or more viable polymetallic mines may develop in the basal contact zone of the Mesoproterozoic Duluth Complex. The zone of prime exploration and development interest in this regard crosses the southeastern corner of the Vermilion Lake map sheet.

For the first time, the Vermilion Lake compilation merges well-exposed Neoproterozoic rocks of the Tower–Soudan area with more scattered exposures to the west into a single structural and lithologic interpretation. The map highlights a large, regional anticlinal structure that is cored by the steeply dipping Tower–Soudan anticline (Fig. 2). Tracing this fold structure westward into sedimentary rocks of the Lake Vermilion Formation, it becomes a broad and complex nappe structure that extends at least 30 kilometers. The Vermilion greenstone belt is comparable in its geologic attributes to other Neoproterozoic belts in Canada that contains significant deposits of gold, copper, zinc, and other metals. This general analogy has been recognized for decades and has stimulated several waves of mineral

exploration in the area. Although past exploration efforts have been substantial, they have not been exhaustive. A major handicap was the lack of detailed geologic mapping, a situation that has been largely corrected over the past 25 years through the efforts of the Minnesota Geological Survey and the exploration industry itself.

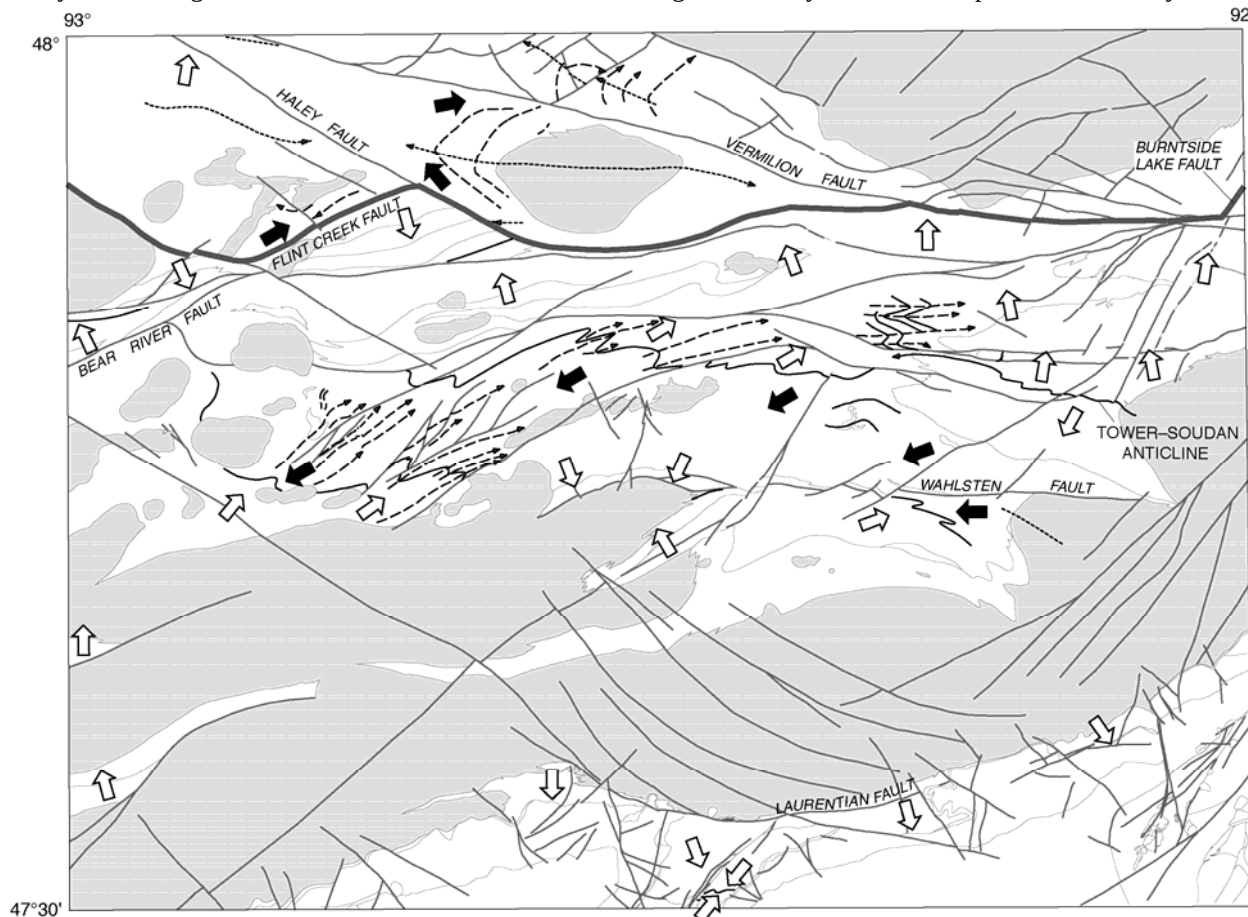


Figure 2. Schematic geologic map of the Vermilion Lake 30' x 60' quadrangle (Jirsa and Boerboom, 2003) showing folds, faults, and stratigraphic facing in Archean strata. Archean intrusions are gray. Three generations of folds are shown: F_1 —solid; F_2 —long dash; F_3 —short dash. Open arrows indicate horizontal facing directions in steeply dipping supracrustal sequences and upright facing directions where bedding is shallower. Solid arrows indicate the direction of downward stratigraphic facing. The bold fault line is the boundary between the Quetico subprovince to the north, and the Wawa subprovince to the south.

The regional compilations of mapping data at scale 1:100,000 may prove to be valuable tools for the next cycle of exploration, which inevitably will come when local and global economic conditions appropriately conjoin.

The compilation effort underway for the Ely and U.S. portions of the Basswood Lake 30' x 60' quadrangles involves many of the same geologic entities as depicted on the Vermilion Lake sheet. Because it includes areas within the BWCAW, which are generally protected from exploration and mining, this map will serve a slightly different purpose from that of the Vermilion Lake map, by providing regional geologic context. This effort will pave the way for such products as a “geologic user-guide” to the BWCAW, which has been initiated by the Minnesota Geological Survey.

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Douglass Houghton's 1840 Field Excursion to Lake Superior

JOHNSON, Allan M., Professor Emeritus, Department of Geological & Mining Engineering & Sciences, Michigan Technological University, Houghton, Michigan 49931

In 1840, as the first State Geologist of Michigan, Douglass Houghton was near the end of the first geological survey of the state. In 1837, when Michigan entered statehood, and 1838 he was involved with and oversaw the reconnaissance surveys of the southern peninsula. In 1839 the survey work progressed to the northern peninsula, along the north shores of Lakes Huron and Michigan. For 1840, the program was much more ambitious, for he and his assistants (Bela Hubbard and C.C. Douglass) would undertake a survey along the south shore of Lake Superior. Detroit businessman, Charles Penny, also accompanied the group.

The party left Detroit near the end of May 1840 and through the spring and early summer made their way from Sault Ste. Marie westward along the south shore of Lake Superior in their flotilla consisting of a larger Mackinaw boat and several smaller craft. This survey resulted in the mapping of rocks exposed adjacent to the shore, with more detailed mapping along major streams and rivers flowing into the big lake. Special attention was given to mapping volcanic and sedimentary rocks of the Keweenaw Peninsula and taking samples of previously known locations of copper bearing rocks (copper oxide at Copper Harbor and native metal from the copper boulder on the Ontonagon River). At the end of July, Houghton's assistants returned to southern Michigan to continue with ongoing geologic investigations including boring a salt well at Grand Rapids.

Houghton remained on Lake Superior with his voyageurs through mid-September. When his assistants left from LaPointe on Madeline Island, Houghton continued reconnaissance mapping at Isle Royale, the Porcupine Mountains and Portage Lake, and more detailed work on the Black and Eagle Rivers.

It was on the Eagle River where Houghton discovered numerous occurrences of native copper and the presence of native silver which gave him the confidence to express cautious optimism in the potential for copper mining on the Keweenaw Peninsula in his early 1841 report to the Michigan Legislature.

Word of this report soon led to the US War Department establishing a land office at Copper Harbor to issue mining permits and ultimately to the first great mining rush in the United States. For 150 years the native copper district of the Keweenaw was active in supplying a growing nation and the world with high purity lake copper with over 12 billion pounds of production.

It is of interest to note that the 1840 journals of Hubbard and Penny have been published, while Houghton's 1840 geologic notes became 'lost'. It was not until 1978 that the notes appeared at public auction in New York City advertised as "the notes of an early Michigan surveyor", where they became the property of Central Michigan University.

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REGIONAL GEOCHEMISTRY SURROUNDING THE NORTON LAKE Cu-Ni-PGE DEPOSIT, UCHI SUBPROVINCE, ONTARIO

JOHNSON, J.R.*, HOLLINGS, P., and KISSIN, S., Department of Geology, Lakehead University, Thunder Bay, ON, P7B 5E1

The Norton Lake Cu-Ni-PGE deposit (delineated in 1981 as 944,000 tonnes at 0.72% Ni and 0.56% Cu) is located within the northern most unnamed assemblage of the Miminiska-Fort Hope Greenstone Belt approximately 50 km northeast of Fort Hope, northwest Ontario (Fig. 1). The deposit is hosted within a sheared amphibolite unit that is typically found at, but not limited to, the contact between an upper basalt and a lower sedimentary unit. Due to both its remote location and sparse outcrop only limited geological investigations have been undertaken within the belt to date. Consequently, the belt has been subdivided based on available regional stratigraphic and structural interpretations. Previous work by the Ontario Geological Survey has tentatively correlated the unnamed assemblage with the McGruer assemblage of the North Caribou, located to the west, based on a similarity of rock types and a pervasive aeromagnetic anomaly that extends between the two (Stott and Corfu, 1991).

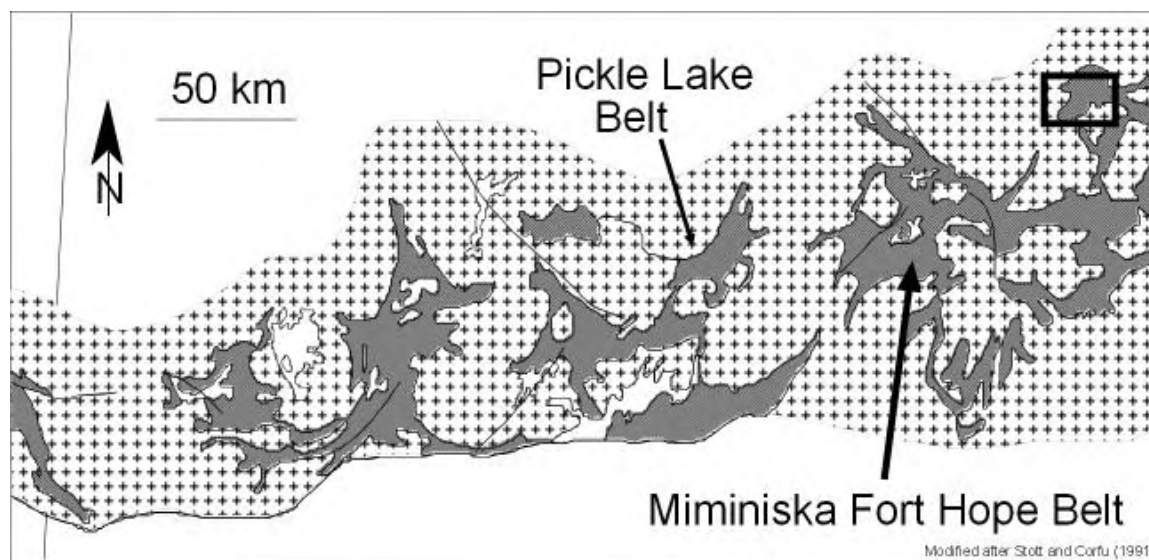


Figure 1: Uchi Subprovince, northwestern Ontario, study area outlined.

A 12 km east-west by 6 km north-south block surrounding the Norton Lake Deposit has been mapped and sampled to allow characterization of the volcanic assemblages. In addition to field mapping, drill core left in the area by previous exploration programs was examined (covering an area of 20 km by 10 km). Samples selected to provide good areal coverage and minimal alteration were analysed by XRF and ICP-MS. Three suites can be recognised within the assemblage; Suite I basalts are characterized by weakly depleted to enriched LREE $[(La/Sm)_n=0.9-1.2]$ and weakly fractionated HREE $[(Gb/Yb)_n=1.1-1.2]$ in conjunction with flat to positive Nb anomalies. Suite II is characterized by LREE depleted basalts $[(La/Sm)_n=0.4-0.7]$ and unfractionated HREE $[(Gb/Yb)_n=0.9-1.1]$, while Suite III consists of basalts to dacites that are LREE enriched with weakly fractionated HREE $[(La/Sm)_n=2.6-4.7, (Gd/Yb)_n=0.8-2.4]$ and pronounced negative Nb anomalies.

Sm-Nd isotope work on select samples is currently underway with initial epsilon-Nd values indicating little to no crustal contamination of the samples. Preliminary interpretations suggest the Norton Lake area formed in a tectonic setting analogous to modern island arcs and is best compared with the Northern Pickle Assemblage of the Pickle Lake belt rather than the McGruer assemblage of the North Caribou terrane.

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Platinum Mineralization at Drill Hole A4-11 of the Wetlegs Area of the Partridge River Intrusion, Duluth Complex, Northeast Minnesota

KAUKONEN, R.J., and ALAPIETI, T.T., University of Oulu, Oulu, Finland

Apparently either the more peculiar PGE mineralization at DU-15 of the South Kawishiwi Intrusion or the vast but low grade deposits of disseminated base-metal sulfides may have been the reason why, as it seems, the platinum potential of the Wetlegs area of the Partridge River Intrusion has almost been forgotten. The whole rock analyses from drill core A4-11 (Gladen, 1990) show significant PGE values (Fig.1), which undoubtedly warrant an investigation.

Unfortunately the best parts of the drill core A4-11 have been previously used for analysis and hence material for thin sections was not available throughout the core. The cryptic variation paths of the main rock-forming silicates are presented in Fig. 1. Compared to data from drill core A4-14 (Kaukonen, 1994), the crystallization paths of olivine and pyroxenes show distinctive similarities. The general upward increasing trend of primitiveness is particularly evident in olivine. Plagioclase compositions on the other hand don't really present any clear trends aside from perhaps a slight decrease down the drill hole in the lower half of the core.

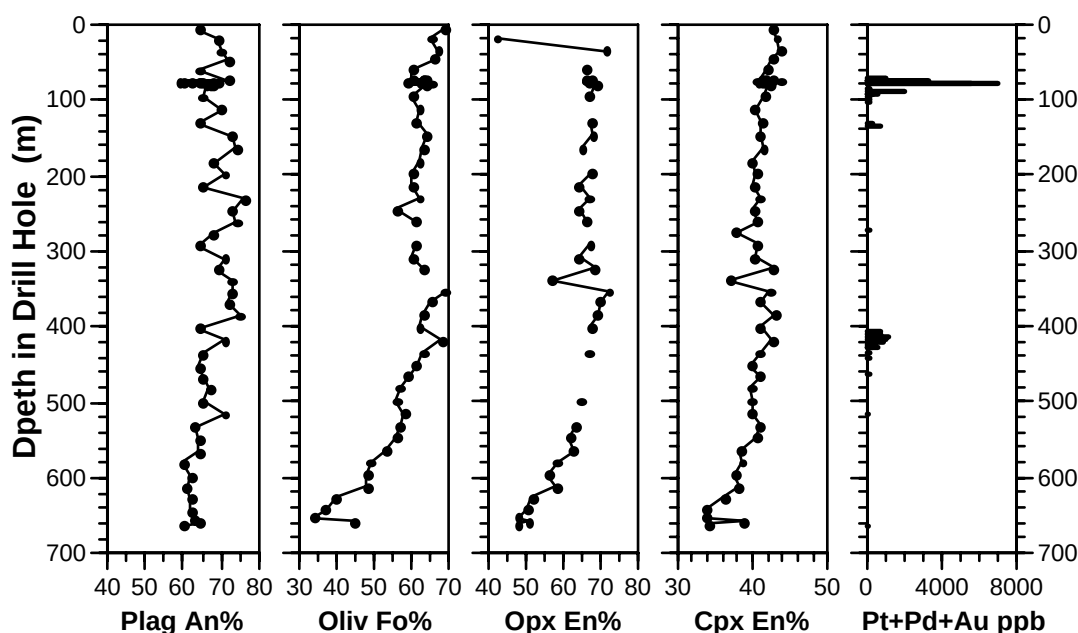


Fig.1. Cryptic variation paths of the main rock-forming silicates and the determined concentrations of noble metals in drill hole A4-11.

The best PGE values are found between 70-80 meters down hole. The highest Pt+Pd+Au value is about 7 ppm, of which Au accounts for just less than 1 ppm (Fig.1). Petrologically the mineralization seems to be a somewhat 'classic' base-metal sulfide type PGE mineralization where the platinum-group minerals are mainly associated with disseminated base-metal sulfides, mainly chalcopyrite and pyrrhotite. The most significant difference to the classic or often referred to as *orthomagmatic* PGE mineralizations is probably related to the silicates rather than sulfides, as the host rock is essentially troctolite rather than orthopyroxenite. This feature, however, is well in accordance with the crystal mush theory of Miller and Weiblen (1990).

As each mineralization has some unique characteristics, the A4-11 PGE mineralization also has its own signature. One of the most striking features is the notable occurrence of native copper, which is widely present. The grain size of copper is usually very small, yet it is readily distinguishable with an ore microscope using a relatively small magnification. The presence of native copper is possibly an indication of a reducing environment, and here it is mainly an alteration product of chalcopyrite. The platinum-group mineralogy of the A4-11 mineralization is also rather special. The most common PGMs are stannides and plumbates (Komppa, 1998). The minerals identified and analyzed for this investigation included atokite (Pd_2Sn) and zvyagintsevite (Pd_3Pb). However, as pointed out by Cawthorn et al. (2002), the platinum-group mineralogy of any given deposit is not necessarily a reflection of the primary processes involved in the enrichment of the PGE in a stratiform deposit, but rather a product of secondary processes that shape the mineralization further.

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MAGNETIC SUSCEPTIBILITY ANISOTROPY AND REMANENT MAGNETISM OF QUARTZITE AND PHYLLITE FROM BARABOO WISCONSIN

KEAN, William F., Department of Geosciences, UW-Milwaukee, P.O. Box 413, Milwaukee WI 53201, wkean@uwm.edu

The Baraboo quartzite and the associated phyllite are paleomagnetically well behaved rocks, with single magnetic directions carried by hematite, but with different directions for the rock types. The magnetism in the quartzite is associated with single domain hematite grains, is pre-folding, and is consistent with an ~1760 Ma age of formation (Kean and Mercer, 1986). The phyllite is dominated by multidomain hematite, (Kelly and Kean 2001), and although the magnetic directions are internally consistent at any one site, they are scattered between sites both before and after a fold test. The presence of multidomain hematite grains (up to 100 μ) suggests the remanence was developed during metamorphism which could have occurred during the folding in the region, or from fluids introduced at a later time when the radiometric ages were reset (Medaris et al., 2003).

In an attempt to better understand these differences in magnetic directions, a large block of rock that contained quartzite and phyllite was collected from the south limb of the Baraboo Syncline at an outcrop on Highway 12. A series of 2.5-cm. diameter cores were drilled from each of the layers for thermal demagnetization and anisotropy of magnetic susceptibility (AMS) measurements. The results presented in Figure 1 show that the phyllite has higher values of AMS (P') than the quartzite, and the magnetic grains are more oblate in shape (T) compared to the quartzite.

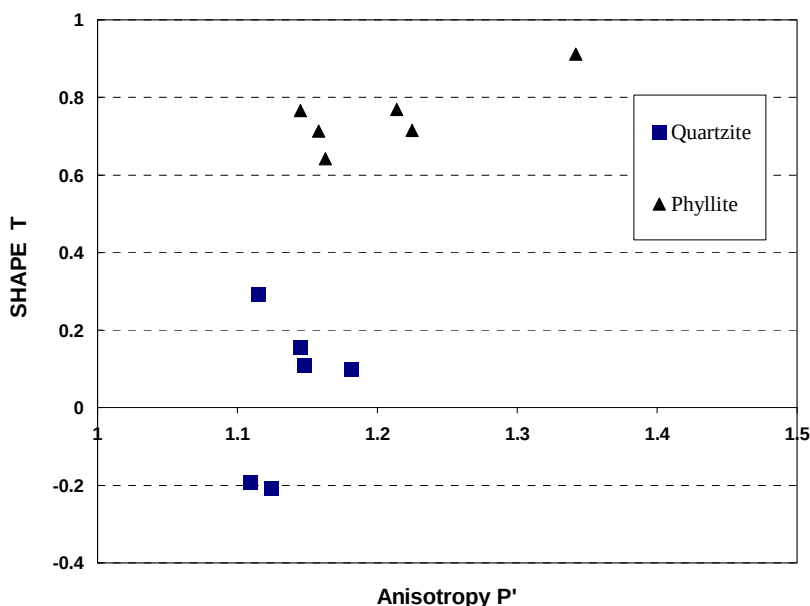


Figure 1. Anisotropy of Magnetic Susceptibility (AMS) P' versus shape factor T for samples

from the Baraboo region. T values below zero are prolate in shape, values near zero are neutral, and values above zero are oblate in shape. The phyllite shows large values of anisotropy and is strongly oblate. The quartzite is close to neutral in shape and of lower anisotropy.

The comparison between remanent magnetic directions and AMS ellipsoid axes for the two rock types is presented in Figure 2. The magnetic direction for the phyllite is perpendicular to the minimum anisotropy axis and is rotated toward the bedding plane. The magnetic direction for the quartzite appears to be unrelated to the susceptibility anisotropy.

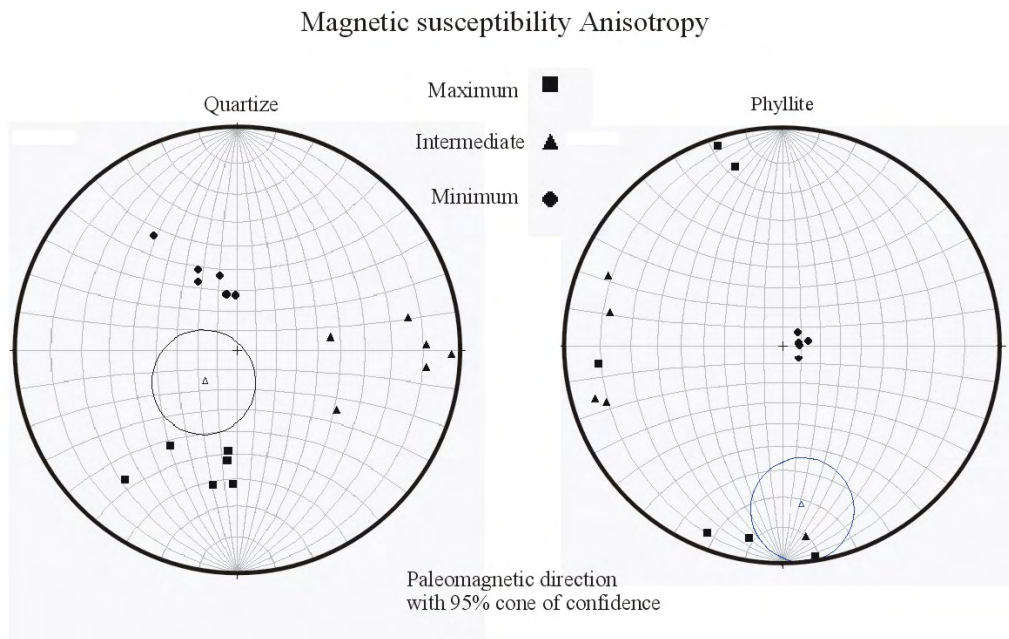


Figure 2: Comparison of paleomagnetic directions and AMS for quartzite and phyllite samples at Highway 12 outcrop.

It appears that the disparity in the magnetic directions in the phyllite zone is related to the amount of local strain that occurred during the metamorphism and formation of the Baraboo syncline, and not related to later fluid injection associated with the Wolf River batholith intrusive event. Limited AMS results from other phyllite sites in the region provide similar results.

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Lithic Materials and Archaeology in the Western Lake Superior Region

KLAWITER, Brian, Superior National Forest, Duluth, Minnesota 55808, USA

The most prevalent and enduring artifacts left behind by prehistoric cultures are those made of stone. The study of these cultural material remains shows that prehistoric people were very perceptive and discerning “geologists” when it came to choosing the stone materials that they would use. The available lithic materials had a broad range of useful properties that were to be carefully considered when choosing the raw material for a particular tool or purpose. Prehistoric people developed a keen eye for the desired physical properties of stone, and they knew where to get it. One enduring legacy from these prehistoric and early historic people is in the form of place-names such as *Gunflint Lake* and *Knife Lake*; both translated from the earlier Ojibwe names (Upham, 1920), and both of which have subsequently passed their names along to major geologic features: the Gunflint Iron Formation and the Knife Lake Group metavolcanics and metasediments. This presentation will display and describe many of the geologic materials and their prehistoric uses as discovered by archaeologists working in the western Lake Superior region.

In addition to studying prehistoric cultures, it is often equally interesting to study the modern archaeologists who study the ancient cultures. Most archaeologists are students of the Social Sciences whose occupation requires them to acquire a basic working knowledge of geology. This geologic education is often acquired in the field or in the lab by peer interaction, rather than in the classroom by professional geologists. As a result, the field of archaeology has in many ways developed its own sub-culture of geology, which is best displayed in the naming systems applied to the geologic materials recovered from archaeological excavations. This ad hoc (and locally territorial) nomenclature is often confusing to archaeologists and bewildering to geologists. For those interested in the overlap of geology and archaeology, this presentation outlines the archaeological nomenclature applied to geologic formations and materials in the western Lake Superior region, and highlights the efforts of this author and others to “reform” the archaeological nomenclature to more generally conform to geologic standards.

Keywords: archaeology, lithics, Gunflint, Knife Lake, nomenclature, Superior National Forest

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REGIONAL TILL SAMPLING IN THE VERMILION GREENSTONE BELT, MINNESOTA: PRELIMINARY RESULTS AND INTERPRETATIONS

LARSON, P.C., Department of Geological Sciences, University of Minnesota, Duluth, MN 55812, plarson2@d.umn.edu

A project of regional till sampling was undertaken over the Vermilion greenstone belt during the 2001 and 2003 field seasons. Samples were collected to provide coverage of ~1 sample per 3 km² in the area between Tower and Ely, MN. The silt+clay fraction (<63µm) of B- and C-horizon till samples was analyzed for gold, platinum, and palladium by fire assay and for 47 major- and trace-elements by ICP-MS and ICP-AES. The regional sampling program provides information on the background concentrations of various elements in till, as well as the presence and location of anomalous gold and base metal indicator concentrations. In conjunction with the sampling, observations on the character and distribution of glacial sediments overlying the greenstone belt were made to provide a framework for interpretation of the till geochemical data set.

The study area records a simple record of Quaternary events. Till cover is generally thin and discontinuous over the study area, with the exception of the Vermilion and Wahlsten moraines. Essentially all glacial sediments were deposited during the final retreat of ice from the study area (the Vermilion Phase). Moraine orientations indicate ice was flowing at 180° to the Wahlsten moraine, and 195° to the slightly younger Vermilion moraine.

Elements in till associated with the granite-gneiss Vermilion granitic complex to the north of the greenstone belt (Be, K, Rb, Ba) show a systematic decrease in concentration along glacial flow-lines south of the Vermilion fault (the contact between the granitic complex and greenstone belt). This demonstrates that the composition of till overlying the greenstone is overwhelmingly a function of physical transport by glacial action. Till overlying the greenstone is therefore a mixture of material transported from the Vermilion granitic complex and material eroded from the greenstone belt; quantification of this mixing trend indicates a mean transport length of ~8 km for till-forming material.

The till sampling program has clearly identified a number of areas with anomalous precious and base metal concentrations. Highlights include a number of samples with >50 ppb gold, including one sample with 940 ppb gold. Copper values up to 314 ppm, zinc values up to 368 ppm, and platinum values of up to 8 ppb were also reported. Higher density follow-up sampling is recommended to more clearly define and determine the significance of anomalies, as well as determine the location of potential source rocks. The results of this survey clearly demonstrate the utility of till compositional surveys for exploration in the Vermilion greenstone belt, as well as nearby areas with a similar glacial geological setting.

EARLY ADVANCE OF THE ST. LOUIS SUBLOBE: A REVISED CHRONOLOGY OF THE DEGLACIATION OF NORTHEASTERN MINNESOTA

LARSON, P.C., MOOERS, H.D., and MARLOW, L.M., Department of Geological Sciences, University of Minnesota, Duluth, MN 55812, plarson2@d.umn.edu

The general retreat of the Laurentide Ice Sheet (LIS) from Minnesota during the Late Wisconsin was characterized by a fluctuating boundary between ice originating in the Keewatin and Labradoran accumulation centers. Recent investigations into the glacial geology of central and northern Minnesota have newly recognized stratigraphic relationships prompting revision of the deglacial chronology.

A prominent event during deglaciation was the advance of the Keewatin-provenance St. Louis Sublobe (Alborn phase) from the Red River Valley across northern Minnesota into the area vacated by the retreating Labradoran-provenance Rainy Lobe. This advance has previously assigned a relatively late age (~12 ka) and correlated with post-Vermilion phase margins of the Rainy Lobe, implying that ice-free conditions existed between the Rainy Lobe and the Giant's Range at the time of the advance. However, the absence of Keewatin till north of the Giant's Range despite the presence of such till at the crest of the Giant's Range, combined with evidence for abundant stagnant Rainy Lobe ice south of the Giant's Range, suggests the St. Louis Sublobe advance occurred while active Rainy Lobe ice was present immediately north of the Giant's Range. A newly identified Rainy Lobe ice margin confirms this relationship; this margin is probably correlative with the previously described Allen moraine. We refer to the phase of the Rainy Lobe responsible for its formation as the *Northofnashwauk phase*.

The relationships above indicate that the Alborn phase occurred significantly earlier than previously believed. Retreat of the St. Louis Sublobe from its Alborn phase maximum occurred by stagnation and wastage of a large mass of ice. The next prominent recessional moraine formed at the suture between active and stagnant ice in southern Beltrami County (*Rabideau moraine*). Here, ice-contact meltwater channels emanated outward from the ice margin, terminating as outwash fans at the edge of the stagnant ice. The Rabideau moraine is correlative with the post-Northofnashwauk *Big Rice phase* and moraine of the Rainy Lobe. Much of the meltwater drained into *Glacial Lake Sucre*, a western extension of Glacial Lakes Aitkin and Upham II. Sucre drained after abandonment of the Hellwig Creek outlet of Upham II. The Rainy and St. Louis Sublobes retreated from the Big Rice and Rabideau moraines to the Vermilion and Big Stone(?) moraines, respectively.

These newly recognized stratigraphic relationships indicate that the St. Louis Sublobe advanced immediately after recession of the Rainy Lobe. Consequently, Glacial Lakes Aitkin-Upham I were much shorter lived, and Aitkin and Upham II much longer lived, than previously believed.

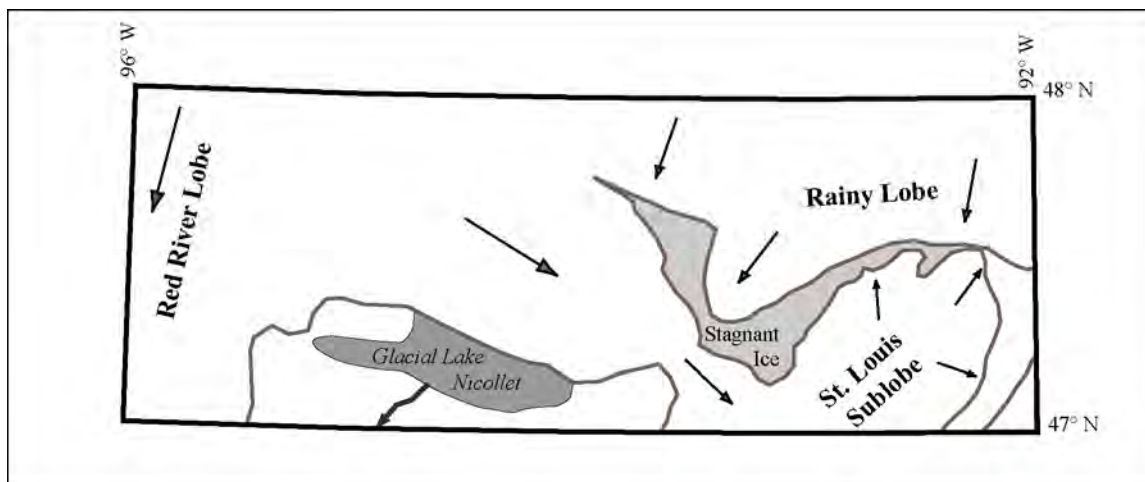


Figure 1. Ice margin positions during Northofnashwauk and Alborn Phases, ca. 13.5 kyr BP.

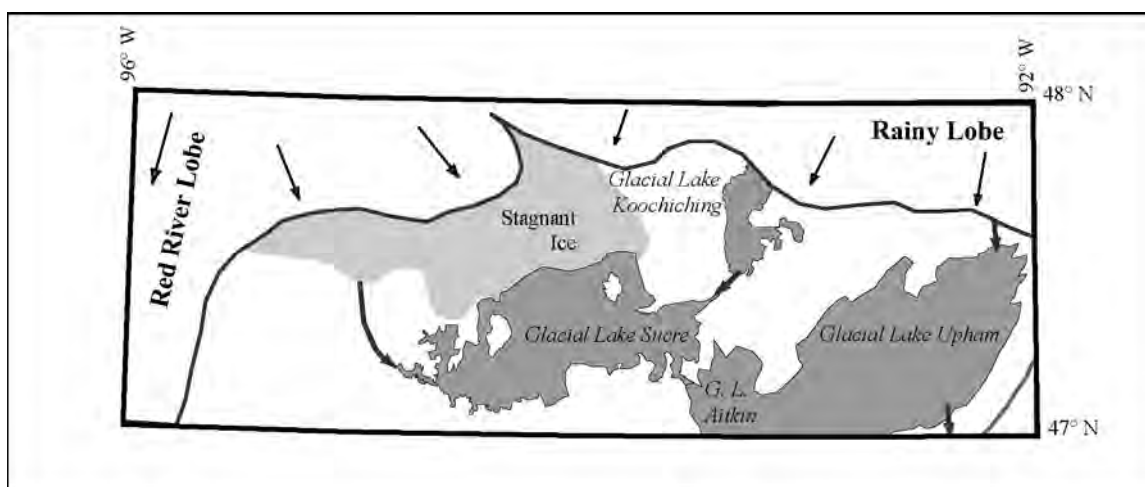


Figure 2. Ice margin positions during Big Rice Phase, ca. 13 kyr BP.

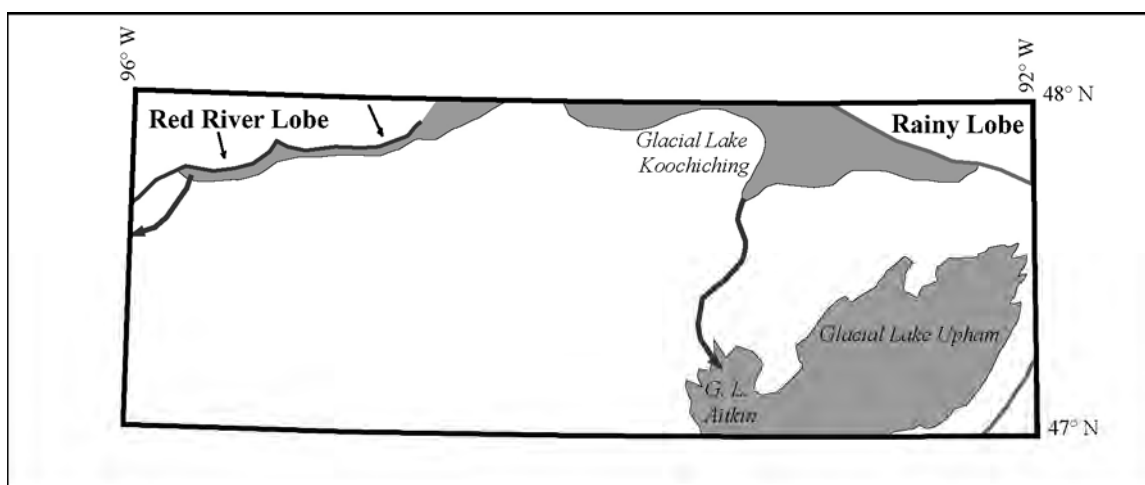


Figure 3. Ice margin positions during Vermilion Phase, ca. 12.5 kyr BP.

Lake Nipigon Region Geoscience Initiative: Results of Bedrock Mapping in the Northern Part of the Western Nipigon Embayment, Northwestern Ontario, Canada

MacDONALD, C.A. and TREMLAY, E.

Precambrian Geoscience Section, Ontario Geological Survey, Ministry of Northern Development and Mines, Sudbury, Ontario, Canada, P3E 6B5

As part of the Lake Nipigon Regional Geoscience Initiative (LNRGI), a 2-year, 1:50 000 scale mapping program was begun in 2003 to better understand the geology of the western Nipigon Embayment. This talk presents results based on mapping of an area of roughly 1200 km² during the 2003 field season, and focuses on Proterozoic rocks in the map area (Fig. 1) (MacDonald 2004; MacDonald et al. 2004a, 2004b). This project is funded by the Northern Ontario Heritage Fund Corporation (NOHFC) through the Ontario Prospectors Association.

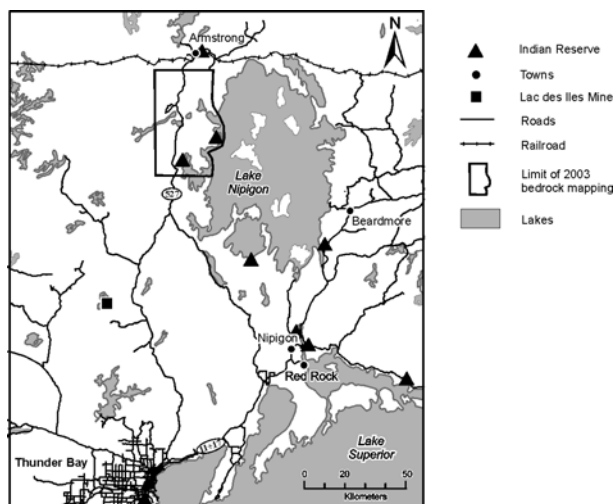


Figure 1. Key map showing the location of the 2003 map area.

The 2003 map area is located approximately 190 km north of Thunder Bay and is partially bordered by the shore of Lake Nipigon on its east margin (Fig. 1, 2). Rocks of both the Superior and Southern provinces occur in the map area and include Archean rocks of the volcanic-plutonic central Wabigoon Subprovince that are disconformably overlain by Mesoproterozoic sedimentary rocks of the Sibley Group, all of which are intruded by Mesoproterozoic mafic igneous rocks.

Archean rocks consist dominantly of variably foliated to gneissic, felsic to intermediate, granitoid rocks and mafic to felsic metavolcanic rocks. A 30 metre thick flat-lying succession of mafic volcanic pillowed flows occurs in the northern part of the map area. The undeformed nature of these flows, combined with the well-preserved nature of relatively delicate features such as hyaloclastite suggests that these rocks may be Proterozoic rather than Archean in age. If so, they would be the first Proterozoic

mafic volcanic rocks reported this far north of the Midcontinent Rift. Alternatively, they could represent a previously unrecognized greenstone belt within the Superior Province.

Pre-Keweenawan rocks include anorogenic igneous and associated metavolcanic rocks of the English Bay complex and sedimentary rocks of the Sibley Group. The English Bay complex (~1540 Ma, Davis and Sutcliffe 1985) consists mainly of massive quartz and feldspar crystal tuffs with a variety of fragment types suggesting an extrusive, volcanic origin for most of the complex. Sibley Group clastic and chemical sedimentary rocks are few, and a combination of paleotopography on the Archean surface as well as the erosional level of the overlying diabase sills probably controls their distribution.

At least one olivine gabbro sill, referred to as the Jackfish Island sill, intrudes the English Bay complex. The Jackfish Island sill has geochemical affinities (Fig. 3) with the Kitto peridotite intrusion located on the east side of the Nipigon Embayment (Hart 2003). Both the Jackfish Island and Kitto peridotite are roughly coeval with the ~1110 Ma Nipigon diabase sills (Davis and Sutcliffe, 1985).

Nipigon diabase sills intrude and overlie all previously noted rock types and are part of the 1.11 to 1.09 billion-year-old Midcontinent Rift. The Nipigon sills are generally massive, medium-grained, intergranular-textured and gabbroic in composition with local variations including ophitic and poikilitic textured diabase, oikocrystic diabase and magnetite-rich to locally glomeroporphyritic magnetite phases. Coarse-grained pods, veins and/or monzogabbroic phases also occur within the diabase and could represent a late magmatic phases of the sills or assimilation of Sibley Group sedimentary rocks, or both (Hart and Magyarosi, 2004). The diabase sills intrude and typically overlie all other rock units. The diabase sills are tentatively subdivided into 2 types: 1) The Inspiration sills, located in the northern part of the map area, which have higher trace element ratios (Fig. 3) and normal

remnant magnetization than typical Nipigon sills, and 2) Sills located in the southern part of the map area that are reversely polarized and which have lower trace element ratios. This southern group of sills are grouped with the typical Nipigon sills (Fig. 3).

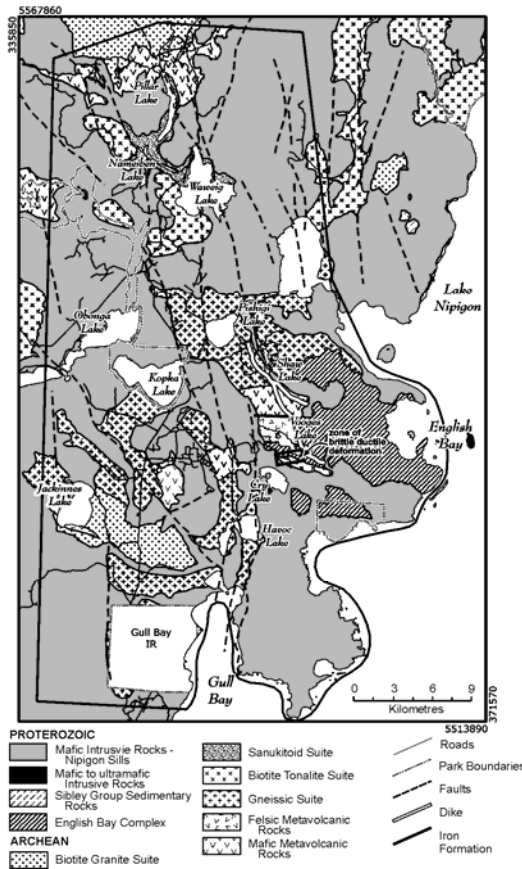


Figure 2. General geology of south Armstrong–Gull Bay area

A series of subparallel north- and northwest-trending faults that occur within the Black Sturgeon Fault corridor may be related to the formation of the Midcontinent Rift (Fig. 2). These faults may also in part control the location of Archean inliers. Vertical displacement on both fault sets range from 200 to 400 metres.

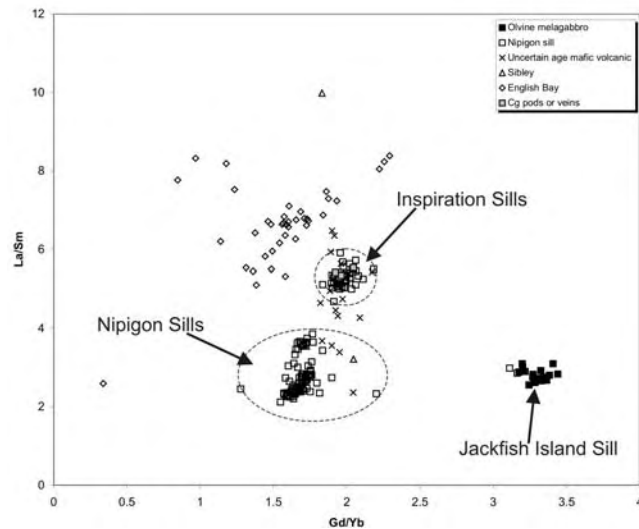


Figure 3. La/Sm versus Gd/Yb for samples from the English Bay complex, Jackfish Island Sill, Nipigon sills and Inspiration sills.

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Precambrian Geology of the South Armstrong–Gull Bay Area, Nipigon Embayment, Northwestern Ontario, Canada

MacDONALD, C.A., and TREMBLAY, E.

Precambrian Geoscience Section, Ontario Geological Survey
Ministry of Northern Development and Mines, Sudbury, Ontario, Canada, P3E 6B5

As part of the Lake Nipigon Regional Geoscience Initiative (LNRGI), a 2-year, 1:50 000 scale mapping program was begun in 2003 to better understand the geology of the western Nipigon Embayment. As part of LNRGI, this study mapped an area of roughly 1200 km² during the 2003 field season (MacDonald 2004; MacDonald et al. 2004a, 2004b). The project was funded by the Northern Ontario Heritage Fund Corporation (NOHFC) through the Ontario Prospectors Association. This poster presentation highlights some of the preliminary results of this mapping program.

The south Armstrong–Gull Bay area is located approximately 190 km north of Thunder Bay and is partially bordered by the shore of Lake Nipigon on its east margin. Rocks of both the Superior and Southern provinces occur in the map area and include Archean rocks of the volcanic-plutonic central Wabigoon Subprovince that are disconformably overlain by Mesoproterozoic sedimentary rocks of the Sibley Group, all of which are intruded by Mesoproterozoic mafic igneous rocks.

Archean rocks consist dominantly of variably foliated to gneissic, felsic to intermediate, granitoid rocks and mafic to felsic metavolcanic rocks. A 30 metre thick flat-lying succession of mafic volcanic pillowed flows occurs in the northern part of the map area. The undeformed nature of these flows, combined with the well-preserved nature of relatively delicate features such as hyaloclastite suggests that these rocks may be Proterozoic rather than Archean in age. If so, they would be the first Proterozoic mafic volcanic rocks reported this far north of the Midcontinent Rift. Alternatively, they could represent a previously unrecognized greenstone belt within the Superior Province.

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At least one olivine gabbro sill, referred as the Jackfish Island sill, intrudes the English Bay complex. The Jackfish Island sill has geochemical affinities with the Kitto peridotite intrusion located on the east side of the Nipigon Embayment (Hart 2003). Both the Jackfish Island and Kitto peridotite are roughly coeval with the ~1110 Ma Nipigon diabase sills.

Nipigon diabase sills intrude and overlie all previously noted rock types and are part of the 1.11 to 1.09 billion-year-old Midcontinent Rift. The Nipigon sills are generally massive, medium-grained, intergranular-textured and gabbroic in composition with local variations including ophitic and poikilitic textured diabase, oikocrystic diabase and magnetite-rich to locally glomeroporphyritic magnetite phases. Coarse-grained pods, veins and/or monzogabbroic phases also occur within the diabase and could represent a late magmatic phases of the sills or assimilation of Sibley Group sedimentary rocks, or both (Hart and Magyarosi, 2004). The diabase sills intrude and typically overlie all other rock units. The diabase sills are tentatively subdivided into 2 types: 1) The Inspiration sills, located in the northern part of the map area, which have higher trace element ratios and normal remnant magnetization than typical Nipigon sills, and 2) Sills located in the southern part of the map area that are reversely polarized and which have lower trace element ratios. This southern group of sills are grouped with the typical Nipigon sills.

Several northwest- and north-trending faults are prominent in the map area. Northwest-trending faults appear to correlate with structures in the central Wabigoon Subprovince and may control the distribution of Archean inliers. A series of subparallel north-trending faults, which include the Black Sturgeon fault, may represent faults related to the formation of the Midcontinent Rift. The vertical displacement on both fault sets range from 200 to 400 metres.

The mineral potential within the map area consists of previously undocumented areas of Archean mafic and felsic metavolcanic rocks that may hold potential for Pb-Cu-Zn volcanogenic massive sulphide (VMS) deposits. Two areas of brittle-ductile deformation within the metavolcanic rocks may also hold potential for shear zone-hosted gold deposits. The mafic to ultramafic portions of an Archean sanukitoid multiphase intrusion should be investigated for platinum group element potential, since gabbroic to pyroxenitic rocks with disseminated chalcopyrite, pyrrhotite and pyrite from the Roaring River Complex have returned assays up to 2.1 g/t Pt+Pd+Au (Schnieders et al. 2002). Cr-Ni-Cu-platinum group element potential exists in both Proterozoic mafic to ultramafic bodies within the map area. Several areas within the Nipigon Embayment may have potential to host iron oxide-copper-gold (i.e., Olympic Dam type) deposits, particularly the English Bay complex.

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Magnetic Fabric Constraints on Magmatic Flow: Insizwa Sill, South Africa and the Sonju Lake Intrusion, Minnesota.

MAES, Stephanie, TIKOFF, Basil, BROWN, Phil, Department of Geology and Geophysics,
University of Wisconsin, Madison, Wisconsin 53706

FERRÉ, Eric, Department of Geology, Southern Illinois University, Carbondale, Illinois 62901

Layered mafic intrusions are an important aspect of plate tectonics, commonly related to large igneous provinces and potentially acting as conduits for continental flood basalts. Although they are the source for most of the world's PGE (platinum group element) and Cr deposits, as well as important Cu and Ni reserves, a large degree of uncertainty exists as to how these systems evolve.

Magnetic fabrics, which often closely relate to the mineral fabric, allow us to document magmatic structures and map out the direction(s) of flow within an intrusion. Magnetic fabrics are determined using anisotropy of magnetic susceptibility (AMS) analysis. Knowledge of flow direction may permit us to place constraints on the location of ore deposits as well as to test models of magmatic sulfide deposition. In addition, these techniques allow us to evaluate the importance of vertical cumulus processes versus horizontal particle flow in the formation of layering.

When applied to the study of mafic intrusions, standard magnetic techniques such as low field AMS do not always provide a fabric that reflects the flow field. This is due to the complex magnetic behavior of mafic rocks. Mafic rocks often contain multiple magnetic carriers and magnetite domain sizes, which can negatively affect the AMS fabric. A new magnetic approach, high field AMS (HFAMS), has been used to separate these complex anisotropies. By applying HFAMS techniques the ferromagnetic (magnetite) and paramagnetic (mafic silicate) components of the anisotropy can be separated. Hysteresis properties are then used to identify the domain size of magnetite.

Our approach is to compare magmatic fabrics in two intrusions with contrasting genetic histories. In a closed system, such as the Sonju Lake intrusion, petrologic models predict a gradual upward increase in magnetite. In contrast, open systems, where episodes of recharge, eruption and/or assimilation can occur, result in a multimodal distribution of magnetite. The Insizwa sill, South Africa represents a system open to magmatic recharge.

Bulk magnetic susceptibility measurements of closely spaced samples from vertical borehole cores within the Insizwa sill have documented significant variation in magnetic properties with depth (see attached figure). Variation in the magnetic signal results from changes in concentration and/or mineralogy of the magnetic material. In addition, a strong correlation exists between petrology of particular layers and bulk susceptibility. Preliminary high field results show consistent high field slopes, indicating a constant paramagnetic contribution to the susceptibility. Hysteresis ratios indicate magnetite is predominantly pseudosingle- and multi-domain, with minor single domain in the lower portions of the sill.

In the Sonju Lake intrusion, a more straightforward interpretation of the magnetic properties is expected due to the nearly closed system nature. The same magnetic techniques will be applied to Sonju Lake to fully describe the intrusion and provide insight to the various fabric forming processes occurring in open and closed systems.

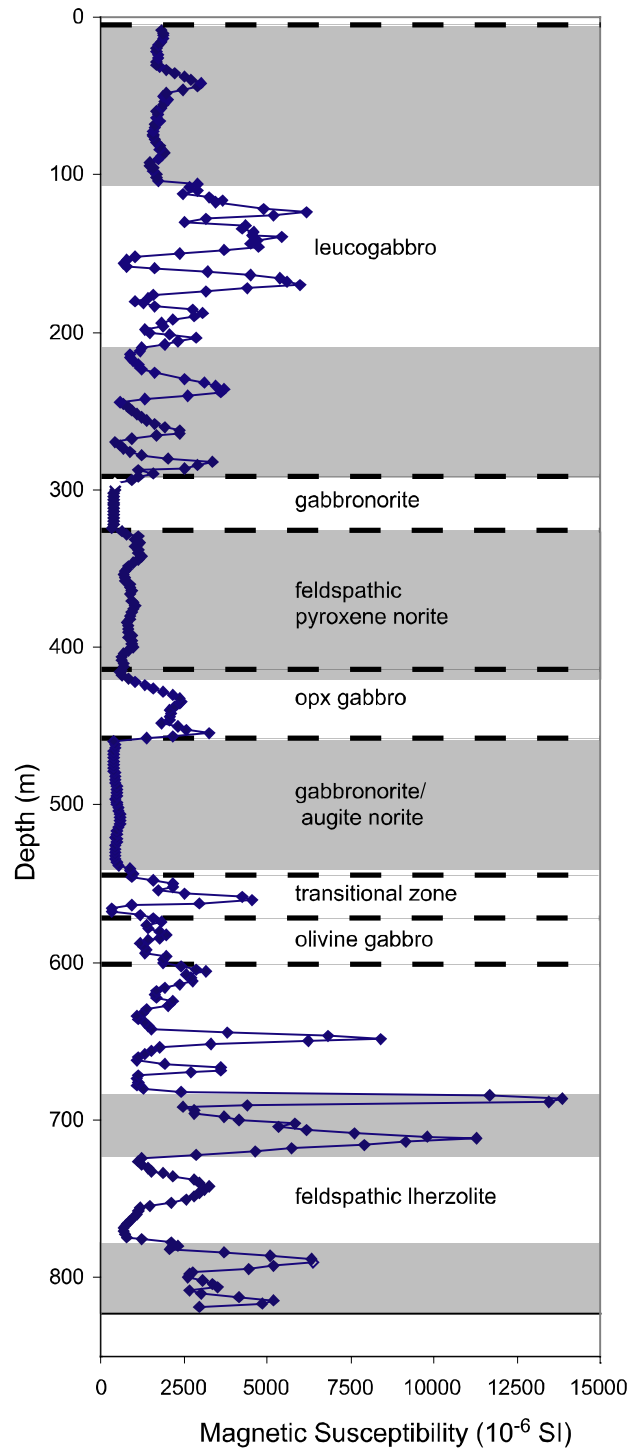


Figure 2. Downcore variability of magnetic susceptibility in Insizwa borehole core INS98-08. Dashed lines denote petrologic units defined by Falconbridge mining during borehole logging. Gray and white fields show magnetic units that were defined based on consistent magnetic properties

MINING AND EXPLORATION ACTIVITY IN NORTHWESTERN ONTARIO

MAGEE, Angelique, Ontario Geological Survey, Ministry of Northern Development and Mines, Suite B002, 435 James St. South, Thunder Bay, ON P7E 6S7 CANADA

Northwestern Ontario experienced a significant upswing in mining and mineral exploration in 2003. Six mines produced a total of 1.8 million ounces of gold in 2003, approximately 70% of Ontario's total.

Gold producers included:

Campbell Mine (*Placer Dome (CLA) Ltd.*);

David Bell Mine (*Teck Cominco Limited and Barrick Gold Corporation*);

Golden Giant Mine (*Newmont Canada Limited*);

Musselwhite Mine (*Placer Dome (CLA) Limited / Kinross Gold Corporation*);

Red Lake Mine (*Goldcorp Inc.*); and

Williams Mine (*Teck Cominco Limited and Barrick Gold Corporation*).

North American Palladium Ltd. produced 288 000 ounces of palladium and 24 000 ounces of platinum at its Lac des Iles Mine and recently announced it would develop an underground operation below its open pit mine.

There are approximately 300 active exploration projects in the northwest, the vast majority of which are focused on gold. Areas receiving the most interest from exploration companies were, the Red Lake greenstone belt, Shoal Lake area, Dogpaw Lake area, Shebandowan greenstone belt, Fort Hope greenstone belt, Onaman-Tashota belt and the Pickle Lake greenstone belt. If metal prices continue their upward trend, northwestern Ontario may well experience levels of exploration activity not seen since the mid-1980s.

THE DISCOVERY AND GEOLOGY OF THE L-K MASSIVE SULFIDE DEPOSIT, MENOMINEE COUNTY, MI

MAHIN, Robert A., Aquila Resources Corp., Duluth, MN

QUIGLEY, Thomas O., Minerals Processing Corp, Duluth, MN

LYNOTT, Jeffrey S., Environmental Compliance Consultants, Inc, Rhinelander, WI.

The L-K zinc-gold deposit is a recently discovered major volcanogenic massive sulfide (VMS) of the early Proterozoic Penokean volcanic belt. Several events led to the eventual drilling of discovery hole LK-2, (37 meters @ 9.15 % Zn and 5.85 grams/tonne Au) none of which were part of earlier Wisconsin VMS exploration efforts. Prior AEM surveys to the north, west, and south failed to include the immediate deposit area, an area that despite proximal outcrops of intensely sericite-pyrite-altered rhyolite tuffs, was mapped as granitic intrusives and Paleozoic cover. The discovery of L-K can be attributed to Harry Kleiman, a water-well driller who deepened a local camp owner's water well, his partner Rich Lassen, who recognized the sphalerite-rich drill cuttings as a potential VMS and subsequently located a nearby outcropping gold-rich gossan, and Tom Quigley, who later joined the partnership and pinpointed a significant gravity/conductive anomaly that turned out to be the L-K deposit. A joint venture with American Copper and Nickel Company, a subsidiary of Inco, resulted in a drilling program of 71 holes for over 20,000 meters of core. The drilling outlined a significant zinc-gold rich VMS within what appears to be a major felsic center. Significant portions of the deposit contain consistent grades of zinc in excess of 10 percent. Gold grades within massive sulfides range from 1 to 6 grams/tonne. Significant gold mineralization also occurs in proximal sulfide stringers (e.g., 4.2 meters @ 25.3 grams/tonne Au), and in peripheral silicified zones in rhyolite tuffs and QFP dikes (e.g., 12.5 meters @ 7.4 grams/tonne Au). The near-surface gossan averages approximately 16 grams/tonne Au. The stratigraphy of the deposit consists of a stacked series of quartz-feldspar rhyolite crystal tuffs, locally fragmental, with intermittent fine-grained ash-tuff horizons, overlain by fine-grained, laminated tuffaceous sediments. Mineralization occurs as massive (>80%) pyrite+sphalerite±chalcopyrite±galena localized at two stratigraphic contacts. Host rocks are intensely sericitized and silicified quartz-feldspar rhyolite tuffs and tuffaceous sediments. Structurally, the deposit and surrounding host rocks have been folded into a west/southwest-plunging, south verging antiform. The deposit is located both in the core of the antiform, where it appears to be tectonically thickened, and in the limbs of the fold. Numerous syntectonic, west-southwest-striking, steeply dipping, quartz-feldspar dikes intrude proximal to the deposit. Drilling has traced the massive sulfide along strike for 700 meters with vertical projections of the deposit ranging from 50 to 270 meters wide. Down-plunge, massive mineralization has been traced to a depth of approximately 300 meters. The deposit remains open at depth and along strike.

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MAHIN Robert A., Aquila Resources Corp., Duluth, MN

QUIGLEY, Thomas O., Minerals Processing Corp, Duluth, MN

LYNOTT, Jeffrey S., Environmental Compliance Consultants, Inc., Rhinelander, WI

The L-K deposit is a newly discovered volcanogenic massive sulfide deposit in the Beecher Formation of the early Proterozoic Penokean volcanic belt in western Menominee County, Michigan. The major economic metals at L-K are zinc and gold, with locally high concentrations of silver and copper. Mineralization occurs as massive (greater than 80%) pyrite+sphalerite+chalcopyrite+galena localized at two stratigraphic contacts within a large felsic volcanic center dominated by intensely sericitized and silicified quartz-feldspar, rhyolite tuffs. The stratigraphy consists of a stacked series of quartz-feldspar rhyolite crystal tuffs, locally fragmental, with intermittent fine-grained ash-tuff horizons, overlain by fine-grained, laminated tuffaceous sediments. The main-zone massive sulfide is hosted by altered hanging wall and footwall rhyolite crystal tuffs that are visually identical, but readily distinguishable by whole-rock geochemistry, e.g., ratios of Al and Ti (Cattalani 2003, Shriver 2003). Tuffaceous zone mineralization, while not as consistently thick as the main zone, contains impressive grades and is focused along the contact between hanging wall rhyolites and overlying tuffaceous sediments. The massive sulfides are enveloped by gold (and to a lesser extent copper) bearing stockwork stringer sulfides (10 to 80% sulfide) that grade into a disseminated pyritic halo. Structurally, the deposit and surrounding host rocks have been folded into a west-southwest-striking, southwest plunging, south verging asymmetric antiform. Tectonically thickened portions of the deposit occupy the core of the fold and large sections of mineralization are also found in the limbs. Numerous syntectonic, west-southwest striking, steeply dipping quartz-feldspar dikes intrude the deposit. Faulting has resulted in minor offsets. Drilling has traced the massive sulfide along strike for 700 meters, with vertical projections of the deposit ranging from 50 to 270 meters wide. Portions of the deposit sub-crop at the east-northeast up-plunge extension where an iron-oxide-rich, precious metal-enriched gossan has developed. Down-plunge, massive mineralization has been traced to a vertical depth of approximately 300 meters and remains open. Gradewise, drill intercepts of greater than 10 meters in excess of 10% zinc are common. Gold grades within massive sulfides range from 1 to 6 grams. Significant gold mineralization also occurs in proximal sulfide stringers (e.g., 4.2 meters @ 25.3 grams/tonne Au), and in peripheral silicified zones in rhyolite tuffs and QFP dikes (e.g., 12.5 meters @ 7.4 grams/tonne Au). Intercepts of the near-surface gossan average 3 meters thick and approximately 16 grams/tonne Au.

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MINERAL CHEMISTRY AND STRATIGRAPHY OF THE BIWABIK IRON FORMATION, NEAR THE VIRGINIA HORN, MESABI IRON RANGE, MINNESOTA

McSWIGGEN, Peter L., and MOREY, G.B., McSwiggen & Associates, P.A., 2855 Anthony Lane South, Suite B1, St. Anthony, MN (PMcS@McSwiggenAssoc.com; morey001@umn.edu)

The mineralogy of the Biwabik Iron Formation changes dramatically from west to east as the formation nears the basal contact of the Duluth Complex. This reflects a contact metamorphism that took place with the emplacement of the igneous Duluth Complex. However, the mineralogy of the Biwabik Iron Formation also varies vertically through the stratigraphy of the unit. A number of detailed studies have been done on the mineralogy of the contact zone (Bonnichsen, 1975). This investigation focused on the western Mesabi Range through the characterization of the E.J. Longyear Drill Hole #1 (S1/2, SW1/4, SE1/4, sec 23, T57N, R18W), which penetrated the entire section of the Biwabik Iron Formation from the overlying Virginia Formation through to the underlying Pokegama Quartzite (Fig.1).

The iron-formation has been subdivided into four broad stratigraphic units (Fig. 2), lower cherty, lower slaty, upper cherty, and upper slaty, and into four lateral mineralogical zones (1-4) that reflect the zonation resulting from the contact metamorphism. Zone 1, the westernmost zone and the one in which the Longyear drill hole is located, is characterized by quartz, magnetite, hematite, carbonates, talc, chamosite, greenalite, minnesotaite and stilpnomelane. Talc and minnesotaite are the Mg- and Fe-end members, respectively, of the talc group [$\text{Mg}_6\text{Si}_8\text{O}_{20}(\text{OH})_4$ – $\text{Fe}_6\text{Si}_8\text{O}_{20}(\text{OH})_4$]. Minnesotaite is the dominant end member in the Biwabik Iron Formation, and typically occurs as a fibrous mineral, though it is also found in a tabular form. Chamosite is a Fe-chlorite [$(\text{Fe}, \text{Al})_6(\text{Si}, \text{Al})_4\text{O}_{10}(\text{OH})_8$], and generally occurs as a platy mineral in granules within the iron-formation. These granules are sand size grains that are the result of the reworking of previously deposited materials, which reflects a higher energy depositional environment. Greenalite is the iron serpentine [$\text{Fe}_6\text{Si}_4\text{O}_{10}(\text{OH})_8$]. It is reported generally as having a platy, lizardite-like structure, and in the iron-formation occurs in granules. Stilpnomelane [$(\text{K}, \text{Na}, \text{Ca})_{0.6}(\text{Fe}, \text{Mg})_6\text{Si}_8\text{Al}(\text{O}, \text{OH})_{27.2-4\text{H}_2\text{O}}$] is a sheet silicate, but in the iron-formation it can occur in either a platy form or in a fibrous form. The above-described silicates do not occur uniformly throughout the stratigraphic section. In the Longyear core, chamosite + stilpnomelane is the dominant silicate assemblage in the upper three units (upper slaty, upper cherty and lower slaty). The assemblages minnesotaite + stilpnomelane, minnesotaite + talc, and greenalite + minnesotaite are the main silicate assemblages in the lower cherty.

The carbonates have a wide range of compositions and include calcite, dolomite-ankerite, siderite, and kutnahorite, the manganese equivalent of ankerite. Carbonates occur throughout the Biwabik Iron Formation, but become more dominant in the lower cherty interval. The manganese component of the carbonates varies greatly, ranging from less than 1 mole% MnCO_3 to as much as 25 mole percent.

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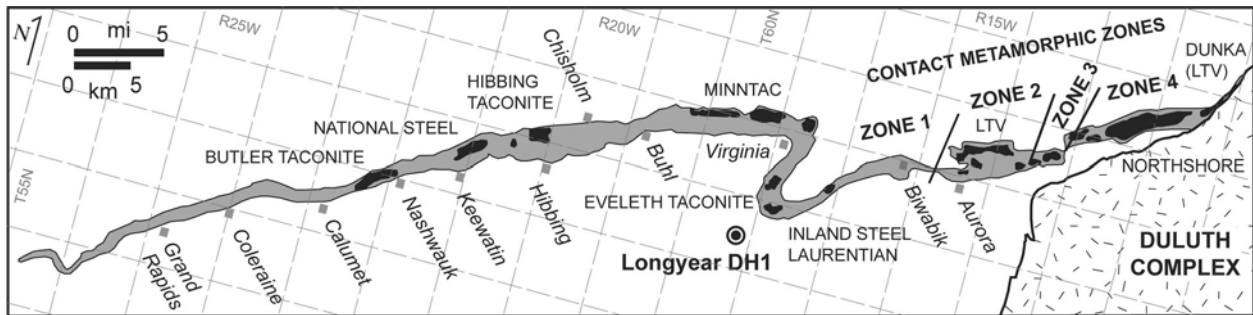


Figure 1. Simplified geologic map of the Mesabi Iron Range. The main geologic unit is the Biwabik Iron Formation (shown in gray) (after Jirsa and others (in press)).

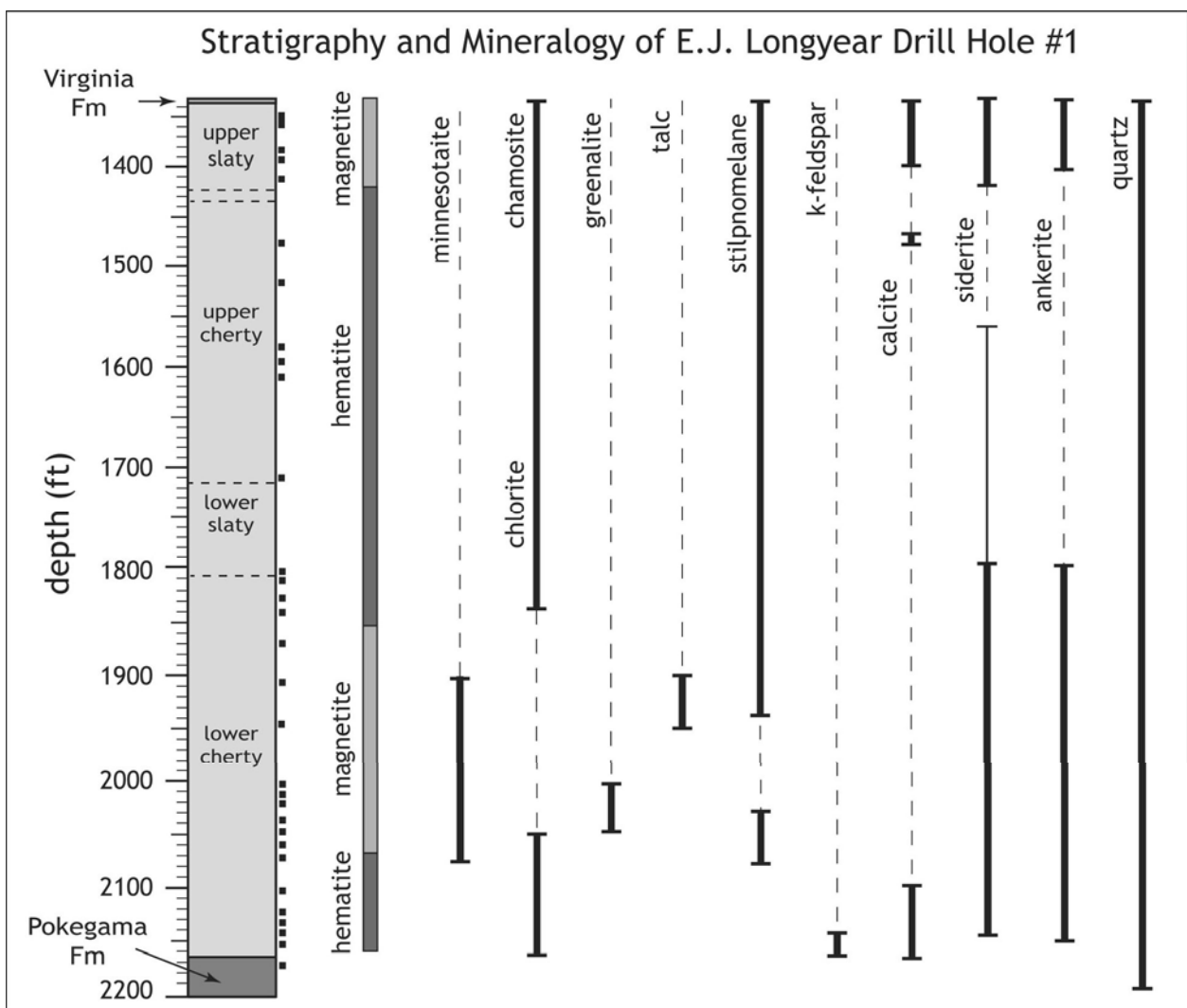


Figure 2. Stratigraphic section and mineralogy of the E.J Longyear Drill Hole #1. It was drilled as a long stratigraphic test hole and was finished in 1910.

GEOCHRONOLOGY OF PRECAMBRIAN ROCKS IN CENTRAL WISCONSIN: A REVIEW AND NEW $^{40}\text{Ar}/^{39}\text{Ar}$ ANALYSES

MEDARIS, Jr., Gordon and SINGER, Brad, Dept. of Geology & Geophysics, Univ. Wisconsin
Madison, Madison, WI, 53706; medaris@geology.wisc.edu; bsinger@geology.wisc.edu

Most of the Precambrian evolution of Wisconsin is recorded by basement rocks in the central part of the state. Reported here are new $^{40}\text{Ar}/^{39}\text{Ar}$ analyses of hornblende, muscovite, and microcline, which bear on the thermal history of this important area. Because this is the 50th meeting of ILSG, it seems appropriate to provide a selective review of geochronological investigations over the past half century and to place our new results in a historical context.

Review The framework for a modern classification of Precambrian rocks in the Great Lakes region was provided in 1961 by the seminal work of Goldich *et al.*, who analyzed a large number of igneous and metamorphic rocks by the K/Ar and Rb/Sr methods. A three-fold Precambrian division was proposed, with boundaries at 2.5 and 1.7 Ga, corresponding to the Algoman and Penokean orogenies, although it was recognized that the apparent K/Ar and Rb/Sr ages might reflect subsequent metamorphism.

In 1975 Van Schmus *et al.* established an apparent Rb/Sr age of ~1.65 Ga for a wide variety of igneous and metamorphic rocks in central and eastern Wisconsin. The few available U/Pb zircon data for such rocks yielded protolith ages of 1.8-1.9 Ga, and it was suggested that a widespread, low-grade metamorphic event, whose origin was poorly understood, affected the western Great Lakes region at 1.65 Ga. Also in 1975, Van Schmus *et al.* recognized the Wolf River batholith as a major igneous component in Wisconsin and determined equivalent Rb/Sr whole rock and U/Pb zircon ages of 1468 ± 34 and 1485 ± 15 Ma, respectively. With the continued acquisition of U/Pb analyses of zircon in the 1970s and 1980s, the Marshfield terrane in central Wisconsin was shown to consist of Archean gneiss (2.87-2.52 Ga) intruded and overlain by a wide variety of granitic rocks and associated felsic to intermediate volcanic rocks, ranging in age from 1.89 to 1.82 Ga (Sims *et al.*, 1989).

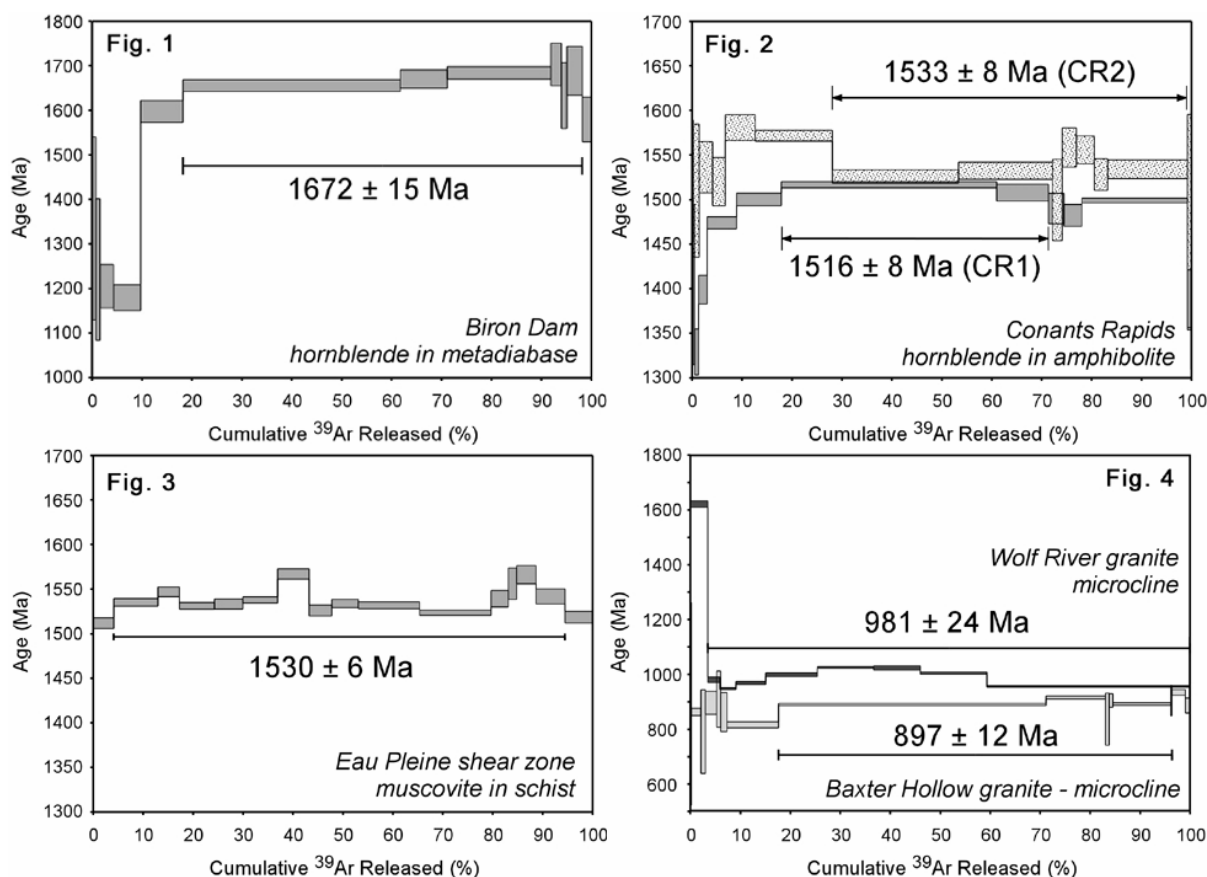
In 1983 Dott suggested that folding of Baraboo Interval quartzites was the result of plate collision to the south at ~1.65 Ga, and this concept was expanded by Van Schmus *et al.* (1993), who related 1.65 Ga deformation and low-grade metamorphism in the Great Lakes region to emplacement of the Outer Tectonic Belt onto the southern margin of Laurentia during the Mazatzal Orogeny. In 1998 Holm *et al.* located the tectonic and thermal front of Mazatzal deformation in northern Wisconsin, based on the distribution of folded and flat-lying quartzites and cooling ages (Rb/Sr, K/Ar, $^{40}\text{Ar}/^{39}\text{Ar}$) of mica in basement rocks, *e.g.* 1.75-1.70 Ga vs. ≤ 1.63 Ga. The position and nature of the Mazatzal front in Wisconsin was confirmed by Romano *et al.* (2000), who showed that micas from basement rocks outside the front yield $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of 1.76-1.75 Ga, and those inside, 1.61-1.58 Ga. Five samples of hornblende from Archean and Paleoproterozoic rocks within the front yield $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of 1830, 1796, 1782, 1733, and 1638 Ma, which are thought to represent partial to complete Mazatzal resetting. Subsequently, $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 1.45-1.47 Ga were obtained for muscovite in Baraboo Interval quartzites, reflecting widespread, but stratigraphically localized, hydrothermal activity related to Wolf River magmatism (Medaris *et al.*, 2003).

Central Wisconsin Precambrian Rocks The basement in NE Wood and NW Portage counties consists predominantly of Archean gneiss and a variety of Paleoproterozoic igneous rocks, including tonalite, granodiorite, granite, and associated felsic to intermediate volcanic rocks. U/Pb zircon ages are ~2780 Ma for migmatitic gneiss at Linwood Quarry, and 1892, 1851, 1841, and 1824 Ma for different varieties of tonalite along the Wisconsin River (Sims *et al.*, 1989; Van Wyck, 1995). Many of the igneous rocks have been deformed and recrystallized, exhibiting a range of foliated and lineated fabrics. Amphibolite layers in Archean gneiss at Conants Rapids yield a temperature of 665 °C and amphibolite (metadiabase) dikes cutting foliated tonalite at Biron Dam give 700 °C (calculated by the hornblende-plagioclase geothermometer at $P = 4$ kbar; Holland & Blundy, 1994).

Laser step-heating yields plateau ages of 1672 Ma for hornblende in metadiabase at Biron Dam (Fig. 1), 1516 and 1533 Ma for hornblende from two samples of amphibolite at Conants Rapids (Fig. 2),

1530 Ma for muscovite in low-grade schist from the Eau Pleine shear zone (Fig. 3), and 981 Ma for microcline in Wolf River granite and 897 Ma for microcline in Baxter Hollow granite (located in the Baraboo Range) (Fig. 4). We interpret the ages of hornblende at Conants Rapids, 3.9 miles from the Wolf River batholith, and muscovite in the EPSZ, 6.7 miles from the batholith, to represent partial resetting by the Wolf River thermal pulse. The age of hornblende at Biron Dam, 13.3 miles from the batholith, may also reflect partial resetting by Wolf River heating, although this age lies within the range for hornblende reported by Romano *et al.* (2000) and ascribed by them to Mazatzal disturbance. The closure temperature of microcline can be as low as 150 °C, thereby allowing for the possibility that it may record cooling of the craton in central Wisconsin, following 1.1-1.0 Ga Keweenawan rifting and magmatism.

The Ar ages reported here seem to result from degassing in response to regional thermal events, rather than pervasive internal deformation and recrystallization (also observed by Romano *et al.*, 2000). Thus, although there has been widespread disturbance of Rb/Sr and Ar isotopic systems in Wisconsin Precambrian basement, many rocks in central Wisconsin have preserved their Penokean structures, textures, and mineralogical compositions.



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Geochemistry and Petrography of Altered Basement Rocks Underlying the Middle Proterozoic Sibley Group

METSARANTA, R.T.*, and FRALICK, P.W., Department of Geology, Lakehead University, 955 Oliver Rd., Thunder Bay, Ontario, P7B 5E1, Canada. rtmetsar@lakeheadu.ca

The Sibley Group is a relatively thin Mesoproterozoic mixed carbonate-clastic succession deposited, at least in part, under restricted shallow marine or lacustrine conditions (Franklin et al., 1980; Cheadle, 1986; Rogala 2003). A diverse mixture of genetically distinct chemical sediments is preserved within various depositional sub-environments of the Sibley Basin. These include: dolomitic mudstones and sandstones, stromatolitic carbonates, calcretes and nodular gypsum/anhydrite. In addition to these chemical sediments, possible weathering profiles are developed in various underlying basement lithologies and at higher stratigraphic positions. Given the diversity of chemical sediment types and possible weathering profiles within the basin the potential exists to develop a detailed model for the hydrology and paleoenvironmental evolution of the Sibley Group.

Weathering is an important control on the composition of clastic sediments (e.g. Nesbitt et al., 1996) and also restricted basin brines (Rosen, 1994). As a first step towards an overall model of the hydrology of the Sibley Basin, the purpose of this paper is to investigate the petrography and geochemistry of altered rocks at the unconformity between the Sibley Group and underlying Archean and Paleoproterozoic lithologies. To be of value in an analysis of overall basin hydrology and paleoenvironmental conditions, the relative importance of primary pedogenically induced geochemical changes vs. later diagenetic or hydrothermal effects must be addressed.

Suites of samples were collected from 4 areas spanning a variety of basement lithological types. Altered Quetico sandstones and Neoarchean granite were sampled from drill core at variable depths below the Sibley Group contact. Altered and unaltered Paleoproterozoic black shales of the Rove Formation were sampled from outcrop as were Mesoproterozoic anorogenic granites and overlying pebbly sandstones. Polished thin sections were cut from each sample and analysed petrographically using both optical and scanning electron microscopy. Whole rock powders were obtained for each sample and were analysed at Lakehead University via ICP-AES for a selection of major and trace elements.

Petrographic evidence such as the progressive destruction of plagioclase upwards in the profiles coupled with extensive development of Fe-Ti oxides along grain boundaries and cleavage planes in biotite and chlorite is consistent with a weathering profile. Pebbles in sandstones associated with the anorogenic granite profile are also strongly iron enriched containing up to 30% total iron suggesting a highly oxidizing atmosphere during pre-Sibley Group weathering conditions.

The presence of authigenic, euhedral potassium feldspars and the potassium-rich nature of clay minerals in the altered horizons suggest secondary potassium enrichment. The presence of barite, fluorite and sulphide mineralization near the Sibley Group contact with Neoarchean granites also reveals that hydrothermal alteration may have had an influence on primary pedogenic geochemical signatures. Preliminary assessment of the major element geochemistry using a simple alteration index (CIA) and A-CN-K diagrams (e.g. Nesbitt and Young, 1982; Nesbitt et al., 1996) also suggests that primary pedogenic alteration may have been effected by later potassium enrichment.

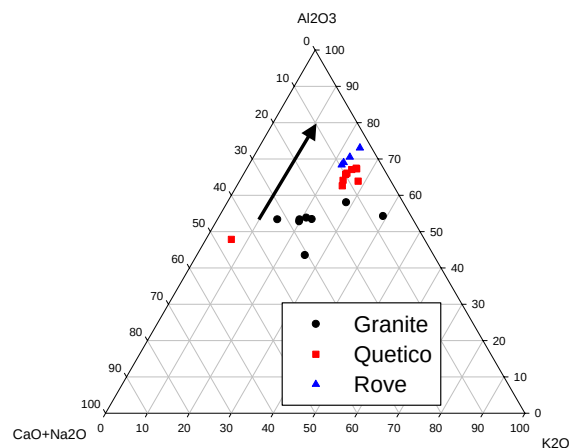


Figure 1. Altered samples from three profiles plotted as molar proportions Al, Ca+Na, and K (as oxides), showing divergence of observed alteration trends towards more K-rich compositions from those expected due to weathering (arrow)

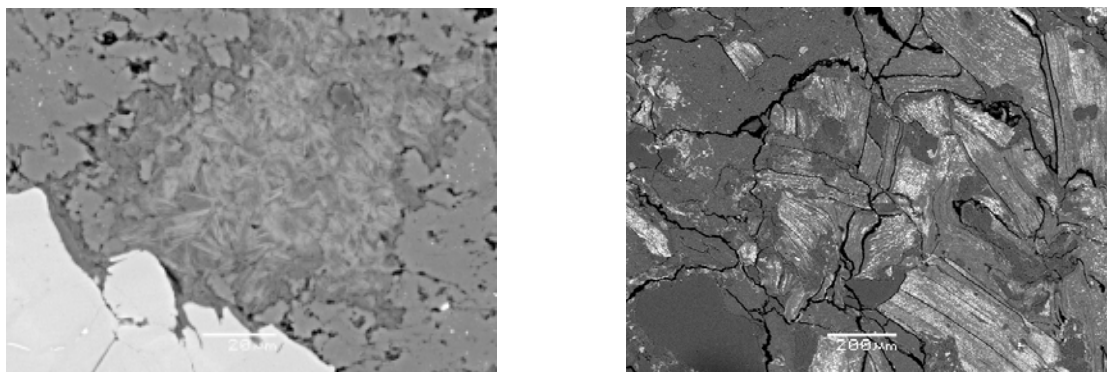


Figure 2. Left: backscatter SEM image of K-rich clay mineral aggregates associated with altered primary K-feldspar (altered Neoproterozoic granite) and right: altered biotite grains with extensive development of Fe and Ti oxides (altered Quetico metasediment).

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N.H. Winchell's Study of the Keweenawan Supergroup Rocks of Northeastern Minnesota, 1872-1900

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

In 1872, fourteen years after its admission to the Union, the state legislature of Minnesota granted an initial appropriation of one thousand dollars per year to the University of Minnesota to create a geological and natural history survey of the state. In July of that year, Newton Horace Winchell (1839-1914) was hired to lead this survey, a task to which he committed 28 years of his life. There is little debate as to the contribution Winchell made to our understanding of diverse aspects of Minnesota's geology, especially in light of the paucity of existing research. Much of the survey's observations and interpretations of Paleozoic and Quaternary geology still stand up today. However, Winchell's greatest difficulties came in his attempts to make sense of the "crystalline rocks" of northeast Minnesota. As he stated in the preface to the fourth volume of the Final Report: "Here [among the crystalline rocks] the geologist is deprived of his usual guides and guys, and finds himself floundering in a muddy sea of innumerable conflicting currents" (Winchell, 1899, p. xiv).

This talk focuses on Winchell's struggles with deciphering the complexities of what is now known as the Keweenawan Supergroup in northeastern Minnesota. My interest in this topic began while researching the history of geologic mapping in the Duluth Complex (Miller and others, 2002). My characterizations and interpretations of Winchell's ideas in this presentation come from selected readings of the 24 annual reports of the Geological and Natural History Survey of Minnesota, the final two volumes of the Final Report (Winchell, 1899, 1900), and Geological and Natural History Survey of Minnesota Bulletins 1, 2, 6, and 8. From this still incomplete sampling of Winchell's prolific writing on the Keweenawan rocks, I have come to conclude that most of his ideas, which seem unconventional by today's standards, were based on paradigms that were accepted by many, if not a majority, of geologists in his day. In the late nineteenth century the principles of stratigraphy and sedimentology were already well established, but the science of igneous and metamorphic petrology was in its infancy. At that time, numerous different ideas about the origin of magmas, volcanic processes, and progressive metamorphism existed. There was no accepted conventional wisdom. Winchell took advantage of the new field of petrographic petrology, which saw widespread use and growth in the last half of the century. He did not, however, have the benefit of the knowledge gained by experimental petrology, which started to emerge just as the survey was being completed.

At the beginning of the Survey, Winchell's views of Lake Superior geology were strongly influenced by the early federal survey of the region (Owen, 1852), as well as by reports of Canadian geologists and the preeminent geologists from his native New York and New England. Over the course of the survey, Winchell regularly compared his observations to those of his U.S. and Canadian colleagues, but more often than not, he seemed to go his own way with many of his interpretations of the crystalline rocks. In fact, he often disagreed with the interpretations of his fellow survey colleagues, many of whom were his relatives—Alexander Winchell (his brother), Horace V. Winchell (his son), and U.S. Grant (his brother-in-law). One of his more curious relationships was with R.D. Irving of the University of Wisconsin, and later of the U.S. Geological Survey. Following up on his work on the Keweenawan rocks of northwestern Wisconsin for the third Wisconsin Geological and Natural History Survey report in 1880, Irving published the first thorough summary of Keweenawan geology in the Lake Superior region in a U.S. Geological Survey monograph (Irving, 1883). In this report, Irving recognized the volcanic character of the mafic and felsic rocks of the shore, and the intrusive nature of the gabbros. It included a remarkably accurate map of the geology of Minnesota's North Shore, in which Irving estimated that the volcanic pile from Duluth to the Temperance River exceeds 18,000 feet, relatively close to current estimates of 28,000 feet (Miller and others, 2002, Chapter 5). Irving relied exclusively on his own fieldwork and gave only passing acknowledgement to the work of the Minnesota survey, then in its tenth year. Winchell, for his part, rarely cited Irving's work, and then commonly only to point out some inconsistency or discrepancy with his observations or interpretations. Winchell's displeasure with the growing influence and overreaching of the U.S. Geological Survey, perhaps triggered by Irving's work, prompted him to found and edit the *American Geologist* journal in 1888. The journal was meant to highlight North American geology, but regularly featured articles critical of the U.S. Geological Survey (Bain, 1916). Irving died the year of its initial publication.

Some of the major aspects of Keweenawan geology that Winchell wrestled with over the course of the state survey were:

Potsdam Sandstone—With a strong belief in uniformitarianism, Winchell consistently held to the notion that all red quartzose sandstone lying unconformably on crystalline rocks was equivalent to the Lower Cambrian Potsdam Sandstone of upstate New York and New England, which has a similar lithology and unconformable geologic setting. Despite their lack of fossils, Winchell opined that the Puckwunge, Nopeming, Fond du Lac, and Hinckley sandstones, and even the Sioux Quartzite, were all Potsdam equivalents. He suggested that the lava

flows overlying the Puckwunge and Nopeming Sandstones and interlayered with stratigraphically higher sandstone units (such as the sandstone at Cutface Creek near Grand Marais) represented localized volcanism during what was generally a time of sandstone deposition, a period he termed the Manitou epoch.

Red rock—Winchell also consistently believed that all granophyre and rhyolite were metamorphosed and fused sedimentary rocks—a commonly held view at the time. He considered the "granophyre range," which arcs through the central part of the Duluth Complex, as a raised ridge of Animikie sediments that were fused by the eruption of the gabbro (see below). Rhyolites were thought to be strongly metamorphosed sandstone interleaved with and metamorphosed by basalt flows. In Winchell's view, quartz and feldspar-phyric flows represented less severe metamorphism because phenocrysts of quartz and feldspar were considered to be preserved detrital grains.

Basaltic lava flows—Early on, Winchell adopted J.G. Norwood's interpretation (Owen, 1952) that the basaltic lava flows of the North Shore were intrusive sills (flow interiors) into volcanic sediments (amygdaloidal tops). Midway through the survey he recognized the physical stratigraphy of basalt flows.

Duluth Complex—Winchell variably characterized the Duluth Complex as "the great gabbro flood," "the crowning overflow," "the great gabbro outflow," "a basic eruptive," and "the gabbro eruption." From these and other descriptors, it is clear that he saw the gabbro as a great volcanic outpouring of basic magma that spilled out over (and metamorphosed) its Animikie rampart and flowed downslope toward the Lake Superior basin. The Beaver Bay Complex and the gabbros at Duluth represent the distal part of this great gabbro flood.

Anorthosite inclusions—Winchell interpreted the anorthosite inclusions of the Beaver Bay Complex as earlier-formed feldspathic gabbros of the Duluth Complex (what is now termed the anorthositic series) that were picked up by later surges of the great gabbro eruptive. This idea was commonly accepted until recently (see Stop 24 in Field Trip 5).

Age of the gabbro—Winchell changed his interpretation of the age of the gabbro many times over the course of the survey. Based on interlayering of the gabbro with rocks he thought to be upper Keewatin (the Pewabik Quartzite, which is actually metamorphosed Pokegama Quartzite), he saw the gabbro as syn-Keewatin to pre-Animikie. Until Lawson (1893) showed that the Logan sills are intrusive into the Animikie Group rocks, rather than interlayered as lava flows, Winchell saw them and the gabbro as syn-Animikie. In the end, Winchell believed the gabbro to be younger than the Animikie Group and older than the Puckwunge Sandstone and overlying lavas. Winchell called the epoch during which the gabbros were emplaced the Norian and later the Cabotian.

Origin of the gabbro magma—Winchell does not speculate on the origin of the basic magma that formed the gabbro and related volcanics until the Final Report. Following the idea that all granites formed by fusion of siliceous sediments, he concluded that the gabbro formed by the melting of greenstone-derived sediments. He considered hornfels basalt inclusions, which he called muscovodyte, an intermediate stage of metamorphism of these basic sediments.

In the end, Winchell was certain that the facts of his numerous and well recorded observations would hold up to future scrutiny, and unquestionably most have. He was admittedly less confident in his interpretations, however and speculated that new facts, "...not included in our field of observation, will in the future place different interpretations on those which we have attempted..." (Winchell, 1899, p. xiv). This has happened to be sure, but more significantly, the changes in our geologic paradigms and our greater understanding of igneous petrology have allowed those of us who follow in his footsteps to reinterpret his many detailed observations.

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Twenty-One Years in a Caldera: UMD Geology Students and Sturgeon Lake, Ontario

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

Over the past 20 years students from the University of Minnesota-Duluth have been involved in studying the Sturgeon Lake Caldera Complex located in northwestern Ontario. Their work, based on outcrop mapping, logging of more than 200,000 meters of diamond drill core, thin section, microprobe, and chemical studies has shown that the complex comprises a well-preserved, north facing, moderately to steeply north-dipping, homoclinal sequence that is up to 30 km in strike length and contains more than 3000 m of subaerially and subaqueously deposited volcanic and sedimentary strata.

The Pre-Caldera Sequence, worked on by Groves (1984)*and Heine (1985) contains subaerial to shallow subaqueous basalt to andesite lava flows, tuffs and lapilli-tuffs with subordinate rhyolite lava flows. The Early-caldera Sequence, worked on by Walker (1993), Hudak (1989), Beszenek (1992) and Drews (1990) along with Rog (1991) and Murphy (1994) comprises subaerially to subaqueously deposited polymict breccias and aphyric or quartz-phyric, rhyodacite-rhyolite tuffs with reworked tuffs and minor andesite to rhyolite lava flows. The Late-caldera Sequence, worked on by Jongewaard (1989) and Hudak (1996) contains syn-eruptive and reworked quartz- and plagioclase-phyric rhyodacite to rhyolite tuffs and lapilli-tuffs, and subaqueous basalt-andesite to rhyolite lava flows, domes, and cryptodomes. Volcanic-hosted massive sulfide deposits occur in the Early and Late Caldera Sequences.

Synthesizing these studies, with additional contributions by Peterson (2001), provides a detailed picture of caldera development and associated massive sulfide formation and hydrothermal alteration.

The work of the above geologist's shows this piecemeal caldera complex formed upon a subaerial to shallow subaqueous basalt -andesite shield volcano with associated local fields of scoria and tuff cones. Caldera formation was characterized by more than a kilometer of collapse accompanied by voluminous pyroclastic eruptions, deposition of laterally extensive meso-and mega-breccias, minor effusive volcanism, and massive sulfide ore deposition with widespread hydrothermal alteration. Later stages of caldera development were dominated by submarine effusive volcanism and intracaldera sedimentation, with subordinate pyroclastic volcanism and ore deposition.

The lithostratigraphic sequence, caldera diameter, and estimated eruption volumes, determined from geographic information system (GIS) analysis, are consistent with those that characterize modern ash flow caldera complexes. The Sturgeon Lake Caldera Complex illustrates the following:

- 1) The necessity of long term, detailed field and laboratory studies to understand complex volcanic systems.
- 2) That evolutionary and mineralizing processes associated with "ash flow" calderas have been remarkably similar since at least Neoproterozoic time.
- 3) That good students do very good work and make professors look great!

* Year of degree or year started work at Sturgeon Lake

Status of Publicly Available Mid-Continent Reflection Seismic Data

MUDREY, M.G., Jr. Wisconsin Geological and Natural History Survey, 3817 Mineral Point Road, Madison, WI 53705 mgmudrey@wisc.edu

CANNON, W.F., U.S. Geological Survey, National Center MS 954, Reston, VA 22092
wcannon@usgs.gov

The Midcontinent Rift was identified by potential field and geologic studies in the 1950s. However, much of the detail of this largely buried structure was obscure except in a few well exposed areas around Lake Superior. Interest in frontier petroleum rose in the 1970s and the recognition of documented petroleum seeps from the Nonesuch Formation led to the acquisition and evaluation of industrial reflection seismic data. From 1978 to 1986 a series of seismic reflection profiles was obtained by a combination of academic (COCORP), petroleum company, and government (GLIMPCE) research programs. The U.S. Geological Survey and the Geological Survey of Canada acquired 536 line-km in Lake Superior, L.D. McGinnis and Argonne National Laboratory purchased 1,816 line-km in Lake Superior from Grant-Norpac, and A.B. Dickas University of Wisconsin-Superior negotiated the release of 1,336 line-km from Lake Superior south to Iowa from Petty-Ray/Geosource.

The profiles provided access to a wealth of new details of the lateral and vertical extent of the rift and its internal structure and stratigraphy from Lake Superior to Kansas. Some of the major findings include:

- Particularly significant was the discovery that 20 to 30 km of basalt flows and secondary syn-rift volcanoclastic and post-basalt sedimentary rock produced exceptionally strong and coherent reflections that enabled accurate estimates of the volumes of basalt.
- Moho reflections recorded in Lake Superior over the rift range from 46 to 58 km in contrast to 36 to 42 km beneath the surrounding Great Lakes. This provides evidence of magmatic underplating and intrusions within the lower crust and upper mantle contemporaneous with crustal extension...in effect, the mantle was changed into crust by a decrease in seismic velocity.
- ! Individual basins within the Midcontinent Rift have been delineated by long reflection lines and cross lines -- clearly developed unconformities remove ambiguities of correlation among various volcanic sections within and between basins.

Although individual seismic lines have been interpreted, the entire collection of lines, along with newly acquired gravity and magnetic data, have yet to be collectively used to refine our understanding of this 2,000 km rift.

GLIMPCE data are available from

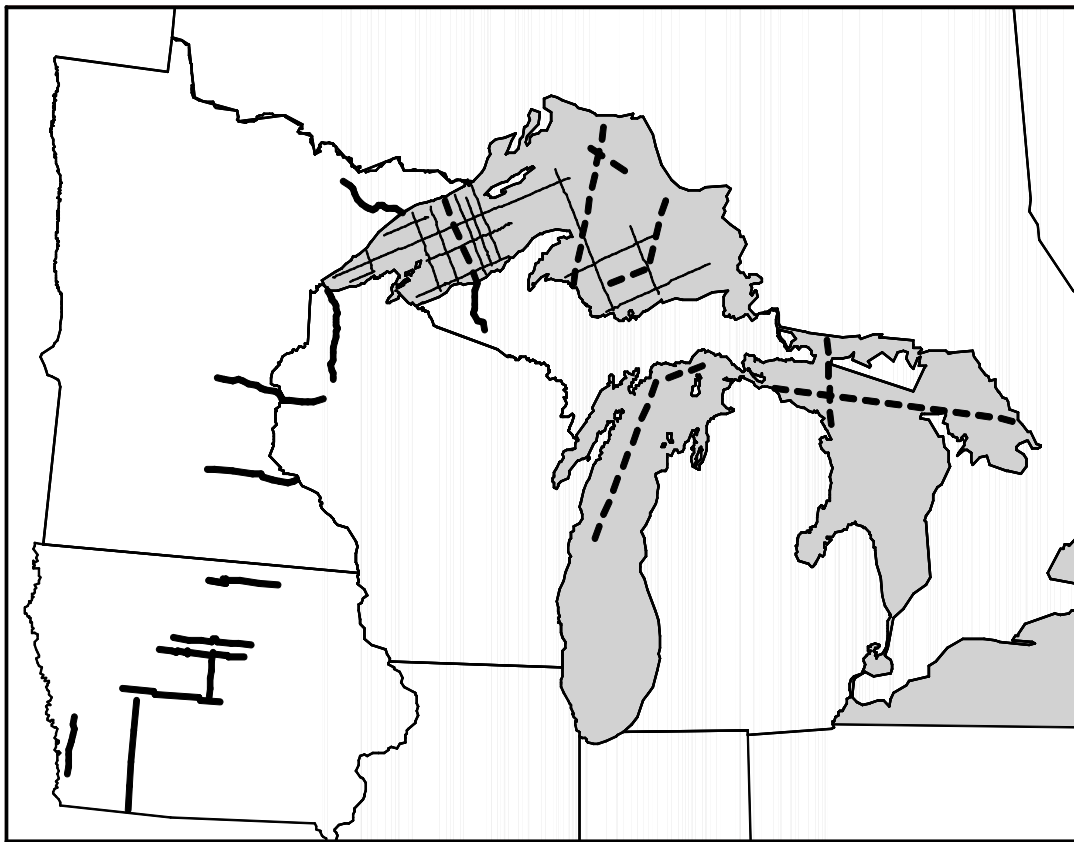
Robin R. Warnken, National Geophysical Data Center, NOAA/NESDIS/NGDC/
Mail Code E/GC3, 325 Broadway, Boulder, CO USA 80305-3328. phone: (303) 497-
6338. Email: Robin.R.Warnken@noaa.gov

Argonne National Laboratory/Grant-Norpac data are available from

McGinnis, L.D., and Mudrey, M.G., Jr., 2003, Seismic reflection profiling and tectonic evolution of the Midcontinent Rift in Lake Superior: Wisconsin Geological and Natural History Survey Miscellaneous Report MP 91-2, 15 pl. 1 CD-ROM. Files on CD are in PDF format.

Petty-Ray/Geosource data are available from

Dickas, A.B. and Mudrey, M.G., Jr., 2002, Regional-Scale Geologic Interpretation of Seismic Reflection, Gravity, and Magnetic Profiles Collected along the Western Arm of the Midcontinent Rift System, Upper Peninsula of Michigan, Wisconsin, Minnesota and Iowa: Wisconsin Geological and Natural History Survey Open-file Report 2002-01, 1 CD-ROM. Files on CD are in HTML format.



1. Location of reflection seismic lines: GLIMPCE, heavy dashed; Grant/Norpac, light solid; Petty-Ray/Geosource, medium solid.

**“GOLD IS WHERE YOU FIND IT! SO IS Ag AND Cu AND Fe!”
(THE OLD PROSPECTOR: GOLD RUSHES AND MINERAL PROSPECTING, 1848 TO
1900 IN WESTERN NORTH AMERICA AND THE LAKE SUPERIOR REGION)**

OJAKANGAS, Richard W. (a.k.a., The Old Prospector), University of Minnesota Duluth,
Duluth, MN 55812, rojakang@d.umn.edu

Gold has long provided a chance for the “little guy” to make a fortune. The “Old Prospector” relates factual and illustrative information about several gold rushes, beginning with the 1849 gold rush in California. (“Go West, young man, go West!”) Where did the 200,000 “Forty-Niners” come from? From everywhere! Because it took 11 months for the news to reach the east coast, people living on the Pacific Rim got there first. How many (how few?) hit it rich? Even Captain Sutter and the actual discoverer, Jim Marshall, died poor.

The Comstock Lode in Nevada, “discovered” by Henry Comstock, led to the gold and silver rush of 1860, with many of the fortune-seekers crossing back over the Sierra Nevada with their donkeys.

A group on their way to California in 1850 found gold in Colorado at the present site of Denver, but the rich California gold was their goal. There were several discoveries in Colorado over the next decades. It was the gold at Cripple Creek, discovered by cowboy Bob Womack in 1890 that really brought the prospectors in. Bob sold his claim for \$300 -- \$ 7.5 million came out of that gulch!

Looking for gold, silver and copper in Montana attracted many prospectors in the '60s and '70s. The copper ore was “so pure that it could be shipped to hell and back for smelting and still make a profit.” (Swansea, Wales, was the location of early smelters.)

In 1876, the rush was to the Black hills for gold. General Custer had gone in to look for gold in 1874, and his favorable report brought in a horde of prospectors. All of this was in violation of the Fort Laramie Treaty of 1868. The Indians were embittered, and Custer was sent in to force the Indians back onto their reservations. In the Battle of the Little Big Horn on June 25, 1876, all 265 soldiers in 5 companies of the U.S. 7th Cavalry died.

Meanwhile, what was going on in the Lake Superior region? Native copper had been discovered on the Keweenaw Peninsula by Douglas Houghton in 1840, and mining began soon after. Actually, the copper was “rediscovered” by Houghton, as “Old Copper Complex Indians” had been mining it from numerous pits on the peninsula and on Isle Royale for the previous 6000 years.

Iron ore was discovered in the UP near Negaunee in 1844 by William Burt and his party, who were running a line using a sun compass and noticed a large deviation in the magnetic azimuth of a regular compass. Chief Manjekijik of the Chippewas led explorers to another outcrop of iron-formation the next year. Major ore shipments began in 1855. Ore in the Menominee district was discovered in 1845 and began production in 1877. Iron ore on the Gogebic was first noted in 1848 by A. Randall and Charles Whittlesey, but production didn't begin until 1884.

Gold was mined from the Ropes Mine in the Marquette area in the early 1880s, and sporadically thereafter.

In 1868, silver was discovered at Silver Islet near Thunder Bay.

In 1865, there was a gold rush to Lake Vermilion. Had it been based on a valid discovery of gold, or was the rush a ruse to generate business for suppliers? (There are no authentic reports of gold having been found there.)

The gold activity in the Lake Vermilion area led to the 1865 discovery of iron ore by George Stuntz, a surveyor who had a trading post on Minnesota Point in Duluth... The first ore was shipped in 1882 from Soudan, and in a few years 5 mines were producing at Ely.

Many men had crossed the Giants Range (the “Mis-sa-be” hills of the Indians) on their trek to Lake Vermilion (Ona-ma-sa-ga-i-gan, or the “lake of the beautiful sunset”) along the 84-mile Vermilion Trail surveyed and built by Stuntz. Some, including Lewis Merritt of Duluth, noted the presence of magnetic iron-formation in the eastern Mesabi. However, it was not until 1890 when the Merritt brothers (sons of Lewis Merritt), with their concept of ore “basins” within the iron-formation, discovered the first high-grade soft ore at Mountain Iron and a year later at Biwabik. (These discoveries ended the fledgling developments on the Gunflint Range.) Within a few years, mines reached 30 miles westward, discovered by Frank Hibbing, Archibald Chisholm, Erwin Eveleth, and others. Within 20 years, most of the Mesabi ore had been located. In 1904, 58 Mesabi mines produced more ore than the 78 mines of Michigan and the Vermilion district.

Meanwhile, the search for gold continued wherever bedrock was exposed. In 1894, it was discovered in a quartz vein on Little American Island on Rainy Lake, and a mine was developed to a depth of 212 ft. This was Minnesota’s only legitimate gold mine, having produced \$5600 worth of gold. Rainy Lake City grew quickly, and died almost as quickly. There were not many steam gravels on bedrock to be panned in this glaciated country, although to the north in Ontario, prospecting continued unabated.

The news of the discovery of the Klondike gold in the Yukon Territory by George Carmack in 1896 reached the West Coast, and even Minnesota, in 1897. Several Minnesota prospectors joined 100,000 others who were heading north to Dawson. Perhaps 40,000 made it, maybe 20,000 prospected, and about 4,000 shared in the total gold find of \$10,000,000 (an average of \$2,500 each). The good stream beds were rapidly staked.

In 1898 near Nome, Alaska, on the Bering Sea, 1,000 miles west of the Klondike, gold was discovered by the “Three Lucky Swedes” (Jafet Lindeberg, Eric Lindblom, and John Brynteson, all greenhorns) who became millionaires. Then gold was found in the beach sands of Nome in 1900, and the beaches became “the poor man’s paradise”. More than 23,000 people sailed there from Seattle, Portland, and San Francisco to get rich in one way or another. At the height of beach mining, 2,000 men, women and children were at work, and produced about \$2,000,000 worth of gold, an average of \$1,000 each. This was the last great placer gold stampede in North America, and really lasted for only the 3 months of the summer of 1900.

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DEPOSITION OF PALEOPROTEROZOIC SILICICLASTICS AND IRON-FORMATION IN A TIDALLY INFLUENCED SHELF ENVIRONMENT, ANIMIKIE BASIN, LAKE SUPERIOR REGION

OJAKANGAS, Richard W., University of Minnesota Duluth, Duluth, MN 55812, rojakang@d.umn.edu;

OJAKANGAS, Gregory W., Drury University, Springfield, MO 65802; gojakang@drury.edu

The Paleoproterozoic Animikie Basin is interpreted as a northward-migrating foreland basin situated north of the Penokean orogen. Basal siliciclastic units are the Pokegama Formation on the Mesabi Range in Minnesota, the Palms Formation on the Gogebic Range in Michigan-Wisconsin, and the Kakabeka Quartzite on the Gunflint Range in Ontario and adjacent Minnesota. The overlying iron-formations are the Biwabik, Ironwood, and Gunflint, respectively. The iron-formations of these three ranges are in turn overlain by the Virginia Formation, the Tyler and Copps Formations, and the Rove Formation, respectively.

We interpret the siliciclastics and the iron-formations to have been deposited on the northern edge (i.e., the peripheral bulge and foreland) of the basin about 1900 Ma. Those in Michigan-Wisconsin were likely continuous with those farther north in Minnesota and Ontario prior to their separation by the development of the Mesoproterozoic Midcontinent Rift System at 1100 Ma. However, the units are likely diachronous, with those in Michigan and Wisconsin somewhat older than those in Minnesota and Ontario. They are interpreted to have been deposited on a shelf near a peneplaned surface on Archean rocks. The siliciclastics were deposited near shore and the iron-formations were deposited farther seaward. As the sea transgressed northward, the iron-formations were deposited upon the siliciclastics. Walther's Law applies, with the vertical facies indicating the lateral facies.

The siliciclastic formations consist of lower argillaceous members, middle members of argillite, siltstone, and sandstone, and upper members of mature sandstone (all gradational), interpreted to have been deposited, respectively, in upper tidal, middle tidal, and lower tidal (subtidal?) environments in a transgressing sea. The well-exposed Palms Formation exhibits abundant tidal evidence including bimodal-bipolar paleocurrent plots (N=250) for the formation as a whole and also for specific localities, tidal bedding (lenticular, wavy, and flaser), and minor flat-topped ripple marks and mudcracks. Also present in the middle member are thin sand-textured beds composed of iron silicates that were apparently transported shoreward into the siliciclastic zone.

The Pokegama Formation is poorly exposed, but tidal evidence can be interpreted from limited exposures and a few drill cores. Sequences of thicker and thinner laminae in siltstone beds of the lower member are interpreted as evidence of the diurnal inequality that is an alternation in the heights of successive high tides in a twice-daily tidal environment. The diurnal inequality occurs when the moon is above or below Earth's equatorial plane, because under these conditions any non-equatorial location will pass through different parts of the tidal deformation ellipsoid during each successive high tide. Ideally the diurnal equality disappears at the equator, and therefore our data are suggestive of a non-equatorial depositional location. Poorly exposed packets of progressively thinner and progressively thicker laminae may indicate neap and spring tidal cycles. These investigations are continuing, with a search for longer sequences of laminae in drill cores.

The iron-formations have thick-bedded and granular (“sandy”) members and thin-bedded and fine-grained (“muddy”) members. The former make up the lower and upper “cherty” members and the latter comprise the lower and upper “slaty” members. The granules are composed of iron oxides, iron silicates, iron carbonates, and chert, whereas the fine-grained units are made up largely of iron silicates and iron carbonates. It has commonly been thought that fine-grained precipitates of silica, iron carbonates and/or iron silicates formed on the shelf edge where upwelling waters supplied the iron and silica to a location below wave-base. Reworking of these fine-grained precipitates by tidal and/or storm currents resulted in the formation of the granules. The granules were then transported into higher energy locations shoreward of the deeper shelf.

The Ironwood Iron Formation is poorly exposed, whereas the Biwabik and Gunflint are well exposed. The Biwabik is exceptionally well exposed in taconite pits. In the Minorca Mine just northeast of Virginia, a paleocurrent plot of 102 cross-beds, including rare herringbone cross-beds, is strongly unimodal to the NNE, perpendicular to the paleogeographically determined shoreline, but with 10 % of the readings in the opposite sense. Therefore, flood tides were dominant. In some pits, such as at Minntac, channels of granular iron-formation are cut into the fine-grained and thinly bedded iron-formation. These are as wide as 1 km and 25 m deep, are oriented perpendicular to the paleogeographically determined shoreline, and are interpreted to be tidal channels in which granular sediment was transported seaward into the realm of fine-grained precipitates.

A shallow water environment for the deposition of the granular members is supported by the rounded nature of the grains, the cross-bedding, and two major stromatolite horizons. Stromatolite columns in a bed that has since been mined away were all inclined at 30 degrees to the vertical, suggestive of an environment of deposition at about 30 degrees latitude. The vertical sequence of members—lower cherty, lower slaty, upper cherty, and upper slaty—is due to transgression, regression, and transgression.

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THREE-DIMENSIONAL GEOMETRY AND STRAIN OF THE BARABOO SYNCLINE: KINEMATIC IMPLICATIONS

ORMAND, Carol J., Department of Geology, Wittenberg University, Springfield OH 45501, cormand@wittenberg.edu

CZECK, Dyanna M., Department of Geosciences, University of Wisconsin - Milwaukee, P.O. Box 413, Milwaukee, WI 53201

INTRODUCTION

Paleoproterozoic sedimentary rocks of the “Baraboo interval” were deposited on a stable cratonic margin with subdued topography, in a warm, humid climate, as evidenced by their physical and chemical maturity (e.g. Dott, 1983; Medaris et al., 2003). The southern deposits, including the Baraboo Quartzite and associated rocks, subsequently underwent both low-grade thermal metamorphism and simultaneous deformation during the Mazatzal orogeny, ~1650-1630 Ma (Holm et al., 1998; Romano et al., 2000). During this collisional event, the flat-lying marginal sediments were crumpled into tight, asymmetric, southward-verging folds. The foreland fold-and-thrust belt of this collision is preserved in isolated outcrops in southern Wisconsin including the Baraboo hills (LaBerge and Klasner, 1986).

Approximately 40 kilometers long by 15 kilometers wide, the geometry of the Baraboo Syncline is strikingly three-dimensional. The fold axis trends approximately N80E. The northern limb of the fold is subvertical to slightly overturned; the southern limb dips around 35 degrees northward; the eastern termination plunges approximately 35 degrees westward; and the western termination plunges approximately 25 degrees eastward.

DEFORMATION FEATURES

Strain on the limbs of the Baraboo Syncline is as three-dimensional as the fold itself. Both limbs of the fold have axial planar phyllitic cleavage, refracted into quartzitic strata. Within the southern limb, however, where quartzite beds are sandwiched within phyllitic layers, three-dimensional pinch-and-swell structures (“chocolate tablet boudinage”) show extension parallel to layering, both along strike and down dip. Strain data from quartz grain shapes also indicate three-dimensional strain, with extension either layer-parallel or layer-normal (McKiernan, 2002; Craddock, pers. comm.). In addition, slickensides on the southern limb of the fold indicate one paleostress direction, while slickensides on the northern limb show multiple paleostress solutions (Kirschner et al., 1989).

KINEMATIC MODEL

Both the fold geometry and the extension within the gently dipping limb of the syncline are consistent with formation in a top-to-the-south simple shear environment (Cambray, 1987). In such an environment, non-cylindrical fold trains would verge southward. In this model, the longer, north-dipping fold limbs are favorably oriented for localized layer-parallel extension, while the shorter, steeply dipping limbs rotate and shorten during deformation. The location of boudinage exclusively on the south limb is consistent with this model. The multiple paleostress directions on the north limb, inferred from slickensides (Kirschner et al., 1989), are also consistent with the rotation of the north limb explicit in the model. Therefore, this simple shear

model is consistent with the majority of the field data. However, it is a two-dimensional model that does not account for the strongly three-dimensional fold geometry. To account for the three-dimensional shape of the syncline, we invoke a component of non-plane strain. We envision a variation in degree of shearing along strike, resulting in extension along the fold axis. This model therefore could explain both the strong change in plunge along trend and the three-dimensional boudinage within the southern limb of the Baraboo Syncline. We are analyzing microstructural data on both limbs of the fold to further evaluate this kinematic model.

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DULUTH COMPLEX BULK SAMPLES

PATELKE, Richard, and SEVERSON, Mark, Natural Resource Research Institute, University of Minnesota Duluth, Duluth Minnesota 55811, rpatelke@nrri.umn.edu, mseverso@nrri.umn.edu

Since copper-nickel exploration began in the Duluth Complex with the first drill hole in 1951, there have been numerous bulk samples taken for metallurgical testing. Our current project is an attempt to develop a narrative history of this work. The project began for two reasons: 1) there is a perception that these bulk samples have usually returned metal grades lower than was expected by the pre-excavation testing; and 2) there was no consolidated listing for where data about these projects might be found.

The issue of sample head grade in bulk samples being lower than expected is real, but is not documented well enough to discern an overall cause or to propose a solution beyond more rigorous outcrop stripping, mapping, and drilling before choosing a test site. Most sites have been located based on a single drill hole and as far as we can tell no sites have been rejected after a location has been chosen or once excavation began.

There is probably a distinction between a geologist's definition of a successful test and a metallurgist's definition. A geologist's definition of a successful bulk sample is one where the overall grade and mineralogy is what was predicted from assaying, drilling, or outcrop study (a "scientific success"). A metallurgist might define a successful bulk sample as one that represents, or is typical of, the bulk composition and the mineralogical ratios of the deposit, and therefore allows reliable conclusions to be drawn from testing certain steps in the beneficiation process (a "practical success").

The primary source of information for this study is company publications and records in files at MDNR and NRRI, little was found at other locations.

Samples in the South Kawishiwi intrusion include: a small outcrop (and drill core?) sample by the USBM; two surface bulk samples from the INCO Spruce Road deposit; samples from the shaft and drift of the INCO Maturi deposit; large excavation and incidental exposure at the Dunka Pit iron mine (over 14 million tons of Duluth Complex material on the surface); and a small incidental exposure of Duluth Complex rock and massive-sulfide related to iron-formation stripping in the Peter Mitchell Taconite mine.

Bulk samples at the Babbitt (Mesaba) deposit in the Partridge River intrusion include: work on one surface sample pit and multiple samples from the shaft and drift by AMAX; numerous drill core composites by AMAX; two test pits by Arimetco in the 1990s; one test pit by Teck Cominco in 2001; and a 50,000 ton pit planned by Teck Cominco in the near future. The Dunka Road (NorthMet) deposit had three samples at two locations by USS; a 1991 drill core composite from new large diameter holes by Nerco and Fleck; and a large pilot plant sample by PolyMet from reverse-circulation cuttings.

The Longnose Oxide-bearing Ultramafic intrusion (OUI) had two samples taken from pits for beneficiation and process testing of the Fe-Ti oxides. Two complete drill holes in the Water Hen OUI were taken for process testing by the USBM in the 1980s.

The major bulk samples are listed in Table 1, the references for the table are in the document below.

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SOUTH KAWISHIWI INTRUSION						
Project	Responsible party	Year(s)	Tonnage	Comment	Grades	Reference
Spruce Road	USBM	3 holes drilled in 1953, report issued in 1955		Lab / bench tests on composite from 3 drill cores and / or outcrop samples?	Reported head grade of 0.38% Cu, 0.14% Ni, 0.88% S	Grosh et al., 1955, USBM Report 5177
	INCO	1966-1967	1,150 tons	Source of sample uncertain, test work done uncertain	No data found.	1974 INCO project description on file at MDNR in AMAX archive
	INCO	1974	10,000 tons	Pit along south side of Spruce Road, processed by INCO at Sudbury (?)	Reported head grade of 0.47% Cu, 0.15% Ni, 1.08% S	1974 INCO project description on file at MDNR in AMAX archive
Maturi	INCO	1968	700 tons (?)	Shaft at Maturi, sample sent to INCO lab at Sudbury (?)	No data found.	1974 INCO project description on file at MDNR in AMAX archive
	INCO	1968?		Drift at Maturi, some drilling done from drift, but little information in NRRI or MDNR files. Assume some material must have been sent for metallurgical tests.		Misc. files at MDNR and NRRI
Serpentine	Reserve Mining	Before 1989	Uncertain tonnage	An exposure of massive sulfide assumed to be similar or related to the Serpentine deposit is seen in the Peter Mitchell Mine. Exposed during iron-formation stripping. Assayed by MDNR in 2001.		Ruhanen, 2001 for MDNR, Severson South Kawishiwi report
Dunka Pit	Erie / LTV	1975 to 1998?	14-20 million tons in stockpiles?	Stockpiles at Dunka Pit represent Duluth Complex material removed for iron ore mine development.	0.23% Cu, 0.09% Ni, 2.20% S are the approximate values from exploration drilling. MDNR reports values of 0.29% CuO, 0.10% NiO (uncertain about whether these are oxide or sulfide assays)	Files at MDNR, and Ron Graber at CCI
PARTRIDGE RIVER INTRUSION						
Project	Responsible party	Year(s)	Tonnage	Comment	Grades	Reference
Babbitt (Mesaba) deposit	AMAX At B1-341	1978	1,150 ton excavation, 560 tons sent as sample	Surface pit in NE corner of deposit. Sample may actually have been taken in South Kawishiwi intrusion, not Partridge River intrusion	0.43% Cu, Ni est. at 0.12%	Various files in AMAX archive at MDNR
	AMAX	1976		Shaft samples listed as "disseminated." Some of this material used by MDNR for various leaching and ARD tests	Various disseminated ore samples. Est. at 0.43% Cu, 0.13% Ni, S unknown	Various files in AMAX archive at MDNR
	AMAX	1976		Drift samples listed as "massive" or "semi-massive." Some of this material used by MDNR for various leaching and ARD tests	Various massive and semi-massive sulfide samples.	Various files in AMAX archive at MDNR
	Arimetco at B1-374	1994	200 tons excavated, sample split to 85 and 115 ton portions	Surface pit. Sample probably in weakly mineralized pegmatitic zone of Unit 3	0.22% Cu, 0.06% Ni, 0.52% S from blast holes; sorted sample had head grade of 0.30% Cu, 0.08% Ni, 0.63% S	MDNR and NRRI files
	Arimetco at B1-411	1995-1996	150 tons sent to CMRL, January 1996	Surface pit. Sample in western part of deposit, location in Unit 1. Reasonably typical material.	0.61% Cu, 0.12% Ni, 1.02% S from blast holes; CMRL reports head grade at 0.36% Cu, 0.08% Ni, 0.76% S	MDNR and NRRI files
	Teck Cominco at B1-321	2001	5,000	Surface pit at location drilled by Severson for Arimetco, in Unit 1, near center of north edge of deposit. Very typical material. Final sample much larger than 460 tons outlined by Severson.	Severson estimate 460 tons at 0.62% Cu	Communication w/Teck Cominco and NRRI files
	Teck Cominco at B1-321	Future	50,000	Planned surface pit, at same location as Teck Cominco B1-321. EAW approved by State in 2003		EAW approved June, 2003
Dunka Road (NorthMet) deposit	USS Bulk No 1	1971(?)	unknown tonnage, but small	Surface pit near drill hole (26058) with mineralization only in top few feet. Small pit, found by Zanko and Severson in 1995, no definitive records available.	Drill hole 26058 grade from 8 to 20 ft. was 0.82% Cu, 0.20% Ni, 1.21% S; below that hole is not mineralized for hundreds of feet; head grade of bulk sample was 0.39% Cu, 0.14% Ni, 0.50% S	NRRI files
	USS Bulk No 2	1971	300 tons	Surface pit near drill hole 26105. Intended to intercept mineralization seen in that hole. Material contaminated with hornfels, poor grade.	Expected grade based on ddh 26105 was 0.77% Cu, 0.28% Ni(?), 1.23% S; head grade of sample was 0.40% Cu, 0.13% Ni, 0.97% S	NRRI files
	USS Bulk No 3	1971	20 tons	Surface pit near drill hole 26105. Re-entry of Bulk No 2 site to get material not contaminated with hornfels	Expected grade based on ddh 26105 was 0.77% Cu, 0.28% Ni(?), 1.23% S; head grade of sample was 0.58% Cu, 0.22% Ni, 0.98% S	NRRI files
	Fleck / Nerco	1990	2 large diameter core holes	PolyMet report states they have no records for this work, other than that it was done in 1991. Two large diameter holes and two smaller twins for submission to state. Nerco holes twin two existing USS drill holes.	No data	PolyMet January 2000 Prospectus
	PolyMet Composite	1998-2000	At least 37 tons shipped to testing laboratory	Reverse circulation drilling composite from about 55(?) reverse circulation holes. Data not available on how many or which holes constituted the bulk sample.	Head grade in 1999 SME/AIME presentation is 0.43% Cu, 0.12% Ni, PolyMet has not published sulfur numbers.	PolyMet press releases and 2001 pre-feasibility study
Longnose Fe-Ti oxide (OUI)	American Shield	1984		Surface pit, sample sent to CMRL for process testing		CMRL reports in 1990s on projects, but ore sources for individual projects uncertain
	American Shield	1999		Surface pit, sample sent to CMRL for process testing		CMRL reports in 1990s on projects, but ore sources for individual projects uncertain
Water Hen Fe-Ti Oxide (OUI)	Water Hen drill holes SL-27 and SL-28	Drilled in 1975	about 400 ft. of drill core	USBM samples to test reduction processes on Fe-Ti ore; with goal of producing saleable or processable titanium slag product. Work done in 1985	Study concluded that a high TiO2 product could be made, but that concentration that removes iron is important. High MgO content is not mentioned as a processing issue	Nafziger and Elger, 1987, USBM report; drill hole desc. in Ross, 1985

Table 1. Major bulk samples of the Duluth Complex.

UNTESTED TARGETS IN THE DULUTH COMPLEX

PATELKE, Richard, SEVERSON, Mark, and PETERSON, Dean, Natural Resource Research Institute, University of Minnesota Duluth, 5013 Miller Trunk Highway, Duluth Minnesota 55811, rpatelke@nrri.umn.edu, mseverso@nrri.umn.edu, and dpeters1@nrri.umn.edu

Introduction

There are at least four, presently sub-economic, large, copper-nickel +/-PGE deposits defined along the western and northwestern margins of the Duluth Complex, as well as many smaller prospects (more than ten?). Development has been slowed by metallurgical problems and the perception of permitting difficulty. Exploration for more of the large low-grade deposits would seem unneeded until some of the known ones are developed.

We present a few exploration ideas for less studied areas of the Duluth and Beaver Bay Complexes (with profuse apologies to all who may also have mentioned these in the past). We hope to encourage a discussion about smaller, higher-grade, targets. All of the targets listed here point to the need for detailed field mapping and integration of geophysical data. Remember that five hundred million tons of rock forms a cube about 1,750 feet on a side, and that a viable deposit can be relatively small.

The Schroeder-Forest Center crustal ridge target

Regional aeromagnetics and gravity data indicate that the Duluth Complex occupies two deep “bowls”. The separation between these two deep zones is the Schroeder-Forest Center crustal ridge. In general, mapped surface geology does not carry across this basement ridge zone. The presence of inclusions of Archean supracrustal rocks could also indicate that the base of the Complex is closer to the surface in this area (Boerboom, 1994). The Wilder Lake intrusion strikes parallel to the ridge and dips northeastward, also indicating that there is a division in the Complex. So, if one applies a model based on what we see for the copper-nickel-PGE deposits, i.e., most economic mineralization is close to the basal contact, then determining the depth to the basal contact along the ridge could open up areas for future exploration if the footwall is found to be reasonably shallow. Also, this area would probably be a much different structural regime than we see at the western and northwestern margins of the Duluth Complex.

Cloquet Lake layered series

This area is grossly similar to the situation along the Schroeder-Forest Center crustal ridge or the western margin. A group of three holes, drilled near the edge of this funnel-shaped intrusion in 1982, went to the base of the intrusion and hit massive sulfide with magnetite. PGE values were low and no further drilling was done, but scattered thin intercepts (3 ft.?) of about 0.5% copper were seen within 250 ft. of the surface. In this case, the footwall was older Keweenawan intrusive rocks.

PGE in oxide-rich, pegmatitic, and other rocks

The highest average value in the Complex for combined Pt + Pd + Au are in oxide-rich rocks, particularly those at Birch Lake. Pegmatitic zones, massive sulfides, anorthositic rocks, and massive chlorite also return higher than average values. However, these five rock types represent a small percentage of the over 52,000 feet of sample in Severson and Hauck (2003) that record assays for all three metals (troctolitic rocks make up about three fourths of the Pt + Pd + Au assay footage). These five minor rock types are not often mineralized, but when they are, the mineralization is copper-rich. Could there be larger, near-surface zones of these anomalous rock types? So far, localized copper-rich, semi-massive sulfides (some with high PGE values) have been documented at Dunka Road, Dunka Pit, on trend with the Siphon Fault, and at Skibo.

Oxide-bearing Ultramafic Intrusions (OUIs)

While the Fe-Ti rich OUIs are not particularly rich in sulfides or PGE, and have not yet proved economic as sources of titanium, they are still viable targets for chromium and vanadium oxides. There is less than 1,000 feet of assaying for these oxides available for the Complex (Severson and Hauck, 2003; Patelke 2003). The

OUIs are enigmatic: the alignments of large OUIs in the Western Margin and Partridge River intrusions would indicate a relation to large and as yet undefined faults. Similar fault-related OUI are present south of the Babbitt deposit. However, information from drill core gives no hint to the geometric nature of the root zones of the OUIs. As the OUI formed along fault zones, often late in the crystallization history of the various intrusions, they may mark zones with potentially vigorous hydrothermal activity that could have concentrated PGE.

For example, drill hole SL-19A at the Water Hen OUI has a thin platinum and chrome-bearing horizon that has had no known follow up work for PGE, or chromium and vanadium. INCO records show extremely high copper and nickel values, with widely varying ratios, near the Skibo OUI; again with little follow up. Overall, the OUIs may be worthy of attention beyond being a source of titanium.

Structural targets

Two major scissor-like faults that lie perpendicular to the line of the basal contact near the Babbitt and Dunka Road deposits are relatively unexplored. The Siphon Fault begins in the former LTV pit and extends some distance into the Complex. The Grano Fault starts in the Peter Mitchell taconite pit, passes through the Serpentine deposit, and lies along the border between the Partridge River intrusion and the South Kawishiwi intrusion. The Grano Fault is inferred to be a vent that formed high-grade copper-PGE enriched massive sulfide at the Local Boy ore zone of the Babbitt deposit. Both of these large faults cross mapped W-NW to E-SE trending faults passing through the Dunka Road deposit and to the south of the Babbitt deposit. The intersection of these systems has not been well examined either by drilling or field mapping.

These fault intersections could present two types of targets: 1) massive sulfide in locations where space opened during faulting, especially in the footwall (a Sudbury or Local Boy model); and 2) pathways for altering and /or mineralizing fluids to intersect particular geologic horizons (such as in the Birch Lake model or postulated for the top of Unit 1 in the Partridge River intrusion).

Voisey's Bay targets

Peterson's discussion of "feeder zone sulfide mineralization" in Miller et al., (2002), points to the possibility of such a target south of the Spruce Road area (a.k.a. the Highway One Corridor area). There, the potential conduit between the Bald Eagle intrusion and the South Kawishiwi intrusion is confined below a large raft or pillar of earlier formed anorthosite. Mapping of assay copper-nickel grade and ratios indicates that the highest grades in the area may be in a channel or vent area below this raft.

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THE PROPOSED NATIONAL UNDERGROUND SCIENCE AND ENGINEERING LABORATORY AT THE SOUDAN MINE, NORTHEASTERN MINNESOTA: A GEOLOGICAL SITE INVESTIGATION

PETERSON, Dean M., Natural Resources Research Institute, Duluth, MN,

dpeters1@nrri.umn.edu

PATELKE, Richard L., Natural Resources Research Institute, Duluth, MN,

patelke@nrri.umn.edu

In 2000, the National Science Foundation (NSF) convened a committee chaired by Dr. John Bahcall, of Princeton University, to evaluate the scientific justification for a national facility for deep underground science. The committee's charge was to evaluate the potential physics research that could be completed by the next generation of solar neutrino, double beta decay, proton decay, dark matter, and related background-sensitive experiments. In addition, the committee considered the possible relevance of such a facility to other disciplines, including geoscience, microbiology, materials development and technology, and monitoring nuclear tests. NSF received the recommendations of the Bahcall Report titled "Underground Science" in 2001 (available online at <http://www.sns.ias.edu/~jnb/Laboratory/science.pdf>). One of the results of the NSF-sponsored workshop on Neutrinos and Subterranean Science in 2002 was the June 2003 publication "EarthLab, A Subterranean Laboratory and Observatory to Study Microbial Life, Fluid Flow, and Rock Deformation". This publication sets a framework for geological research that could be undertaken in a deep underground setting, and is available online at <http://www.earthlab.org>. Three unsolicited proposals to fund (each ~ \$275 million) the development of a National Underground Science and Engineering Laboratory (NUSEL) were submitted to NSF, and include the University of Washington's Homestake Mine site at Lead, South Dakota (<http://mocha.phys.washington.edu/nusel/proposal.html>), the University of Minnesota's Soudan Mine site in northeastern Minnesota (<http://www.soudan.umn.edu/NUSEL/>), and the University of California Irvine's Mt. San Jacinto site near Palm Springs, California (<http://www.ps.uci.edu/~SJNUSL/>). On May 28, 2003, a NSF site panel report on developing a NUSEL concluded that the Homestake Mine in South Dakota was the most favorable. In addition, the panel considered the Soudan Mine a possible back up site for NUSEL, and that the San Jacinto site is not a viable NUSEL candidate. The evaluation criteria of each of the sites were partitioned into two broad categories: (1) geological suitability; and (2) relative costs. Geological suitability issues for the Soudan Mine included the uncertainty of the geology and rock mass conditions at depth.

On June 2, 2003, Barrick Mining Company, the owner of the Homestake Mine, turned off the pumps and began flooding the deep portions of the Homestake mine, which consequently jeopardizes most of the earth science initiatives outlined in EarthLab. On February 6, 2004, the NSF returned without prejudice all of the unsolicited NUSEL proposals, and will soon publish a three-stage request for new NUSEL proposals, which will include: Stage 1 - develop a preliminary plan of research activities requiring deep underground access, to aggregate the plans into science modules, and to define the physical requirements needed for each module; Stage 2 - fund grants for conceptual planning of infrastructure as related to each site; and Stage 3 - fund grants for technical designs for the underground infrastructure, detailed geological characterization and environmental permitting, and development of management plans.

Between mid April and mid June of 2003, geologists from the Economic Geology Group of the Natural Resources Research Institute, University of Minnesota Duluth completed detailed geologic mapping around the proposed NUSEL site at the Soudan Mine, and wrote a detailed report describing the results of the study (Peterson and Patelke, 2003). The geological report, geological maps, and GIS data files generated as a result of this work are available online at <http://www.nrri.umn.edu/egg/>. This poster presents the three plates that accompany the geological site investigation report of the suitability of the Soudan Mine area for hosting a NUSEL. Based on this recent detailed field mapping and interpretation, the geological and structural setting of the Soudan Mine is perfectly suited for hosting a NUSEL. In addition, a Soudan Mine NUSEL contains all the requirements outlined in the EarthLab document. The report by

Peterson and Patelke (2003) outlines the geological suitability of the area for a NUSEL and an integrated EarthLab. The five major themes addressed in this report include:

Bedrock Geology - The Neo-Archean bedrock geology of the Soudan Mine area is divided into five major lithostratigraphic units. These units include the: (1) Fivemile Lake sequence, moderate to shallow-water bimodal volcanic rocks; (2) Central Basalt sequence, deep-water tholeiitic basalts; (3) Upper Sequence, Algoma-type iron formation, tuff, and epiclastic rocks; (4) intrusive rocks, felsic porphyries, granodiorite, diorite, gabbro, and lamprophyre; and (5) sheared rocks, distinct curvilinear zones of chlorite-sericite-ankerite-pyrite schists.

Structural Geology - The field area is divided into four main structural domains that include: (1) the Murray shear zone; (2) the Mine Trend shear zone; (3) the Linking Zone; and (4) the Collapsed Hinge Zone. These domains appear to be internally structurally coherent, and are separated from each other either by areas of relatively undeformed rocks or discrete sheared boundaries.

NUSEL Site Selection - The geological criteria deemed most important for NUSEL construction include: (1) definition of a competent rock mass for excavation of large caverns at depths of 1,450 m and 2,500 m; (2) minimizing the occurrence of major lithologic contacts that would be encountered during construction of shafts, drifts, and the helical decline; and (3) minimizing the occurrence of major structural features in the area proposed for construction of the helical decline. A large area in the competent pillowed basalts of the Central Basalt sequence appears to meet all of the criteria for construction of the helical decline, and large laboratories could probably be excavated out of a large, highly indurated dioritic sill.

Compatibility with EarthLab - One of the main requirements for EarthLab is a very large, instrumented rock volume and access to great depths. At Soudan, the volume of rock that can be reasonably be accessed for EarthLab research in a Soudan Mine NUSEL is approximately 30 km³. The scientific themes of study proposed for EarthLab are: (1) microbial life at depth; (2) the hydrologic cycle; (3) rock fracture and fluid flow; (4) rock-water chemistry; (5) deep seismic studies; and (6) geophysical imaging. The compatibility of a Soudan Mine NUSEL with each of these themes is favorable. Although the conceptual design plans for the Soudan Mine NUSEL requires relatively high-cost new construction at depth, the pristine nature of this geological environment is highly desirable for EarthLab research. In addition, the close proximity of the Soudan Mine NUSEL to the four structural domains minimizes the cost of drilling and drifting into these structural settings for EarthLab research.

Outstanding Geological Research Opportunities - The geological and structural setting of the rocks within and adjacent to the proposed Soudan Mine NUSEL provides a unique opportunity for advances in several areas of earth science. Ideas on outstanding research opportunities include: (1) the structural control of lode-gold mineralization; (2) the hydrothermal alteration of subaqueous volcanic rocks and associated massive sulfide copper-zinc mineralization; (3) the origin of massive hematite ore bodies within Algoma-type iron-formation; (4) the genetic evolution and temporal development of a Neo-Archean volcanic arc; (5) the Neo-Archean tectonic architecture of the southern Laurentian margin; (6) the Pleistocene hydrogeology of the Superior Craton; and (7) the permeability of crystalline bedrock.

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PETROTECTONIC EVOLUTION OF PALEOPROTEROZOIC GRANITIC ROCKS ACROSS THE CENTRAL PENOKEAN OROGEN, NORTHERN MI & WI

PIERCEY, P., SCHNEIDER, D.A., Department of Geological Sciences, Ohio University,
Athens, OH 45701 USA

HOLM, D.H., Department of Geology, Kent State University, Kent, OH 44242 USA

Recent U-Pb single-crystal zircon geochronology of Paleoproterozoic post-Penokean granitic rocks of northern Michigan and Wisconsin, historically interpreted as an "anorogenic suite," has revealed a distinct age trend: magmatic pulses apparently migrated southward from ca. 1800 to 1750 Ma, after cessation of Penokean orogenesis (Holm et al., 2004; figure1). Yavapai-aged subduction slab rollback has recently been hypothesized to explain this magmatic pattern. In this model, the subducting slab steepens, and while depth of melting remains static, the locus of melting migrates trenchward (figure 2). Granitoid bodies intrude the Archean gneissic basement, Proterozoic metasedimentary marginal sequences, and an accreted juvenile arc (the Wisconsin Magmatic Terrane) across the breadth of the orogen. Nine samples from eight localities (the Radisson granite was sampled twice due to significant differences in mineralogy) were analyzed petrologically and geochemically, using major-, trace-, and rare-earth element analysis, to discriminate the tectonic setting into which emplacement occurred. Petrologic analysis shows a grain size decrease to the east. Major-element classification (K_2O vs. SiO_2) indicates a calc-alkaline to shoshonite trend for all localities sampled, indicating subduction-related genesis. Nevertheless, trace element tectonic discrimination diagrams after Pearce et al. (1984) indicate a correlation to the local lithology rather than tectonic setting. That is, Humboldt and Montello granites, which intrude Archean gneissic basement, are classified as within-plate granite (WPG); Park Falls syenite, intruding Proterozoic metasedimentary sequences, is categorized as a collisional granite (COLG); and the remaining granites (Radisson, Lugerville, Jennings, Amberg, and Chequamegon) that intrude the accreted arc of the Wisconsin Magmatic Terrane are classed as volcanic arc granites (VAG). For this reason, caution must be exercised in using this technique, especially on single localities. A rare-earth element spidergram, normalized to chondritic values, shows the COLG as the most evolved and WPG as the least, highlighting relative continental crust evolution/component. In this study, the geochemical analyses did not illustrate an age or geographical trend as expected, but rather a correlation of source area and/or relative crustal contribution. Therefore, the suite is interpreted as products of subduction-induced melting across a variable source terrane.

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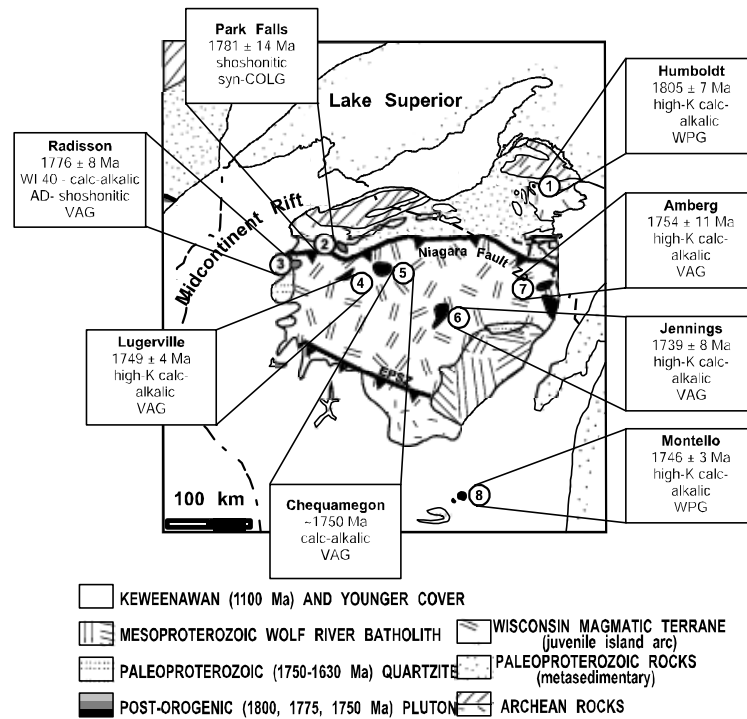


Figure 1. Simplified tectonic map of the Lake Superior region, northern Michigan and Wisconsin (after Sims, 1992), including summarized ages and geochemical classifications. EPSZ = Eau Pleine Shear Zone

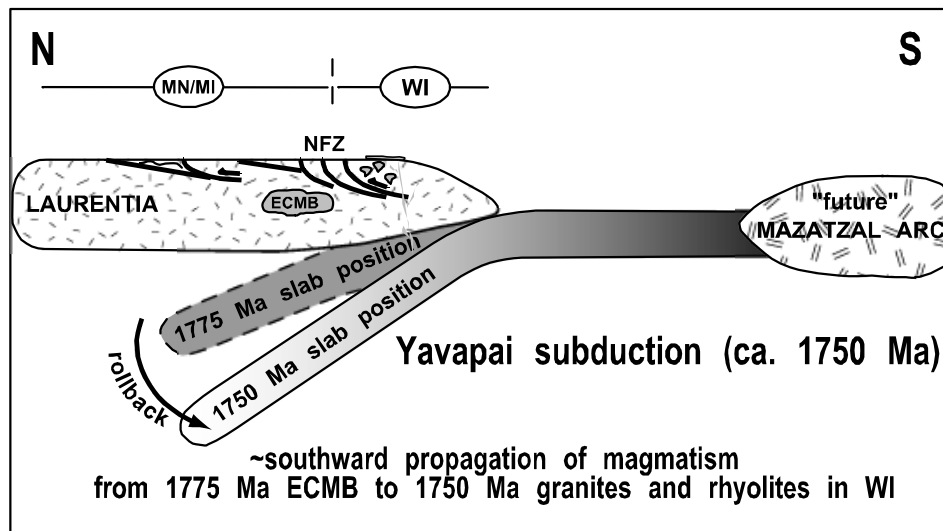


Figure 2. North-south cross-section through the Penokean orogen of the proposed model to explain the age trend in granitic bodies. ECMB = East Central Minnesota Batholith.

BLOWING IN THE WIND: THE COPPER HARBOR STROMATOLITES REVISITED

PLANAVSKY*, Noah, and BJORNERUD, Marcia, Geology Department, Lawrence University, Appleton WI 54912

The Copper Harbor Conglomerate is the basal unit of the sediment-dominated upper part of the Keweenawan series. This sedimentary sequence was deposited within the central basin of the Mid-Continent Rift System beginning at approximately 1087 Ma. The coarse grain size, rounded clast shapes, low clay content, large trough cross bed sets, channel structures and ripple marks observed in the conglomerate are best explained by a prograding alluvial fan complex in an arid environment with rugged topography (Daniels, 1982). Locally, the conglomerate is matrix-supported, indicating that debris flows also contributed to its formation. The clasts within the conglomerate appear to have been derived exclusively from the underlying volcanic flows of the rift, suggesting that the basin was only a relative low within a topographically elevated region – probably a thermally supported high similar to the modern East African rift. All sedimentary features of the Copper Harbor Conglomerate point to a nonmarine depositional setting.

In the upper part of the Copper Harbor Conglomerate, thin, discontinuous clayey layers with dessication cracks are interbedded with the coarse and thick conglomerate strata, suggesting that ephemeral playa lakes existed within the basin. Some of the lacustrine deposits contain finely laminated, hemispherical, calcareous stromatolitic structures. In many cases these structures drape around the upper surfaces of large boulders that are partly enclosed by clayey sediment. The external shape and fine internal layering of the hemispheroids as well as the presence of detrital sand grains on their inclined sides (indicating organic stabilization) all suggest that they are true biogenic stromatolites (Elmore, 1983). That is, the Copper Harbor stromatolites appear to record a terrestrial microbial community that established itself far above sea level in middle Proterozoic time.

Most modern microbial lithifying mats are complex symbiotic communities of more than one genus (Stal, 2000), although there are modern freshwater stromatolites formed exclusively by cyanobacterial activity (Eggleson and Dean, 1976). The current paradigm is that the mucilaginous sheath excreted by cyanobacteria is essential for formation and lithification of the stromatolite structure. Whether the Copper Harbor stromatolites represent multi-genus communities or simple cyanobacterial mats, it is interesting to consider how the microbes might have found their way into a high, dry basin that had previously been the filled with ponded basaltic lavas.

Most modern and fossil stromatolites occur in near-shore marine settings, and migrate over time via aqueous fragmentation or microbial mat bifurcation. The Copper Harbor Basin, however, was clearly high and isolated. The nearest continental margin is thought to have lain some 800 km away, beyond the Grenville front (Ojakangas et al., 2001). Paleocurrent directions and the absence of extrabasinal clasts in the conglomerate, furthermore, exclude the possibility of fluvial transport from another terrestrial community.

We suggest, therefore, that the basin was colonized through *akinetes anemochory*, or wind transport of dormant reproductive structures. Colonization by this means is consistent with the inferred wind patterns of the time. Localized aeolian dune deposits within the Copper Harbor

conglomerate indicate paleo-wind directions that were orthogonal to fluvial paleocurrent directions, blowing from the southeast (in paleogeographic coordinates), the azimuth of the Grenville coast. This is consistent with the inferred paleolatitude of 20° N, which would have placed the Copper Harbor basin in a paleo-trade wind region (Taylor and Middleton, 1990), with prevailing winds blowing from the Grenville coast toward the Lake Superior region. Long distance aeolian transport of akinete structures is physically plausible. Cyanobacterial akinetes are on the order of 10µm in diameter (Lang and Whitton, 1973), and several recent studies have documented regional and even transoceanic transport of fine sediment (Prospero, 1999), spores (Josefsson, 2002) and pollen grains (Rogers and Levetin, 1998) of similar size.

The stromatolites of the Copper Harbor Conglomerate are among the few known records of Proterozoic terrestrial biological communities, and they provide a glimpse of the early stages of colonization of a barren landscape. Aeolian dissemination of microbes and nutrients may have been an important mechanism of dispersal in the Precambrian biosphere.

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A Geochemical Study of the Sills of the Nipigon Basin, Ontario

RICHARDSON*, A., and HOLLINGS, P., Department of Geology, Lakehead University, 955 Oliver Rd., Thunder Bay, Ontario, P7B 5E1, Canada; ajrichar@lakeheadu.ca

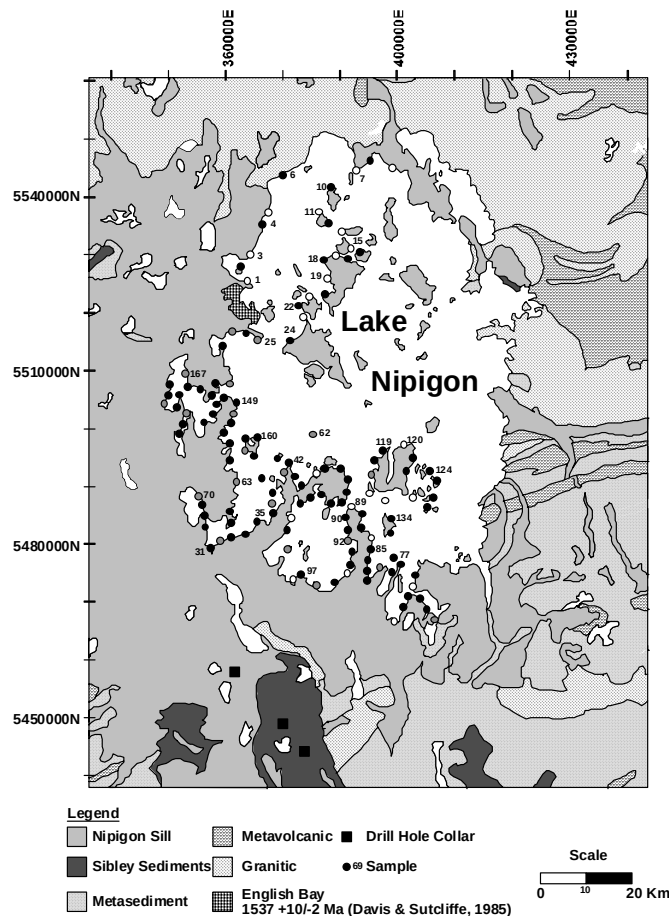


Figure 1. Regional Geology with sample locations

Introduction and Background

The Nipigon Sills are a relatively flat-lying Proterozoic tholeiitic diabase sequence associated with the Keweenaw mid-continent rift (MCR) event centered on the Lake Superior region. The MCR was active approximately 1100 My ago with published U-Pb zircon ages of $1108.8 \pm 4/-2$ Ma, and 1097.6 ± 3.7 Ma from the Nipigon Sills and Osler volcanics respectively (Davis and Sutcliffe, 1985). These sills are up to 200 metres in thickness and dominate the geology of the Lake Nipigon basin. The sills currently cover an area of approximately $11\,000\text{ km}^2$ representing a minimum volume of $10\,000\text{ km}^3$ (Fig. 1; Sutcliffe, 1986).

Although related to the Logan sills found further south in the Thunder Bay area, they differ in rare earth geochemistry, mineralogy, and paleomagnetic character. First noted by Sir William Logan in a report to the crown in 1863, the region was not mapped in detail until the first decade of the twentieth century by Andrew Wilson, whose report in 1910 included an accurate representation of the sills, in addition to Archean geology and limited geology of the Sibley Group sediments. Wilson's report brought to light the question of whether the sills represent an

extrusive flood basalt sequence or a hypabyssal intrusive unit. The lack of extrusive characteristics (pillows, ropy flow tops, vesicles, etc.) as well as a billion years of erosion makes interpretation based on direct observation difficult.

Project

This research is funded as part of the Lake Nipigon Regional Geoscience Initiative (LNRGI) in order to further the understanding of the Lake Nipigon region and promote mineral exploration and development through a public/private sector partnership. The aim of this study is to develop a model of sill emplacement using detailed whole rock and isotope geochemical data, as well as petrographic work and mineral chemistry, to develop a formational model for the sills.

Preliminary Results

Of the 170 outcrop samples and 530 diamond drill hole (DDH) samples collected in 2003 (Fig. 1), 80 have been analyzed using XRF, ICP-AES, and ICP-MS methods. Preliminary results point to the sills being a remarkably uniform sequence of olivine basalt with a pronounced

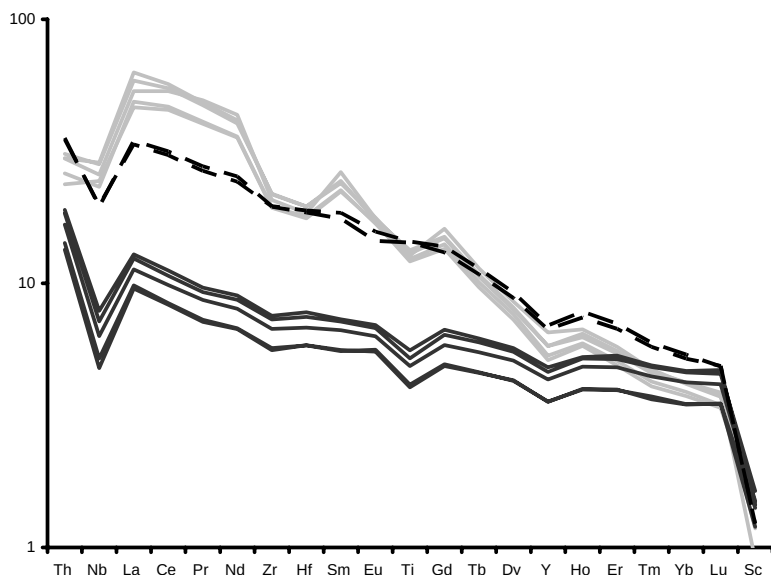


Figure 2. REE profiles of three sill types. Type 1 (black), Type 2 (grey), Type 3 (dashed)

negative Nb anomaly, LREE enrichment and slightly fractionated HREE (Fig. 2, grey) with $\text{La}/\text{Sm}_{\text{cn}}$ and $\text{Gd}/\text{Yb}_{\text{cn}}$ ratios for normal sill averaging 1.74 and 1.40 respectively. A geochemically distinct sill with $\text{Gd}/\text{Yb}_{\text{cn}}$ and $\text{La}/\text{Sm}_{\text{cn}}$ ratios of 3.64 and 13.3 respectively was found in the top of drill holes DDH3 and DDH5. This distinct signature was also observed in the basal unit of drill hole SW08-5 of the ultramafic portion of the Seagull intrusion. A

third distinct sill, identified in two outcrop samples along the

southern shore of Lake Nipigon was found to have $\text{La}/\text{Sm}_{\text{cn}}$, and $\text{Gd}/\text{Yb}_{\text{cn}}$ ratios of 6.46 and 1.89 respectively. Though petrographically indistinguishable, this geochemistry indicates that there were at least three magma sources for the sill complex, of which all possess a significant Nb anomaly indicative of crustal contamination

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THE GEOLOGY OF THE EAGLE NICKEL-COPPER DEPOSIT: MARQUETTE COUNTY, MICHIGAN

ROSSELL, D.M., dean.rossell@kennecott.com, Kennecott Exploration Company, 10861 N. Mavinee Dr. #141, Oro Valley, AZ. 85737

COOMBES, S., Kennecott Canada Exploration Inc., #354-200 Granville Street, Vancouver, B.C. V6C 1S4

Kennecott's discovery of the Eagle nickel-copper deposit in 2002 marked the culmination of more than a decade of exploration work by Kennecott in the Baraga Paleoproterozoic sedimentary basin. The discovery hole, YD02-02 completed in July 2002, intersected 84.2m of massive sulfide mineralization averaging 6.3% Ni and 4.0% Cu. The resource estimate for the Eagle deposit at the end of 2003 was 5 million tonnes at 3.68% Ni, 3.06% Cu and 0.1% Co.

The Eagle deposit is hosted in the westernmost of two small peridotite bodies historically referred to as the Yellow Dog Peridotite. The Yellow Dog intrusions, which lack penetrative foliations and truncate Penokean tectonic fabrics in the surrounding meta-sediments, are believed to be Keweenawan in age (Klasner, et. al., 1979). The intrusions are mainly comprised of coarse-grained, variably serpentinized peridotite and feldspathic peridotite. A fine-grained, olivine poor phase is found along the margins of the intrusions and as xenoliths within the peridotite. Possible amygdules in the olivine poor phase(s) suggest a shallow level of intrusion.

Three principal types of sulfide mineralization are recognized in the Eagle deposit: disseminated (blebby), semi-massive (matrix) and massive. Although the nickel contents of massive sulfides are relatively uniform throughout the deposit, copper contents vary significantly. Platinum group metals (PGM) and gold values are significantly higher in the copper rich massive sulfides. Copper rich veins and disseminations, with significant PGM and gold, in the surrounding meta-sediments may constitute a fourth type of ore.

Massive and semi-massive sulfide ore types in the Eagle deposit are irregularly distributed. The contacts between different ore types are sharp and show little evidence of the gradation that might be expected if gravity driven accumulation of sulfides from an overlying, sulfide saturated, silicate magma was the principle mechanism of ore formation. Sequential emplacement of various mixtures of silicate and sulfide magma and cumulus minerals, derived from a lower stratified magma chamber, may provide a better model.

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Geologic Reconnaissance of the Spaulding Mine Area, Cook County, Minnesota

RUHANEN, Richard W., 1746 Janet Park Dr. Hibbing, MN 55746

The Spaulding “mine” consists of a series of exploration pits, shafts and trenches constructed on a fissure vein at the east end of Spaulding Lake in northeastern Cook County, MN. William P. Spaulding prospected this area during the late 19th century, from about 1875 until the summer of 1897, with the target being silver mineralization. Silver was being mined in Ontario during this time at the Rabbit Mountain and Silver Mountain areas just 20 miles to the northeast in veins of a similar nature, as well as at Silver Islet near the Sibley Peninsula on the shore of Lake Superior.

The Spaulding Lake area is remote, accessible only by canoe, and consists of east-striking hills and ridges with predominantly north-facing cliffs. Porphyritic diabase sills cap the hills and ridges while the low lands are occupied by lakes and swamps underlain by Rove formation sediments. The rocks dip 12 – 16 degrees to the south.

Spaulding’s work exposed an east-striking vein on the south side of Spaulding Lake at the base of a north-facing cliff of Rove formation capped by a sill. The vein consists of a breccia of angular, porphyritic sill and Rove formation fragments cemented by quartz, calcite and perhaps barite. Vugs lined with drusy quartz crystals are common. Sparse pyrite is the only mineralization seen, no silver or other sulfide minerals have been observed. Dump piles near the pits and shafts consist almost entirely of this breccia vein material.

During October 2003, two traverses were made by the author on the north shore of Crystal Lake 1 and 2 miles, respectively, to the west of the exposed vein. Rocks noted are porphyritic sill(s), granophyre, small basaltic dike-like bodies, and hornfelsed to partially melted blocks of Rove sediments. At each traverse location, a north-south fracture forms a 1 to 2 foot scarp facing west. Gabbroic rocks of the Duluth Complex crop out ¼ mile to the south, forming a low ridge on the southwest shore of Crystal Lake. Inclusions of Rove formation are common in the sills and in the Duluth Complex rocks.

At the Spaulding “mine” location, the sill – Rove formation contact rises in elevation to the east while curving towards the south. The exploration pits were sunk along depressions thought at the time to be ancient mining features created by copper culture peoples. At the shaft, the last excavation on the vein to the east, the breccia consists entirely of Rove formation. On one dump pile near the eastern extent of the working, granophyre with quartz-filled fractures was found, indicating that granophyre occurs at some depth beneath the sill. The vein disappears under glacial drift to the east of the main shaft.

At the southwest end of Spaulding Lake, an east-west striking zone of fault gouge cuts a sill of porphyritic diabase, indicating that the vein structure may continue further west of the Spaulding workings.

OCEAN-FLOOR-TYPE-ALTERATION OF DRILLED MRS VOLCANIC ROCKS IN IOWA

SCHMIDT, Susanne Th., Département de Minéralogie, Rue des Maraîchers 13, CH1205 Genève, Switzerland, susanne.schmidt@terre.unige.ch

SEIFERT, Karl, Department of Geological & Atmospheric Sciences, Iowa State University, Ames, IA 50011, kseifert@iastate.edu

In the Thor Group of the buried Midcontinent Rift System of Iowa well cuttings and cores of basalts and diabases were studied from five sites to determine the alteration pattern within a subsurface zone of 250 x 50 km (Fig. 1). The metamorphic assemblage, metamorphic grade, bulk rock composition and the chemical composition of the metamorphic minerals such as actinolite, pumpellyite, epidote, and chlorite, were determined. Equilibrium phase diagrams were calculated using the DOMINO-Theriak Software.

At sites 3 and 5 the metamorphic assemblage is similar and contains the minerals pumpellyite-actinolite-chlorite (Mg-rich)-albite. However, at site 3 this assemblage is restricted to a thin alteration band along a vein and the rock is unaltered away from the vein, whereas at site 5 the rock is almost totally altered and relicts of the primary magmatic minerals, such as clinopyroxene or Ca-rich feldspar, are rarely observed in thin section. At site 4 the assemblage pumpellyite-albite-chlorite is present in a diabase. For site 2 chlorite and epidote were determined. Chlorites are present at all sites showing a wide range of composition (Fig. 2). Chlorite is Mg-rich in less altered units and Fe-rich in strongly altered units. Cross cutting relationships between these minerals imply the later formation of Fe-chlorites. The observed pattern points to greenschist-facies conditions in site 3 and 5 and probably higher temperatures at sites 2 and 1 (epidote-chlorite assemblage).

The fact that alteration is focused along veins such as observed at site 3 indicates that infiltration of a fluid at elevated temperatures occurred at some stage of the alteration. For the assemblage amphibole-chlorite-albite-epidote in the pervasively altered diabase of site 5, an equilibrium diagram was calculated using the DOMINO-THERIAK Software (de Capitani, 1994). It restricts the assemblage to a temperature interval between 210 to 260 °C and a pressure of up to 3 kbar. The presence of pumpellyite in another sample of the same site and its upper temperature stability limit of ca. 250 °C at 3 kbar (Potel et al., 2002) are in agreement with the calculated P-T field.

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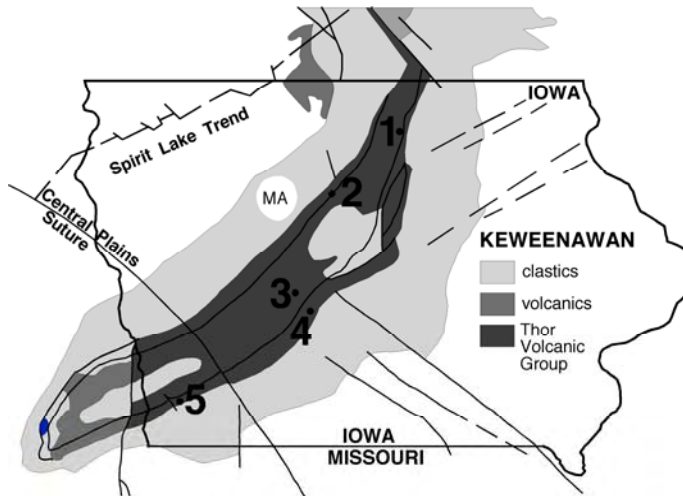


Fig. 1 Location of drill sites in the buried MCR in Iowa (after Seifert & Anderson, 1996)

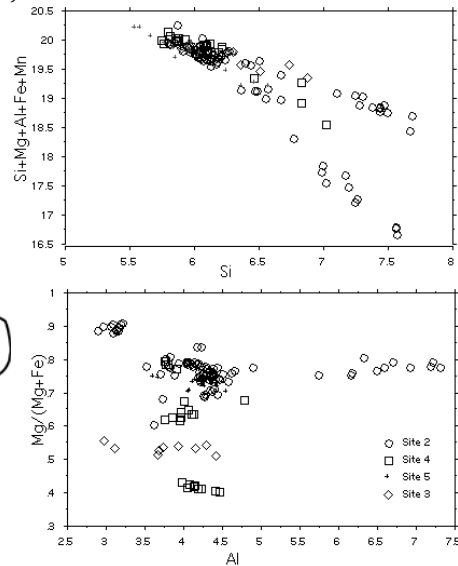


Fig. 2 Composition of chlorite in the Thor group

Depth Migration of Seismic Reflection Data: An Example for Lake Superior Studies

SCHNEIDER, Robert V., Energy Institute, University of Louisiana at Lafayette, P.O. Box 43612, Lafayette, LA 70504-3612, USA

2-D reflection seismic profiling is a useful geophysical tool for understanding geologic structures in the Earth's subsurface. For example, it is the primary tool of choice in hydrocarbon exploration on a worldwide basis. A seismic section, under the right circumstances, can provide an accurate picture of geologic formations. The main differences between seismic and geologic sections are: 1) Seismic data are recorded and displayed in time, not depth; 2) Seismic reflections are caused primarily by velocity changes, which may (or may not) be coincident with geologic boundaries.

A key process in preparing a seismic data set for interpretation is application of a concept called migration. This step moves seismic amplitudes from where they are recorded (i.e. at the receiver) to where the reflection actually occurs in the geologic section (Gray et al., 2001). Because seismic data are recorded in time, this requires an accurate understanding of the velocities in the subsurface, which carries the seismic wave field. Seismic time processing, however, depends on several assumptions to simplify complexities in seismic wave theory. Of fundamental importance is the presence of a horizontally smoothly varying velocity field. Where this assumption is violated, the resulting seismic profile is degraded below the velocity change. In other words, structures displayed in such sections are misplaced both horizontally and vertically. In extreme cases, even the edges of bodies with significantly different velocities than the surrounding country rock are difficult to image (Larner et al., 1989).

Near-surface velocity changes, especially in marine acquisition, are relatively rare examples of this problem. Where they occur, the subsurface image may be degraded even after the application of time migration. An example is found at the Florida Escarpment in the eastern Gulf of Mexico (Figure 1a). Here the steep slope of the ocean bottom, which approaches 45° over a 2000m interval, creates a lateral step change in velocity from water to a rock column. To minimize the effects of this problem, careful velocity analysis must be performed in depth (Schneider et al., 2000). The resulting velocity model was used to migrate the seismic data, which were recorded in time, and to output an image in depth (Figure 1b).

The depth of the water bottom of Lake Superior varies over short horizontal distances (Figure 2). This similarity to the Florida Escarpment indicates that a reflection profile acquired over portions of the lake may suffer similar effects. Resulting interpretations may therefore be error-prone. Experience suggests that careful velocity modeling in depth followed by depth migration will be required to maximize our understanding of crustal structure in this region.

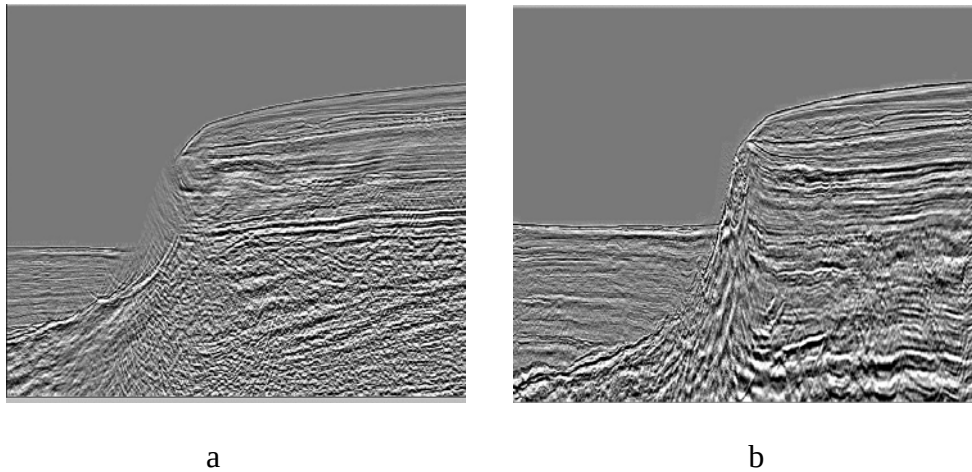


Figure 1. (a) Example of seismic mis-imaging due to time processing across the abrupt Florida Escarpment velocity change. (b) Depth migrated data showing improvement in the image of the water bottom and the subsurface image (*data courtesy of TGS-NOPEC*).

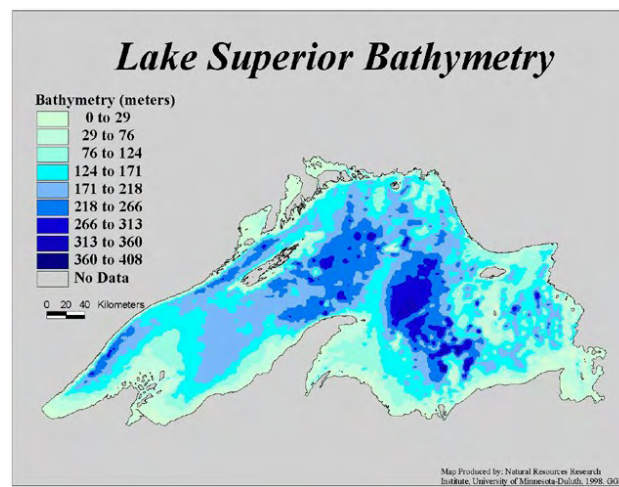


Figure 2. Bathymetric profile showing rapid variation in depth in Lake Superior (Natural Resources Research Institute, 1998).

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WHATEVER HAPPENED TO THOSE Cu-Ni DEPOSITS?

SEVERSON, Mark J., and HAUCK, Steven A., Natural Resources Research Institute, University of Minnesota Duluth

Large resources of low-grade copper-nickel sulfide ore that locally contain anomalous Platinum Group Element (PGE) concentrations are well documented by drilling in the basal zones of the Partridge River and South Kawishiwi intrusions. At least nine subeconomic deposits have been delineated in the basal 100 to 300 meters of both intrusions. The mineralization consists predominantly of disseminated sulfides that collectively constitute over 4.4 billion tons of material averaging 0.66% Cu and 0.20% Ni (Listerud and Meineke, 1977).

Serious exploration for Cu-Ni deposits at the base of the Duluth Complex (Complex) began about 13 km (8 miles) to the southeast of Ely, MN, in 1948, when strongly mineralized rocks were uncovered in an excavation used to build a forest service road (Spruce Road). Local prospector Fred S. Childers of Ely noted copper stains in the material and he, along with Roger V. Whiteside of Duluth, began searching along the basal contact in the vicinity of the Kawishiwi River. In 1951, they diamond drilled a 57 meter (188 feet) deep hole and intersected mineralized gabbro that averaged 0.36% Cu and 0.13% Ni. In 1952, both Bear Creek Mining Company (BMC) and the International Nickel Company (INCO) began intensive exploration efforts along a 61 km-long zone (38 miles) that coincided with the basal contact. INCO eventually picked up the Childers-Whiteside properties (Spruce Road and Maturi deposits); whereas, BMC concentrated most of their effort near the town of Babbitt (Babbitt and Serpentine deposits). By 1960, these exploration efforts indicated that large tonnages of disseminated Cu-Ni deposits were present along the basal contact. However, the low-grade nature of the deposits and the unavailability of state-owned mineral lands led to suspension of activities.

In 1966, state mineral leases were offered by the Minnesota Department of Natural Resources (DNR) and were awarded to successful bidders. Since 1966, over 20 companies have been actively involved in exploration for Cu-Ni and Fe-Ti-V deposits along the basal contact of the Complex and over 1,700 holes totaling over 1.5 million feet of core have been drilled. During the early 1970s, the Spruce Road and Babbitt deposits came the closest to development. Mining plans were submitted, test shafts were sunk (one each at the Maturi and Babbitt deposits), surface bulk samples were collected (3 deposits), and various land-use and water-use permits were requested from State and Federal agencies. Many of these activities drew strong opposition from environmental groups and some state legislators. In 1974, the Environmental Quality Board required that a regional Environmental Impact Statement (EIS) be conducted prior to acceptance of any site-specific EIS mining-related proposals. The DNR discontinued lease sales of State lands (1974-1982) until completion of the regional EIS. However, by the time the regional EIS was submitted in 1979, development of the Cu-Ni deposits was put on hold by the mining industry due to weakened copper and nickel markets, smelter-related problems with cubanite in the copper concentrate, and other financial reasons.

Enter the “PGE era.” During the early period of drilling (prior to 1980), all of the exploration companies recognized that the Cu-Ni deposits had some potential for hosting PGEs. Based on very limited sampling, the companies assumed that the typical Cu-Ni ore contained no more than a few hundred parts per billion (ppb) combined platinum and palladium. In 1985, the DNR and Minerals Resource Research Center (MRRC of the U of M) conducted a geochemical evaluation of portions of drill hole Du-15, from the Birch Lake area, and found significant values of 9 parts per million (ppm) combined Pt and Pd (Sabelin and Iwasaki, 1986). A short time later, Morton and Hauck (1987) compiled all of the known PGE data for the Complex and reported the presence of anomalous PGE values, often associated with high Cu values, at several other Cu-Ni deposits. These discoveries sparked renewed interest in the Cu-Ni deposits as potential polymetallic deposits (Miller et al., 2002; and references therein). Additional drill holes were sampled and

analyzed for PGEs throughout the Duluth Complex, and as a result, significant PGEs were found at several more deposits.

Some of the PGE-enriched zones were found to be “stratabound” in that they are correlative with certain units of the igneous stratigraphy as determined by Severson and Hauck (1990), for the Partridge River intrusion, and Severson (1994), for the South Kawishiwi intrusion. Still other PGE-enriched zones were found to be related to either localized structural conditions (Local Boy massive sulfide zone of the Babbitt deposit; Severson and Barnes, 1991) and/or combinations of stratigraphy and structure (Birch Lake). For example, four stratabound horizons, each containing generally 1.0 ppm Pd, have been documented at the Dunka Road deposit (Geerts, 1991) and appear to be related to magma mixing. A single stratabound PGE-enriched horizon is present at the Birch Lake PGE prospect and also appears to be related to magma mixing (albeit, the PGE-mineralization is also related to variably digested iron-formation inclusions). However, the PGE-horizon at Birch Lake is quite variable (thickness and PGE contents) and cases can also be made that favor a late hydrothermal origin and redistribution of PGE along a fault zone or an early magmatic origin based on proximity to a feeder zone along the same fault. At present, close proximity to a vent, along with local magma mixing, appears to have been the major factor in controlling the PGE tenor in the above cases (Hauck et al., in prep). Localized modification of the PGE content by a later hydrothermal event, while not ruled out, appears to have been of lesser importance.

Enter the “hydromet era.” In the mid to late 1990s, the potential of developing the Cu-Ni deposits using hydrometallurgical techniques has once again sparked renewed interest in the Duluth Complex. PolyMet Mining Corporation has acquired the Dunka Road deposit (NorthMet deposit) and plans to use its patented PlatSol technique to recover Cu, Ni, Co, and PGE. Teck Cominco has leased the Babbitt deposit (Mesaba deposit) and plans to use its patented CESL (Cominco Engineering Services Laboratory) process to recover the same metals. If it can be proven that these processes are feasible and economical, the next phase (the “permitting era”) in developing the low-grade Cu-Ni deposits of Minnesota could begin in the near future. The “permitting era” is anticipated to span at least a 2.5-3.0-year interval wherein an Environmental Assessment Worksheet (EAW), EIS, and applications for eight mining-related permits would be submitted.

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Hydrogen Stable Isotopic Evidence for Hydrothermal Alteration and PGE Concentration Involving Meteoric Water in the Birch Lake Area, Duluth Complex, MN

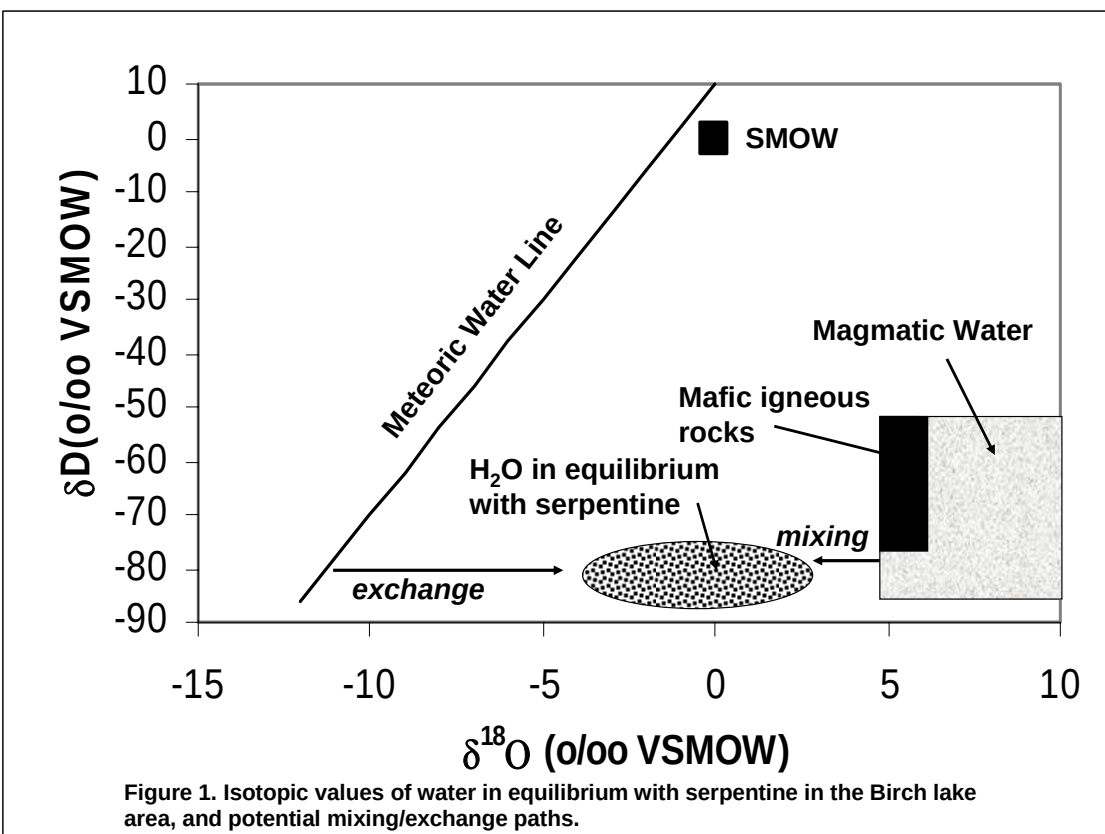
SHAFFER, Paula L., and RIPLEY, Edward M., Department of Geological Sciences, Indiana University, Bloomington, IN 47405

The Birch Lake prospect, located along the western margin of the 1.1 Ga Duluth Complex, contains local concentrations of platinum group elements (PGEs) of up to 8 ppm. Footwall rocks in the area are the Early Proterozoic Biwabik Iron Formation and the Archean Giant's Range Batholith. Petrographic analyses indicate minor to extensive late stage alteration of the troctolitic sequence of the Duluth Complex in the Birch Lake area. Olivine has been converted to serpentine, plagioclase has been locally replaced by chlorite, albite and sericite, and pyroxene has been partially converted to a mixture of chlorite and amphibole. Previous studies, both mineralogic and isotopic, (Sabelin and Iwasaki, 1986, Sabelin, 1987, Marma, et al., 2002, Shafer and Ripley, 2002, and Shafer, et al., 2003) have noted that: 1) some, but not all, PGE mineralization is associated with Cr enrichment, 2) oxygen isotopic studies are not supportive of Biwabik Iron Formation assimilation as a major control on either Cr or PGE enrichment, and 3) Re-Os isotopic studies clearly indicate extensive involvement of crustally derived Os in the ore forming process. Due to the intensity of alteration in the Birch Lake area, hydrothermal fluid transport or concentration of PGEs has been proposed as a key factor in the enrichment process. Hydrogen isotopic studies (primarily involving serpentine and sericite) have been undertaken to accompany our previous isotopic measurements, and to aid in the assessment of the alteration process.

δD values of serpentine (-87‰ to -96‰) and sericite (-79‰ to -84‰) are very similar to whole rock values found previously (-78‰ to -98‰). Assuming a temperature between $\sim 200^\circ$ and $350^\circ C$ for serpentinization (Allen and Seyfried, 2003), computed δD values for the water in equilibrium with serpentine and sericite range from -75‰ to -84‰. When compared to the average δD of fluid liberated from the Virginia Formation (-53‰), an origin from a metamorphic fluid is unlikely. Considering the suspected low temperature nature of the extensive alteration and low $\delta^{18}O$ values of serpentinized oxide melatroctolites (2.35‰ to 3.39‰), a magmatic fluid is also considered unlikely. The $\delta^{18}O$ value of water in equilibrium with serpentine at temperatures between 200° and $300^\circ C$ is in the range of -3‰ to 3‰. Although mixing between a magmatic fluid and a variously evolved meteoric water can not be ruled out (Fig. 1), we suggest that the geologic and isotopic data are more consistent with hydrothermal alteration involving a fluid of primarily meteoric origin. The water isotopic compositions could be attained via exchange with either igneous rocks of the Complex or with country rocks. The lack of evidence for widespread ^{18}O exchange in the country rocks suggests that fluid flow was dominantly via fractures, and that isotopic exchange occurred over long path lengths at low time-integrated water/rock ratios. This fluid has locally concentrated PGEs, possibly as a result of differential solubility and removal of previously present sulfide minerals.

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SILVER THREADS AND GOLDEN NEEDLES: GEOLOGICAL MILESTONES IN NORTHWESTERN ONTARIO

SMYK, Mark C., and **MAGEE, Angelique**, Ontario Geological Survey, Ministry of Northern Development and Mines, Suite B002, 435 James St. South, Thunder Bay, ON P7E 6S7 CANADA

Northwestern Ontario has been the focus of much geological inquiry and noteworthy discoveries over the past 140 years, many of which put the region in a worldwide limelight and continue to attract research interest. Some of these geological milestones form the basis of this retrospective paper.

Reconnaissance mapping and seminal works by pioneers such as Logan, Macfarlane, Bell, McKellar, Lawson and Wilson helped establish the fledgling Geological Survey of Canada in the mid- to late-19th and early 20th centuries and developed the basic framework of local Precambrian geology. The area was part of the first geologic map in Canada, *Geology of Canada*, in 1869. Earlier mineral discoveries in the lake Superior area, followed by the discovery of silver in the Thunder Bay District in 1868 at Silver Islet prompted not only detailed surveys of mineral deposits, but also the development of rudimentary mineral policy in Canada. Despite its short-lived (1870-1884) history, Silver Islet was host to a number of “firsts”, including the introduction of the Burleigh drill, the Frue Vanner and the first use in Canada of the diamond drill. The Thunder Bay silver district also attracted E.D. Ingall and Ontario Bureau of Mines geologists, including a young N.L. Bowen, who later attained international fame as an igneous petrologist and geochemist.

Evidence of the oldest life in North America is found in the *ca.* 3.0 Ga stromatolites at Steep Rock Lake. The discovery by Lawson in 1911 of the pseudofossil *Atikokania* there, named and described by Walcott (1912), led to its hailing as the world’s oldest fossil. Despite the ensuing debate and the widespread ascription of *Atikokania* to inorganic processes, the region once again gained notoriety when Tyler and Barghoorn (1954) discovered the best-preserved and most diverse microfossil assemblage in North America in the Paleoproterozoic Gunflint Formation. At the time of their discovery, they were deemed the world’s oldest fossils, “the oldest structurally preserved organisms that clearly exhibit cellular differentiation and original carbon complexes which have yet been discovered in pre-Cambrian sediments”. It was a benchmark, a monumental “first” in global paleontology.

Several minerals’ type localities are found in northwestern Ontario. The discovery of the Hemlo gold deposit in the 1980’s near Marathon yielded criddleite ($\text{TiAg}_2\text{Au}_3\text{Sb}_{10}\text{S}_{10}$), vauhnite ($\text{TiHgSb}_4\text{S}_7$) and hemloite ($(\text{As,Sb})_2(\text{Ti,V,Fe,Al})_{12}\text{O}_{23}\text{OH}$). Nisbite (NiSb_2); and paracostibite (CoSbS) were discovered in drill core at Trout Bay, Mulcahy Township, in the Red Lake area. The secondary minerals romarchite (SnO) and hydroromarchite ($\text{Sn}^{2+}_3\text{O}_2(\text{OH})_2$) were discovered on tin pannikins lost from a voyageur’s overturned canoe between 1801 and 1821, and found 4.5 m below the surface of the Winnipeg River at Boundary Falls, near Kenora. The discovery of these tin-bearing minerals is fittingly related to northwestern Ontario’s colourful history.

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Late Paleoproterozoic Rhyolite-Quartzite Sequences in the Southwestern U.S.: Speculative Relationship to Rocks of the Baraboo Interval

SOUTHWICK, D.L. (Minnesota Geological Survey (retired); davidsouthwick@earthlink.net)

At least 14 mappable units of supermature quartz arenite (quartzite) occur within Proterozoic terranes in the southwestern U.S. These typically are hundreds of meters in thickness, contain relatively minor interbeds of conglomerate and aluminous shale, and quasi-conformably overlie thick sections of high-silica rhyolite and/or rhyolitic pyroclastic rocks (Williams, 2003). Sedimentological features suggest that the quartzite units were deposited in fluvial to shallow marine environments, the latter having been influenced locally by tidal currents (Soegaard and Eriksson, 1985). The rhyolitic rocks beneath the quartzites range in age between 1665 and 1710 Ma. Extrusion apparently peaked in two pulses, the earlier one about 1700 Ma and the later one about 1670 Ma. Various geochronological methods indicate that several of the quartzite units are no more than a few million years younger than the subjacent rhyolite. Thus, as a first approximation, the quartzite formations were deposited in the interval 1700-1660 Ma with apparent depositional maxima around 1700-1695 Ma and 1665-1660 Ma.

The rhyolite-quartzite sequences rest unconformably on previously deformed and metamorphosed Proterozoic rocks, and have themselves been involved in one to three fabric-forming tectonothermal events (Williams, 1991; Williams and others, 1999). Although the deformational history of the rhyolite-quartzite sequences is complex and is the topic of continuing research and debate, there is general agreement that the older fabrics were imposed during one or more pulses of the ~1650 Ma Mazatzal orogeny. Some of the younger fabrics and preserved metamorphic assemblages developed during a 1400 Ma tectonothermal event that probably was related to "anorogenic" plutonism in the southern Rocky Mountains and the southern Midcontinent.

There are striking temporal, sedimentological, geochemical, and petrographic similarities between the 1700-1660 Ma quartzites in the Southwest and the 1712-1630 Ma quartzites of the Baraboo interval in the Upper Midwest (Medaris and others, 2003). However, the nearly ubiquitous stratigraphic association of quartzite with slightly older rhyolite observed in the Southwest has not been documented in the Upper Midwest. Essentially undeformed rhyolite occurs locally below the basal unconformity of the Baraboo Quartzite in Wisconsin. Clasts of undeformed porphyritic rhyolite and devitrified rhyolite tuff occur very locally in the Sioux Quartzite of extreme southwestern Minnesota (Southwick and others, 1986; Southwick, 1994), and 19th-century drilling in northwestern Iowa reportedly intersected rhyolite units (poorly described) interbedded with and beneath basal strata of the Sioux (Beyer, 1893; 1897). These rhyolites are texturally pristine and unmetamorphosed, although the Sioux occurrences are metasomatically altered. They have been interpreted as extrusive equivalents of late Penokean plutonism (ca. 1770 Ma) (Southwick, 1994), but as yet there is no solid geochronological evidence of their actual crystallization age.

If future geochronological investigations should demonstrate a significantly post-Penokean age for the rhyolites beneath quartzites of the Baraboo interval (say 1715-1700 Ma), the possibility of a tectonic connection between the Baraboo rocks and the rhyolite-quartzite sequences of the southwest would become much more tenable. Specifically, the documentation of pre-quartzite rhyolitic volcanism would strengthen the speculative hypothesis that the Sioux Quartzite and related units were deposited in fault-bounded depressions (Southwick and others, 1986) that

originally were volcanically active graben-like basins. Such basins may have been a far-field response to crustal stretching associated with Yavapai and transitional Yavapai-Mazatzal tectonism.

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Close Proximity of Kimberlite Pipes to Diabase Dykes: Structural Controls and Predictiveness in the James Bay Lowlands, Ontario

STOTT, G.M., Ontario Geological Survey, Sudbury, ON P3E 6B5, greg.stott@ndm.gov.on.ca

In the northernmost region of Ontario, Paleozoic sedimentary rocks (Figure 1a) cover the Archean Superior Province to form the Hudson Bay (HBL) and James Bay (JBL) lowlands. Diamondiferous kimberlite pipes of Early Jurassic (*circa* 190 Ma) and Mesoproterozoic (*circa* 1100 Ma) age occur in two separate clusters in the James Bay Lowlands (Figure 1b). Early Jurassic kimberlite pipes, including the Victor diamond deposit of De Beers Canada Exploration Inc., are close to the Winisk Fault, a major Archean dextral transpressive fault. However, the presence of this fault by itself does not adequately account for the linear chain of these kimberlite pipes near the Victor deposit nor the more scattered distribution, farther west, of Mesoproterozoic “Kyle” kimberlite pipes. Not all of the Kyle intrusions lie close to the Winisk Fault. More significantly, there is a spatial association between Proterozoic diabase dykes and these two clusters of kimberlite pipes.

A geological interpretation of regional aeromagnetic maps is being completed of the Precambrian basement underlying the Phanerozoic cover in the JBL and HBL. This analysis includes identification of the various Proterozoic diabase dyke swarms in that region. From this there is reason to suspect a correspondence between both of these kimberlite pipe clusters and two diabase dyke swarms. The Early Jurassic pipes mainly lie in a linear northwestward trend close to a Matachewan (*ca.* 2446 Ma) diabase dyke. This dyke is part of a parallel bundle of northwest-striking dykes across an approximately 20-kilometre width near the Winisk Fault. It is suggested here that deep crustal fractures associated with these dykes, arising from the giant Matachewan magmatic event, were reopened during subsequent episodes of displacement along the Winisk Fault. Over 90 km farther west, the 2121 Ma Marathon swarm forms an approx. 20 kilometre wide bundle of dykes trending northwards in the vicinity of the Kyle kimberlite pipes. Individual pipes lie close to aeromagnetic traces of the dykes. The occurrence of both sets of kimberlite pipes, close to but generally not on the Winisk Fault, implies the possibility that dyke-associated fracture swarms served as second-order, extensional “splays” near this major fault and provided preferred emplacement pathways for pipe intrusions at least in the middle to upper crust. Similar observations have been made in the Lac de Gras area in the Slave Province where Paleoproterozoic dykes show a moderate to strong spatial association with kimberlite pipes (Wilkinson et al., 2001).

In the context of this model, other areas of potential exploration interest include:

- 1) an area approximately 60-80 km farther east of the Victor deposit, where there is an overlap of another set of Matachewan and Marathon dyke bundles (*see* Figure 2) transected by the east-trending Winisk Fault, and where no kimberlite pipes have as yet been discovered;
- 2) 2) a set of aeromagnetic anomalies near a Marathon dyke 120 km east of Fort Hope; and
- 3) 3) an area that straddles the Manitoba – Ontario border near the Hudson Bay Lowlands where a set of reversely magnetised, north-striking dykes (and fractures?) occurs between the North Kenyon fault and the Winisk fault. This dyke swarm lies “up-ice” from an area of glacially deposited kimberlite indicator minerals found to the southwest (Stone 2001).

These three areas might serve as exploration tests of this empirically apparent correlation between pipe intrusions and dyke and fracture swarms, especially in proximity to the Winisk Fault. It is to be expected that the aeromagnetic expression of the pipes might be masked by the presence of these dykes. This is a testable hypothesis and further research requires dating fracture materials in these diabase/fracture swarms and episodic movement along the Winisk Fault. The apparent correspondence between kimberlite pipe emplacements and geophysically traceable bundles of diabase dykes and accompanying fractures provides a potentially important structural control, especially where subjected to reactivated tensile stress near major transcurrent faults.

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Figure 1a. Map of Ontario showing the location of the James Bay and Hudson Bay lowlands. The Winisk fault underlies the Phanerozoic cover rocks of the lowlands. Location of Figure 1b is outlined.

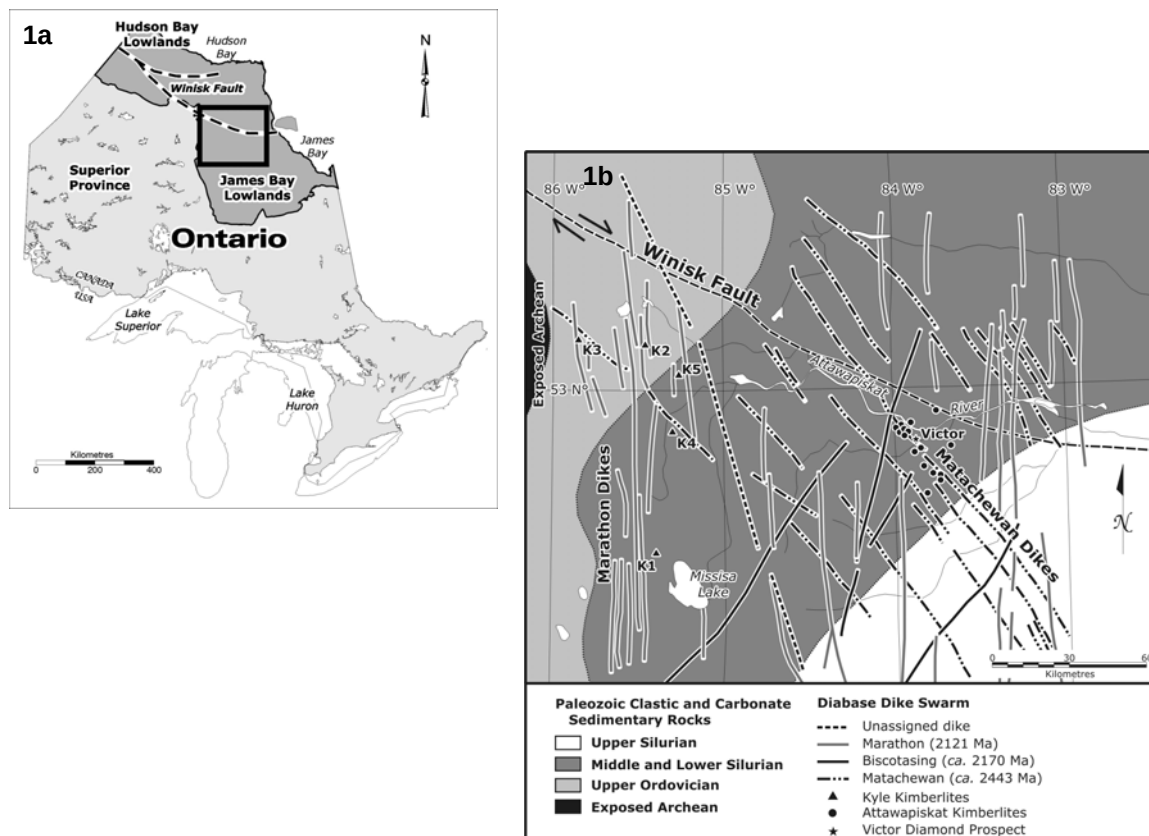


Figure 1b. A map highlighting the distribution of diabase dyke swarms under the Phanerozoic cover rocks of the James Bay Lowlands and the spatial correlation with kimberlite pipes. Early Jurassic kimberlite pipes, the Attawapiskat kimberlites, including the Victor diamond deposit, concentrate in a train parallel to one dyke in a group of northwest-striking Matabechewah (2446 Ma) diabase dykes and inferred associated fractures. Mesoproterozoic (1100 Ma) kimberlite pipes, the Kyle kimberlites, are spatially concentrated near individual diabase dykes in a group of north-striking Marathon (2110-2121 Ma) dykes.

ORIGIN OF PRE-WISCONSINAN GLACIAL UNITS IN NORTHERN WISCONSIN BASED ON LITHOLOGIC CHARACTERISTICS

SYVERSON, Kent M., syverskm@uwec.edu, Dept. of Geology, University of Wisconsin,
Eau Claire, WI 54702

Till and outwash units deposited before the Wisconsin Glaciation are found in weathered, isolated erosional remnants that are difficult to interpret. The goal of this paper is to obtain input from other geologists with regards to lithologic trends observed in pre-Wisconsinan till and outwash units in northern Wisconsin (Syverson and Johnson, 2001; Syverson, 2004).

Pierce Fm. till in western Wisconsin and till of the Medford Mbr. (Marathon Fm.) in central Wisconsin are very dark gray to yellowish brown, silty, and calcareous (Table 1, Fig. 1). Potential carbonate sources include Hudson Bay and the Winnipeg Lowland. Baker and others (1987) proposed that a pre-Illinoian Des Moines Lobe from the Winnipeg Lowland deposited the Pierce and Medford tills during the same glacial event based on lithologic similarities, reversed paleomagnetic signatures, and boulder trains and till fabrics suggesting ice flow from the NW/NNW. Thornburg and others (2000) noted much higher kaolinite concentrations in Pierce till than in Marathon Fm. till (Table 1). Syverson and Johnson (2001) proposed four possible origins for the Pierce and Medford tills and suggested that the Pierce and Medford tills may have been deposited synchronously by different lobes flowing from the northwest. Question: Do different source areas exist along reasonable flow lines that would cause higher kaolinite values in western Wisconsin than in central Wisconsin?

Table 1. Data for calcareous, pre-Wisconsinan till units (from Thornburg and others, 2000; Syverson, 2004). Mean values are reported (the carbonate ratio is for weight % coarse silt fraction; K=kaolinite; V=vermiculite; number of samples in parentheses).

Till Unit	Snd:Slt:Cl %	Calc:Dolo	%K	V/K
Pierce Fm.	39:37:24 (41)	4.2:1 (5)	23.3 (13)	0.5 (13)
Edgar Mbr., Mar. Fm.	40:40:20 (283)	0.7:1 (105)	6.8 (3)	2.4 (3)
Medford Mbr., Mar. Fm.	35:46:19 (26)	0.3:1 (8)	5.7 (2)	3.2 (2)

The easterly extent of the Superior Lobe before the Wisconsin Glaciation is also uncertain. Reddish-brown, sandy till of the River Falls Fm. unconformably overlies the Pierce till in western Wisconsin (Fig. 1). Syverson (2004) has mapped River Falls Fm. outwash in western Chippewa County that is up to 35 m thick, extremely eroded, and enriched in pedogenic clay to depths of 5 m below the land surface. This outwash commonly contains ice-proximal cobbles, boulders, and large Lake Superior agates. Late Wisconsinan outwash of the Chippewa Lobe in adjacent areas is cobble poor, is relatively unweathered, and rarely contains Lake Superior agates. It is proposed that the Superior Lobe flowed into western Chippewa County (farther east than previously thought) before the Wisconsin Glaciation. Agate-rich outwash of the River Falls Fm. in Chippewa County might have been deposited in the interlobate junction between the Superior and Chippewa Lobes as the ice wasted from its maximum extent.

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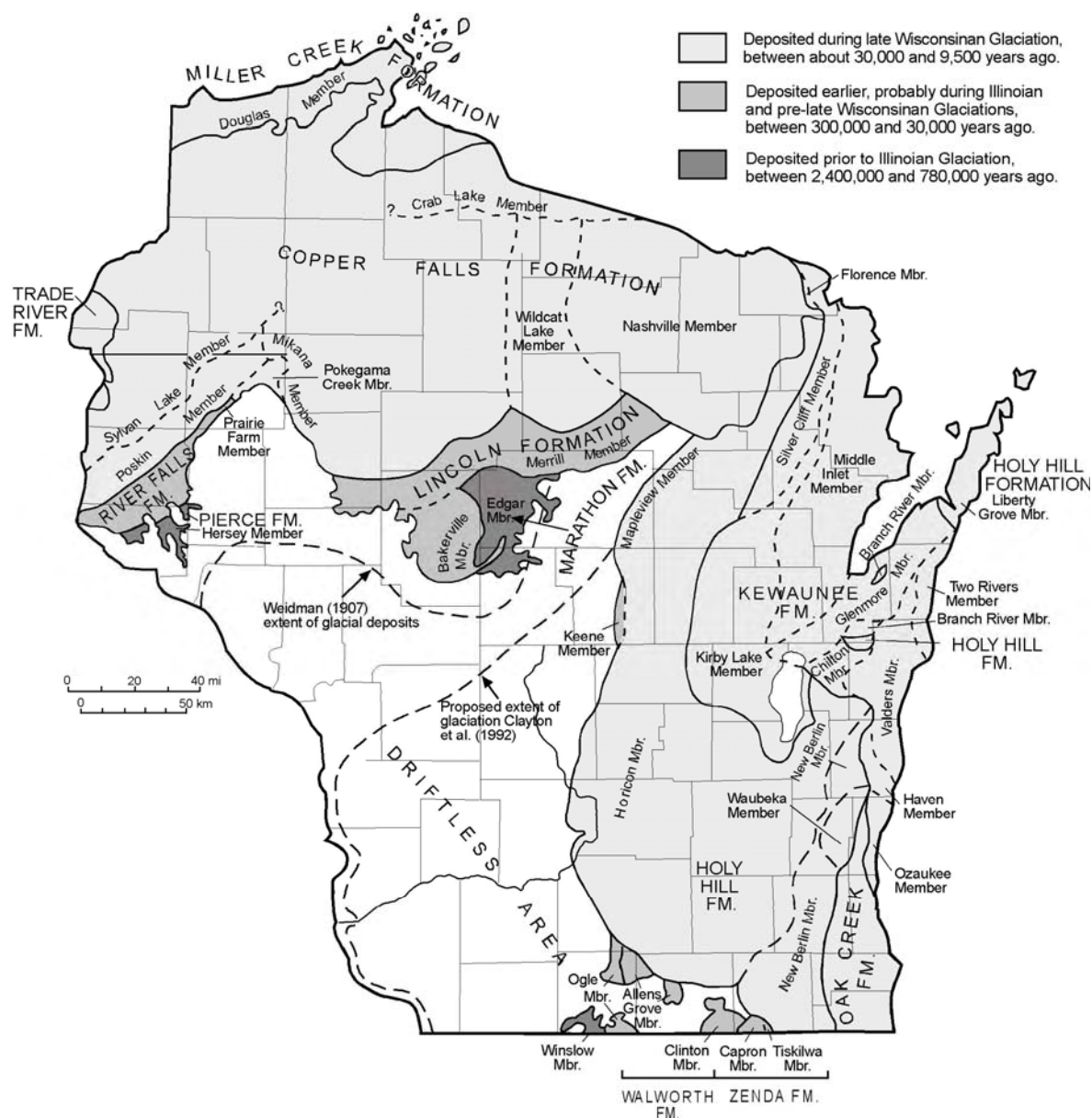


Figure 1. Pleistocene lithostratigraphic units of Wisconsin (from Syverson and Colgan, 2004; modified from Clayton and others, 1992). The Medford Mbr. of the Marathon Fm. (mentioned in the text) is found in the subsurface below the Edgar Mbr. of the Marathon Fm.

DOWSING EMPLOYS CLASSICAL MECHANICS AND STATIC ELECTRICITY TO LOCATE SELF-POTENTIAL ANOMALIES INDUCTIVELY AND RAPIDLY

TROW, Jim, Geological Sciences, Michigan State University, emeritus, 540 Lake Avenue #2, Hancock, Michigan 49930

At last year's 49th ILSG I showed where dowsing in the Michigan Copper Country could identify SP anomalies associated with four new (-) ore targets, seven historic (-) lodes, three historic (-) fissure veins, and four major (+) faults. A few of these examples are here illustrated as geophysical profiles. This year I should like to show you how this procedures works.

A French physicist and a Czech physicist independently ascribed the dowsing phenomenon to magnetics, but this cannot be because famous Russian dowsers could not detect the enormous Kursk magnetic anomaly. The two physicists elicited human dowsing response in magnetic fields caused by direct electric currents. The Czech thought that a head shield of low-reluctance metal blocked the magnetic stimulus (but of course the metal was also a low-resistance Faraday cage which blocked electrical fields.) My experiments with permanent magnets have drawn a complete blank; experiments with static electric charge producers have been a big success. Try them!

Over the past 31 years of examining ore deposits in six states and one province, one learns that the linear forces of static electric attraction and repulsion interact with mechanical lever arm, torque, moment of inertia, kinetic energy, and power factors to enable many humans to detect SP anomalies with 3/16" – diameter bare low-fuming bronze welding rods of two configurations: for me, 1) the more sensitive two-pronged 6" x 15" U-rods identify gentle SP gradients (dv/dx), and repeated turnings indicate the electrical magnitude of the SP anomaly by iteration of gradients, whereas 2) the less sensitive single-pronged 6"x15" L-rods identify steep or vertical SP gradients over target boundaries. One needs both kinds.

At waist level, with elbows against your sides hold the short rod segments vertically in your hands with the long segments horizontal at essentially the same altitude, free to rotate in horizontal planes, immune from gravity. Extend your hands in front of you at body width with your lower arms horizontal, and aim the horizontal long rod segments away from you, parallel to each other. **This is the standard state.** Point the horizontal segments in the direction of your traverse, which should be at more than 45 degrees mapwise from the strike of an anticipated anomalous mass.

As you walk, **keep your eyes straight ahead on the traverse.** Head orientation is critical, as the twin sensors are in the brain, as demonstrated by Faraday cage masking of the head and by family members' CT Scans after strokes which obliterated their dowsing skills. For most people, as a negative SP anomaly is approached each rod swings inwards 90 degrees. At each such turning record location, **reset the rods to the standard state,** and walk on, recording every 90 degree turning and its location. If you do not reset the rods to the standard state the rods cannot indicate additional small dv/dx increments, and you will forfeit valuable information concerning the magnitude of the anomaly. Eventually, you will encounter a point where each rod swings outwardly 90 degrees for a positive dv/dx , as you finally climb out of the SP electrical "valley". These readings may spread over hundreds of feet with these rods, which through the sum of incremental gradients, give you an idea of total SP voltage (v) **magnitude.**

To determine the precise **location and width of the shallow part of the anomalous mass, rerun the traverse with the 6" x 15" L-shaped rods.** The 90 degrees inward turning of each rod indicates the steep to vertical negative dv/dx of the negative SP anomaly. Record data, **reset the rods to the standard state** and traverse a short distance more until the 90 degree outward turning of each rod at the positive steep to vertical dv/dx , as you start to climb out of the negative SP "valley". Trench or drill between these – and + turnings.

While one's head contains the twin "sensors", one's rods, arms, body, and legs constitute the "meter". The static charge to attract or repel the positively charged rods' ends emanates from one's body and legs, when activated by an involuntary signal from one's brain. These conclusions follow from Faraday cage masking of one's waist-to-knee area (which kills the "meter"), or by one's shuffling side-ways along a traverse while one's "eyes-right" head aims along the traverse as usual.

Mechanics calculations show that the two sensitive 6" x 15" U-rods require a power of .0064 Watts for both to turn 90 degrees, whereas the less sensitive 6" x 15" L-rods require a power of only .0008 Watts for the same 90 degrees rotation. However, these sensitive U-rods each rotate 90 degrees with half of the torque-causing linear electric force per prong that it takes to rotate each less sensitive L-rod 90 degrees.

For simplest interpretation start every traverse on electrically neutral ground. It would take a week to illustrate all the caveats and intricacies of the dowsing art, and then no two of us would react in the same way unless we individually standardized the lengths of our rods over known SP anomalies.

To avoid physiological differences among humans, eliminate the human components of the electrical circuits: Connect a 13- or 20-cm.-diameter hollow spun aluminum sphere (the sensor) to an insulated rod handle, and connect the sphere by a wire to a rugged battery-powered center-zero electrometer (the meter) which records millivolts, and observe induced total SP millivoltage, v (not dv/dx). However, use station spacing of five feet or less if you want to make a second derivative (curvature, d^2v/dx^2) analysis of the data. Thusly, an ancient art transfigures into science.

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ORIGIN OF THE RHYOLITES AND GRANOPHYRES OF THE MIDCONTINENT RIFT, NORTHEAST MINNESOTA

VERVOORT, J.D., Department of Geology, Washington State University, Pullman, WA, 99164, vervoort@wsu.edu

WIRTH, K.R., Geology Department, Macalester College, St. Paul, MN, 55105.

Throughout Earth history continental rift volcanism has been characterized by voluminous outpourings of dominantly mafic magma. Rhyolites and other evolved compositions are occasionally erupted in these rifts—sometimes in significant proportions (e.g., Paraná)—but in most cases they are subordinate or absent. This is also generally true in the Midcontinent Rift (MCR) where magmatism is predominantly basaltic with subordinate rhyolite; intermediate compositions are rare. An exception to this is in northeastern Minnesota where the rhyolite and granitic intrusive complexes comprise a significant percentage (10-25%; Green and Fitz, 1993) of the magmatic volume. Here we present U-Pb zircon and Nd isotopic data from the rhyolites and granitic complexes in order to constrain the timing and origin of these evolved magmas in the context of the dynamic evolution of the rift.

Most of the rhyolitic volcanism is contained within a few exceptionally large eruptive units, the largest of which may have exceeded 600 km³ in volume (Green and Fitz, 1993). The rhyolites are characterized by having large areal extent, large aspect ratios, and high-T mineral assemblages all indicative of high-temperature, superliquidus eruptions (Green and Fitz, 1993). The granitic complexes are of comparable size to the rhyolites and occur as tabular concordant intrusions (up to 35 km by 1 km) that consist dominantly of granitic compositions and exhibit granophyric textures. Although dominantly silicic, the granophyres have a wide range of compositions (e.g., 47-76 wt. % SiO₂) and plot along linear trends on many variation diagrams. The major and trace element compositions of the rhyolites and the silicic portions of the granophyre complexes are broadly similar and it is tempting to think of the granophyres as rhyolite magmas that never reached the surface.

The magmatism of the MCR in the northeast limb of the rift is divided into two main magmatic stages (Miller and Vervoort, 1996): an “early stage” (1108-1105 Ma) of reversed magnetic polarity and a “main stage” (1100-1094 Ma) of normal magnetic polarity (Figure 1). Previous U-Pb zircon geochronology on the rhyolites (Davis and Green, 1997) indicate that whereas a few rhyolitic units were erupted during the early magmatic stage, the majority of these units, including the most voluminous rhyolites, were erupted at 1100-1097 Ma during the later main stage of magmatism. The granophyre complexes we examined have U-Pb

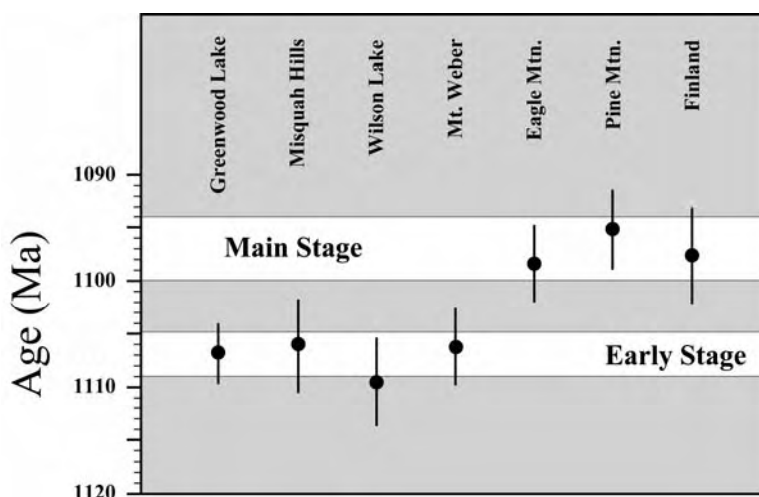


Figure 1. Plot of U-Pb zircon ages of granophyres compared with stages of rift evolution proposed by Miller and Vervoort (1996).

zircon ages consistent with this chronology. The stratigraphically lowest complexes (Misquah Hills, Greenwood Lake) have reversed magnetic polarity and ages of 1106 ± 6 Ma and 1106 ± 3 Ma (2σ SE), respectively. The southern complexes (Eagle Mountain, Pine Mountain) are higher in the stratigraphy, have normal magnetic polarity, and have ages of 1098 ± 4 to 1095 ± 4 Ma. The rhyolites and granophyres have Nd isotopic compositions that are related to magmatic stage (Figure 2). Compared with the mafic volcanic rocks of the rift (epsilon Nd 0 ± 2), the early-stage rhyolites have slightly negative initial epsilon Nd values (~ -4) and the younger, more voluminous, main-stage rhyolites have highly negative initial epsilon Nd values (-10 to -15). A similar correlation exists in the granophyres. The early stage granophyres are isotopically homogenous with epsilon Nd values of 0 to -2 . In contrast, the main stage granophyres have more highly negative initial epsilon Nd values (-3 to -8). Thus for both the rhyolites and the granophyres, the main stage magmas appear to have been more highly contaminated by older evolved crust than those of the early stage.

Based on these isotopic and age constraints we propose the following scenario for the magmatic evolution of the MCR. During the early stage, rapid extension allowed magmas to migrate through the crust with minimal interaction. Melting higher Sm/Nd (mafic) material in the lower crust at this time may have generated small volumes of silicic melts with slightly negative epsilon Nd values. Reduced extension during the latent stage (1105-1100 Ma) led to ponding of magma near the base of the crust and widespread crustal heating. Renewed extension during the main magmatic stage led to increased magma migration through the crust; prolonged crustal heating and magma flux resulted in increased crustal melting. The main stage rhyolites and granophyres represent melts of older, more evolved (lower Sm/Nd) compositions (Animikie sediments, Archean TTGs) perhaps at mid- to upper-crustal levels.

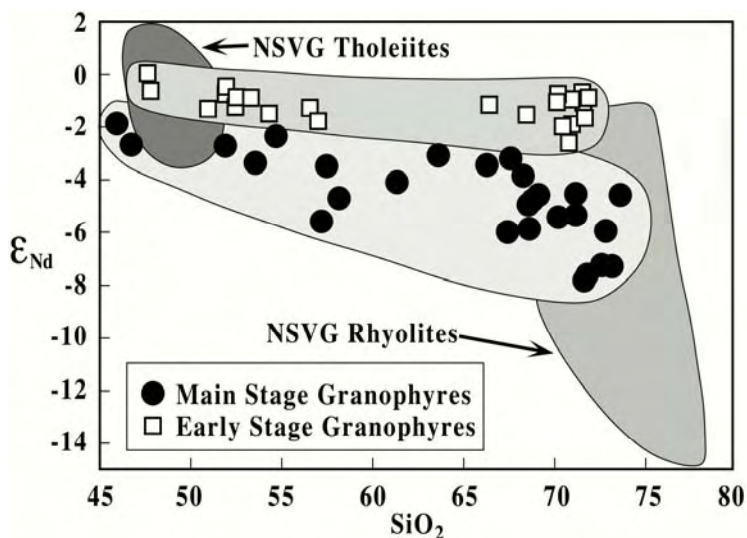


Figure 2. Plot of epsilon Nd versus SiO₂ values for North Shore Volcanic Group (NSVG) tholeiites, rhyolites, and granophyres.

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Taconite Aggregate Potential of Coarse Tailings from the Biwabik Iron Formation, With an Emphasis on Geology, Mineralogy, and Microscopy

ZANKO, Lawrence M., ORESKOVICH, Julie A., Economic Geology Group, Center for Applied Research and Technology Development, Natural Resources Research Institute, 5013 Miller Trunk Highway, Duluth, MN 55811

NILES, Harlan B.(retired), Coleraine Minerals Research Laboratory, Natural Resources Research Institute, One Gayley Avenue, Box 188, Coleraine MN 55722

A study by Zanko et al. (2003) was undertaken to assemble a body of technical data that could be used to better assess the potential of using a crushed taconite mining byproduct (coarse tailings) for more widespread construction aggregate purposes, primarily in roads and highways. Fundamental to the project was the collection and generation of geological and mineralogical data.

The major Biwabik Iron Formation stratigraphic units from which the samples were derived were identified, and their relative contribution to each sample was quantified. An important part of the mineralogical assessment included X-ray diffraction (XRD) analyses and microscopic evaluation of the size and shape (morphological) characteristics of potentially respirable microscopic mineral particles and fragments. Quantitative mineralogy, based on XRD analyses, showed that the dominant mineral in all samples was quartz (55 to 60 percent), followed by much smaller amounts of iron oxides, carbonates, and silicates. Specialized microscopic analyses and testing performed by the RJ Lee Group, Monroeville, PA, on both pulverized (-200 mesh, or 0.075 mm) and as-is sample composites showed that no regulated asbestos minerals or amphibole minerals were present. A very small number of mineral cleavage fragments/mineral fibers were detected, but these were mostly minnesotaite, a silicate mineral common to the Biwabik Iron Formation. Amphibole minerals, absent in coarse tailings samples from the five western Mesabi Range taconite operations, were present in a single eastern Biwabik Iron Formation sample collected in 2003 for Lake County from the Cliffs Northshore operation in Silver Bay, MN.

Importantly, the Superfund Method for the Determination of Releasable Asbestos in Soils and Bulk Materials, EPA 540-R-97-028 (1997), as modified by Berman and Kolk (2000) failed to generate any protocol fibers, i.e., fibers longer than 5mm and thinner than 0.5mm, from either the western coarse tailings samples or the single eastern Biwabik Iron Formation sample. The combined findings suggest coarse tailings and other taconite mining byproducts should be treated with the same common sense safety and industrial hygiene approach practiced for all mineral-based materials that have the potential to generate respirable dust.

Overall, the project showed that: 1) a significant source of fine aggregate (coarse taconite tailings) is available at each of the taconite operations studied; 2) coarse tailings are suitable for use in road construction applications; 3) no amphibole or asbestos minerals were present in any of the tailings samples evaluated; and 4) low-cost transportation, workable distribution logistics, and market acceptance will be key for expanded use of taconite mining byproducts like coarse tailings in markets beyond northeastern Minnesota. Furthermore, making greater use of materials that have long been considered “waste” byproducts makes environmental sense, because doing so maximizes the utilization of resources that have already been mined and crushed, and it could reduce pressures to expand existing, or develop new, “natural” aggregate sources. Permitting of pit and quarry expansions and new aggregate mines has become more complex and difficult, both

environmentally and socially, given the growing “not in my back yard” (NIMBY) reaction to such projects.

Future research initiatives intend to compile and generate baseline technical information on the quality of potential higher-value aggregate products (e.g., Class A-type aggregate, concrete aggregate, railroad ballast) derived from the major stratigraphic units within the Biwabik Iron Formation. Because the Biwabik Iron Formation is not monolithic, the goal will be to map and identify units that are the best potential sources for various construction aggregate applications. Its major cherty and slaty members, while laterally persistent, have variable geological, mineralogical, physical, and chemical characteristics across the Mesabi Range.

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