



Institute on Lake Superior Geology

45th Annual Meeting

Ramada Inn

Marquette, Michigan

May 4-8, 1999

Sponsored by
Northern Michigan University
and Michigan Technological University

Proceedings Volume 45:

Program and Abstracts

Robert S. Regis and Theodore J. Bornhorst, editors

45TH ANNUAL MEETING INSTITUTE ON LAKE SUPERIOR GEOLOGY

Volume 45 consists of

Part 1: Program and Abstracts

Part 2: Field Trip Guidebook

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INSTITUTE ON LAKE SUPERIOR GEOLOGY

PROCEEDINGS

Volume 45

Part 1: PROGRAM AND ABSTRACTS

Editors: Robert S. Regis and Theodore J. Bornhorst

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Editors: Robert S. Regis and Theodore J. Bornhorst

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INSTITUTE ON LAKE SUPERIOR GEOLOGY

<u>INSTITUTE NUMBER</u>	<u>DATE</u>	<u>PLACE</u>	<u>CHAIRS</u>
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	E.N. Cameron & R.A. Hoppin
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. Meyers
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

CONSTITUTION OF INSTITUTE ON LAKE SUPERIOR GEOLOGY

- 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 inure 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 or who have indicated interest in being a member according to membership guidelines approved by the board of directors and have paid any applicable dues.
- Article V** **Meetings**
The organization shall meet once a year, preferably during the month of April. 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 Chair; 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 Chair so as to bring the membership of the board up 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 by a majority vote of members 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 INSTITUTE ON LAKE SUPERIOR GEOLOGY

I. Duties of the Officers and Directors

- A. It shall be the duty of the Annual Chair 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

- 1. Regular membership dues of \$5.00 or less on an annual basis shall be assessed each member as determined by the board of directors.
- 2. 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 graduate 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

GOLDICH MEDAL GUIDELINES

Preamble

The Institute on Lake Superior Geology was born on or around 1955, as documented by the fact that the 27th annual meeting was held in 1981. The Institutes are exemplary in their continuing objectives of dealing with those aspects of geology that are related geographically to Lake Superior; of encouraging the discussion of subjects and sponsoring field trips which will bring together geologists from academia, government surveys, and industry; and of maintaining an exceedingly 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 medalists 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.
- 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, will inform the medalist immediately, and will 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.

Nomination Procedures

- 1) Nominations shall be taken at any time by the Goldich Medal Committee. Committee members may themselves nominate candidates. The deadline for nominations is November 1.
- 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.

Last Amended 1997

GOLDICH MEDAL COMMITTEE 1998-99

John Klasner	(1999) Western Illinois University, Macomb, Illinois
Mark Smyk	(2000) Ontario Geological Survey, Thunder Bay, Ontario
Rod Johnson	(2001) Rod Johnson and Associates, Negaunee, Michigan

GOLDICH MEDALISTS

*1979 Samuel S. Goldich
1980 not awarded
1981 Carl E. Dutton, Jr.
1982 Ralph W. Marsden
1983 Burton Boyum
1984 Richard W. Ojakangas
1985 Paul K. Sims
1986 G.B. Morey
1987 Henry H. Halls
1988 Walter S. White
1989 Jorma Kalliokoski
1990 Kenneth C. Card*

*1991 William J. Hinze
1992 William F. Cannon
1993 Donald W. Davis
1994 Cedric Iverson
1995 Gene LaBerge
1996 David L. Southwick
1997 Ronald P. Sage
1998 Zell Peterman
1999 Tsu-Ming Han*

1999 Goldich Medal Recipient

Tsu-Ming Han

Citation
Tsu-Ming Han
1999 Goldich Medal Recipient

The 1999 Goldich Medal recipient epitomizes the characteristics required to receive this unique and prestigious award. He has devoted his professional life to solving nature's myriad challenges in the field of geology and sharing his findings with colleagues both verbally and through published and unpublished mineral papers.

He was born during the 1920's in the Hunan Province of China. His family stressed the importance of education. He pursued his education during a series of difficult periods that included being kidnapped and held by bandits, pursued by Japanese forces, and the imposition of Nationalist control followed by the cultural upheaval caused by the ascendancy of the Communists after World War II. After graduating from Northwest University in Sian Province in 1945 and a brief stint with the Bureau of Mineral Exploration, he immigrated to the U.S. in 1947 to complete graduate work at the University of Cincinnati and the University of Minnesota. His mentors at the University of Minnesota included Drs. Goldich, Gruner, and Schwartz.

After summer employment with Cleveland-Cliffs in 1952, he accepted permanent employment at the Ishpeming Research facility. Soon after, he met and married Joy. They have three children who have also benefited professionally by achieving advanced educational degrees.

He has published numerous articles on the genesis of iron formations with emphasis on textural relations during diagenesis and metamorphism.

What is not generally known is that he is an expert on all facets of the beneficiation and pelletizing process that has dominated the North American iron ore industry for half a century. His studies have assisted in continual improvement in the pelletizing process to keep the industry competitive.

He has a special interest in the preserved algae present in several areas of the Negaunee Iron-formation at the Empire Mine and has published his findings.

It should be noted that he delivered a paper at the first Institute meeting in 1955 and continues his scientific inquiry as evidenced by his current presentation at the Institute. Indeed, the only change noticeable since his formal retirement in 1992 is that he now wears tennis shoes to the office.

It is my pleasure to introduce to the Institute the 1999 recipient of the Goldich Medal, my friend and our colleague, Tsu-Ming Han.

Tom Wagonner

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 1997-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 \$300 US.
- 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.

1999 STUDENT PAPER COMMITTEE

Allan Blaske, STS Consultants, LTD, Lansing, MI

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

STUDENT TRAVEL AWARD

The 1986 Board of Directors established the I.L.S.G. Student Travel Award to support student participation at the annual Institutes. The awards will be made from a special fund set up for this purpose. This award is intended to help defray some of the direct travel costs to the Institute and includes a waiver of registration fees, but excludes expenses for meals, lodging, and field trip registration. The number of awards and value are determined by the annual Chairman in consultation with the Secretary-Treasurer and will be announced at the annual banquet.

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

- 1) The applicants must have active resident (undergraduate or graduate) student status at the time 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.
- 5) Each travel award request shall be made in writing, to the annual Chairman, with an explanation of need, possible author status or other significant details.

Successful applicants will receive their awards at the time of registration for the Meeting.

INSTITUTE ON LAKE SUPERIOR GEOLOGY	
<i>Student Travel Award Application</i>	
Please print:	
Student Name: _____	Date: _____
Address: _____	
I certify that the above named person is an active resident student.	

Department Head - Typed	
_____	_____
Department Head - Signature	Date
Educational Status: _____	
Are you the Senior Author of an oral or poster paper? Yes ____ No ____	
Will any other students will be traveling with you? ____ How many? ____	
Statement of Need: (If you need more room, please use the back of the page.)	
Other Significant Details:	
Please return to:	

BOARD OF DIRECTORS

Theodore J. Bornhorst, Chair (2002)

Michigan Technological University, Houghton, Michigan

James D. Miller (2001)

Minnesota Geological Survey, St. Paul, Minnesota

Ronald P. Sage (2000)

Ontario Geological Survey, Sudbury, Ontario

Laurel G. Woodruff (1999)

U.S. Geological Survey, Mounds View, Minneapolis

Mark A. Jirsa (2000) Institute Secretary-Treasurer

Minnesota Geological Survey, St. Paul, Minnesota

LOCAL COMMITTEES

GENERAL CO-CHAIRS

Robert S. Regis

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Department of Geological Engineering and Sciences, Michigan Technological University, Houghton, Michigan 49931

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FIELD TRIP GUIDEBOOK EDITOR

Theodore J. Bornhorst

Department of Geological Engineering and Sciences, Michigan Technological University, Houghton, Michigan 49931

SESSION CHAIRS

Dave Baxter, PayDay Resources, Lansing, MI

Shawn Carlson, Ashton Mining, North Vancouver, BC, Canada

Ron Graber, Cliffs Mining Services Company, Ishpeming, MI

John Green, University of Minnesota, Duluth, MN

Rod Johnson, Rod Johnson & Associates, Inc., Negaunee, MI

Gene Laberge, University of Wisconsin, Oshkosh, WI

Jim Small, Edward Kraemer & Sons, Burnsville, MI

Tom Waggoner, retired Cliffs Mining Services Company, Ishpeming, MI

1999 BANQUET SPEAKER

Nelson R. Ham
Department of Geology
St. Norbert College
De Pere, Wisconsin

Ice-Flow Dynamics and Landform Development Along the Southern Margin of the Laurentide Ice Sheet

**REPORT ON THE 44th ANNUAL MEETING OF THE
INSTITUTE ON LAKE SUPERIOR GEOLOGY
MINNEAPOLIS, MINNESOTA**

The 44th Annual Meeting of the Institute on Lake Superior Geology was held in Minneapolis, Minnesota on May 6-10, 1998. The meeting was sponsored by the Minnesota Geological Survey and was held at the Holiday Inn on the West Bank of the University of Minnesota campus.

Proceedings *Volume 44* of the meeting was published in two parts:

Part 1: Program and Abstracts (including extended abstracts of the special overview session)

Part 2: Field Trip Guidebook

- 1—Early Proterozoic intrusive rocks of east-central Minnesota*
- 2—Geology of the southeastern portion of the Midcontinent Rift System, eastern Minnesota and western Wisconsin*
- 3—Glacial exotica of the Twin Cities area*
- 4—Stratigraphy and hydrogeology of the Paleozoic rocks of southeastern Minnesota*
- 5—Minnesota River Valley and vicinity, southwestern Minnesota (Precambrian and Quaternary geology)*

By most measures, the meeting was a great success. We saw a considerable jump in attendance this year to 200 participants, compared with recent average attendance on the order of 125. Fifty-six participants were first-time attendees to the ISLG; split about equally between students and related fields people—that is, those involved in Quaternary, Paleozoic, environmental, and engineering geology that are not traditional topics of the Institute. We attribute some of this increase simply to the metropolitan location of the meeting and our fairly aggressive appeal to the local geoscience community. To attract local and more broadly based interest, we broke somewhat with tradition by conducting a special half-day session overviewing the geology of the Lake Superior region. To make the meeting even more attractive to new-comers, we offered a first-day-only registration at a reduced rate for those interested in attending just the special overview session; however, few took advantage of the offer.

The special overview session consisted of six 30 minute talks that outlined current ideas and new research directions on the main geologic provinces of the Lake Superior region. Presentations were given by Ken Card (Archean), Dick Ojakangas (Early Proterozoic), Bill Cannon (Middle Proterozoic), Tony Runkel (Paleozoic), Carrie Patterson (Quaternary), and Dave Southwick (New directions in Lake Superior geology). The talks were well presented and well received; comments from the participants were overwhelmingly favorable. The general sessions included 23 oral presentations covering not only the typical fare of Precambrian topics, but also included several talks related to groundwater. In addition, 24 poster presentation were on display during the course of the meeting. The banquet speaker was Dr. Bevan French of the Smithsonian Institution, who gave an excellent talk on the role of meteorite impacts on the geologic history of earth and other planets. At the banquet, Zell Peterman of the USGS was awarded the Goldich Medal for his important geochronologic and

geologic studies of Precambrian geology in the Lake Superior region. Another highlight of the meeting for 40 participants was a night of baseball at the Metrodome.

This meeting also broke the mold a bit by offering five field excursions that covered a similarly wide breadth of geology as was presented in the special overview session. Although the emphasis remained with Precambrian geology, trips highlighting the Paleozoic and Quaternary geology of central and southern Minnesota were also included. Three pre-meeting field trips were run on Wednesday, May 6th; 1) the Early Proterozoic geology of east-central Minnesota led by Terry Boerboom, Mark Jirsa, and Daniel Holm (26 participants); 2) the Keweenaw geology of the Taylor's Falls area led by Karl Wirth, Bill Cordua, Bill Kean, Mike Middleton, and Zach Naiman (46 participants); and 3) Glacial exotica of the Twin Cities area led by Howard Hobbs, Alan Knaeble and Gary Meyer (21 participants). Two post-meeting trips included a one-day trip on the Paleozoic stratigraphy, sedimentology, and hydrogeology of southeastern Minnesota led by Tony Runkel and Bob Tipping (11 participants), and a two-day excursion investigating the Quaternary and Archean geology of the Minnesota River Valley led by Carrie Patterson and David Southwick (33 participants).

The meeting was also a financial success; that is, if your measure of success is to at least break even (which has been the traditionally held view). We actually turned a small profit of several hundred dollars. Although registration was more costly than we had hoped, the cost was unavoidable given the metropolitan location. Part of the registration we all pay is applied to encouraging student participation in the Institute by granting awards for student travel and best student papers. Eight travel awards totaling \$750, and two best paper awards of \$150 each were granted. Best paper awards went to Kathleen Abbott (Macalester College) for her undergraduate work on geochemistry and petrography of Keweenaw-Chengwatana volcanic rocks of Minnesota and Wisconsin, and to Dean Peterson (University of Minnesota-Duluth) for his graduate presentation on GIS-based mineral potential analyses of Archean rocks in Minnesota. Congratulations to you both!

The Institute's Board of Directors met on May 7th, and the following is generalized from minutes of that meeting:

1. Accepted the Report of the Chair 43rd ILSG
2. Accepted the 1997-1998 ILSG Financial Report.
3. Approved Zell E. Peterman as 1998 Goldich Medal recipient.
4. Modified the language for Goldich Awards regarding dates for receipt of nominations (now November 1) and final decision (now the end of November).
5. Approved the end-of-term replacement of Dan England (Eveleth Fee Office) as Goldich Medal committee member by Rodney Johnson (Trans Superior Resources). Rod begins a 3-year term in November of 1998.
6. Changed the student travel award's title to "Eisenbrey Student Travel Awards". This satisfies a request from individual and corporate contributors to the 1996 meeting that such a fund be established in honor of Ned Eisenbrey, and permits the use of all investment income for encouraging student participation in the Institute.
7. Approved the host location—Marquette—for the 1999 ILSG meeting. Co-chairs will be Ted Bornhorst (Michigan Technological University) and Bob Regis (Northern Michigan University).

8. Discussed a potential Y2K meeting location—Thunder Bay or other access point to the Atikoken area.
9. Discussed a potential 2001 meeting location—Sault Ste. Marie, MI.
10. Other business—contact the secretary-treasurer for details

We hope that with the success of the 1998 meeting, the ILSG took an important step toward achieving the goal of expanding its reach, both in terms of the range of geological topics and the background of participants. While we may not be able to repeat the attendance success of this meeting as we move to the more typically remote conference sites, future organizers and those of us who are long-time participants must do all we can to actively promote the ILSG to the broadest possible audience. If we had to pinpoint one reason for the success of the 1998 meeting, it would be our relentless promotion of the meeting to local geoscience organizations, colleges, and individuals. For our part, we will encourage Twin Cities geoscientists to continue their involvement, now that they have been exposed to what the ILSG has to offer.

We wish to thank all of the presenters, in particular the special session speakers who wrote extended abstracts that will serve as summaries of their fields for years to come. This institute was built on its tradition of fine field trips, and this year's trips maintained that tradition, thanks in large part to efforts of the leaders. Acknowledgment is also due to the session chairs, the best student paper award committee, the local planning committee, and the ILSG board members for making our jobs much easier by doing theirs well. A special thanks to Terry Boerboom for his flawless organization of the field trips and guidebook, and to Lori Day, the meeting coordinator, for doing all that it takes. Finally we want to thank our director of the Minnesota Geological Survey, David Southwick, for giving us the freeboard and staff time needed to pull the meeting together.

Jim Miller and Mark Jirsa
Co-chairs of the 44th Annual ILSG

45TH ANNUAL MEETING
INSTITUTE ON LAKE SUPERIOR GEOLOGY

Program

Program of Events

Tuesday, May 4

0800-1730 Field Trip 2

Field Trip 2: Archean Ishpeming Greenstone Belt and Gold Mineralization, Michigan - Leader T.J. Bornhorst, D.J. Duskin, R.C. Johnson, R.A. Mahin, T.O. Quigley, and G.W. Scott

Wednesday, May 5

0800-1730 Field Trip 1 and 2

Field Trip 1: Early Proterozoic Strata of the Marquette Iron Range, Michigan - Leader: W.F. Cannon

Field Trip 2: Archean Ishpeming Greenstone Belt and Gold Mineralization, Michigan - Leaders: T.J. Bornhorst, D.J. Duskin, R.C. Johnson, R.A. Mahin, T.O. Quigley, and G.W. Scott

1700-2000 Registration - Ramada Inn, Marquette, Michigan

1900-2100 Poster Session and cash bar in Ramada Inn
(Authors at posters 1930 to 2100)

Thursday, May 6

All technical sessions are in Ramada Inn, Marquette, Michigan

0730-1600 Registration - Ramada Inn

Technical Session I

Session Chair: Gene LaBerge (University of Wisconsin, Oshkosh)
Shawn Carlson (Ashton Mining)

0820-0830 Opening - 45th Annual Institute on Lake Superior Geology
R. S. Regis and T.J. Bornhorst, Co-Chairs

0830-0930 Invited Presentation
Sarah A. Green and Judy Wells-Budd
Cross Margin Transport in Lake Superior

0930-1000 Invited Presentation
W. Charles Kerfoot, John A. Green, and Lawrence J. Weider
A New Approach to Historical Reconstruction: Combining
Descriptive and Experimental Paleolimnology

1000-1030 Coffee Break

1030-1050 Ojakangas, R.W.
Sedimentology of two Deep Wells in the Keweenawan
Midcontinent Rift System Near Munising, Upper Peninsula,
Michigan

1050-1110 Puschner, U., Schmidt, S.Th., and Bornhorst, T.J.
Low Grade Metamorphism and Hydrothermal Alteration of the
Upper Keweenawan Portage Lake Volcanics, Michigan

1110-1130 Maki, J.C. and Bornhorst, T.J.
The Gratiot Chalcocite Deposit, Keweenaw Peninsula, Michigan

1200-1340 Lunch Break

1200-1340 Board of Directors Meeting

Technical Session II

Session Chairs: Rod Johnson (Rod Johnson & Associates, Inc.)
Jim Small (Edward Kraemer & Sons)

- 1340-1400 Easton, R.M.
Metamorphic Map of the Canadian Shield of Ontario, Michigan,
Minnesota, and Wisconsin
- 1400-1420 Vitton, S.J. and Subhash, G.
Dynamic and Static Strength of Aggregates: An Estimate of
Rate Sensitivity of Geological Materials
- 1420-1440 Yeo, G.M.
Is the Janice Lake Unconformity a Link between the Hearne Craton
and the La Ronge - Lynn Lake Volcanic Arc?
- 1440-1510 Coffee Break
- 1510-1530 Czeck, D.M. and Hudleston, P.J.
Structural Fabric and Strain for the Seine River Conglomerates at the
Wabigoon-Quetico Subprovince Boundary Near Mine Centre,
Ontario
- 1530-1550 Cannon, W.F. and Woodruff, L.G.
Mercury Distribution in Bedrock, Native Copper Ore and Soils - Isle
Royale National Park, Michigan
- 1830-1930 Social - Cash Bar
- 1930-2130 Annual Banquet at Ramada Inn

Friday, May 7

Technical Session III

Session Chair: Ron Graber (Cliffs Mining Services Co.)
Tom Waggoner (Cliffs Mining Services Co.)

- 0830-0850 LaBerge, G.L.
Regional Patterns on the Penokean Continental Margin in the
Southern Lake Superior Region
- 0850-0910 Ottke, D.
Early Descriptions of the Natural Features on the Marquette
Iron Range
- 0910-0930 Webster, C., Cambray, W., Scott, G., Nordstrom, P., Wilson, E.
Palmer Gneiss: A Large, Low-grade Shear Zone
- 0930-0950 Diedrich, T.R., and Morton, P.
Investigation of CaO at Thunderbird Mine, Mesabi Range:
Mineral and Stratigraphic Relationships
- 0950-1020 Coffee Break
- 1020-1040 Medaris, L.G., Fournelle, J., Boszhardt, R., and Broihahn, J.
Chemical and Mineralogical Comparison of Baraboo, Barron,
and Sioux Argillite, Metapelite, and Pipestone
- 1040-1100 Graber, R.G. and Strandlie, A.J.
Where are the Metamorphosed Natural Orebodies of the Mesabi
Range?
- 1100-1120 Scott, G.W. and Lukey, H.M.
Geology of the Tilden Mine, Marquette iron range, Michigan
- 1120-1140 Meier, J.G.
Republic Wetland Preserve
- 1140-1300 Lunch

Technical Session IV Session Chair: John Green (University of Minnesota, Duluth)
Dave Baxter (PayDay Resources)

- 1300-1320 Boerboom, T.J. And Severson, M.
Geologic Map of the Western Penokean Orogen, East-Central
Minnesota
- 1320-1340 Daniels, D.L., Nicholson, S.W., Cannon, W.F., and Bracken, R.E.
Preliminary Aeromagnetic Map of Wisconsin
- 1340-1400 Johnson, R.C. and Bornhorst, T.J.
Ishpeming greenstone belt - Evidence for Archean tectonic evolution
of the southern edge of the Superior Province in Michigan
- 1400-1420 Yeo, G.M.
Low-Resolution Sequence Stratigraphy of Early Proterozoic
Paragneisses, Wollaston Domain, Saskatchewan
- 1420-1450 Coffee Break
- 1450-1510 Bickford, M.E. and Steinhart, W.E.
Distribution of the Archean to earliest Paleoproterozoic Sask craton
beneath deformed orogenic rocks in the Trans-Hudson orogen and its
tectonic implications: Evidence from common Pb and Sm-Nd isotopic
data
- 1510-1530 Miller, J.D. Jr.
Potential for stratiform PGE mineralization in mafic layered
intrusions of the Duluth Complex
- 1530-1550 Peterson, D.M. and Morton, R.L.
Development of Volcanogenic Massive Sulfide Deposit Exploration
Targets in Northern Minnesota from GIS Spatial Analysis of
Geological, Geochemical, and Geophysical Criteria
- 1550-1610 Loughry, J.E., Johnson, Matthew M., and Cotter, J.F.P
A Geochemical and Petrologic Study to Determine the Origin of the
Crowduck Lake Group, Kenora, Ontario: A Problematic
Metaconglomerate

Poster Session

Posters will be up from Wednesday 1900 to Friday 1200

Authors will be at posters on Wednesday from 1930 to 2100

Ams, D. and Holm, D., Characterization and Timing Constraints of Post-Penokean Meso-Scale Structures in the Watersmeet and Republic Gneiss Domes of Northern Michigan

Barber-Delach, R.D. and Cannon, W.F., Re-examining Stream Sediment Geochemical Data from the National Uranium Resource Evaluation Program (NURE), Wisconsin and Northern Michigan

Han, T.M., Megascopic Fossils and Their Possible Contribution to the Development of the Silicate Unit of the Negaunee Iron Formation, Empire Mine, Marquette Range, North Michigan

Holm, D., Romano, D., and Mancusco, C., Comparison of Mica Ar/Ar and Rb/Sr Thermochronology Results from Northern Wisconsin and Northern Michigan

Klasner, J.S., Cannon, W.F., Schulz, K.J., and LaBerge, G.L., The Iron River Syncline: An Allochthonous Structural Panel in the Penokean Foreland of Northern Michigan

Miller, J.D. Jr, and Chandler, V.W., New Geologic Map of the Central Duluth Complex

Rausch, D.E., and Wattrus, N.J., Lake Superior's Rings: Clues to the Origin of Polygonal Fault Systems

Saturday, May 8

0800-1730 Field Trip 3 and 4

Field Trip 3: Tilden and Empire Mines of the Marquette Iron Range,
Michigan - Leaders: G.W. Scott, P.M. Nordstrom and H.M. Lukey

Field Trip 4: Paleozoic and Glacial Geology from Au Train to Grand
Marais, Michigan - Leaders: R.S. Regis and J.B. Anderton

45TH ANNUAL MEETING
INSTITUTE ON LAKE SUPERIOR GEOLOGY

Abstracts

CHARACTERIZATION AND TIMING CONSTRAINTS OF POST-PENOKEAN MESO-SCALE STRUCTURES IN THE WATERSMEET AND REPUBLIC GNEISS DOMES OF NORTHERN MICHIGAN

David Ams (undergraduate student) and Daniel Holm, Department of Geology, Kent State University, Kent OH 44242

We have measured late, meso-scale, ductile and brittle structures present in Early Proterozoic gneiss domes of northern Michigan in order to assess their origin. The Watersmeet and Republic gneiss domes lie north of the region of pervasive post-Penokean 1600-1650 Ma shortening (Holm et al., 1998, *Geology*) and southeast of thick-skinned thrusting which closed the Keweenawan rift at ca. 1080-1860 Ma (Cannon, 1994, *Geology*). The challenge then is to determine whether meso-scale brittle and ductile shear zones formed during the late stages of Early Proterozoic gneiss dome formation or if they represent deformation associated with these younger events.

Watersmeet gneiss dome.

Our observations were made on the north-east side of the dome, south of its contact with the overlying metasedimentary rocks (Hwy 45 exposures). The dominant steep east-west fabric in Archean rocks of the dome are cross-cut by steep ductile, semi-brittle, and brittle shear zones. The ductile and larger semi-brittle to brittle shear zones show a dominant N70-80E strike orientation and dip steeply both north and south (Fig. 1). Where relative motion indicators exist (offset dikes, pegmatites, etc.), the apparent sense of motion is south-side up. Small scale brittle faults and fractures tend to be oriented NS (with steep east dips) or NW (with steep southwest dips). Slickenlines on the NW oriented set plunge gently to the NW (Fig. 1).

The coarse, steep, EW fabric of the dome interior becomes more gentle to the north toward the contact with the metasedimentary rocks and shows a reduction in grain size due to ductile shearing. We attribute this to ductile overprinting of the steep fabric along a basement-cover shear zone. The timing of shearing during gneiss dome formation is constrained by a 1765 Ma hornblende Ar/Ar plateau date obtained from the core rocks and from a concordant muscovite plateau date obtained from metasedimentary rocks just north of the contact (Fig. 2; see also Schneider et al., 1996, *CJES*).

We propose that the ductile and semi-brittle shear zones formed during the late stages of unroofing of the gneiss dome (at ca. 1765-1755 Ma). In our model they represent internal deformation of the footwall dome rocks as they were unroofed from beneath the metasedimentary cover rocks along a north-dipping detachment fault at the basement-cover contact. The brittle shear zones have a completely different orientation from the ductile and semi-brittle ones. Their orientations and subhorizontal lineations suggest they may be related to closure of the Keweenawan rift.

Republic gneiss dome.

We focused on the numerous chlorite mineralized brittle fracture zones which occur in the Republic gneiss dome north of Republic (Fig. 3). They cross-cut the ~1735 Ma post-tectonic alkali red granite (Xgaf of Sims, 1992) and must be younger than mica cooling ages within the dome (1680-1720 Ma). They have a dominant north-northwest strike and dip moderately to steeply to the west. Most of the lineations plunge gently to the northwest. Kinematic indicators (crystal fiber steps) on a few of these show left-lateral, reverse motion. Ductile shear zones within the dome strike dominantly northwest and dip steeply and must be older than the mica cooling ages.

The brittle fractures do not appear to be kinematically related to the older ductile shear zones along which the gneiss dome block was probably uplifted. The dominant left-lateral strike-slip motion and north-northwest attitude indicates they might be also be deformational features associated with closure of the Keweenawan rift. This interpretation is consistent with prior thermochronologic evidence for a low temperature Keweenawan age disturbance of this region (Schneider et al., 1996, *CJES*).

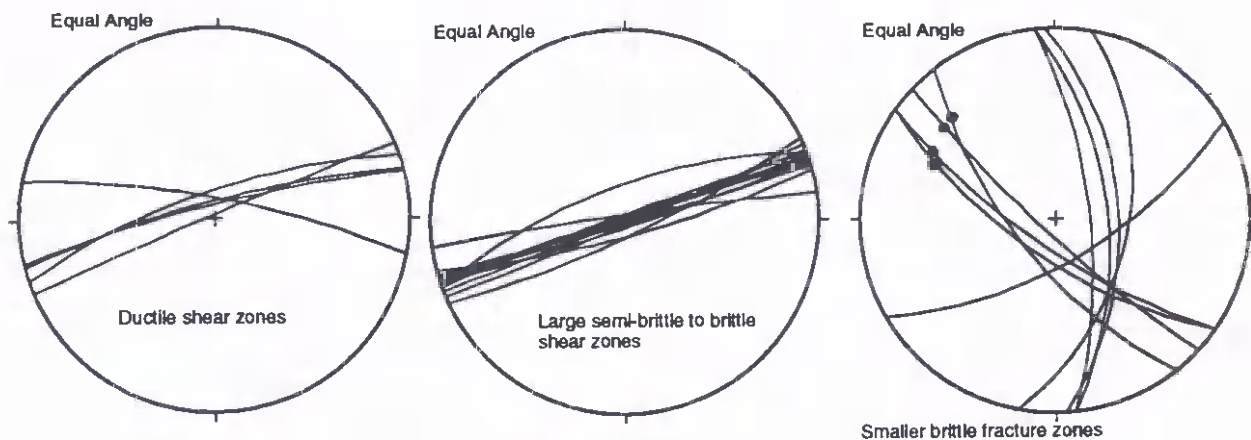


Fig. 1. Stereonet plots of ductile, semi-brittle, and brittle shear zones within the Watersmeet gneiss dome.

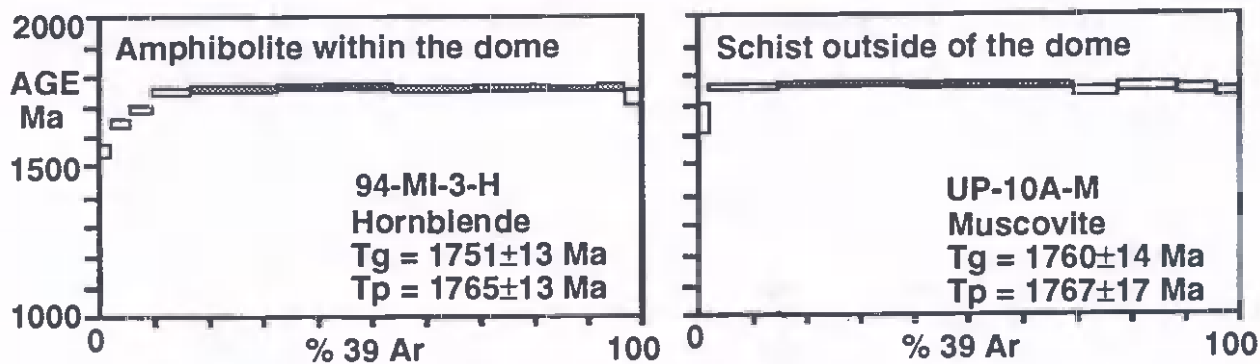


Fig. 2. Ar/Ar mineral age spectra from the Watersmeet gneiss dome region. Tp is plateau date. Tg is total gas date.

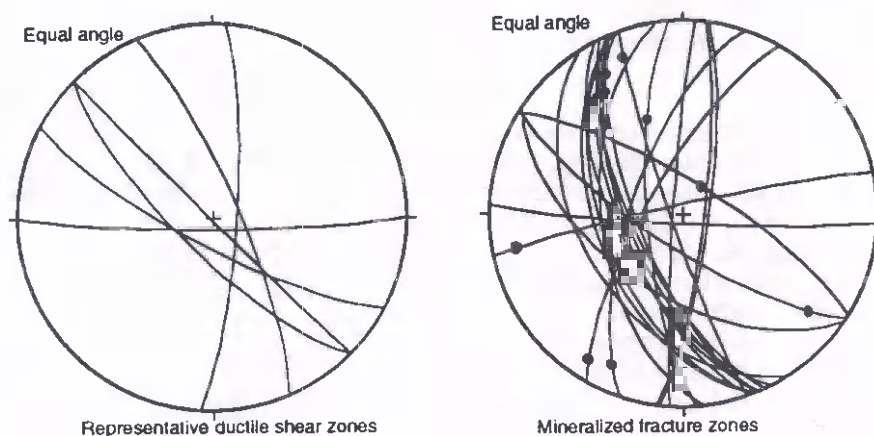


Fig. 3. Stereonet plots of representative ductile shear zones and mineralized brittle fracture zones, Republic gneiss dome region.

Re-examining stream sediment geochemical data from the National Uranium Resource Evaluation Program (NURE), Wisconsin and northern Michigan

Robert D. Barber-Delach, Oak Ridge Associated Universities, at U.S. Geological Survey, Mail Stop 954, Reston, VA 20192

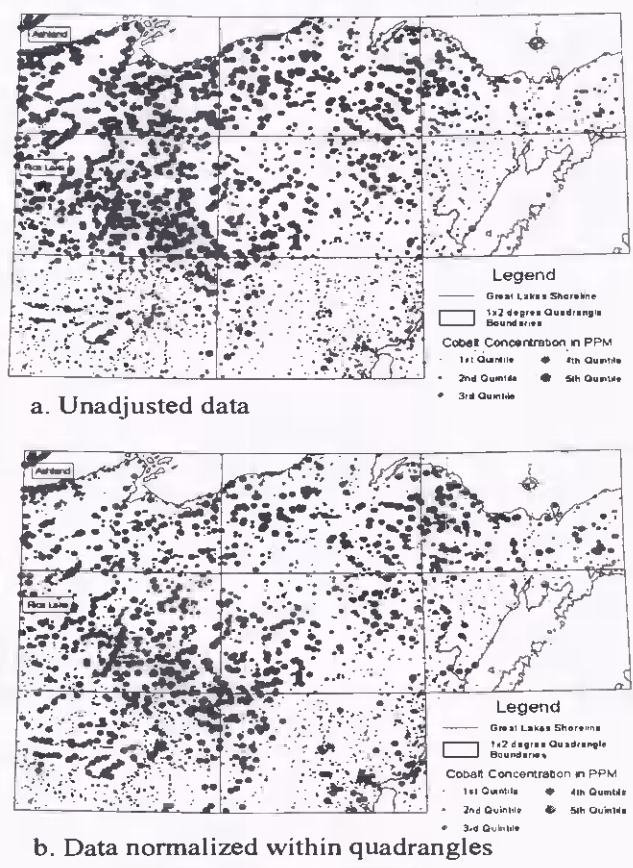
W.F. Cannon, U.S. Geological Survey, Mail Stop 954, Reston, VA 20192

In the latter 1970's a stream sediment geochemical survey was conducted in parts of northern Wisconsin and northern Michigan by the NURE program of the United States Department of Energy. A data set consisting of multi-element analyses of 3185 samples was developed spanning eight $1^{\circ} \times 2^{\circ}$ quadrangles. The data were intended for use in evaluating undiscovered uranium resources, but also have application for establishing regional variations in geochemical background and baseline concentrations. The U.S. Geological Survey is expanding research on regional geochemical patterns, and the NURE data set is being re-examined as part of that effort.

In many places the NURE data shows obvious biases in values between adjacent quadrangles, in some cases apparent only by visual examination of element concentration maps. For instance, Figure 1a shows significant discontinuities of cobalt values between quadrangles in the original NURE data. Biases were probably introduced by somewhat different sampling, processing, and analytic techniques between various quadrangles, and probably also by time-dependent changes in analytical instrument calibration that appear not to have been fully accounted for over the duration of the NURE program. These quadrangle-based biases render use of the data problematical without careful assessment and correction of analytical biases. Here we present two approaches by which the NURE data set can be corrected for quadrangle biases.

First, systematic biases in analytical data between quadrangles can be normalized by displaying data for each quadrangle as a function of the statistical distribution of values for only that quadrangle. Figure 1b shows the same data for cobalt as shown in Figure 1a, but with the values within each of the eight quadrangles classified separately into percentiles of the data set from that quadrangle. The between-quadrangle bias is largely removed and natural patterns of cobalt variation are more

Figure 1. Comparison of unadjusted (a) and normalized (b) cobalt concentrations for use in displaying NURE stream sediment data.

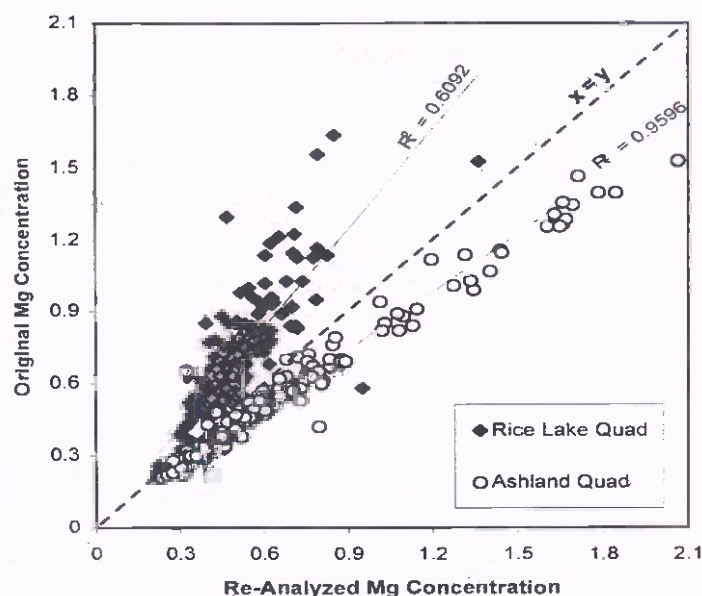


evident. This technique has the advantage of ease and simplicity in that standard desktop GIS software can perform and display the results with minimal statistical manipulation of data and time required for processing. Also, the technique does not require acquisition of new analytical data. However, two important shortcomings of the technique are: 1) it presents only relative variations of element concentrations and does not improve the overall accuracy of the NURE data, 2) it masks true variations that occur at the approximate scale of a $1^{\circ}\times 2^{\circ}$ quadrangle.

A second technique requires new analytical data. In the 1980's, the USGS became the official archiving agency for NURE data and samples, and maintains a sample repository in Denver, Colorado in which all NURE samples are accessible for restudy. We have re-analyzed a subset of those samples for the Ashland and Rice Lake $1^{\circ}\times 2^{\circ}$ quadrangles in northern Wisconsin and compared the results of our re-analyses to the original data reported by the NURE program. Our analyses were done using routine 40-element inductively coupled plasma-atomic emission spectroscopy (ICP-AES) technique supplemented by more precise single-element techniques for arsenic and selenium. Analytical precision and accuracy were monitored by replicate analyses of standard samples.

Comparison of our new values to concentrations reported by NURE show quadrangle-based biases in virtually all elements for which a significant number of samples exceed detection limits (about 20 elements). Figure 2 shows an extreme case in which NURE magnesium analyses are strongly and consistently quadrangle-dependent and in which both quadrangles vary significantly from our new analyses. This consistency of bias within a quadrangle allows derivation of equations that can adjust the original NURE data to correct for previous analytical biases and produce a better accord with new analytical data. Although this technique has inherent statistical uncertainty, that uncertainty is quantifiable, and the resulting element maps are significantly more accurate than those made from the original NURE data. Although this technique does require the cost and time of re-analyzing a significant number of NURE samples, the result produces a much improved data set without the cost of re-analyzing the entire sample set. We plan to proceed with this technique during the coming year.

Figure 2. Scatterplot of magnesium concentration (ppm) demonstrating the quad bias of original NURE data, with fitted regression lines and correlation indices (R^2).



Distribution of the Archean to Earliest Paleoproterozoic Sask Craton Beneath Deformed Orogenic Rocks in the Trans-Hudson Orogen and its Tectonic Implications: Evidence from Common Pb and Sm-Nd Isotopic Data

M. E. Bickford and William E. Steinhart, III, Department of Earth Sciences, Heroy Geology Laboratory, Syracuse University, Syracuse, NY 13244-1070

Late, undeformed, ca. 1.8 Ga pegmatites, leucogranitic sheets, and post-orogenic plutons in the Glennie, Hanson Lake, and La Ronge Domains, and parts of the Hearne Province, were studied to determine whether they were derived by melting of juvenile orogenic crust or of Archean lower crustal rocks equivalent to those exposed in structural windows in the Glennie and Hanson Lake Domains. The isotopic composition of Pb from feldspars ($^{206}\text{Pb}/^{204}\text{Pb} = 14.3 - 15.2$; $^{207}\text{Pb}/^{204}\text{Pb} = 15.1 - 15.25$; $^{208}\text{Pb}/^{204}\text{Pb} = 34.4 - 36.4$) and Sm-Nd T_{DM} ages of ca. 3.2 Ga for ca. 1.8 Ga post-orogenic intrusions reveal that Archean rocks are not only exposed in the windows, but also extensively underlie parts of the Glennie and Hanson Lake Domains in which only juvenile Paleoproterozoic rocks are exposed. In contrast, feldspar Pb from pegmatites in the La Ronge Domain is isotopically similar ($^{206}\text{Pb}/^{204}\text{Pb} = 15.4 - 15.6$; $^{207}\text{Pb}/^{204}\text{Pb} = 15.1 - 15.2$; $^{208}\text{Pb}/^{204}\text{Pb} = 34.8 - 35.2$) to that of juvenile, ca. 1.85 Ga Paleoproterozoic plutons with T_{DM} ages of ca. 1.80-2.0 Ga, indicating derivation from similar oceanic materials. Sm-Nd data from two La Ronge Domain aplites, in which Sm and Nd are apparently unfractionated, yield T_{DM} ages of 1.8-1.9 Ga. Surprisingly, feldspar Pb data ($^{206}\text{Pb}/^{204}\text{Pb} = 15.5 - 15.8$; $^{207}\text{Pb}/^{204}\text{Pb} = 15.1 - 15.2$; $^{208}\text{Pb}/^{204}\text{Pb} = 35.0 - 35.2$) from pegmatites that intrude Archean rocks of the Hearne Province, in the hinterland west of the Needle Falls Shear Zone, also indicate derivation from juvenile sources. Thus, while these data support the view that an Archean microcontinent ("Sask Craton") underlies parts of Glennie and Hanson Lake Domains, they suggest that crust beneath La Ronge Domain, and also beneath at least parts of Hearne Province, is of juvenile mantle derivation. Alternatively, Archean crust may be present beneath the La Ronge Domain and Hearne Province, but was below the zone of melting when the ca. 1.8 Ga pegmatites were formed. These observations are consistent with interpretation of northwesterly-dipping reflectors beneath Hearne Province, as revealed by Canadian Lithoprobe seismic data, as representing subducted oceanic lithosphere. The presence of oceanic lithosphere between Hearne Province and Glennie Domain indicates that the Archean microcontinent beneath the Glennie Domain is probably not subducted Hearne crust, but more likely an exotic crustal fragment.

GEOLOGIC MAP OF THE WESTERN PENOKEAN OROGEN, EAST-CENTRAL MINNESOTA

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The Minnesota Geological Survey, in cooperation with the Natural Resources Research Institute, has recently completed a revised geologic map of the western portion of the Penokean Orogen in east-central Minnesota. The geologic framework for the western Penokean Orogen has been previously interpreted by Southwick and others (1988) using plate-tectonic theory (see discussion below). This map builds on that base by utilizing new drilling information and better geophysical data. Although thousands of exploratory holes were drilled in this area from the late 1800s to the 1950s, nearly all focused on locating iron, manganese, or sulfur ore. As a result, the distribution and form of the major iron-formations both within and outside the iron-mining districts are fairly well established, but little is known about the areas in between. Thus, any geologic compilation necessarily relies heavily on geophysical interpretations.

GEOLOGIC FRAMEWORK

Southwick (1988) interpreted the Penokean Orogen to consist of several structural panels that range from sedimentary rocks filling a foreland basin, through a main fold-and-thrust belt of sedimentary and volcanic rocks, to a complex metamorphic-plutonic terrane. The major terranes, referred to as panels in the list below, are separated by linear, northeast-trending aeromagnetic anomalies, which are interpreted as thrust faults that truncate stratigraphy-related aeromagnetic anomalies within the panels. The following summary of the structural panels is condensed from Southwick and others (1988) (Fig. 1), and modified accordingly for this study based on new information.

1. The Animikie basin is filled with essentially unmetamorphosed sedimentary rocks (Pokegama Quartzite, Biwabik Iron Formation, and Virginia Formation). The Animikie strata generally have a shallow south dip, but along the southern basin margin, and hence this map area, are deformed into fairly tight upright folds. In this area of the map, these strata unconformably overlie rocks of the fold- and thrust-belt.
2. The North Range panel is dominated by weakly metamorphosed argillite, siltstone, quartzite, iron-formation, graphitic slate, graywacke, and minor limestone and chert. Volcanic and hypabyssal mafic rocks are a minor component of the North Range. Structurally, the North Range is dominated by a large northwest-inclined, doubly plunging synclinorium. Geophysical models (Carlson, 1985) show that the folded Trommald iron-formation continues to the east beneath rocks of the Animikie Basin. The structural and stratigraphic attributes of North Range rocks are characteristic of those deposited in an external tectonic zone.
3. The South Range panel also contains an abundance of slaty and argillaceous rocks, but unlike the North Range, it has a substantial component of mafic volcanic and hypabyssal intrusive rocks, all of which have undergone low-grade metamorphism. The iron-formation in the South Range resembles Algoma-type iron-formations in that it occurs as a series of lenses closely associated with mafic volcanic rocks and graphitic slate. This panel is characterized by narrow linear aeromagnetic anomalies. The structure of the South Range is dominated by elongate east-northeast-trending overturned folds.

The South Range panel is separated from the Moose Lake-Glen Township panel to the south by a narrow zone of graphite-rich, crenulated phyllitic schist that curves from northeast to east-west. This graphitic schist may have absorbed a great deal of strain during thrust faulting.
4. The Moose Lake-Glen Township panel is dominated by quartz-rich metaclastic rocks and by mafic volcanic and hypabyssal intrusive rocks, along with graphitic argillite and schist; all were subjected to lower greenschist-facies metamorphism. This panel includes the Glen Township Formation, a sulfide-rich graphitic schist grading into a sulfide iron-formation that contains pyrrhotite, pyrite, lesser chalcopyrite, and minor sphalerite. The stratigraphic section at Glen Township consists of amygdaloidal basalt overlying the sulfidic-graphitic schist, which in turn overlies graywacke. In places the latter two are separated by slaty iron-formation. The base of the sequence comprises quartz-rich sedimentary rocks that typically contain up to several percent magnetite, which causes a moderate magnetic anomaly. Several prominent linear aeromagnetic anomalies apparently reflect some combination of thrust faults with relatively minor displacement, and stratigraphic and lithologic variation. The Glen Township strata have undergone at least two generations of folding that produce complex aeromagnetic patterns.

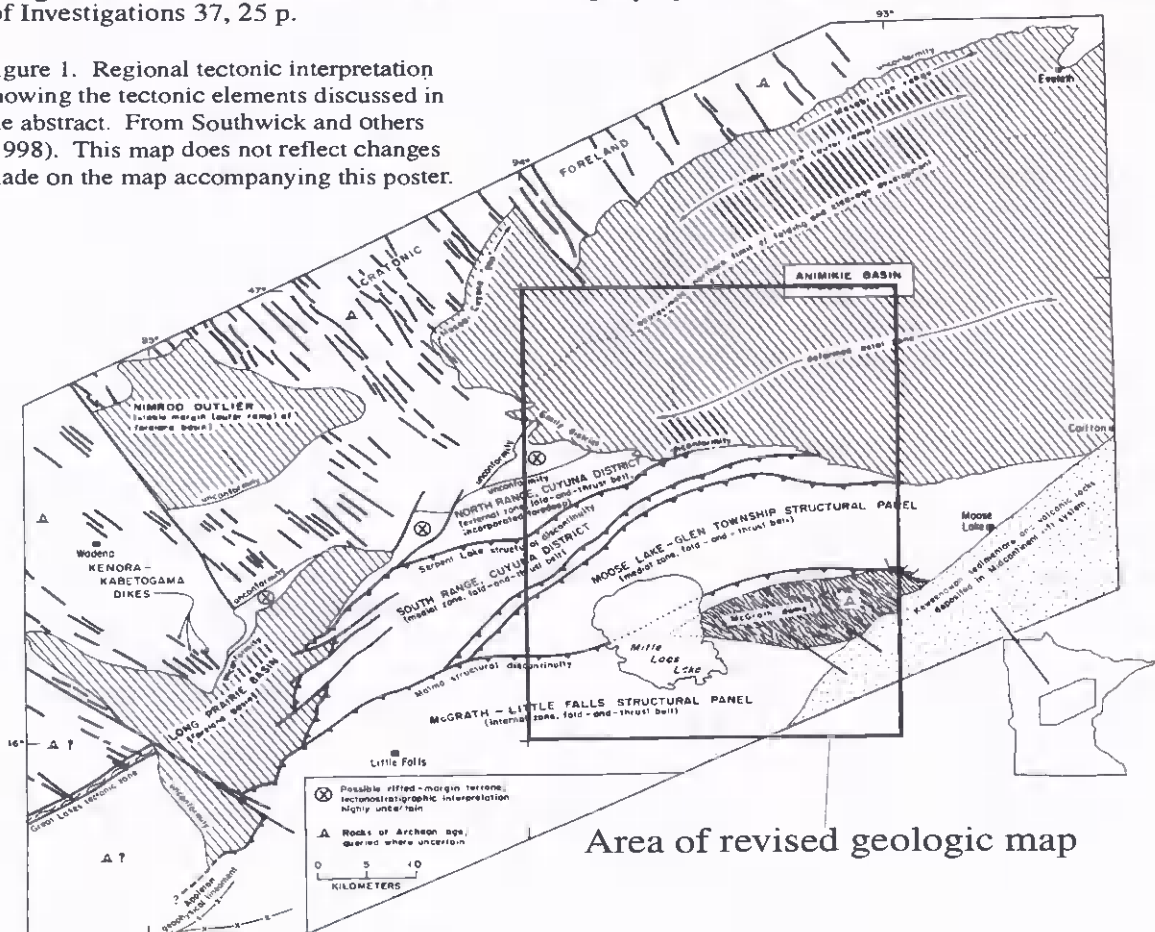
A previously unrecognized, syn- to late-orogenic monzonitic intrusion with a well-defined circular aeromagnetic anomaly was intersected by core drilling just northwest of Mille Lacs Lake. Another core hole drilled on this anomaly intersected ten feet of a brick-red, unmetamorphosed quartz-pebble conglomerate. This unit is geophysically invisible and its extent is thus unknown, but it may represent a conglomerate that was deposited during Mesoproterozoic time in a shallow basin on the backside of the Midcontinent rift, and thus is correlative with Keweenaw rocks to the east.

5. The McGrath-Little Falls panel, the southern- and internal-most component of the fold- and thrust-belt, comprises granitic to tonalitic gneiss, amphibolite-facies pelitic schist, and late- to post-tectonic granitic intrusions. An uncommon lamprophyre dike that post-dates Penokean granites is composed of fresh, euhedral clinopyroxene in a groundmass of poikilitic feldspar; it can be traced across the entire map area by its pronounced reverse aeromagnetic anomaly. Abundant small circular to elongate positive magnetic anomalies are indicative of mafic-ultramafic plugs similar to those that have been drilled at several locations to the south and east. Based on aeromagnetic data, these plugs post-date the lamprophyre dike. The dike is conjectured to be related to the waning stages of Penokean granite magmatism.

References:

- Carlson, K.E., 1985, A combined analysis of gravity and magnetic anomalies in east-central Minnesota: M.S. thesis, University of Minnesota, Minneapolis, 138 p.
 Southwick, D.L., Morey, G.B., and McSwiggen, P.L., 1988, Geologic map (scale 1:250,000) of the Penokean Orogen, central and eastern Minnesota, and accompanying text: Minnesota Geological Survey Report of Investigations 37, 25 p.

Figure 1. Regional tectonic interpretation showing the tectonic elements discussed in the abstract. From Southwick and others (1998). This map does not reflect changes made on the map accompanying this poster.



Mercury distribution in bedrock, native copper ore, and soils—Isle Royale National Park, Michigan

W.F. Cannon, U.S. Geological Survey, Reston, Va

L.G. Woodruff, U.S. Geological Survey, St. Paul, MN

In response to recent findings of elevated mercury in fish in some inland lakes on Isle Royale, we have begun a study of mercury concentration in natural geologic materials of the island. Initially we aimed to determine if elevated mercury from native copper deposits could be contributing mercury to the impacted lakes. Small native copper deposits on the island were mined sporadically in the 1800's. Those deposits, waste dumps at abandoned mines, and wastes from small processing operations, do contain anomalous amounts of mercury. Our analyses have found individual samples with as much as 14 parts per million (ppm) mercury, and stamp sands were found to contain from 0.6 to 0.7 ppm. In contrast, typical bedrock of the island, a sequence of volcanic basalt flows, appears to be uniformly very low in mercury. Samples we have analyzed all had no detectable mercury at a detection limit of 5 parts per billion (ppb).

To determine if mercury contained in mineral deposits could be a source of mercury to impacted lakes we sampled and analyzed soil and glacial deposits on which the soils formed in two test areas. Samples were taken around the Minong mine, the largest mine on the island, to determine the extent to which anomalous metal content of the ore and surrounding altered rocks affected the trace element content of soils. Also, samples were taken within the drainage basins of Sargent Lake and Lake Wagejo, two of the lakes with elevated mercury in fish. No copper deposits are known within those basins, but deposits could be concealed beneath extensive glacial deposits, and, if present, could be a contributor of mercury. In total, samples were taken at 65 sites. At each site a sample was taken from the A soil horizon, a dark organic mineral soil, 1-6 inches below the surface. A second sample was taken from a depth of about 2 feet, consisting of either reddish sandy glacial till or till slightly modified by soil-forming processes (referred to here as BC horizon).

Results show that the copper deposit at Minong mine produces a very distinct trace element anomaly in soil, especially the copper content of the BC horizon. Mercury also is somewhat elevated in samples of the BC horizon closest to the copper deposit. Mean copper content of BC soils in the Minong mine area is 342 ppm and that of mercury is 44 ppb. Highest values are 1160 ppm copper and 110 ppb mercury. The A soil horizon near the Minong mine averages 290 ppm Cu and 70 ppb Hg. In the drainage basins feeding Lake Wagejo and Sargent Lake, BC soils average 60 ppm Cu, nearly five times lower than near Minong mine, and 38 ppb Hg, essentially the same as at Minong mine. A-horizon soils in the Sargent-Wagejo drainage average 63 ppm Cu and 133 ppb Hg. The maximum value for Hg is 370 ppb, an exceptionally high value for soil in this region. For comparison, similar soil geochemical studies that we are conducting in the Chequamegon National Forest in northern Wisconsin show A-horizon soils to have a mean Hg content of about 54 ppb with a maximum detected concentration of 260 ppb. C-horizon soils in that area have a mean of 19 ppb Hg and a maximum of 80 ppb. With respect to soils, Isle

Royale appears to be a more Hg-rich environment than northern Wisconsin. Both A and BC horizon soils are at least twice as high on the island as in northern Wisconsin.

The results suggest that the very elevated mercury content of soils in the Sargent Lake-Lake Wagejo area is not caused by concealed native copper deposits because there is little or no elevated copper content of those soils. Results from the Minong mine area show that concealed deposits, if present, would produce readily detectable elevated copper content of the soils. Neither is there reason to conclude that local bedrock is the source for mercury because all tested samples of the chemically very uniform bedrock have very low mercury content. Because of the general lack of mercury in the most common rocks of the island and the very limited occurrence of native copper deposits that do contain some mercury, the mercury content of the soils on Isle Royale seems very likely to result largely from airborne deposition. The processes causing the great variability of mercury content of similar appearing soils over short distances that we have observed in our survey remain only speculative. Nevertheless, it appears certain that mercury must be very mobile in the soil zone in order to redistribute what must be a relatively uniform amount of deposited mercury into the highly variable observed concentrations.

STRUCTURAL FABRIC AND STRAIN FOR THE SEINE RIVER CONGLOMERATES AT THE WABIGOON-QUETICO SUBPROVINCE BOUNDARY NEAR MINE CENTRE, ONTARIO.

CZECK, Dyanna M. and HUDLESTON, Peter J., Department of Geology and Geophysics, University of Minnesota, 310 Pillsbury Dr. SE, Minneapolis, MN 55455, dyanna@geolab.geo.umn.edu

INTRODUCTION

The Superior Province consists of approximately east-west trending subprovinces defined by lithological differences, metamorphic grade, and structural boundaries (Card & Ciesielski 1986). This study concentrates on the boundary between the Quetico metasedimentary subprovince and the Wabigoon metavolcanic subprovince. The Seine River Metasedimentary Group, including the Seine River conglomerates, are distinctive rocks found within a wedge along this boundary.

Structural work along the Quetico and Wabigoon describes subvertical foliation overprinting large lithological folds (Poulsen 1986, Tabor & Hudleston 1991). These structures indicate a strain history consisting of an early recumbent nappe deformation followed by a more ubiquitous overprinting of a subvertical flattening fabric and shear zones attributed to dextral transpression. Strain is pervasive throughout the boundary, but also localized into more discrete shear zones including two main, connecting shear zones coincident with the Rainy Lake-Seine River and Quetico Faults. These large shear zones are interconnected with smaller shear zones forming an anastomosing pattern. The Seine River conglomerates are located in a wedge between these two shear zones west of their intersection. Poulsen (1986) interpreted the Seine River conglomerates to have formed syn-kinematically during transpression, possibly in structures similar to pull-apart basins.

This preliminary structural work made it clear that the Wabigoon- Quetico subprovince boundary is not merely a discrete suture between two tectonic microplates, but is instead a complex network of shear zones which together accommodated oblique collision. The goal of this study is to describe how this complex shear zone geometry is reflected in spatially variable strain magnitudes and structural fabrics.

STRUCTURAL FABRIC

Foliations in the field show a consistent regional orientation with strike of approximately 080 and subvertical dips. This strike is consistent with the dextral transpression model. One exception to this is in the area of Shoal Lake where the strike changes to approximately 045, creating an overall S-like geometry with a map pattern analogous to a dextral shear sense indicator. The same shear sense is observed at a smaller scale within the conglomerate clasts that often form sigma and delta dextral shear sense indicators on the sub-horizontal plane.

Mineral lineations in the field are predominantly defined by chlorite and amphiboles. General transpression theory predicts either vertical or horizontal lineations (Fossen & Tikoff 1993). However, lineation orientations in the field vary remarkably within the foliation plane. Typically, the Seine Group lineations are spatially similar on the scale of 0.5-1 km. Therefore, the lineation variations are not caused by small-scale phenomena such as clast interaction, but by some regional phenomenon. Rather than reflecting different bulk kinematic conditions along the boundary (such as partitioned triclinal transpression), the lineation variations may reflect anastomosing shear zone patterns and variable pressure gradients within the rock.

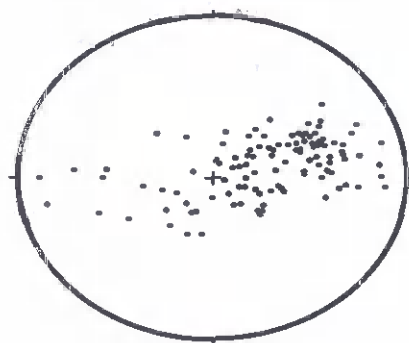
Taken together, foliation and lineation match the variations in the finite strain ellipsoid orientation. The foliation pole aligns with the minimum stretching direction, and the lineations parallel the maximum stretching direction.

STRAIN ANALYSIS

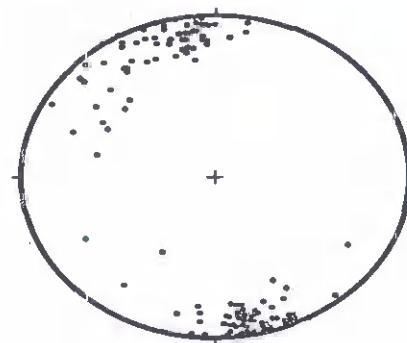
The Seine River conglomerates are useful strain recorders. Qualitative observations and quantitative strain analyses indicate heterogeneous strain distributions within the Seine River conglomerates. Analysis confirms a flattening style strain that could only be a result of a three-dimensional deformational phenomenon such as transpression rather than the two-dimensional strain produced by wrench or thrust movements.

Results to date show that the longest principal axis corresponds to the mineral lineation measured in the field and the shortest principal axis corresponds well with the foliation pole. This supports the idea that structural fabric measured in the field may be used to represent the orientation of the finite strain ellipsoid.

The variations in strain ellipsoid orientations and magnitudes could be used to argue for multiple deformation events or complex and variable kinematic boundary conditions. However, the geometry of the anastomosing shear zone pattern can be used to explain the variations in the orientation of the strain ellipsoid and the heterogeneous strain magnitudes within the Seine Group within a simple dextral transpressional setting.



Mineral lineations
113 Measurements (equal area)



Poles to foliation
138 Measurements (equal area)

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Preliminary Aeromagnetic Map of Wisconsin

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The Mineral Resources Program of the U.S. Geological Survey (USGS) has conducted aeromagnetic surveys in Wisconsin during the past three years to improve the magnetic coverage of the state. State coverage was completed with a survey carried out in 1998/1999. The new aeromagnetic survey fills the southern third of the state not covered by existing good quality surveys (see figure). Flight specifications are: north-south flight lines at ½ mile (800 m) separation draped at 1000 ft (305 m) mean terrain clearance. Flight lines are east-west for a part of southeast Wisconsin.

The results of the first two years of flying were shown at 44th meeting of the ILSG in 1998 (Daniels and others, 1998). These data have been released since that meeting as paper contour maps (Snyder, 1998; USGS Open-File Reports 98-431 through 439). Digital data for the 1997/1998 survey have now been released (Open-File Report 99-28) on CD-ROM (Daniels, Nicholson, and Cannon, 1999).

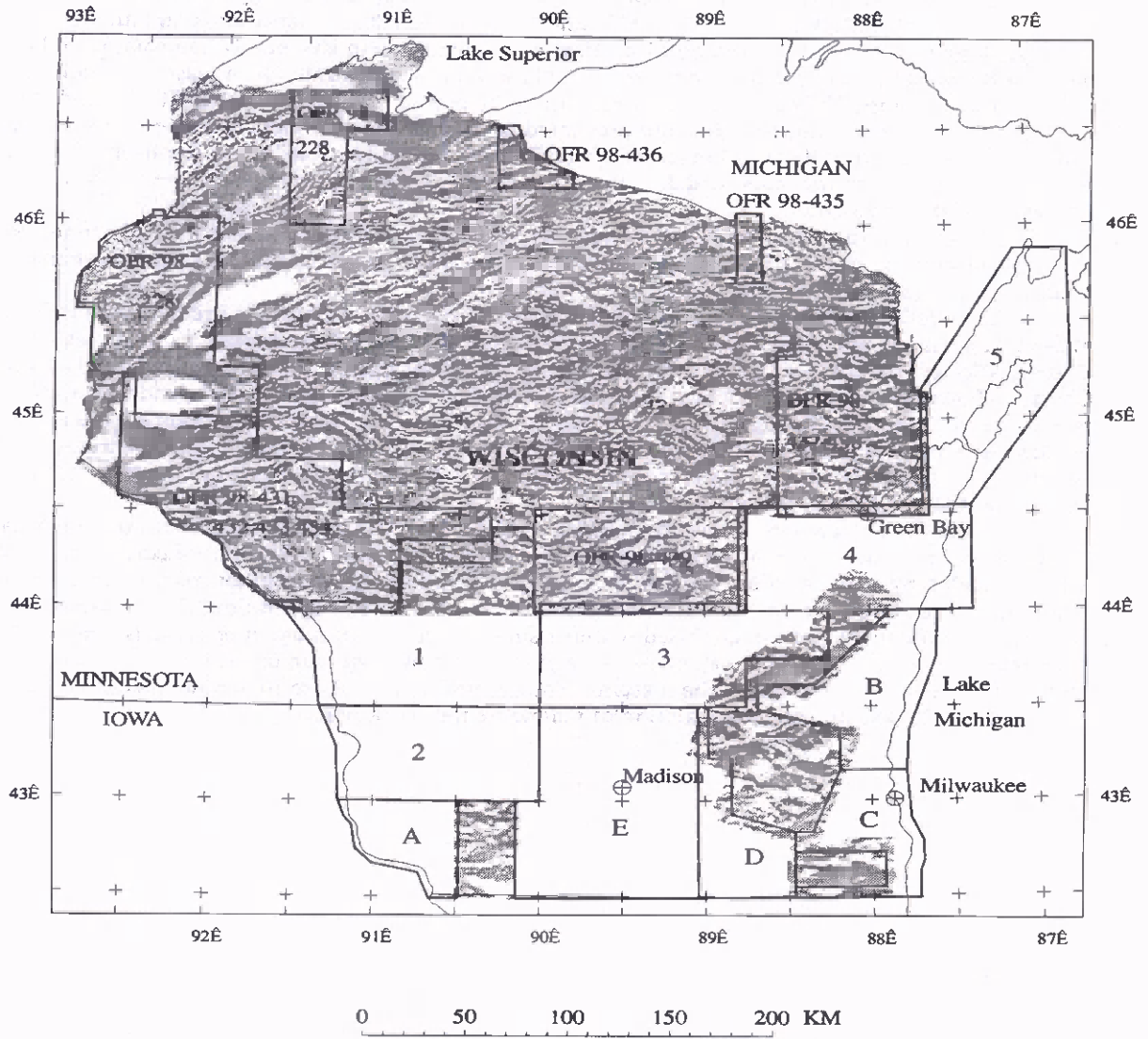
The accompanying figure shows a shaded image of the aeromagnetic field for current data in Wisconsin and the areas of the first 2 years data are blocked and labeled. Three aeromagnetic surveys obtained from industry sources by the Wisconsin Geological and Natural History Survey (M. Mudrey, personal communication, 1997) are shown in southern Wisconsin. The data for the new survey are still preliminary. Blocks 1-5 and A-D represent the areas of the new survey that will be shown and the contour maps that will be available later in 1999.

The rationale for continued aeromagnetic surveying has been to provide higher resolution data with which to interpret basement geology in Wisconsin. The aeromagnetic data image basement structures in detail and give clues to the structural evolution of the Precambrian crust, covered by glacial and Paleozoic cover.

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Index Map of Wisconsin Aeromagnetic Data



INVESTIGATION OF CaO AT THUNDERBIRD MINE, MESABI RANGE: MINERAL AND STRATIGRAPHIC RELATIONSHIPS

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Mine geologists at EVTAC's Thunderbird Mine, a taconite mine in Eveleth, Minnesota, have been tracking the variation of naturally occurring CaO in iron ore concentrate for at least nine months. Information about the CaO is helpful in formulating the partial flux pellets that EVTAC produces. The CaO-bearing phase was unidentified, but presumed to be a carbonate. The objective of this study was to investigate the nature of this CaO in terms of: 1.) The identification of its phase or phases; 2.) Location of major stratigraphic contributors; and 3.) The *in situ* textural relationship between the CaO-bearing phase(s) and the magnetite.

Manual interpretation of X-ray diffraction results identified the CaO-bearing phase in the concentrate to be ankerite. Other constituent minerals include quartz, hematite, siderite, greenalite, stilpnomelane, talc, and goethite.

Thunderbird Mine excavates ore from the Biwabik Iron Formation, a Precambrian unit composed of several horizons of banded iron formation. From top to bottom, these horizons are Upper Upper Cherty, Middle Upper Cherty, Lower Upper Cherty, Lower Slaty, Top Lower Cherty, and Bottom Lower Cherty. Horizons differ in physical characteristics, such as thickness and texture, and chemical composition. When collecting ore for the initial ore mix, a combination of horizons are blasted and blended to achieve a desirable magnetic iron concentration. Statistical analysis demonstrated a strong positive relationship between the percentage of ore derived from the Top Lower Cherty and the amount of ankerite in the resulting concentrate.

Textural relationships between the ankerite and magnetite were observed and photographed. Ankerite occurs in at least four distinct habits, relative the magnetite: 1.) Rhombohedral ankerite crystals are surrounded by much smaller, granoblastic, recrystallized quartz, and minor magnetite; 2.) Fine-grained, irregular ankerite crystals, are intergrown with magnetite of approximately the same size; 3.) An ankerite crystal can be entirely enclosed within a single or cluster of magnetite crystals; and 4.) A single or cluster of ankerite crystals encapsulates a magnetite crystal. The iron ore at EVTAC is processed by magnetic separation. Examining the textural relationship between these two minerals can produce information relevant to make the isolation of magnetite more efficient.

METAMORPHIC MAP OF THE CANADIAN SHIELD OF ONTARIO, MICHIGAN, MINNESOTA AND WISCONSIN

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The Geological Survey of Canada's undertook a project several years ago to produce an updated metamorphic map for the Canadian Shield (GSC Map 1475A), which would also be used to produce a metamorphic map of the world (in conjunction with the Commission for the Geologic Map of the World). At the request of the Geological Survey of Canada, Ontario was asked to compile a metamorphic map of the Canadian Shield in Ontario.

In addition to simply compiling metamorphic information, Ontario approached this project with the goal of attempting to integrate metamorphic information with the tectonic synthesis produced as part of the *Geology of Ontario* project, with the aim of developing improved mineral exploration models. As a consequence, the metamorphic map of Ontario was designed so as to complement the existing set of 1:1,000,000 bedrock, surficial geology, geophysical, and tectonic assemblage maps and time-space charts released in 1991-92 as part of the *Geology of Ontario* series. A draft of this map, at roughly 1:2,500,000 scale, will be presented here.

Also at the request of the Geological Survey of Canada, Ontario has undertaken to produce a preliminary metamorphic map of those portions of the Canadian Shield exposed in Wisconsin, Michigan, and Minnesota. One of the reasons for requesting the involvement of the Ontario Geological Survey in this compilation, as opposed to other organizations, was so as to best integrate the metamorphic pattern present in the shield in the United States with that present across the border in Ontario. In addition, fast approaching deadlines for completion of the project factored into this decision.

Thus, the main focus of this presentation will be on presentation of a preliminary draft of the metamorphic map for the shield rocks in the areas adjoining Ontario, for the purposes of discussion regarding:

- 1) the style of presentation,
- 2) the accuracy of the data presented, and
- 3) solicitation of possible assistance in bringing this project to a conclusion.

The metamorphic map of the Shield is being produced digitally. In the case of Ontario, the Tectonic Map of Ontario was used as the geological base. Key digital aspects of the project include digitization of polygons representing different metamorphic facies (grade) and of linework (e.g. isograds, facies boundary information), into a CAD program. In addition, point-source information (e.g. assemblage data, P-T determinations) is being input into a database. The final map product will be an attributed map, released on CD-ROM, containing all the compiled information. The attributed map will accompany a standard coloured, hard copy map, which will mainly display metamorphic facies distribution. This same approach will be taken in compiling the information for Wisconsin Michigan and Minnesota, except that here, the digital base is being supplied by the Geological Survey of Canada, based on a previously released US geological compilation map of the region.

Two special issues of *The Canadian Mineralogist* on "Tectonometamorphic Studies in the Canadian Shield" are being produced as part of this project. The first (vol. 34, part 5, October 1997), includes results obtained from a variety of ancillary metamorphic studies related to the compilation effort. The second issue, which is in the process of being assembled, includes regional overviews related to the metamorphic map of the Canadian Shield, as well as additional, detailed metamorphic studies.

WHERE ARE THE METAMORPHOSED NATURAL OREBODIES OF THE MESABI RANGE?

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The nearly century-old debate regarding the genesis of the hematite-goethite iron ore deposits of the Mesabi Range has recently been revisited by Morey (1999). The historic debate centers on the origin of the fluids responsible for the combined oxidation and leaching of the Biwabik iron-formation to form the deposits – were they upward moving hydrothermal fluids (hypogene) or downward moving meteoric waters (supergene)?

Morey presents an interesting conceptual model for the genesis of the ores that utilizes continental-scale groundwater flow during the Early Proterozoic, driven by uplift in the Penokean fold-thrust belt to the south of the Mesabi Range. This model relies on the Pokegama Quartzite, which underlies the Biwabik iron-formation, as a regional aquifer for the movement of basinal waters to the northern margin of the Animike basin. A minimum age for ore genesis in this model is believed to be 1650 Ma when loss of the hydraulic gradient for the groundwater flow system occurred due to erosion of the recharge area. This Early Proterozoic age for ore genesis is significantly older than the Jurassic-Cretaceous age that has been generally, albeit not universally, accepted over the last 30 plus years (Sloan, 1964; Morey, 1972).

Constraints on the timing of the hematite-goethite ores are few due to the scarcity of geologic events impacting the Mesabi Range between the Early Proterozoic and the Late Cretaceous. It is on the east end of the Mesabi Range where intrusive events and contact metamorphism associated with the Middle Proterozoic Duluth Complex provide a potential opportunity to put additional time constraints on the genesis of the ores. Hence the title of this paper. If ore formation occurred prior to the Middle Proterozoic, the opportunity should exist to find metamorphosed equivalents of the soft hematite-goethite ores. Detailed drilling both along the iron-formation outcrop belt and downdip as part of exploration for Cu-Ni deposits has failed to find these metamorphosed equivalents. In fact the distinct absence of enriched orebodies of any sort east of the Duluth Complex's metamorphic aureole has long been utilized as support for a post-Middle Proterozoic age for ore genesis. Alternatively, thinning of the Pokegama quartzite in this same general area is cited by Morey to explain the absence of enriched ores on the East Mesabi.

The relative abrupt absence of enriched ores in the Biwabik iron-formation occurs within the mining operations of LTV Steel Mining Company, managed by a subsidiary of Cleveland-Cliffs, which has been active for over 40 years (Figure 1). Detailed data acquired through both field observations and thousands of drill holes provide insight on the controls of the ore-forming process. The following features of the geology at LTV Steel Mining Company are in conflict with an Early Proterozoic genesis of the hematite-goethite ores:

1. Due to the economic significance that metamorphism has on the processing of the magnetic taconites, considerable effort is placed on mapping the metamorphic isograds at this operation. Further refinement of the original zonation of the Duluth Complex's contact metamorphic aureole (French, 1968) has resulted. The relationship of metamorphic grade with the eastern limit of iron-formation enrichment appears stronger than the correlation with either the thickness or distribution of the Pokegama Quartzite. This is manifested by:
 - a) the abrupt termination of enrichment and oxidation along the Wentworth structure due to increasing metamorphic grade; and,
 - b) the presence of enrichment east of the Siphon structure which is the controlling structure for a dramatic decrease in Pokegama Quartzite thickness.
2. The Aurora sill, a sizeable syenitic body that intrudes the Biwabik iron-formation in the western portion of the mining operation, appears to have contributed to the localization of ore formation in the St. James and the Miller-Mohawk mines. This sill has visual similarities to granophyres associated elsewhere with the Duluth Complex and as such has long been considered Keweenawan (White, 1954). If ore genesis in these mines were Early Proterozoic, how could a Keweenawan sill constrain ore formation? Likewise, no metamorphic overprint has been reported from these orebodies. Definitive age dating though is lacking for this intrusive.
3. A large number of the enriched orebodies at the LTV Steel Mining Company operation are very shallow. Drilling has been conducted through the bottom of a number of the natural ore pits successfully finding fresh, unaltered magnetic taconite reserves below. The lack of alteration between the Pokegama Quartzite and the orebodies is problematical for ascending groundwater flow models.

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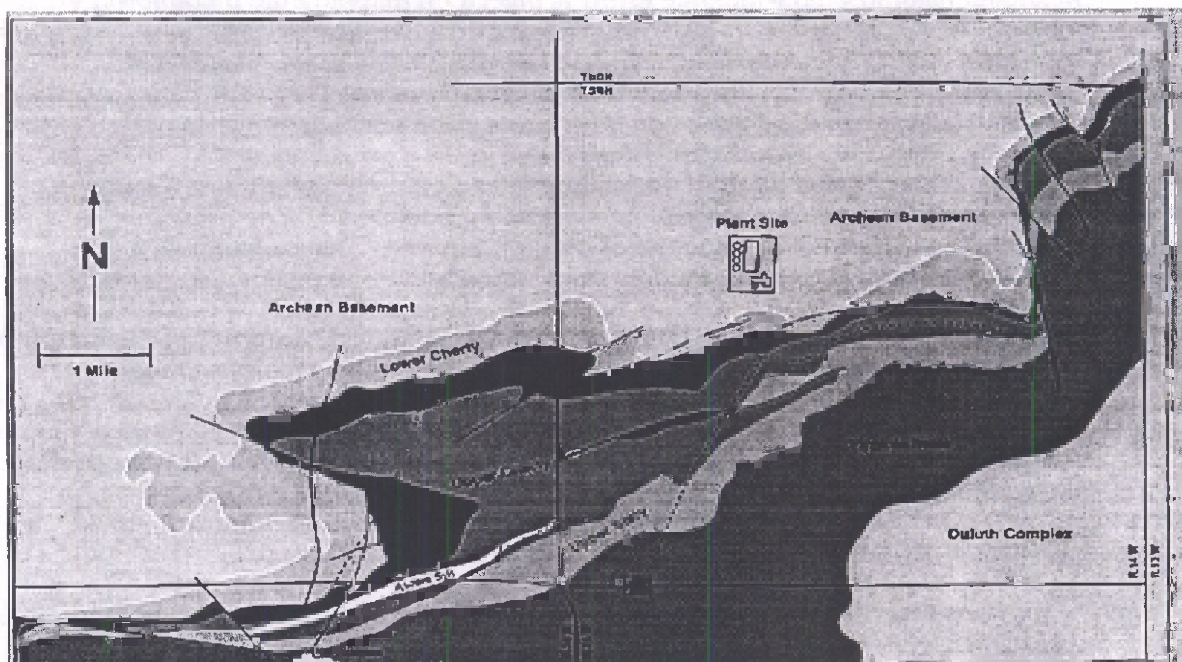
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Figure 1. Geologic Map of LTV Steel Mining Company



Cross Margin Transport in Lake Superior

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The Keweenaw Interdisciplinary Transport Experiment in Superior (KITES) is focused on cross-margin transport processes along the western shore of Lake Superior's Keweenaw Peninsula. The dominant feature of this region is the shore-parallel Keweenaw Current, which flows to the northeast and is strongest near Eagle Harbor. Water, sediment, and hydrographic data are being correlated with satellite imagery to obtain an integrated view of transport of suspended sediments, nutrients, and organic material near and across the current.

Time series SeaWiFS images from May to September, 1998 show cross margin transport events in Lake Superior. These chlorophyll and turbidity maps reveal a highly productive southern corridor from Duluth Harbor to the tip of the Keweenaw. Distinctive sediment and chlorophyll plumes can be seen offshore west of the Ontonagon River and near the tip of the Keweenaw Peninsula. Movement of the plumes offshore was highly variable depending upon the direction of prevailing winds prior to the satellite band pass.

Simultaneously acquired SeaWiFS (Sea-viewing Wide Field-of-View Sensor) and AVHRR (Advanced Very High Resolution Radiometer) images from May 23, 1998 were used to verify cross margin transport events in Lake Superior. The AVHRR lake surface temperature image reveals a dramatic northward flowing offshore eddy current at the tip of the Keweenaw Peninsula. A SeaWiFS turbidity map acquired within hours of the AVHRR SST image suggests that materials were transported offshore north of Eagle Harbor, providing evidence of cross-margin transport. These patterns were not present in AVHRR and SeaWiFS images obtained before or after the May 23rd event (on May 20 and May 27).

Sediment patterns, in-water optical measurements, and physical models are helping clarify transport mechanisms and pathways in the KITES study region.

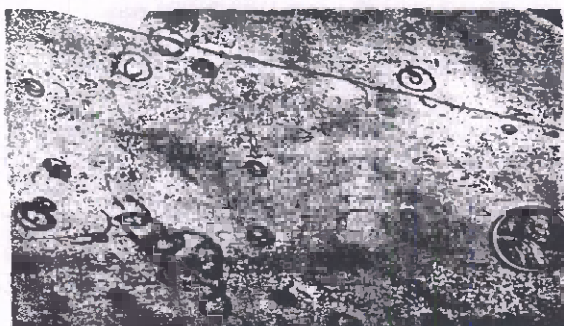
Megascopic Fossils and Their Possible Contribution to the Development of the Silicate Unit of the Negaunee Iron-Formation, Empire Mine, Marquette Range, North Michigan

T. M. Han, Senior Research Scientist (Emeritus), Cleveland-Cliffs Inc.

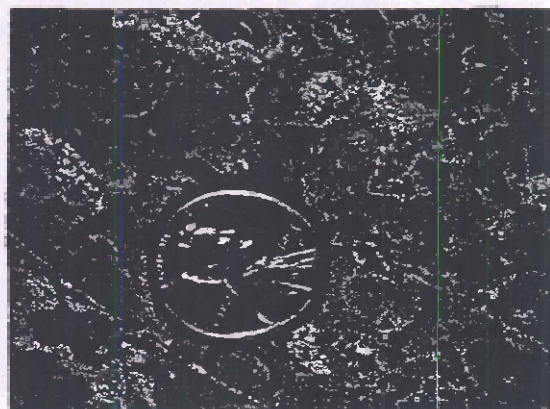
Abstract

The megascopic fossils discovered in the Early Proterozoic Negaunee Iron-Formation are the world's oldest known fossils. These fossils have been reported as eukaryotic algae similar to *Grypania spiralis* (Han and Runnegar 1992). Their existence may have played a key role in the development of the thin banded "silicate unit" of the Negaunee Iron-Formation at the Empire Mine. This unit is composed of magnetite-rich layers alternating with layers having a mineral assemblage of chert, siderite, ankerite, minnesotaite and stilpnomelane in various proportions.

Two fossil types are recognized. One type is fine filaments that are long and uniform in width and coiled like "springs". The other type is short, coarse, in whole and sectional forms, and resembles "coiled garden worms". These fossils were apparently transported by direct current and deposited at distances from their origin. Based on the relationship between the current marks and the orientation of the fossil patches and oval-shaped coils on the outcrops measured, the direction of the paleocurrent at the time of sedimentation was from the southwest where Archean rocks are distributed.



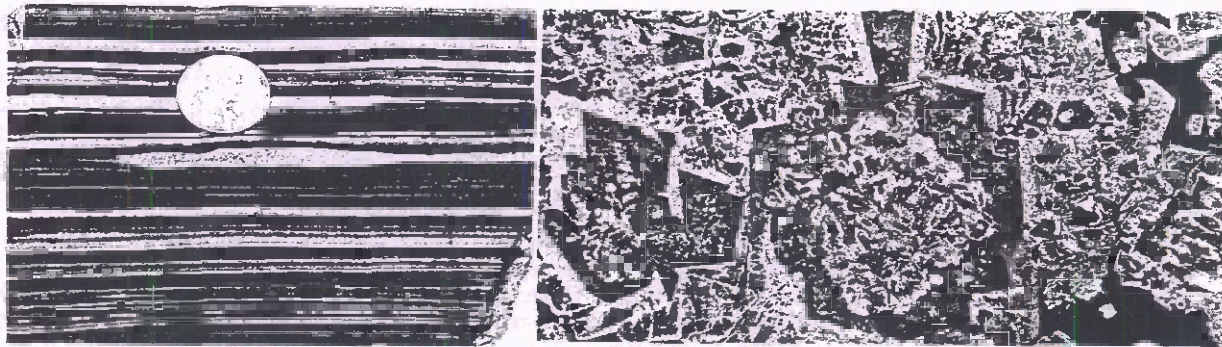
Fossil remains resembling "spring coils"



Fossil remains resembling "coiled garden worms"

An induced oxidation study reveals that much of the magnetite was developed and enriched through Fe^{++} diffusion, using lath-shaped hematite as nuclei. These laths are randomly arranged, either scattered, or in irregular clusters and existed before the magnetite development.

The gangue layers are believed to be derived from a highly siliceous gel with carbonaceous matter and other impurities. They were subsequently recrystallized and replaced by siderite, ankerite, minnesotaite and stilpnomelane during diagenesis and low-grade regional metamorphism.



Magnetite and magnetite granule layers, white; gangue layers, dark.

Microstructure of a magnetite layer. 250x Magnetite, gray; hematite grayish white and gangue, black.

According to LaBarge et al (1987), it is reasonable to assume that the heavily populated megascopic eukaryotic algae were probably one of the principal oxygen suppliers for precipitating Fe^{++} as $\text{Fe}(\text{OH})_3$. The clusters of the lath-shaped magnetite pseudorph in magnetite laminae and granules probably represent dehydrated and crystallized $\text{Fe}(\text{OH})_3$ flocculi, hematite. The effect of flocculation, if any, would cause the segregation between the siliceous gel and the $\text{Fe}(\text{OH})_3$. Furthermore, the specific gravity of the $\text{Fe}(\text{OH})_3$ is significantly greater than the siliceous gel. Consequently, the interbanded structure of the lithological unit is believed to be deposited simultaneously through processes of selective flocculation and differential settling between the $\text{Fe}(\text{OH})_3$ and siliceous gel under a rhythmic and cyclic manner regulated by the life and death of the organism, i.e. the growing season is a period of deposition while the off-season is a period of solution. Furthermore, the carbonaceous matter associated with the precipitates may generate Fe^{++} during diagenesis and metamorphism for the development of various types of iron minerals, particularly, the development and enrichment of magnetite.

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COMPARISON OF MICA Ar/Ar AND Rb/Sr THERMOCHRONOLOGY RESULTS FROM NORTHERN WISCONSIN AND NORTHERN MICHIGAN

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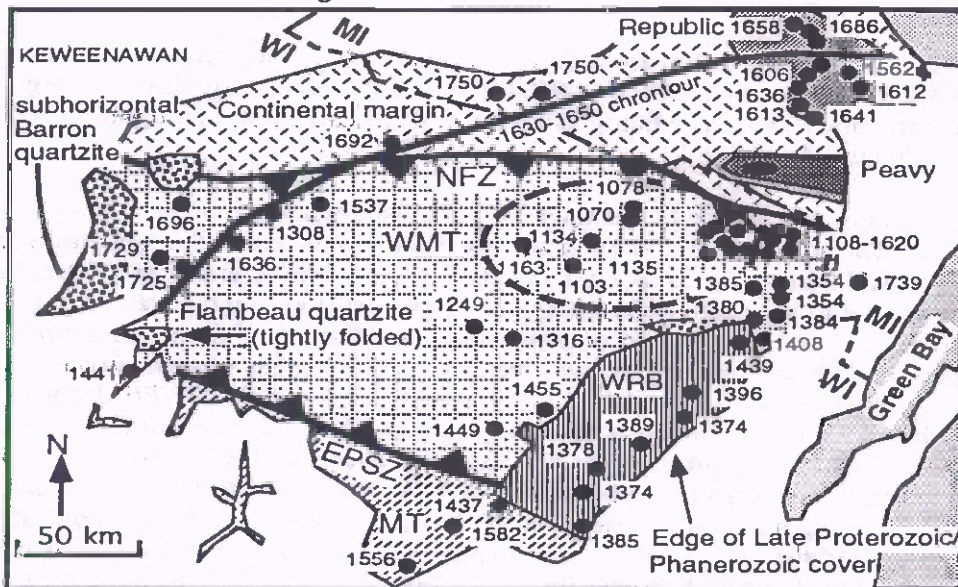
Thermochronologic data from the southern Lake Superior region has historically been dominated by the Rb/Sr method on biotite (Fig. 1; Peterman and Sims, 1988, *Tectonics*). We summarize the results of 45 new mica Ar/Ar age dates from northern Wisconsin and northern Michigan (Fig. 2) and compare these with the Rb/Sr data. Because the Rb/Sr and K/Ar systems in biotite are known to have similar closure temperatures ($300^{\circ}\pm 50^{\circ}\text{C}$), this summary provides an excellent opportunity to compare how susceptible these systems are to partial or complete resetting.

Northwest Wisconsin. Rb/Sr biotite dates from this region vary from 1309 to 1730 Ma. In contrast, Ar/Ar mica dates fall tightly into two groups, an older ~1755 Ma group and a younger ~1600 Ma group. The two groups of Ar/Ar dates are separated by a sharp post-Penokean deformational front in the overlying Early Proterozoic quartzites. The deformational/thermal front here probably represents the northern limit of Mazatzal foreland deformation in the southern Lake Superior region.

Northern Michigan. The 1630-1650 Ma Rb/Sr and Ar/Ar chrontours, which coincide in northwest Wisconsin, diverge eastward into northern Michigan. Given the absence of post-Penokean quartzites in this region, we suggest that the Ar/Ar ages can serve as a proxy for determining the northern limit of Mazatzal deformation. We suggest that the Republic area escaped significant Mazatzal related deformation and higher-temperature metamorphic affects but did undergo some form of lower-temperature, possibly hydrothermal, metamorphism at ~1630 Ma.

Northeast Wisconsin. A large area of <1200 Ma Rb/Sr biotite dates (the Goodman Swell) north of the Wolf River batholith has been interpreted as an uplifted flexural bulge created by rapid loading along the mid-continent rift axis to the north (dashed ellipse of Fig. 1). In contrast, mica Ar/Ar dates from the same region define a much smaller region of <1200 Ma dates (dashed ellipse of Fig. 2). An isolated 1170 Ma Ar/Ar biotite date has also been obtained from basement over 100 km southwest of the swell. We interpret the <1200 Ma dates for both systems to reflect shallow intrusion-related resetting. The larger locus of anomalously young Rb/Sr dates probably reflects the fact that the Rb/Sr system is more susceptible to lower-temperature resetting than the Ar/Ar system. This interpretation also provides an explanation for the problematic Rb/Sr and Ar/Ar dates that fall between 1200 and 1400 Ma. Because much of the 1470 Ma Wolf River batholith and associated plutons (Wausau Syenite complex) intruded into shallow crust and cooled through 300°C by ~1400 Ma (Fig. 1 and 2), it is likely that the surrounding Precambrian country rock to the north and west was also shallow. We suggest, therefore, that the 1200-1400 Ma country rock mineral dates for both systems indicate incomplete mineral resetting related to shallow Keweenaw intrusions.

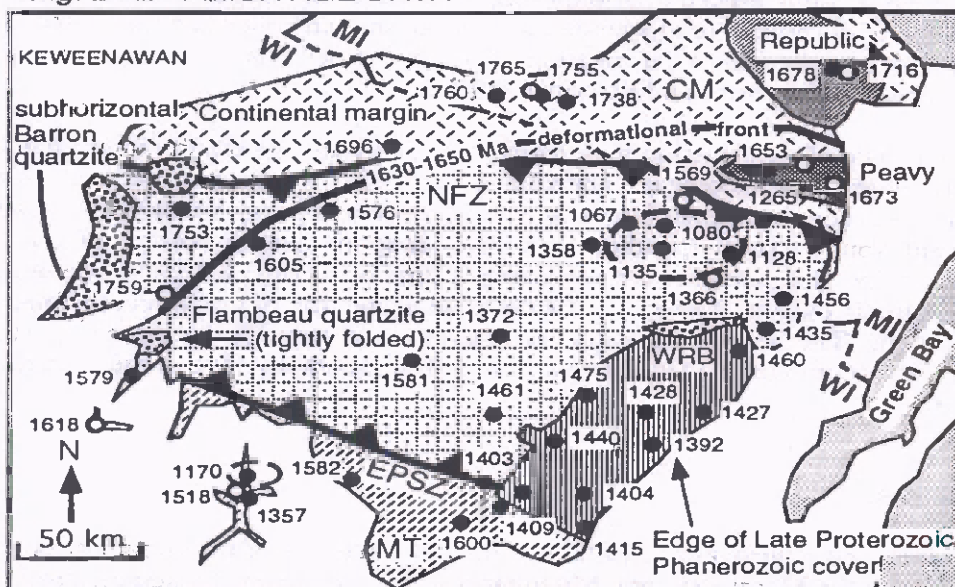
Fig. 1 Rb/Sr BIOTITE AGE DATA



After Peterman and Sims (1988) but excluding data of Aldrich et al. (1965)

Fig. 2 Ar/Ar MICA AGE DATA

● Biotite ○ Muscovite



Compiled from Romano (1999, Kent State M.S. thesis), Mancuso (1999, Kent State M.S. thesis), Holm and Lux (1998, CJES), Holm et al. (1998, GSAA), and Schneider et al. (1996, CJES).

ISHPEMING GREENSTONE BELT – EVIDENCE FOR ARCHEAN TECTONIC EVOLUTION OF THE SOUTHERN EDGE OF THE SUPERIOR PROVINCE IN MICHIGAN

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The Ishpeming greenstone belt is the southernmost greenstone belt of the Superior Province. The southern boundary of the Superior Province and the Ishpeming greenstone belt is the 1,000 km long Great Lakes tectonic zone. Late Archean greenstone and granite terrane to the north (Ishpeming greenstone belt) are juxtaposed against Early to Middle Archean migmatite-gneiss-amphibolite and Late Archean granite terrane (southern complex). The Ishpeming greenstone belt consists of subaqueous tholeiitic basalt to calc-alkalic rhyolite, 10-15 km in total thickness. New U-Pb zircon data establish the age of volcanism at 2705.8 ± 1.6 Ma. (Table 1) Recent field studies define a sequence of multiple deformation and intrusive events following volcanism. The volcanic rocks were enveloped by a tonalite suite just before and during the north-directed thrusting and nappe formation. This was followed by development of strike-slip shear zones and the deposition of clastic sediments into pull-apart basins. A second phase of folding produced upright folds. A trondhjemite to granite suite intruded the belt and deformed earlier fabrics. The timing of deformation is constrained with new U-Pb zircon data yielding an age of $2668.4 \pm 2.1/-1.8$ Ma for an intrusion in this suite. Intrusions of hornblende to syenite (appinite suite) and continued movement along shear zones represent the end of deformation. An undeformed post-tectonic granite intrusion has an age of 2585 (Sims and Peterman, 1992).

This sequence of deformation magmatic/volcanic events are readily interpreted in a modern plate tectonic context. The volcanic arc rocks are the result of north-directed subduction. Tonalite-suite plutons intruded the arc just prior to collision of a small continent from the south (southern complex) along the Great Lakes tectonic zone (suture). Collision occurred over an extended period of time with multiple deformation and magmatic events. The appinite suite is characteristic of modern collision-related magmatism. The field-based sequence of events and new age dates are important data in continuing to unravel the tectonic evolution of the southern edge of the Superior Province.

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Table 1. Summary of deformation sequence, volcanic/magmatic activity and constraining age dates for the Ishepming greenstone belt.

<u>Event</u>	<u>Characteristic</u>	<u>Volcanic/Magmatic Activity</u>	<u>Age Dates</u>
		Undeformed post-tectonic granite	2585 Ma
D ₆	Kink bands with north-easterly striking kink planes and steeply plunging hinges		
D ₅	Dip slip motion along shear zones.		
D ₄	Folding associated with intrusion of plutons.		
D ₃	Upright folding.	Appinite suite	
D ₂	Strike-slip shearing.	Trondjemite-granite suite	2668.4±2.1/-1.8 Ma
D ₁	Recumbent folding.	Tonalite suite	
		Extrusion of mafic and felsic volcanic rocks.	2705.8±/-1.6 Ma

A NEW APPROACH TO HISTORICAL RECONSTRUCTION: COMBINING DESCRIPTIVE AND EXPERIMENTAL PALEOLIMNOLOGY

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Here we introduce a combined experimental and descriptive approach (termed "Resurrection Ecology") to reconstructing historical perturbations, pointing out how direct tests with sediments and hatched resting eggs complement the traditional descriptive calculation of microfossil fluxes. This approach is being studied in both NSF/NOAA Cooperative sites, the KITES Project in Lake Superior and the EGGLEE Project in Lake Michigan. Additional core studies involve Baltic German lakes and the Caspian Sea.

In the Keweenaw Waterway, a freshwater estuary off Lake Superior, turn-of-the-century copper mining impacted the resident biota. Remain fluxes document that diatom, rhizopod, and *Bosmina* production all declined during stamp sand discharges, but recovered rapidly after WWII, moving above background levels due to developing eutrophication. In addition to biogenic silica, we discovered that bromine flux holds promise as an indicator of diatom production and confirmed that this element is present in several genera. Fluxes of *Daphnia* resting eggs also increased dramatically since the 1940's, dominated by a hybrid apparently produced from crosses between offshore and interior Waterway species, after channeling promoted greater mixing of water masses.

Toxicity studies with sediments and *Daphnia* clones directly tested recovery of environments after cessation of mining activities. The studies document that increased concentrations and fluxes of copper in the Waterway during mining discharges were toxic to invertebrates. Once stamp sand discharges ceased, the biota recovered rapidly due to a combination of decreased copper cycling and organic complexation. Although sedimentation has returned to near-background conditions and surficial sediments in much of Portage Lake are no longer toxic, eutrophication and faunal exchange with Lake Superior make it unlikely that the original zooplankton community composition will return to the Waterway system.

THE IRON RIVER SYNCLINE: AN ALLOCHTHONOUS STRUCTURAL PANEL IN THE PENOKEAN FORELAND OF NORTHERN MICHIGAN

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The Iron River syncline (James and others, 1968) lies near the southern margin of the Penokean fold and thrust belt in northern Michigan. It contains sedimentary strata of the Paint River Group and underlying Badwater Greenstone. The syncline has a triangular map pattern and is flanked by strata of the Michigamme Formation on its north and east sides and by intensely deformed Early Proterozoic strata on its southwest side. An unusually complex, multiply-folded structure within the syncline has been recognized since the detailed studies by James and others (1968). Traditional stratigraphic interpretation has been that the strata in the syncline are stratigraphically above the Baraga Group and that the Badwater Greenstone and Paint River Group are the youngest parts of the Marquette Range Supergroup. More recently, an allochthonous origin for the syncline has been advocated (Sims, 1996) and the exact correlation of units in the syncline with autochthonous units elsewhere in the foreland is uncertain. Our recent re-examination of the region lends support to the view that the syncline is an allochthon emplaced by generally northward-directed thrusting. A thrust of considerable magnitude is interpreted to lie at the base of the Badwater Greenstone. This thrust forms the base of the allochthon and separates complexly deformed strata above from more simply deformed strata below. Several sets of structural observations argue for the allochthonous nature of the Iron River syncline, the principal argument being that the syncline has a folding history and fold geometry more complex than surrounding, and presumably underlying rocks. It must therefore have acquired some aspect of its structure either as a geographically separated terrane or during thin-skinned emplacement over the footwall rocks.

Structures in the allochthon

Studies of outcrops of the Paint River Group show that at least two and probably three or more generations of fold axes occur in the Iron River syncline. Most folds are tight to isoclinal with steeply-plunging axes. Similar steeply-plunging fold axes are common in fault panels within the Niagara fault complex, part of which bounds the syncline on the south, but are rare elsewhere in the foreland. Bedding and axial planar foliation are variably oriented, but generally dip steeply. Remnants of sub-horizontal foliation occur in a few places suggesting that recumbent folds may have been significant during early stages of folding. A cross section (James and others, 1968) from iron mine workings at the west end of the Iron River syncline near Staumbaugh, Michigan shows a recumbent fold that is only moderately overprinted by steeply-dipping structures.

The Badwater Greenstone, although largely massive, does contain structures similar to those shown in the Paint River Group and appears to have the same structural history. The Badwater Greenstone is therefore considered part of the allochthon.

Structures in rocks surrounding the Iron River syncline

Rocks within the Niagara fault complex, south of the syncline, have northwest-striking, steeply south-dipping foliation and tight to isoclinal folds that are steeply plunging, like those within the syncline. Structures in Baraga Group rocks (primarily Michigamme Formation), which bound the syncline on the north and east, are much different and generally have west-northwest-striking foliation that dips moderately to steeply south, and horizontal to sub-horizontal fold axes that trend west-northwest. Such sub-horizontal, west-trending fold axes are rare in the Iron River syncline. Several areas of first generation recumbent folding with sub-horizontal axial planar foliation have been found over the past several years within the Baraga Group rocks, suggesting the formation of nappes. Most recently, small recumbent folds with sub-horizontal foliation have been documented near Watersmeet, Michigan, northwest of the Iron River syncline. Together with previous observations of similar structures north and east of the Iron River syncline, there is now widespread evidence of an early phase of recumbent folding and generation of low angle axial planar foliation, now variably overprinted by more upright structures.

Interpretation

Recumbent folds documented by underground mapping in the Iron River syncline (James and others, 1968) and remnants of flat-lying foliation found in outcrops of the Paint River Group suggest that both the Iron River syncline and adjacent Baraga Group had a similar early structural history of recumbent folding and development of low angle foliation. However, multiple generations of steeply-plunging fold axes and steeply-dipping, variably-oriented axial planar foliations of the Iron River syncline, are distinct from the gently west-plunging fold axes with south-dipping axial planar foliation found in the Michigamme Formation north and east of the syncline. Similar steeply plunging fold axes are common in very highly strained rocks along the Niagara Fault and seem clearly to be integral to events related to suturing of the volcanic terranes south of the fault. This suggests that the Iron River syncline was detached from underlying rocks during much of its folding history. The base of the allochthon is interpreted to be a thrust fault along the base of the Badwater Greenstone, along which the allochthon has been thrust northward over foreland basin turbidite deposits of the Michigamme Formation. We suggest that the unusual complexity of folding within the Iron River syncline is a result of thrusting of earlier deformed rocks northward from the suture zone. During this thrusting, an earlier set of recumbent folds was intensely reformed. In contrast, rocks in the structural footwall were little deformed as shown by the fact that the Iron River syncline cross-cuts the west-trending, sub-horizontal fold axes in the adjacent Michigamme Formation.

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REGIONAL PATTERNS ON THE PENOKEAN CONTINENTAL MARGIN IN THE SOUTHERN LAKE SUPERIOR REGION

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Studies of outcrops and exploration drill cores during the past decade reveal several regional patterns in the deposition and subsequent deformation and metamorphism of the Early Proterozoic Penokean continental margin rocks in northern Wisconsin and northern Michigan. These data help constrain models of the depositional and tectonic history of the region.

I. Regional depositional patterns.

A. Thinning westward of the basal arenite of the Chocoley Group. The Mesnard and Sturgeon Formations are prominent arenite units in the Marquette and Menominee districts, respectively, and the Sunday Quartzite forms a thin basal unit on the eastern Gogebic range. However, a basal arenite is absent on the western Gogebic range, where the dolomite unit characteristic of the upper part of the Chocoley Group rests directly on Archean basement. Drill core data from the Park Falls - Mercer area of northern Wisconsin suggests that this pattern extends southward toward the proposed continental margin.

B. An increase in pelitic rocks southward toward the proposed continental margin. Drill cores from the Park Falls - Mercer area intersect abundant pelitic schists, some of which contain interbedded carbonate units. Bedded sulfides are present locally within the pelitic rocks. The stratigraphic position of the pelitic units has not been ascertained, but they may be broadly correlative with the Chocoley Group (Cannon and others, 1998).

C. A consistent pattern of lithologies within the Palms formation of the Menominee Group throughout the Penokean platform. The thin-bedded argillaceous lower member and the thick-bedded orthoquartzite upper member are recognizable from the Marenisco area westward to Lake Namekagon. These members are also recognizable in drill cores from the Pine Lake Subterranean (Cannon and others, 1998) from the Lake Gogebic area southwestward at least to the Butternut, WI area, suggesting a uniform platformal depositional environment.

D. Rift-related volcanic rocks (Sims and others, 1989) are associated with iron-formation of the Menominee Group on the proposed shelf. The Emperor Volcanics are interbedded with iron-formation on the eastern Gogebic (LaBerge and Klasner, 1994), and volcanics are present within the iron-formation on the western end of the Gogebic (LaBerge and others, 1995). Volcanic rocks as well as carbonaceous sediments are associated with iron-formation south of the Gogebic range in a belt that extends from near Lake Gogebic southwestward at least to the Butternut, Wisconsin area, (LaBerge, 1997). This suggests that rifting, with associated volcanism and stagnant basin development, occurred after deposition of the Palms Formation on the continental margin. On the main Gogebic range, then, the iron-formation accumulated on a shallow platform bounded on the east, south and west by rift basins with active volcanism.

II. Regional deformation/metamorphic patterns.

A. Metamorphism of continent margin sediments that increases in intensity southward associated with intense folding and north-directed thrusting. A zone of high pressure metamorphism characterized by kyanite and a high temperature zone

characterized by sillimanite (the Powell Subterranean and the Park Falls Subterranean, respectively of Cannon and others, 1998).

B. Emplacement of post-tectonic potassic, commonly pegmatitic, granites, some of which are two-mica granites, or which contain sillimanite or garnet, typical of anatectic granites.

C. A later deformational event with associated retrograde metamorphism. This is expressed as widespread alteration of high grade minerals such as sillimanite and olivine (in carbonate rocks) to pyrophyllite and serpentine, respectively. This deformation has locally affected the post-tectonic granites associated with the earlier deformation.

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A GEOCHEMICAL AND PETROLOGIC STUDY TO DETERMINE THE ORIGIN OF
THE CROWDUCK LAKE GROUP, KENORA, ONTARIO: A PROBLEMATIC
METACONGLOMERATE.

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The Crowduck Lake Group is a sequence of argillite and a poorly sorted conglomerate (Archean ? age) exposed near Kenora, Ontario. Smith (1988) suggested that the Crowduck Lake Group may be a debris flow deposit, however lithology and geographic location suggest that it may be a correlative of the "Gowganda tillites" (polymictic conglomerates deposited during the Gowganda glaciation 1.8 billion years ago). The goal of this study is to determine if the Crowduck Lake Group is glacial in origin.

Extensive research has been done on the deposits of the Gowganda Glaciation (Summarized by Young 1969, 1973, 1999). Outcrops of the Gowganda are located in Chibougamau, Quebec, Wyoming, and Northern Michigan. Geochemical analysis indicate that there are broad similarities in diamictite constituents. Additionally, Chemical Index Alteration studies provide evidence of regionally cold climatic conditions (Young, 1999). Young (1969), on the basis of outcrop distribution, suggests that elsewhere in Canada there are polymictic conglomerates which on detailed analysis may well turn out to be tillites.

For this study an outcrop at the type locality of the Crowduck Lake Group was described and sampled. Hand samples were analyzed for sedimentary structures, clast provenance and clast shape. Geochemistry of matrix samples was determined using ICP. Thin sections of matrix were used for petrographic analysis.

Geochemistry of the Crowduck Lake Group is similar to that of the type Gowganda Formation of Ontario. However, interpretation of these results is restricted because little is known about the geochemistry of the bedrock at the time of deposition. Additionally, the age of the Crowduck Lake Group is poorly constrained. Thus, several possible origins of the Crowduck Lake Group remain plausible: glacial tillite, turbidite/debris flow, and basal conglomerate. Although the sedimentology, location and age of the Crowduck Lake Group make a glacial origin attractive, evidence is not conclusive. Additional petrographic analysis are underway.

THE GRATIOT CHALCOCITE DEPOSIT, KEWEENAW PENINSULA, MICHIGAN

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ABSTRACT

Michigan's Keweenaw Peninsula is well known for world-class native copper deposits and the lack of significant amounts of copper sulfides. Twelve copper sulfide (chalcocite-dominated) deposits have been discovered in the Keweenaw Peninsula. Robertson (1975) described one small deposit near Mt. Bohemia. Chalcocite-dominated deposits are concentrated in the lower quarter of the Portage Lake Volcanics from Suffolk to Mt. Bohemia (Figure 1). The Gratiot chalcocite deposit (previously termed 543-S) is the largest of the copper sulfide dominated deposits and contains about 4.5 million metric tons of ore with an average grade of 2.3% copper.

The Gratiot chalcocite deposit is hosted by the Portage Lake Volcanics and is about 1.4 km from the Keweenaw fault, a major reverse fault of regional extent. In vicinity of the ore, basalt lava flows are cut by two dacite-andesite dikes. These dikes are nearly subparallel to the orientation of the lava flows. Ore grade intercepts occur mostly in brecciated amygdaloidal flow tops, although lesser amounts are found in flow interiors and dikes. The highest grade and tonnage exists where both dikes are present and where both dikes are thick. Faulting and fracturing are most prevalent in rocks where both dikes exist. The deposit is within a 12 km long fault zone, the Gratiot-Suffolk fault, that has a stratigraphic displacement of about 7 meters and is sub-parallel to the attitude of the basalt flows and sub-parallel to the Keweenaw fault. Two other significant faults that cut the deposit are the Cross-Gratiot fault that is roughly perpendicular to the attitude of the basalt flows with a stratigraphic displacement of about 15 meters and the Gratiot fault that is sub-parallel to the attitude of the basalt flows with very little stratigraphic displacement. The highest grades are associated with the intersection of the Gratiot-Suffolk fault, the Gratiot fault and the Cross-Gratiot fault.

A suite of secondary hydrothermal minerals fill amygdules and fractures within the basalt lava flows and dikes. Chlorite was the earliest secondary mineral, followed by epidote, potassium feldspar, native copper and native silver, prehnite and quartz and calcite (approximate order). Deposition of pyrite clearly follows native copper and was itself followed by chalcopyrite, bornite, chalcocite and hematite. The last phase of secondary mineral deposition was adularia, laumontite and more calcite. Chalcocite is by far the major copper-bearing mineral in the Gratiot deposit, other copper-bearing minerals are trace to rare in occurrence. The relative age of mineral deposition in the Gratiot deposit matches the relative age of mineral deposition in the large native copper deposits in the Keweenaw Peninsula. Butler and Burbank (1929) documented an early suite of minerals associated with native copper followed by chalcocite and then late adularia, laumontite and calcite. Native copper in the Keweenaw Peninsula is interpreted to be temporally and genetically related to compressional tectonics that produced reverse motion along the Keweenaw fault (Bornhorst, 1997). The close temporal relationship of native copper and chalcocite in the Gratiot deposit suggests that chalcocite is also related to compressional tectonics. Native copper ore-depositing fluids are interpreted as very sulfur poor and derived from basalts within the rift (Bornhorst, 1997). Chalcocite ore fluids must

have carried more sulfur than native copper fluids. However, the genesis of fluids generating the chalcocite deposits is currently speculative.

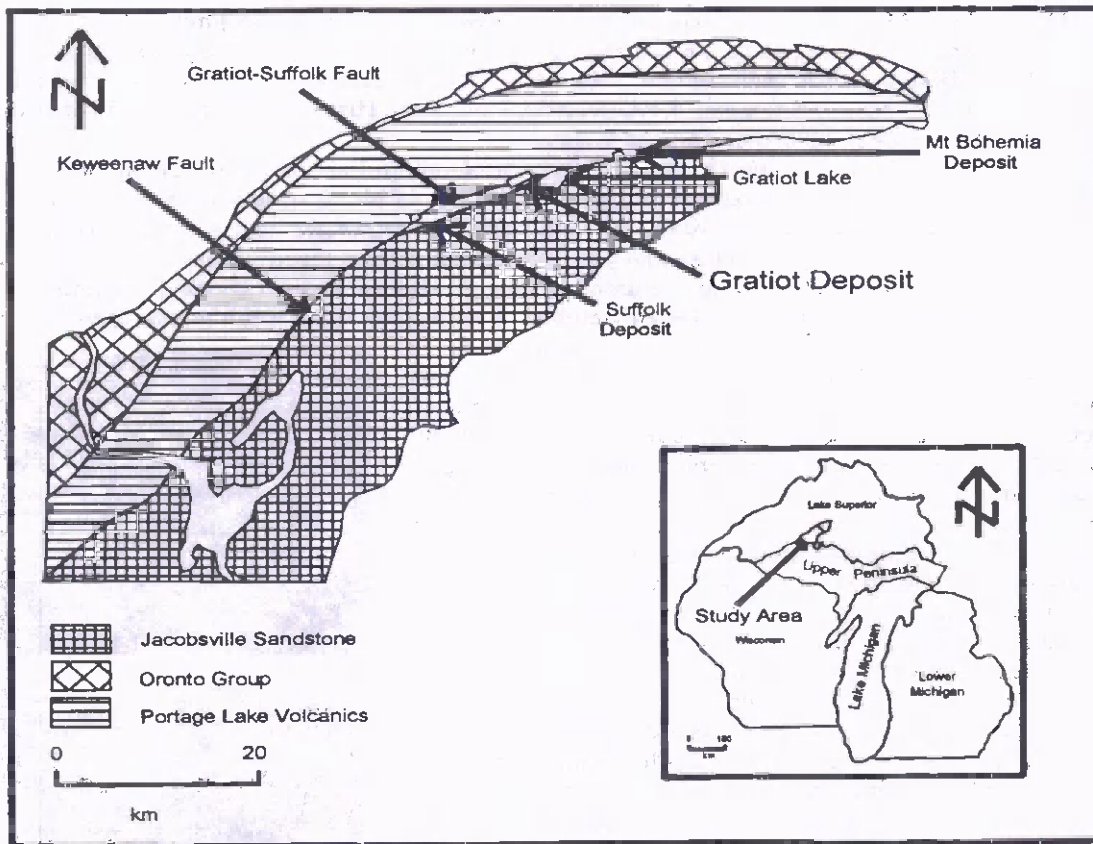


FIGURE 1: LOCATION OF COPPER SULFIDE DEPOSITS

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CHEMICAL AND MINERALOGICAL COMPARISON OF BARABOO, BARRON, AND SIOUX ARGILLITE, METAPELITE AND PIPESTONE

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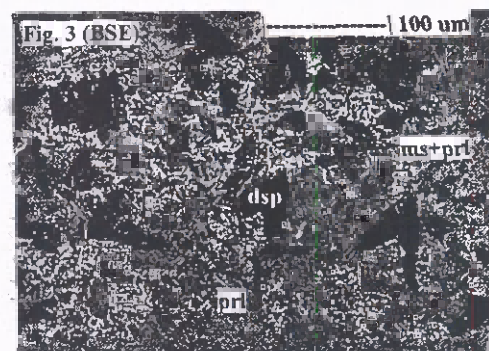
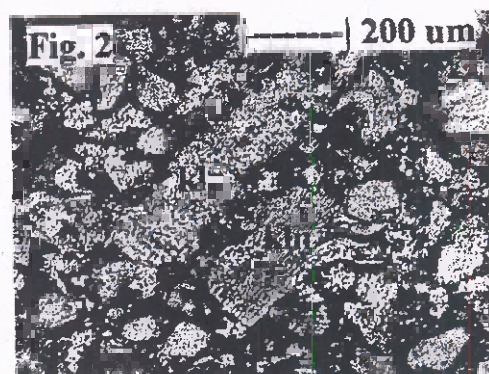
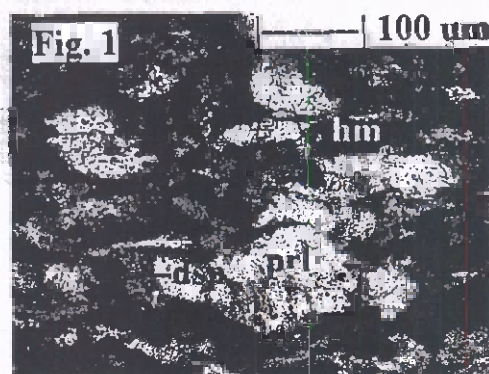
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Early Proterozoic (1760-1630 Ma) red quartzites in the southern Lake Superior region place important constraints on the climatic, sedimentary, and tectonic history of North America, and fine-grained sedimentary and hydrothermally altered rocks in the quartzite sequences have provided material for Native American artifacts. Although argillites and pipestones from several localities have been investigated previously by X-ray diffraction, little attention has been paid so far to their chemical compositions and textural details. Representative samples of Baraboo, Barron, and Sioux argillite, metapelite, and pipestone have been investigated by petrographic microscope, XRF, XRD, and EMP to determine their textural characteristics and chemical and mineralogical compositions. Such information provides a basis for evaluating possible regional variations in chemical compositions and metamorphic conditions among the quartzite localities and for determining artifact provenances.

Baraboo: fine-grained metasedimentary layers, several inches to several feet in thickness, are interbedded with quartzite and vary from pink argillite (metasiltstone) to gray phyllonite (metapelite), depending on the proportions of quartz and pyrophyllite. Pipestone occurs in several small pipestone quarries and one outcrop near the base of the quartzite sequence in the south limb of the Baraboo syncline. The pipestone is a dark purplish-red argillite, consisting of quartz, pyrophyllite, and hematite, which is cut by thin white hydrothermal veins containing pyrophyllite, muscovite, and diaspore. In several pipestone samples, argillite itself has been altered to an assemblage of muscovite-pyrophyllite-diaspore-hematite, in which quartz has been replaced largely by pyrophyllite (Fig. 1). Small amounts of kaolinite in the metasedimentary rocks and pipestone are retrograde in origin, replacing pyrophyllite or muscovite.

Barron: four samples of discarded pipestone were collected in the vicinity of a pipestone quarry in the Doyle Forest Unit, Barron County. The pipestone is a massive to laminated red argillite, which contains quartz, hematite, and large vermicular grains of kaolinite (Fig. 2).

Sioux: two samples of pipestone from Pipestone National Monument and one of flaggy argillite from the Jasper quadrangle (sec. 32, T104N, R4W) were provided by David Southwick and Tony Runkel. The pipestone samples are typical catlinite, being fine-grained and deep red in color,



locally with small pale orange-red reduction spots and pale gray elliptical domains. The pipestone mineral assemblage is pyrophyllite-diaspore-muscovite-hematite, and the pale gray elliptical domains are largely pyrophyllite with minor diaspore and muscovite (Fig. 3). Small amounts of kaolinite are retrograde after pyrophyllite and muscovite. The argillite contains quartz, hematite, pyrophyllite, and traces of detrital muscovite.

Chemical Composition Six samples of Baraboo, Barron, and Sioux argillite and metapelite are essentially devoid of Na_2O and CaO and contain less than 0.39 wt% K_2O , attesting to their extreme chemical maturity and contrasting markedly with the composition of average shale (Fig. 4). Relative to argillite and average shale, the K-rich and Si-poor compositions of Baraboo and Sioux pipestones (0.66-5.62 wt% K_2O and 40.90-54.20 wt% SiO_2) indicate that they may have formed from argillite by addition of K and removal of Si through hydrothermal activity. Such a process could account for the replacement of quartz in Baraboo pipestone and suggests that the elliptical pyrophyllite domains in Sioux pipestone may also be the result of quartz replacement.

Metamorphic Conditions: the Barron argillite assemblage, quartz-kaolinite, is limited to temperatures below 300°C at 2 kbar (Fig. 5). The Baraboo and Sioux argillite assemblage, quartz-pyrophyllite, is stable between 300 and 390°C at 2 kbar, and the pipestone assemblage, pyrophyllite-muscovite-diaspore, is more narrowly confined between 315 and 360°C (Fig. 5). The Baraboo and Sioux assemblages cannot be due to burial alone, because depths on the order of 18-19 km would be required to reach 300°C for a typical stable craton conductive geotherm. The age and source of the thermal pulse responsible for Baraboo and Sioux metamorphism remains uncertain. In addition, kaolinite is widely reported in the Sioux Quartzite, and it is unclear whether metamorphism was ubiquitous in the Sioux Quartzite (as it was in the Baraboo quartzite), or restricted to zones of hydrothermal activity, perhaps related to faulting.

Conclusions: the chemical compositions of argillite and metapelite confirm the chemical maturity of all sedimentary members of the Baraboo, Barron, and Sioux sequences, consistent with derivation from a deeply weathered, low-relief source in an Early Proterozoic warm, humid climate. Comparable mineral assemblages in Baraboo and Sioux pipestones demonstrate that the promoting hydrothermal activity does not coincide with the 1630 Ma thermal front in the southern Lake Superior region, postulated by Holm et al. (1998); whether they are contemporaneous remains to be seen. Regarding artifact provenance, Barron pipestone is easily distinguished from Baraboo and Sioux pipestone by the presence of vermicular kaolinite. Comparable mineral assemblages and textures make discrimination between Baraboo and Sioux pipestones more difficult. Baraboo pipestone may contain quartz, is locally cut by thin, white veins, and is dark purplish red in color; Sioux pipestone is devoid of quartz and veins, commonly has reduction spots and conspicuous, small, pale gray, elliptical pyrophyllite-rich domains, and is deep red to orange in color.

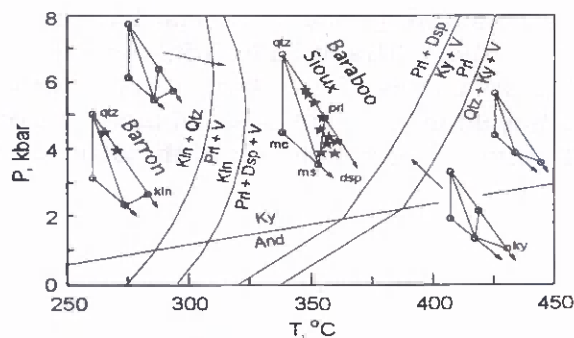
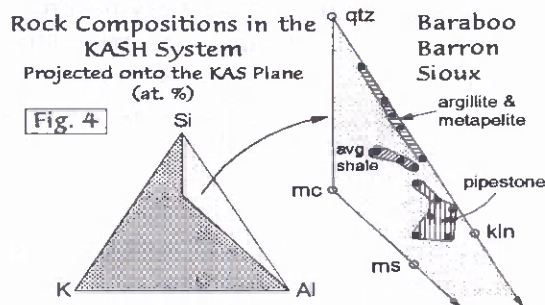


Fig. 5 Reactions in the KASH system and assemblages in Baraboo, Barron, and Sioux rocks

REPUBLIC WETLAND PRESERVE

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**District Manager – Environmental Affairs
Cliffs Mining Services Company**

Iron ore mining, by its very nature, causes large potential impacts to natural resources. Development of mine pits, rock stockpiles and tailings basins impacts wetlands from time to time. Permits to impact wetlands are issued by the Michigan Department of Environmental Quality if the impacts are “unavoidable” and are “minimized to the greatest extent possible”. Each permit requires that “compensatory wetland mitigation” be provided.

The Republic Wetland Preserve is being created at the former Republic Mine tailings basin to provide compensatory wetland mitigation for those unavoidable impacts to wetlands at other mining operations. Instead of merely draining the water from the various tailings and water clarification ponds and converting the land to upland at Republic, Cliffs, with MDEQ oversight, is constructing wetlands in these areas. Several hundred acres of creditable wetland will be created. This wetland area, along with adjacent upland and external preservation area, will be placed in a Conservation Easement for the benefit of the State for long term protection.

POTENTIAL FOR STRATIFORM PGE MINERALIZATION IN MAFIC LAYERED INTRUSIONS OF THE DULUTH COMPLEX

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Economic concentrations of platinum group elements (PGEs) in meter-thick, stratiform, sulfide-bearing horizons (reefs) have long been known to be associated with ultramafic-mafic layered intrusions such as the Bushveld and Stillwater complexes. Recent discoveries of PGE mineralization in the Skaergaard Intrusion and related bodies in Greenland (Bird et al., 1991, 1995; Neilsen and Brooks, 1995; Aranson, et al., 1997; Andersen et al., 1998) have shown that stratiform PGE mineralization can also occur in tholeiitic layered intrusions. The presence of many tholeiitic mafic layered intrusions associated with the 1.1 Ga Midcontinent Rift suggests that the Lake Superior region is fertile ground for exploration of this newly recognized type of PGE mineralization. With the support of the State of Minnesota's Minerals Coordinating Committee the Minnesota Geological Survey has been assessing the potential for stratiform PGE mineralization in two intrusions of the Duluth Complex—the Layered Series at Duluth and the Sonju Lake intrusion (Miller and Ripley, 1996).

Based on empirical observations of PGE mineralization in the Skaergaard and other tholeiitic intrusions, and on theoretical considerations of sulfur and PGE behavior in dynamic, differentiating intrusions, the conditions that favor the formation of PGE-enriched horizons in tholeiitic layered intrusions are:

1. The parent magma is initially sulfide undersaturated.
2. The parent magma has a high initial PGE concentration and/or experiences a considerable amount of fractional crystallization to build up noble metal concentrations prior to sulfide saturation.
3. The initial segregation of sulfide melt is triggered by a process such as magma mixing, decompression, assimilation, or simple differentiation that promotes a large R-factor (silicate/sulfide melt ratio).

These conditions imply that an intrusion that formed from an initially sulfide-undersaturated, tholeiitic parent magma has the best chance for significant PGE mineralization in the mid- to upper-level horizon that marks the first "cumulus arrival" of immiscible sulfide melt. Theoretically, a gabbro cumulate crystallized from a magma saturated in sulfide should contain greater than 400 ppm sulfur (Boudreau and McCallum, 1992). Regardless of how sulfide saturation is triggered, or the way in which sulfide melt arrives at the magma chamber floor, it is likely that the first significant sulfide-saturated melt has the greatest chance of encountering the most PGE-enriched silicate magma. Thus, exploration for a PGE-enriched horizon should attempt to seek out the stratigraphically lowest gabbroic cumulates that contain 400 ppm S or more. The Cu/Pd ratio indicates the effectiveness of the sulfide-saturated melt in scavenging chalcophile metals from the silicate magma. Because Pd is several orders of magnitude more compatible with sulfide melt than Cu, an efficiently scavenged silicate melt should record a significant increase in Cu/Pd after a sulfide-segregation event.

These geochemical criteria were first applied to the Layered Series at Duluth (DLS, Miller, 1998). The DLS is a 3.5- to 4-km-thick, well-differentiated, layered intrusion emplaced into the basal section of comagmatic Keweenawan volcanics in the vicinity of Duluth. The DLS is composed of a unidirectionally differentiated suite of mafic cumulates that grades up from troctolite (Pl+Ol) to gabbro (Pl+Aug+Fe_{ox}+Ol±Ap), and displays a complementary cryptic variation in cumulus mineral compositions. The transition from troctolitic to gabbroic cumulates occurs in an 1-km-thick interval called the cyclic zone wherein Pl+Ol cumulates grade upward to Pl+Aug+Fe_{ox}+Ol cumulates, and regress abruptly back to Pl+Ol cumulates. The cyclic zone is made up of as many as six such macrocycles,

which implies that despite being well-differentiated, the DLS magma system was open to recharge and venting (Miller and Ripley, 1996).

Sulfur concentrations indicate that the DLS was initially sulfide undersaturated and did not reach sulfide saturation until the onset of cyclic zone crystallization. Cu/Pd ratios begin to show irregular though significant increases upsection from the base of the cyclic zone. The irregular increase in Cu/Pd ratios probably reflects the open nature of the DLS system. Interestingly, the anomalous concentrations of sulfur and PGEs occur at macrocycle boundaries, which I interpret to indicate venting and/or recharge events. These observations suggest that a PGE-enriched sulfide reef may exist near the base of cyclic zone, and may correspond to a horizon indicative of open-system perturbations to the DLS magma.

Geochemical studies were recently initiated to study the stratiform PGE potential of the Sonju Lake intrusion (SLI) near Finland, Minnesota. The SLI is a 1-km thick, sheet-like intrusion that was emplaced beneath a granophyre body. It is a completely differentiated intrusion that displays a very regular, unidirectional cumulus paragenesis: $Ol \rightarrow Pl+Ol \rightarrow Pl+Aug+Ol \rightarrow Pl+Aug+Fe_{ox} \rightarrow Pl+Aug+Fe_{ox}+Ol+Ap$. This phase progression and a smooth cryptic variation in mineral composition indicate that the SLI crystallized as an almost closed system. The SLI is the Keweenaw intrusion most similar to the Skaergaard. Geochemical analyses of sulfur and PGEs have not yet been completed for the SLI. Previous analyses included Cu which provides indirect evidence for the abundance of sulfide in the SLI cumulates. The Cu concentration shows a dramatic 5-fold increase (from <100ppm to >500 ppm) at a level above the base of the intrusion approximately equal to 2/3 of its thickness. This change is approximately midway through the $Pl+Aug+Fe_{ox}$ cumulate interval; notably, it is at the equivalent stratigraphic level, and within the same cumulate type as the Platinova reef of the Skaergaard Intrusion (Andersen et al., 1998). I anticipate reporting geochemical analyses for the SLI at the ILSG meeting. They will provide more direct evidence of the potential for a PGE-enriched sulfide-bearing horizon in the upper part of SLI.

In conclusion, these studies suggest that significant PGE mineralization may exist in the medial or upper parts of the DLS and SLI intrusions, as well as in other tholeiitic layered intrusions of the Midcontinent Rift. Moreover, these studies demonstrate that geochemical criteria can be used (1) to evaluate the overall potential for stratiform PGE mineralization in tholeiitic mafic intrusions, and (2) to assist in identification of favorable intervals within individual intrusions. Because potential PGE-mineralized horizons are likely to be meter-scale in thickness, and contain only a few modal percent sulfide, core drilling and systematic geochemical sampling are necessary to confirm their existence.

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NEW GEOLOGIC MAP OF THE CENTRAL DULUTH COMPLEX

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The Minnesota Geological Survey is preparing a new interpretation of the geology of the central part of the Duluth Complex, which will be published as a 1:100,000-scale map this summer. The map will cover a rectangular area of about 1,100 square miles bounded by long. 92°07'30" and 91°15'00" and lat. 47°37'30" and 47°15'00". Both the southeastern corner of the map area, which is anchored to the Lake Superior shoreline near Silver Bay, and the northwestern corner, which covers the basal contact of the Duluth Complex, have adequate bedrock exposure that has been mapped at the scale of 1:24,000 (Miller, 1988; Miller and others, 1993; Severson and Hauck, 1990; Severson and Miller, 1999). However, the intervening area, roughly 90% of the map area, contains little or no bedrock exposure. Geologic interpretations in this area largely depend on evaluation of aeromagnetic and gravity data. Geologic control for the geophysical data is limited to widely and unevenly dispersed drill cores as well as scattered areas of outcrop (Severson, 1995; Chandler and others, 1991; Bonnicksen, 1971).

The bedrock geology of the map area is dominated by intrusive rocks that were emplaced into the lower and medial portions of the largely basaltic North Shore Volcanic Group (NSVG) during the main stages of the Midcontinent Rift magmatism (Paces and Miller, 1993). The intrusive rocks can be grossly subdivided into those belonging to the more plutonic Duluth Complex and those composing the more hypabyssal intrusions of the Beaver Bay Complex. The boundary between two intrusive complexes corresponds to a semi-continuous septa of strongly homfelsed volcanic rocks, locally containing minor intrusions, that trends northeasterly through the middle of the map area (Fig. 1). Large-scale intrusions of differentiated mafic cumulates, gabbroic anorthosites, gabbros, and granophyres compose the Duluth Complex northwest of the volcanic septa. Southeast of the volcanic septa, smaller scale, sheet-like bodies and dikes of mafic cumulate rocks, gabbro, diabase, diorite and granophyre constitute multiple intrusions of the Beaver Bay Complex that were emplaced into higher levels of the volcanic edifice.

A number of intrusive components can be distinguished within the Duluth Complex. The oldest is a structurally complex assemblage of mostly leucogabbroic to anorthositic rocks, small bodies of olivine oxide gabbro, and scattered inclusions of volcanic homfels (collectively termed AGV in Figure 1A). This assemblage corresponds to a very heterogeneous aeromagnetic signature of variable amplitude in the western part of the complex but gives rise to a more subdued signature to the east (upsection). The change may indicate a transition to more consistently anorthositic compositions. Irregular masses of granophyre occur within the eastern part of the AGV, but contact relationships are not exposed in the study area. Aeromagnetic patterns suggest that the subcircular to lensoidal granophyre bodies were emplaced into the AGV, but exposures outside the map area (Boerboom and Miller, 1994) indicate that large granophyre bodies can be older than the anorthositic rocks.

More than half of the Duluth Complex in the map area is composed of six discrete mafic layered intrusions which were emplaced beneath and within the AGV and, in one case, beneath a body of granophyre. The stratiform internal structure of these layered intrusions gives rise to a crudely banded aeromagnetic pattern. Truncations of the patterns imply a general sequence of emplacement and suggest that successive intrusions overplated previous intrusions. Although the igneous stratigraphy of each intrusion is generally poorly known, some notable differences are evident. Apparently, the oldest layered mafic intrusion is the Partridge River intrusion (PRI), which forms the basal contact in the northwestern part of the map area. The preponderance of troctolite in the PRI suggests that it formed by frequent impulses of magma and little internal differentiation. The northeast end of the PRI is truncated by the South Kawishiwi intrusion (SKI). Where it is more completely exposed in the Gabbro Lake quadrangle to the north (Green and others, 1966), the SKI is also dominated by troctolite. At its southern end, the PRI is overplated and ultimately cut out by another intrusive body that is almost entirely unexposed except for a few drill holes along its basal contact and some troctolite emplaced into the AGV hanging wall of the PRI. This intrusion, which we tentatively call the West-central margin intrusion, has a subdued aeromagnetic signature indicative of troctolitic cumulates. The subdued pattern passes upsection into a busy, high-amplitude signature that shows some banding and thus may indicate the presence of upper gabbroic cumulates beneath an AGV roof zone. The Greenwood Lake intrusion (GLI) is a somewhat isolated intrusion that truncates the SKI but otherwise intrudes AGV and granophyre rocks. The GLI is unique in that it contains a complete differentiation sequence that grades from lower troctolite

cumulates to upper oxide gabbro cumulates. The northern extent of the GLI is truncated by the southern margin of the troctolitic Bald Eagle intrusion, apparently the youngest major mafic layered intrusion in the map area. The Osier Lake intrusion is a small, plug-like body of troctolite cored by gabbro cumulates that is known from two drill core and a bull's-eye aeromagnetic signature. It was emplaced entirely into anorthositic rocks of the AGV, and thus, its age relative to other layered intrusions is unknown.

Intrusions of the Beaver Bay Complex occur as several suites of east-dipping, half-saucer-shaped sheets, which produce very distinctive, concentric aeromagnetic anomaly patterns. The largest and earliest intrusive suite is the Cloquet Lake layered series (CLLS), which appears to be a nested set of sheet-like intrusions. It is difficult to accurately determine the compositional variability of the CLLS because it is completely unexposed and penetrated by only a dozen or so drill core. In general, the lower part of the series appears to be composed of at least two differentiated sequences of troctolitic to gabbroic cumulates. The upper part of the series appears to contain more evolved intrusive rocks, including gabbro, ferrodiorite, monzodiorite, and granophyre, as well as an unknown amount of volcanic hornfels. A complex aeromagnetic pattern emanating from the southern margin of the CLLS may be caused by numerous satellite dikes and sheets emplaced into volcanic rocks. The eastern side of the CLLS is cut by another sheet-like body—the Sonju Lake intrusion (SLI). This strongly differentiated mafic layered intrusion is well exposed just to the east of the map area in the Finland quadrangle (Miller and others, 1993) and is capped by ferromonzonitic to granophyric rocks of the Finland granite. Good exposure in the southern Doyle Lake and Silver Bay quadrangles (Miller, 1988; Miller and others, 1993) shows that the Finland granite cuts an early suite of gabbroic to ferromonzonitic rocks of the Lax Lake gabbro. Both the Finland granite and the Lax Lake gabbro may originally have been part of the CLLS but were disassociated from it by the intrusion of the SLI. The youngest intrusions in the map area are the anorthosite-inclusion-bearing dikes and sills of the Beaver River diabase. This intrusive swarm, which is well exposed in the southeastern corner of the map area, is bounded on the west by a prominent dike that feeds into southeast-dipping sheets. The upper parts of these sheets commonly contain ferrogabbroic cumulate bodies, collectively termed the Silver Bay intrusions.

The 1:100,000-scale map of the central Duluth Complex will represent a significant improvement on previous regional geologic maps of the complex. Because this map will be digitally compiled, we intend to revise it periodically as new data become available. An important contribution of this new geologic map is that it will identify many previously unrecognized intrusive bodies that should provide new exploration targets for stratiform PGE deposits.

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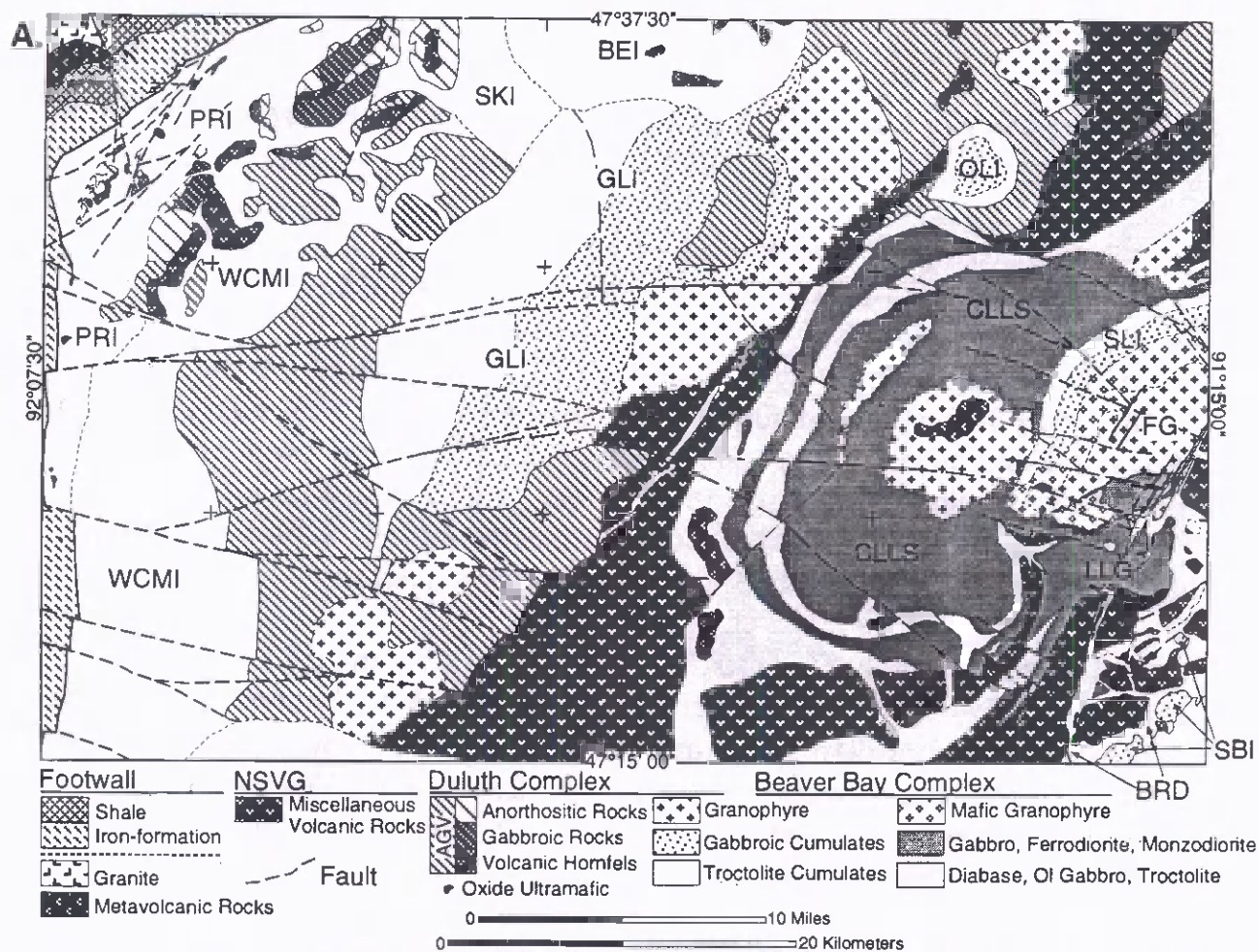


FIGURE 1. A) Preliminary generalized geologic map of the central Duluth Complex. Specific intrusive units are: AGV-Anorthositic-gabbroic-volcanic assemblage (rock types distinguished in the northwest area), PRI-Partidge River intrusion, WCM-West-central margin intrusion, SKI-South Kawishiwi intrusion, GLI-Greenwood Lake intrusion, BEI-Bald Eagle intrusion, OLI-Osier Lake intrusion, CLLS-Cloquet Lake layered series, SLI-Sonju Lake intrusion, FG-Finland granite, LLG-Lax Lake gabbro, BRD-Beaver River diabase, SBI-Silver Bay intrusions. Crosses mark 7.5' quadrangle corners. B) First-vertical-derivative, reduced-to-pole image of aeromagnetic data, which forms basis for the geologic interpretation shown in A.

SEDIMENTOLOGY OF TWO DEEP WELLS IN THE KEEWANAWAN MIDCONTINENT RIFT SYSTEM NEAR MUNISING, UPPER PENINSULA, MICHIGAN

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Amoco Production Company drilled the St. Amour stratigraphic test well in 1987, six miles south-southeast of Munising, MI. The well bottomed at 7,241 ft. Eight miles to the southeast of the St. Amour well, at Hickey Creek, Cliffs Mining Services Company had drilled a 5,345 ft deep well in 1969. These wells are located on the southwest flank of the Midcontinent Rift System (MRS) where the rift starts bending towards the south.

Except for the Pleistocene (110 ft thick in the St. Amour and 88 ft thick in the Hickey Creek), both wells were cored from top to bottom. The youngest bedrock is the Ordovician Au Train Formation, about 280 ft thick in the St. Amour well and 235 ft thick in the Hickey Creek well. The Au Train overlies the Upper Cambrian (?) Munising Formation, a quartz arenite unit that is 135 ft thick in the St. Amour and 310 ft thick in the Hickey Creek.

The Keweenawan rocks in the St. Amour well from the base downward include ≈ 2200 ft of feldspatholithic sandstone ($N=8$: $Q/F/L=72.2/20.7/7.2$) interpreted as Jacobsville Fm.; ≈ 3000 ft of lithofeldspathic sandstone ($N=7$: $Q/F/L=58.1/19.3/22.6$) interpreted as Freda Fm.; ≈ 725 ft of quartz sandstone ($N=4$: $Q/F/L=93.6/1.4/5.0$); 400 ft of basalt flows with interflow black shales and red to brown coarse clastics including conglomerate and lithic sandstone ($N=2$: $Q/F/L=65.0/0.5/34.5$); and 300 ft of dacitic (?) ignimbritic flows.

The Keweenawan rocks in the Hickey Creek well from the base downward include ≈ 1720 ft of dominantly feldspatholithic sandstone ($N=6$: $Q/F/L=78.2/16.7/5.1$) interpreted as Jacobsville Fm. and ≈ 2845 ft of dominantly lithofeldspathic sandstone ($N=9$: $Q/F/L=54.8/19.0/26.3$) interpreted as Freda Fm. The main two types of sand-sized rock fragments in the two wells are metamorphic and felsic volcanic. In the St. Amour well, metamorphic rock fragments (schist and greenstone) are on average twice as abundant as felsic volcanic fragments, whereas in the Hickey Creek well, felsic volcanics are three times as abundant as metamorphic rock fragments. Porosity decreases downward in both wells, with virtually no porosity present below 2750 ft.

The mineralogy in the two wells is quite similar for the upper 5300 ft and the formations, not unexpectedly, correlate well. They also correlate well with Keweenawan outcrops in the Lake Superior region (Ojakangas, 1986; Adamson, 1997). However, the lower portion of the St. Amour does not correlate well with the exposed Bayfield and Oronto Groups. Quartz sandstones occur low in the well, in direct contrast to exposed sections where they are near the top. Quartzose sediments deep in the rift are also present in the Eischeid # 1 well in Iowa (Ludvigson et al, 1990). Clearly, the search for uniformity and correlation where deposition likely occurred in a series of sub-basins (half-grabens) is a tenuous pursuit, as noted earlier by Mauk (1991). Soreghan and Cohen (1993) interpreted relatively quartzose sands (Q to 79%) on hinged margins of modern Lake Tanganyika to be the result of reworking in shallow water. This may be a partial analogue for these quartz sandstones, but eolian activity in the vegetationless Middle Proterozoic terrestrial environment is also likely.

Cliffs Mining Services Company kindly purchased the thin sections.

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EARLY DESCRIPTIONS OF THE NATURAL FEATURES ON THE MARQUETTE IRON RANGE

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The history of the Marquette Iron Range in the upper peninsula of Michigan is integrally linked to the environment. The natural features of the Marquette Range defined the mode of production on the Range, and conversely, as human systems became more adept in these modes of production they became the most important modifiers of the natural systems.

Settlement on the Marquette Iron Range was closely related to two factors of natural environment: the iron ore formations and the hardwood forest. The distribution of three iron ore formations--principally the Negaunee, but also the Bijiki and other Iron-formations within the Michigamme Formation --determined the locations of the sites of extraction of iron ore in the area. Stands of hardwood forest, particularly maple and yellow birch were the major factor determining the location for processing operations that converted iron ore into pig iron. The location of beehive kilns where the hardwood was converted into charcoal, the early forges, and the blast furnaces were reliant foremost on the availability of hardwood. The iron ore formations and the hardwood forest of the Range defined the physical subdivision of the land into tracts owned by individuals. Because a readily available workforce was needed at the mines, forges, kilns, and furnaces of the area, locations of settlement on the Range were within very close proximity to the sites of extraction and processing operations. Transportation, from the earliest trails to the plank road, strap railroad and the Iron Mountain Railroad completed in the 1857 were defined by the natural location of the ore and the processes involved with extracting it.

In the mid 1850's, with advances in transportation associated with the completion of the railroad to the mining areas near Negaunee and Ishpeming and the completion of the Sault Locks near Sault Saint Marie, the production of iron ore reached a level of 11,343 tons per year. By 1868 that number had reached a level of 508,000 tons mined. The depression of 1873 caused a sharp drop in production. However, for the year before the drop one million tons had been withdrawn from 40 pits carved into the ore bodies. In 1880 two million tons were mined and that number rose to seven million tons mined during the year of 1890. The quarrying operations progressed deeper into the earth until by the 1880's shaft mining became a necessity, calling for advancement in technological applications and forcing many of the less wealthy operations out of business. The large amounts of capital involved in diamond drilling exploration, and the operations underground forced industrial consolidation of the many small operations into a few large companies commanding large resources. As mines went underground, the need for timber also increased as supports for the underground workings became a necessity. Between .72 and .92 cubic feet of timber was needed per ton of ore extracted.

In 1868 eleven blast furnaces were in operation on the Marquette Range. Twenty five furnaces total were built in Marquette County. Numerous beehive kilns dotted the countryside. These kilns converted maple, yellow birch and, in some instances, hemlock, pine, and other softwoods into charcoal. The charcoal consumed per ton of iron produced in furnaces varied from 110 bushels to 140 bushels, with a bushel consisting of 20 pounds of charcoal. The Pioneer Furnace, the original blast furnace in the area located in Negaunee, used the timber from 1,500 acres in the year of 1869 to produce 9,500 tons of pig iron. One acre of wood could produce 14 tons of iron. It is estimated that by 1903 thirty acres of hardwood per day was needed to supply the kilns of the Marquette Range. In the first half century of iron production 330,000 acres were cut.

In order to understand more thoroughly how natural and human systems have modified each other on the Marquette Range, the pre-major European settlement natural environment must be

delineated. Beginning in 1838, the Michigan Geological Survey and the Linear Survey of the U.S. Land Office created descriptions of the natural environment of the Marquette Range. These descriptions better enable the understanding of the pre-major settlement natural environment. The descriptions contained within these reports of the location of the original outcrops of iron ore and the stands of trees shows how important these factors were to the early settlement of the Marquette Range. The descriptions also allow us to see how influential that settlement was in modifying the natural systems of the Range.

DEVELOPMENT OF VOLCANOGENIC MASSIVE SULFIDE DEPOSIT EXPLORATION TARGETS IN NORTHERN MINNESOTA FROM GIS SPATIAL ANALYSIS OF GEOLOGICAL, GEOCHEMICAL, AND GEOPHYSICAL CRITERIA

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Volcanogenic massive sulfide (VMS) deposits are syngenetic stratiform iron and base-metal (Cu-Zn-Pb) accumulations that form out of large geothermal systems in subaqueous volcanic environments. At the "bottom" of VMS-producing systems are subvolcanic intrusions, which produce focused heat sources that provide the energy for circulating hydrothermal fluids and leaching reactions, and may add base-metals into the geothermal system. Above the subvolcanic intrusions, the strata have undergone extensive high-temperature alteration, which can include metal depletion, alkali modification, and extensive silicification.

Over the last twenty years, a VMS ore deposit model has been developed from the work of many researchers. Important features of the model include the following:

- VMS deposits are associated with submarine volcanic rocks, and typically are spatially associated with felsic volcanic rocks in greenstone terranes.
- VMS deposits occur with no obvious correlation with age or petrochemistry but do occur in distinct provinces, camps or clusters.
- Deposits often occur at one or more distinctive favorable stratigraphic horizons within a camp. These horizons represent quiescent periods in volcanic activity, tops of volcanic cycles, or a major volcanic-sediment interface. The distal extent of ore horizons may be marked by a siliceous, ferruginous, or a base metal bearing sediment and/or felsic tuff.
- Footwall subvolcanic intrusions are typically sill-like, with irregularly distributed porphyritic and non-porphyritic phases. The intrusions may contain minor porphyry copper occurrences.
- Synvolcanic fault controls are recognized in some deposits, and may control the location of rhyolite domes that occur in the footwall of some deposits. Proximal facies volcanic rocks associated with synvolcanic faults are generally the most favorable horizons for ore deposition.
- Footwall alteration may include a pipe-like zone and/or widespread semi-conformable and cloud-like alteration.
- The massive-sulfide nature of the ore typically makes them conductors of electricity, and therefore can be detected by airborne and ground-based electro-magnetic (EM) surveys.

Many exploration programs for VMS deposits have been based on only one feature of the ore deposit model, specifically, the blind drilling of airborne EM conductors. Although this method of exploration has discovered many major deposits in the past, strictly EM-based VMS exploration has many shortcomings. The drawbacks include any or all of the following:

- Poor geologic control of conductor location
- Poor ranking of conductors in a survey block
- High cost of drilling tens to hundreds of barren or graphitic EM conductors prior to discovery
- Poor rate of discovery (less than 1% of drilled EM conductors lead to mines)

This study formulates a GIS-based exploration model that incorporates all facets of the VMS ore deposit model into a series of digital maps. These maps have ultimately led to the generation of specific VMS exploration targets in the study area of northern Minnesota. The study integrates a new 5880 km² geologic compilation map with mapped alteration zones, over 5400 ground and airborne EM anomalies, and approximately 21,000 copper and zinc assays. Intermediate maps used to predict VMS potential include stratigraphy, heat generation, alteration, Cu-Zn geochemistry, and EM conductors. The methodology used to create the GIS-based model is presented in Figure 1.

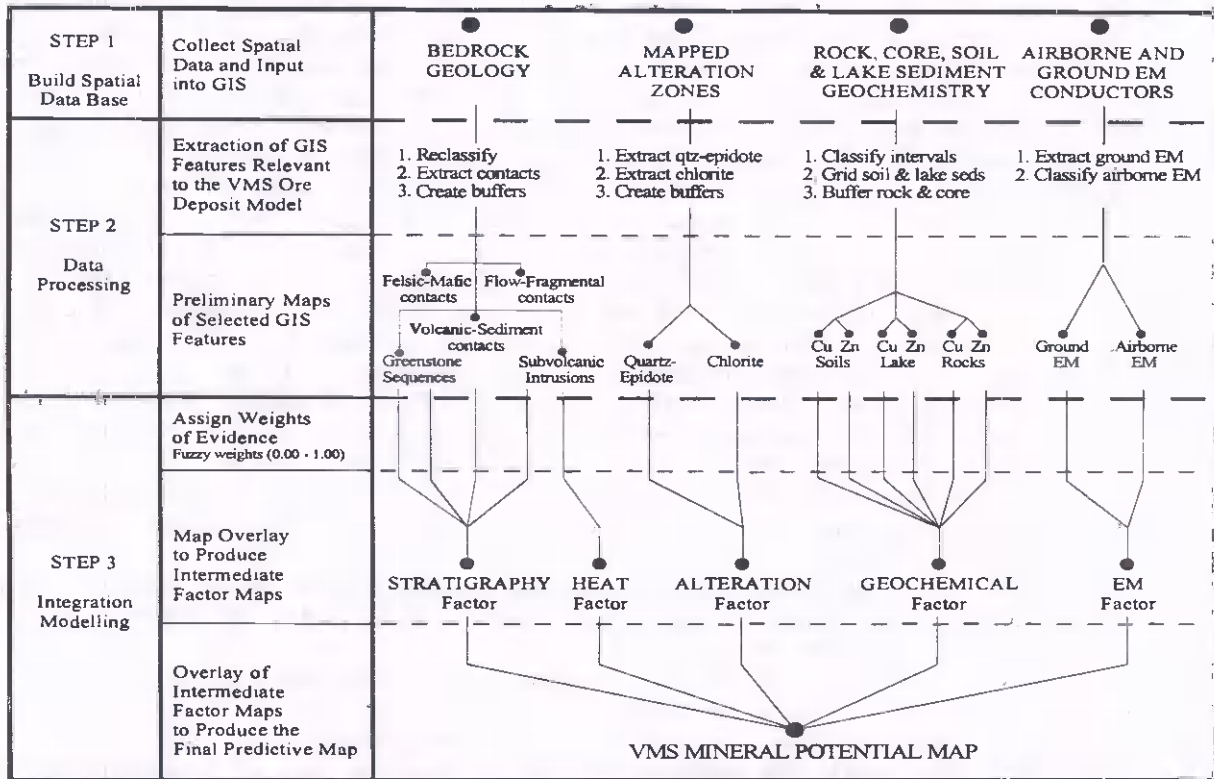


Figure 1. Flowchart for the 3-step GIS modelling of the VMS potential of the Archean Vermilion District and its western extension, northeastern, Minnesota. The three steps in the study are: 1) Detailed geologic mapping and compilation of all available geological, geochemical, and geophysical data. Conversion of all data into primary GIS datasets; 2) Extracting and enhancing the features of the primary datasets that are important for predicting VMS deposits; and 3) Integration of the preliminary maps using GIS modelling techniques that predict mineral potential.

LOW-GRADE METAMORPHISM AND HYDROTHERMAL ALTERATION OF THE UPPER KEWEENAWAN PORTAGE LAKE VOLCANICS, MICHIGAN

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The Portage Lake Volcanics in the Keweenaw Peninsula of Michigan consists of a thick succession of subaerial tholeiitic basalt lava flows with scattered interflow sedimentary layers. These rocks have been subjected to low-grade metamorphic and hydrothermal alteration. The world-class native copper deposits were emplaced during this alteration event. In the Keweenaw Peninsula, and elsewhere, the Portage Lake Volcanics are not widely exposed at the surface because of overlying unconsolidated glacial sediments. However, subsurface drill core were obtained in the Keweenaw Peninsula during exploration for native copper. Much drill core, some over 100 years old, still exists in excellent condition and with original drill core logs and locations. Mr. Gordon Peterson of Calumet owns and continues to maintain much of the existing drill core and allowed us to sample the core for our research. Stoiber and Davidson (1959a, b), in part, used a drill core cross-section to postulate metamorphic zonation within the Portage Lake Volcanics. Four drill core cross sections through the Portage Lake Volcanic have been studied using a combination of microscopic investigation, XRD technique, and electron microprobe analysis, including the drill core section studied by Stoiber & Davidson (1959a, b). These four drill core cross sections are located between Ahmeek and Copper Harbor and provide coverage through 3000m of the Portage Lake Volcanics over a distance of 60 km along strike. Interlayered sediments and selected lava flows can be used as marker horizons to correlate the stratigraphic zones between the different individual drill holes.

Initial results demonstrate that two main mineral associations can be distinguished within the amygdaloidal tops of the basaltic lava flows of the upper part of the Portage Lake Volcanics (above the Greenstone flow) in the Copper Harbor to Ahmeek sections: (1) a zeolite-dominated assemblage with laumontite-chlorite-corrensite±wairakite±quartz±calcite, and (2) a pumpellyite-epidote-dominated assemblage with chlorite±quartz±calcite±prehnite±laumontite. The zeolite-dominated assemblage is more frequent in the upper part of the section, but wairakite occurs only below the Hancock Conglomerate. The pumpellyite-epidote-dominated assemblage is characteristic of the lower part of the sequence. Zeolite minerals are present throughout the whole vertical section. Along strike, a temperature gradient is observed with lower temperature conditions in the Copper Harbor section and higher temperature conditions in the Ahmeek section near Ahmeek to the southwest. This correlates with the distribution of native copper deposits increasing in frequency and size from Copper Harbor towards Ahmeek.

The most abundant phyllosilicates in the upper part of the Portage Lake Volcanics are clinocllore and corrensite. Clinocllore is present in all morphological units of a lava flow, i.e. in the amygdaloidal flow top and in the massive interior, and within all stratigraphic horizons. The mean of the interlayered cations as determined by electron microprobe analysis is around 0.1 indicating only very low mixed-layered components. Corrensite is more abundant in the amygdaloidal flow tops. In the eastern most Copper

Harbor section, smectites (saponite, montmorillonite) as well as paragonite and pyrophyllite are also present in the zeolite-dominated assemblage.

The Portage Lake Volcanics was subjected to a complex metamorphic and hydrothermal alteration event (Stoiber & Davidson, 1959, Bornhorst, 1997). The initial results of this continuing research suggest that the abundant laumontite-chlorite assemblage in most of the upper part of the Portage Lake Volcanics was likely the result of regional zeolite facies metamorphism during burial. The pumpellyite-prehnite-epidote assemblage is likely related to a hydrothermal phase. In the Copper Harbor to Ahmeek section the hydrothermal event occurs only locally, but when present it is pervasive.

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Lake Superior's Rings: Clues to the origin of Polygonal Fault Systems

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Polygonal Fault Systems (PFS) are a recently recognized class of soft-sediment structures. They result from volumetric contraction triggered by syneresis during early compaction of ultra-fine sediments. PFS were first described in Paleogene claystones from the North Sea basin (Cartwright, 1994). In 2D cross-sections, PFS appear as small extensional faults and in map view, the faults have a polygonal appearance. Cartwright and Lonergan (1996) measured the extensional strain and determined that apparent extension on any given horizon was uniform in all directions. They concluded from this that the fault systems could not have a tectonic origin and that the faulting was related to volumetric contraction of sediments during early burial and compaction. From 3D seismic data collected in the North Sea, Cartwright and Dewhurst (1998) identified specific criteria of PFS. These criteria are used to delineate systems in other sedimentary basins. Based on these criteria, PFS are typically close networks of normal faults with small throws that occur over a large area in sedimentary basins. The systems are layer bound and are occasionally tiered. They only occur in very fine-grained sediments (<2 micron). There are no known modern analogues.

Doughnut-shaped rings and subcircular depressions have been observed in the side-scan records collected in Lake Superior (Bergson and Clay, 1973; Johnson et al., 1984; Flood and Johnson, 1984; Flood, 1989; and Anderson, 1997). The described features are 100-300 meters in diameter, 10-30 meters wide and 5 meters deep. Side-scan data collected by the Large Lakes Observatory (LLO) confirms the widespread development of ring structures throughout much of the basin. The rings commonly occur wherever fine-grained glacio-lacustrine sediments are found. High-resolution seismic reflection data collected with boomer and echosounder systems show that the rings are associated with deformation that typically disrupts the thin Holocene surface sediments and glacio-lacustrine sediments below. The echosounder data clearly shows that the underlying glacio-lacustrine exhibits extensive fracturing and small-scale faulting. Some of these fractures and faults continue to the surface where they coincide with a ring or partial ring structure. Many, however, are truncated at the Holocene boundary. Throws on the small faults are often less than 50 cm and the apparent displacement on these faults is typically normal. Some of the echosounder records show evidence of apparently genetically unique deformation sequences in the fine-grained sediments. These sequences are separated by a poorly resolved horizon with little coherent internal reflections. The sequences above and below exhibit well developed internal reflections that do not appear to be concordant. Both systems show well-developed fracture and micro-faulting patterns. This observation suggests that these systems are confined to distinct intervals in the subsurface, and are therefore genetically unique.

It is proposed that the rings in Lake Superior are surface expressions of PFS developed in the near surface clays. A comparison with the criteria outlined by Cartwright and Dewhurst (1998) show that the near-surface sediment and data from Lake Superior meet nearly all of the requirements for PFS development. The seismic data collected thus far indicate that there are basinwide layer bound normal fault systems with small throws. The Lake Superior glacio-lacustrine sediments are characterized by fine grain size, high water content, and a clay fraction composed predominantly of illite.

The following model is proposed to explain the origin of the rings on the floor of Lake Superior. High sedimentation rates associated with the retreat of ice out of the basin produced deposits with high water contents, which behaved like a colloidal fluid. Sometime after deposition, syneresis in the sediments initiated volumetric contraction. This process led to the development of fractures and faulting in the clays. The growth-fault appearance of some of the faults suggests that deformation and faulting was syndepositional and continued for some time. Since many of the fractures and faults truncate against the Holocene boundary, we believe that most of the volumetric contraction ceased before the deposition of the Holocene sediment. Some fractures which continue to the surface appear to act as conduits for the expressed water. This is supported by submersible observations (Flood, 1989) that appear to suggest that water venting from the lake floor removed or prevented the deposition of the fine Holocene material in the vicinity of the ring.

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GEOLOGY OF THE TILDEN MINE, MARQUETTE IRON RANGE, MICHIGAN

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The Tilden Mine produces iron ore from the Negaunee Iron Formation, Menominee Group, Marquette Range Supergroup in the Upper Peninsula of Michigan. As the base of the iron formation is not exposed at the Tilden Mine, the stratigraphic thickness is unknown. The thickness exceeds 1000 feet and is probably underlain by and is gradational into undifferentiated clastics and iron formation of the Empire Mine. The iron ore deposit at the Tilden Mine has been divided into geologic domains based in part on lithology but, more importantly on the metallurgical response based on bench tests and in the processing plant. The interaction of sedimentation and diagenesis within growth fault controlled basin, metamorphism and supergene oxidation has resulted in a complex suite of ore types, each with specific, if not entirely objective, blending characteristics and problems. Production since 1974 has been 126 million long tons of pellets from 355 million long tons of ore at a stripping ratio of 0.94. As of January 1, 1999, the proven and probable long range (30 year) mine plan reserve was 628 million long tons of ore containing 233 million long tons of pellets at a stripping ratio of 0.77.

Chlorite schist defines the footwall of the Tilden ore body. The Martite and main pit Carbonate domains lie stratigraphically below the CDIII Footwall and Main Pit Hanging wall intrusives. This is metallurgically "good ore" and is typically characterized by high weight recovery (35-45+%), low phosphorous, low slime iron and good grinding media. The West Pit/CDIII Hematite domain in the west pit is stratigraphically between the CDIII hanging wall and footwall. In contrast to the martite domain, this is metallurgically 'poor' ore with higher slime iron, phosphorous and poor grinding. Mineralogically and texturally, this domain differs from the martite domain in being dominantly platy hematite with thin (mm scale) chert laminae. The Magnetite domain is the stratigraphically equivalent to the West Pit/CDIII. Mineralogically, the ore consists primarily of magnetite-siderite-chert with variable hematite and silicates. This mineralogy, along with the thin laminations, appears to indicate a restricted basin and a reduced environment of deposition.

There are several igneous horizons at the Tilden Mine. The term 'intrusive' or 'dike' is used for diabasic to porphyritic to aphanitic bodies, which vary from (semi) conformable sill-like horizons, usually interpreted as synsedimentary sills but may be flows, to obviously crosscutting bodies, interpreted as dikes that may be feeders. The sills and majority of the dikes appear to be of early Proterozoic age, related to the Clarksburg Volcanics and/or the Hemlock and Emperor Volcanics, but there are several dikes that are interpreted to be of Keweenaw age based on the magnetic signature.

DYNAMIC AND STATIC STRENGTH OF AGGREGATES: AN ESTIMATE OF RATE SENSITIVITY OF GEOLOGIC MATERIALS

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The Michigan Department of Transportation (MDOT) has initiated research into the dynamic fracture characteristics of aggregates in Portland cement concrete (PCC) pavements. The main focus of this research is to study the fracture and strength characteristics of the coarse aggregate portion in PCC. Due to the wide range of rock types in Michigan, there is a corresponding range of coarse aggregate used PCC. In addition, a significant amount of blast furnace slag is produced and used in PCC. To study the static and dynamic strength of the aggregates, unconfined uniaxial compressive strength of three limestones, four dolomites, two basalts and three blast furnace slags were conducted. In addition, tests were also conducted under dry and saturated conditions. The studies revealed that the slag aggregates exhibited the lowest compressive strength, followed by the limestones and dolomites. The basalt aggregates exhibited the highest compressive strength. The compressive strength data of dry and saturated rocks were found to have a strong correlation to the bulk densities. Both the dry and saturated aggregates revealed a higher compressive strength under dynamic loads compared to the static loads. The percentage increase in dynamic compressive strength over its static strength is identified as a measure of the rate sensitivity of these aggregates, which may have considerable relevance in applications such as rock blasting, underground construction, and geologic interpretation.

The aggregate used in the study were obtained from quarries in Michigan, Ohio and Ontario, while the blast furnace slags were obtained from steel mills in Sault Ste. Marie, Ontario and Detroit, Michigan. The three limestones investigated were from the Fibron Limestone Formation of middle Silurian age (Port Inland Quarry), the Roger City Limestone Formation of middle Devonian age (Presque Isle Quarry), and the Bay Port Limestone of late Mississippian age (Bay County Road Commission Quarry). The dolomites were from the Engadine Dolomite Formation of middle Silurian age (Cedarville Quarry), the Raisin River Dolomite Formation of late Silurian age (France Stone Quarry), the Lucas Dolomite Formation of middle Devonian age (Rockwood Quarry), and a stratigraphically later dolomite from the Lucas Formation (Denniston Quarry). The igneous rocks tested were from the Portage Lake Volcanics (Moyle Quarry) and the Paleoproterozoic volcanics near Bruce Mines, Ontario (Ontario Traprock Quarry).

The aggregates were subjected to uniaxial compressive loads at two different strain rates. Low strain rate experiments (static) were conducted on a MTS servohydraulic machine and high strain rate experiments (dynamic) were conducted on a modified split Hopkinson pressure bar (MSHPB). The Split Hopkinson pressure bar (also called a Kolsky bar, Kolsky, 1949) technique has been widely used for dynamic testing of materials at high strain rates in the range of 10^1 - 10^4 s⁻¹ (Ravichandran and Subhash, 1995). It consists of a striker bar, an incident bar and a transmission bar, as shown schematically in Figure 1. The specimen to be characterized is placed between the incident and transmission bars. The free end of the incident bar is impacted by the striker bar, which is launched from a gas gun, at a predetermined velocity. The impact generates a compression pulse in the incident bar which travels towards the specimen, subjecting it to the required compressive loading. A part of this pulse is transmitted to the transmitter bar and the rest is reflected back into the incident bar as a tensile pulse. Strain gages are mounted at the center of each bar to measure the magnitude and duration of these stress pulses. Based on one-dimensional calculations, it can be shown that the magnitude of the transmitted pulse gives a measure of the stress to which the specimen is subjected and the magnitude of the reflected wave gives a measure of the strain rate within the specimen.

Integrating the strain rate with respect to time yields the strain in the specimen. Thus, the stress-strain response of a material can be obtained at high strain rates.

A minimum of ten samples were tested for each aggregate type in each condition, e.g. dry, saturated, static, and dynamic conditions. The results of the static and dynamic testing for dry conditions are presented in Figure 2, where the blast furnace slags are identified as sample types 1, 2, and 3; the limestones are sample types 4, 5, and 6; the dolomites are sample types 7 through 10; and the basalt sample types are 11 and 12. In addition, the bulk density of the rock types are also presented. It can be seen from this data that the slags exhibited the lowest strength followed by the limestones and dolomites with the basalts having the highest strength. In addition, it can be seen that there is a good correlation with bulk density. With the partial exception of the slags, all of the materials tested showed an increase in dynamic strength over the static strength, indicating that these materials are rate sensitive.

The blast furnace slag showed relatively low strength both in static testing and dynamic testing. However, it can be seen that the air cooled slag had both low strength and strength in the range of the limestones and dolomites. The two data sets shown for the air cooled slag represent samples from two different blocks of slag material assumed to have been cooled at different rates depending on where it was deposited. The blast furnace slag is formed from the gangue and secondary constituents in iron ore as well as coke residue and limestone and has a chemical composition of CaO , SiO_2 , Al_2O_3 and MgO with trace amounts of sulphur and some alkalis (Smolczyk, 1980). The final structure of the slag depends on the cooling conditions of the molten slag. When it is allowed to cool slowly it forms into a dense crystalline structure with properties similar to rock. When the molten slag is quenched quickly with limited amounts of water, it traps steam in the mass and produces a porous, glassy material with poor mechanical properties. However, when the air cooled slag is formed it also has different rates of cooling depending on its location when deposited for cooling. The molten slag exposed to the atmosphere (top) will cool more quickly than the slag at the bottom of the deposit. The stratification when cooling is clearly observed by a color stratification and the appearance of pores. The test data shows this with a significant increase in strength with test samples from two different blocks from the same deposit, i.e., top and bottom locations.

In the case of the basalts tested, it can be seen that the trap rock basalt has a higher strength than the Portage Lake volcanic basalt. In a simplified framework it is assumed that the cooling rate of the trap rock basalt was longer than the Portage Lake volcanics, which were formed near or at the surface. This is also seen in the crystalline structure of the two basalts, with the trap rock basalt having a more uniform crystalline structure and the Portage Lake volcanics a more inconsistent and random crystalline structure.

The sedimentary limestones and dolomites also show rate sensitivity. It is interesting to note in the limestones that the static strength for the three limestones tested are relatively close, while the dynamic strength are higher. In particular, the Silurian limestone (Port Inland) showed significantly higher rate sensitivity than does the Devonian limestone (Preque Isle) or the Mississippian limestone (Bay County). However, this same trend is not seen in the dolomites. With the exception of the Silurian dolomite (Cedarville) there is an increase in both the static and dynamic strength with geologic age.

Previous research has shown that for a brittle material, the damage evolution under applied compressive loading is intimately related to microcracking at defects such as pores, inclusions, second phase particles, twin grain boundary intersections and triple point grain boundary junctions (Lanford, 1977). However, under dynamic loading conditions above a critical strain rate the rate sensitivity of a material is attributed to the inertia-dominated dynamic crack growth from pre-existing flaws. Thus,

response of a defect to loading is inertia dependent, i.e, the time it takes to overcome the inertia of the microcrack, more defects are loaded in the material leading to higher strength. Therefore, it is speculated that if dynamic loading stresses a larger portion of a material's defects, then it may be possible that geologic mechanism such as formational history, compaction and lithification may be better observed under dynamic fracture testing.

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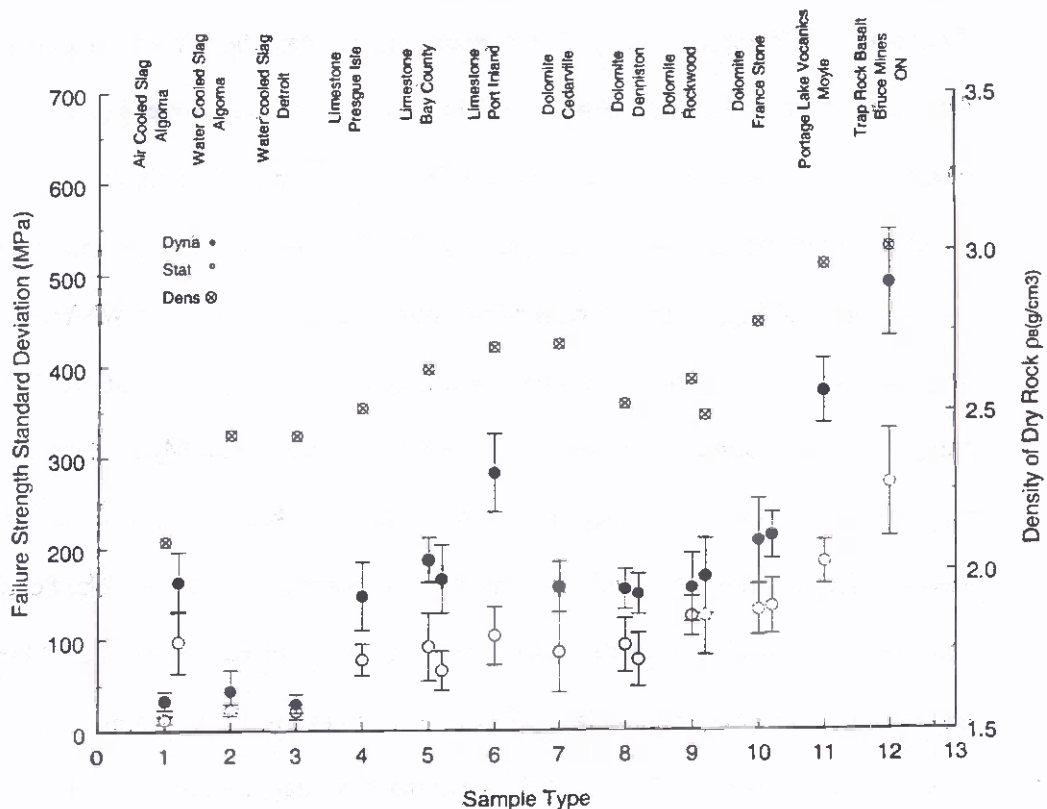
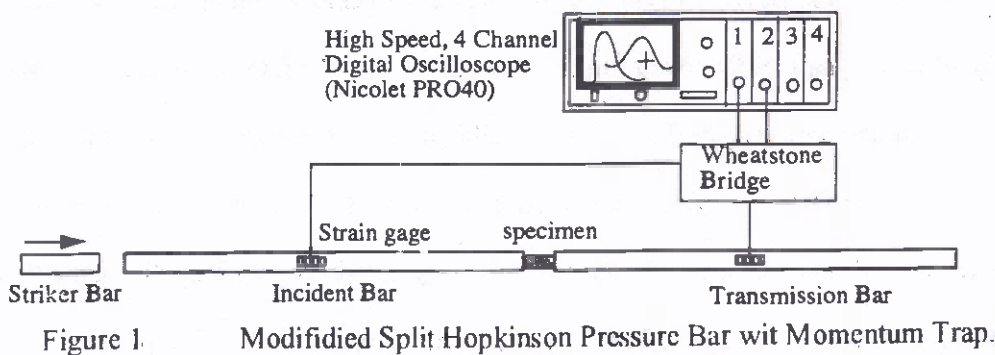


Figure 2 Dynamic and Static Strength Tests in Dry Conditions.

Palmer Gneiss; a large, low-grade shear zone

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The Marquette Trough is interpreted to be an asymmetric rift-related basin; truncated stratigraphy on the southern margin and a rollover structure to the north provides evidence for this interpretation. Marking the southern boundary, between the Archean gneiss and the Early Proterozoic metasedimentary rocks of the Marquette Range Supergroup, is the Palmer Gneiss (PG). Van Hise and Bayley (1897) first interpreted the PG as a comminuted, sericitized and partly silicified phase of the lower Precambrian gneiss. In 1968, Gair and Simmons concurred with their interpretation and offered three possible modes of genesis: (1) alteration and shearing of Precambrian rock during faulting, (2) migration of fluids along the contact between lower and middle Precambrian rocks, and (3) alteration of a regolith during folding. Since the time of mapping by Gair and Simmons, Tilden open pit mining operations have exposed the PG. Large shear bands, with approximately 2.5 meter spacing, indicate the importance of ductile deformation during the formation of the PG in a low-grade shear zone (Figure 1). Foliation measurements show a steep NNE dipping S-foliation being cut by a shallow NNE shear band, indicating a reverse sense of shear (Figure 2). The folds measured in the adjacent iron formation, at the Tilden and Empire mines, consistently plunge gently towards the WNW, reflecting that they were formed under the same strain conditions as the shear zone. The NNE-SSW compressive direction corresponds to previous studies in the area (Myers, 1984). Whole rock chemical analysis of the PG suggests that these altered rocks are not granitic in origin, but rather basaltic. The basaltic nature indicates that the PG is of Proterozoic age. The Penokean Orogeny, collision of an island arc with the Lake Superior Craton, caused closure of the Marquette Trough that reactivated preexisting normal faults and resulted in a reverse dip slip. Strain was concentrated in a portion of a metadiabase sill that was dragged into the shear zone causing

alteration and shearing of the rock to form the PG. A 34% loss of volume is the calculated effect of alteration from the metadiabase protolith to the PG (Gresens, 1967).

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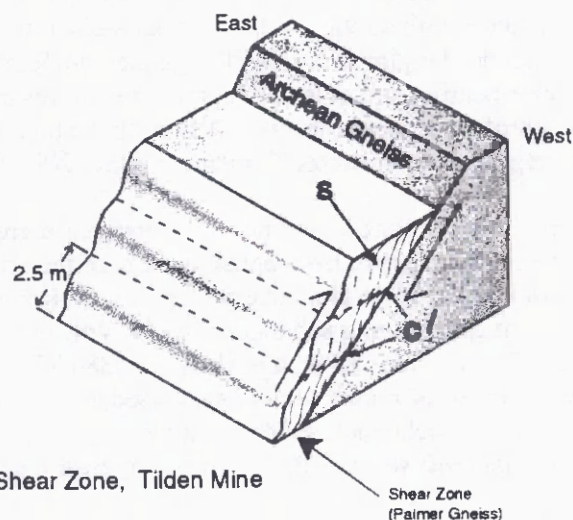


Fig. 1 Footwall Shear Zone, Tilden Mine

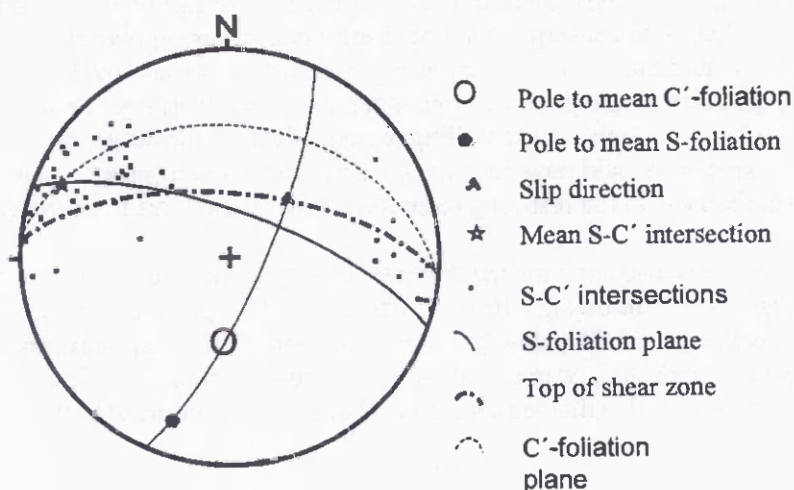


Fig. 2 Stereonet of Footwall Shear Zone, Tilden

IS THE JANICE LAKE UNCONFORMITY A LINK BETWEEN THE HEARNE CRATON AND THE LA RONGE - LYNN LAKE VOLCANIC ARC?

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The Wollaston Domain, a NE-trending, 75 km wide belt of 2076-1860? Ma paragneisses, overlying Archean orthogneisses along the eastern edge of the Hearne Craton in Saskatchewan, is separated from 1910-1875 Ma arc volcanics and sediments of the La Ronge Domain by (a) Archean orthogneisses, poorly known supracrustal rocks, and minor Proterozoic plutons of the Peter Lake Domain, (b) 1855 Ma monzogranite to quartz diorite of the Wathaman Batholith, and (c) the Rottenstone Domain, a migmatitic belt of sediments, similar to those of the La Ronge Domain, intruded by tonalite. The boundary between Wathaman Batholith and Wollaston and Peter Lake domains is the Needle Falls - Parker Lake Shear Zone. While this is a fundamental break between ancient crust to the west and juvenile crust of Trans-Hudson Orogen to the east, there is no evidence that it is a collisional suture.

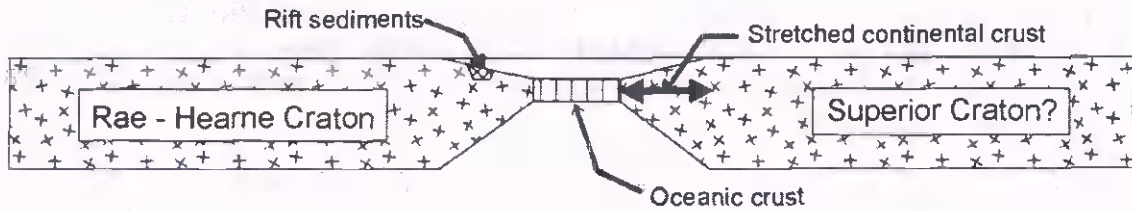
Within the Wollaston supracrustal succession, the Janice Lake Conglomerate, which can be traced discontinuously for 245 km along the eastern margin of the belt, marks a major unconformity. The conglomerate is polymictic, with clasts derived from underlying strata predominating. Locally, it includes fanglomerate. Although the conglomerate cannot be traced westward, younger calc-silicate bearing strata, locally resting on various older lithostratigraphic units, mark the presence of a profound unconformity. A correlative unconformity has been recognized in the Manitoba segment of Wollaston Domain, another 200 km to the northeast.

In the absence of any evidence for thermal uplift (ie. igneous activity), uplift and extension in Janice Lake time must be due to mechanical flexure of the crust. A probable cause is tectonic loading of the eastern margin of the Hearne craton as the La Ronge - Lynn Lake volcanic arc converged towards it over an east-dipping subduction zone. Volcanism in the La Ronge - Lynn Lake arc began about 1910 Ma and reached a peak about 1880 Ma. Following arc-craton collision at about 1860 Ma, the sense of subduction was reversed and the Wathaman Batholith was emplaced at about 1855 Ma. Geochemical evidence suggests that the La Ronge segment of the arc developed in a transitional crust setting, close to or partly over marginal continental crust.

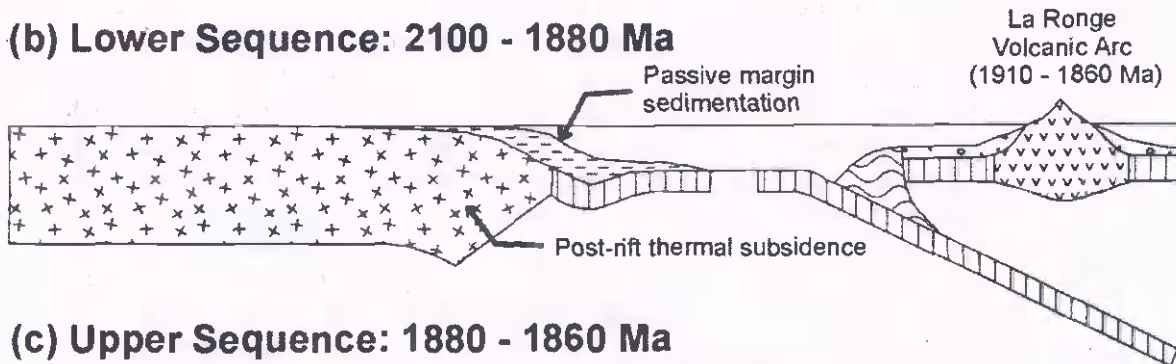
Tectonic loading of the outboard margin of the Hearne Craton would have resulted in an inboard flexural bulge, with consequent normal faulting and erosion over its crest and deposition of coarse clastics on its flanks. As convergence proceeded, the bulge would have migrated cratonward and died out, creating a diachronous regional unconformity. Preservation of coarse clastics would be favoured only on the trailing, eastern flank of the bulge, however. The approaching volcanic arc would have become a barrier to the open ocean, and accumulation of evaporites and carbonates in the resulting restricted basin would have been increasingly favoured.

This hypothesis also explains the dramatic change in sedimentation recorded by the Wollaston paragneisses. Following 2100 Ma rifting, the widespread Lower Sequence of psammopelites, pelites, and feldspathic psammities accumulated on a passive margin. As arc-craton convergence proceeded, coarse clastics were shed off a migrating flexural bulge ahead of the arc. Upper Sequence calc-silicate rich strata subsequently accumulated in the developing foreland basin.

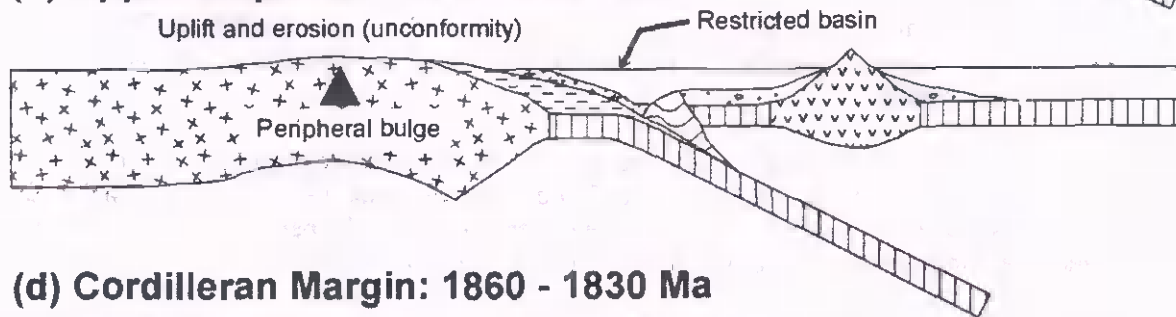
(a) Rift Sequence (Courtenay - Cairns Lake Belt): 2100 Ma



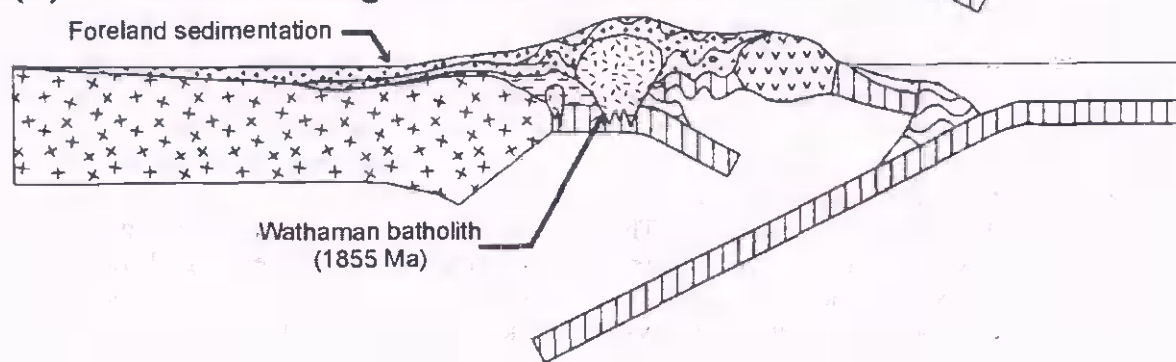
(b) Lower Sequence: 2100 - 1880 Ma



(c) Upper Sequence: 1880 - 1860 Ma



(d) Cordilleran Margin: 1860 - 1830 Ma



Reference

Yeo, G. 1998, A systems tract approach to the stratigraphy of paragneisses in the southeastern Wollaston Domain: Saskatchewan Energy and Mines, Misc. Rep. 98-4, p36-47.

LOW-RESOLUTION SEQUENCE STRATIGRAPHY OF EARLY PROTEROZOIC PARAGNEISSES, WOLLASTON DOMAIN, SASKATCHEWAN

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The Wollaston Domain is a NE-trending, 75 km wide belt of early Proterozoic paragneisses, overlying Archean orthogneisses along the eastern edge of the Hearne Craton; west of the Trans-Hudson Orogen. Bimodal volcanics near the base of the paragneiss succession give a U-Pb zircon age of 2.08 Ga, while minor gabbro and granitic plutons range from 1.81 to 1.84 Ga. A three-year, 1:20,000 scale mapping project was begun in 1997 in the southern part of Wollaston Domain to improve understanding of the stratigraphy and structure of the gneisses, which underlie the unconformity-type uranium deposits of Athabasca Basin. A basic strategy of the project is to map outward from Archean inliers so as to be able to work out the stratigraphic succession in spite of complex deformation and high metamorphic grade.

Four episodes of regional deformation can be distinguished. D1 involved isoclinal folding, local basement overthrusting, and transposition of primary layering into the S1 foliation. D2 involved tight to isoclinal folding about NE-trending axes, superposition of a strong S2 foliation, and local thrust faulting. D3 involved local open folding about SW to NW axes, and local brittle-ductile fault movement. D4 involved minor sinistral offset on a series of N to NNW trending brittle faults.

Two episodes of high T - low P (upper amphibolite - lower granulite facies) metamorphism are associated with D1 and D2 deformation. Peak P-T conditions, reached during D2, were about 750°C and 5 kbar. Along the eastern margin of the belt, however, metamorphic grades are relatively low (upper greenschist - lower amphibolite facies).

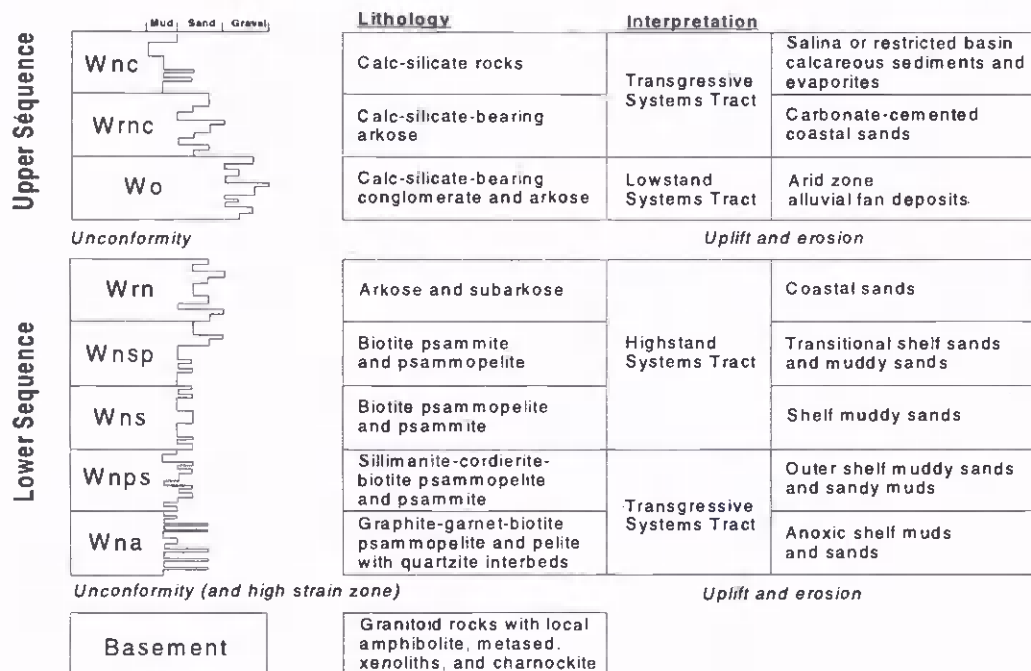
Two widespread paragneiss successions are distinguished in Wollaston Domain: a lower Pelite Unit, and an overlying Psammite Unit. These can be subdivided into at least eight subunits in the Foster - Daly lakes area. Two restricted successions are also recognized: a basal package (Courtenay Lake and Souter Lake Formations), preserved locally along the eastern margin of the domain, and the heterogeneous Hidden Bay Assemblage of interlayered quartzites, pelites, amphibolites, calc-silicates, and marbles, which likely overlies or is correlative with the Psammite Unit near Wollaston Lake. The Courtenay Lake Formation has been demonstrated to be a rift succession, while a passive margin setting is inferred for the overlying Pelite and Psammite units. Attempts to determine the depositional setting of individual lithologic units, however, have been restricted to the low-grade rocks along the eastern margin of the domain.

Although sequence stratigraphy has become a standard technique for analysis of platform and craton margin strata, there have been few attempts to apply it to metamorphosed and deformed rocks. As demonstrated here, it has great potential in interpreting strata in which obliteration of primary features limits application of facies models or comparison with modern sedimentary environments.

Two major sequence boundaries subdivide the succession. The unconformity on Archean basement can be recognized without difficulty. The base of the Janice Lake Conglomerate (Unit Wo) marks a second unconformity. To the west, where the conglomerate is absent, this unconformity corresponds to the base of the calcareous rocks that overlie it. Within each sequence, the mapped lithofacies units can be assigned to a succession of systems tracts.

Lower Sequence: Ferruginous (garnet), anoxic (graphite), muddy sediments of Unit Wna fine upward into aluminous (clay-rich) muddy sediments of Unit Wnps. Such retrogradation is consistent with a transgressive systems tract. The quartzite beds in Unit Wna may be storm-generated flows. Less aluminous muddy sediments of Unit Wns are transitional through Unit Wnsp to Unit Wrm sands. Such a progradational sequence is consistent with a highstand systems tract.

Upper Sequence: Polymict conglomerate of Unit Wo marks a period of uplift and erosion. Most clasts are derived from the underlying sedimentary succession. Although restricted to the eastern margin of Wollaston Domain, the Janice Lake Conglomerate can be traced along strike for at least 245 km. This unit is interpreted as alluvial fan deposits. Non-marine conditions indicate that it is a lowstand systems tract. An upward decrease in clastic input is suggested between calc-silicate bearing Unit Wrnc and calc-silicate rich Unit Wnc. This suggests another transgressive systems tract. The calc-silicate rich rocks may be evaporitic deposits.



References

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