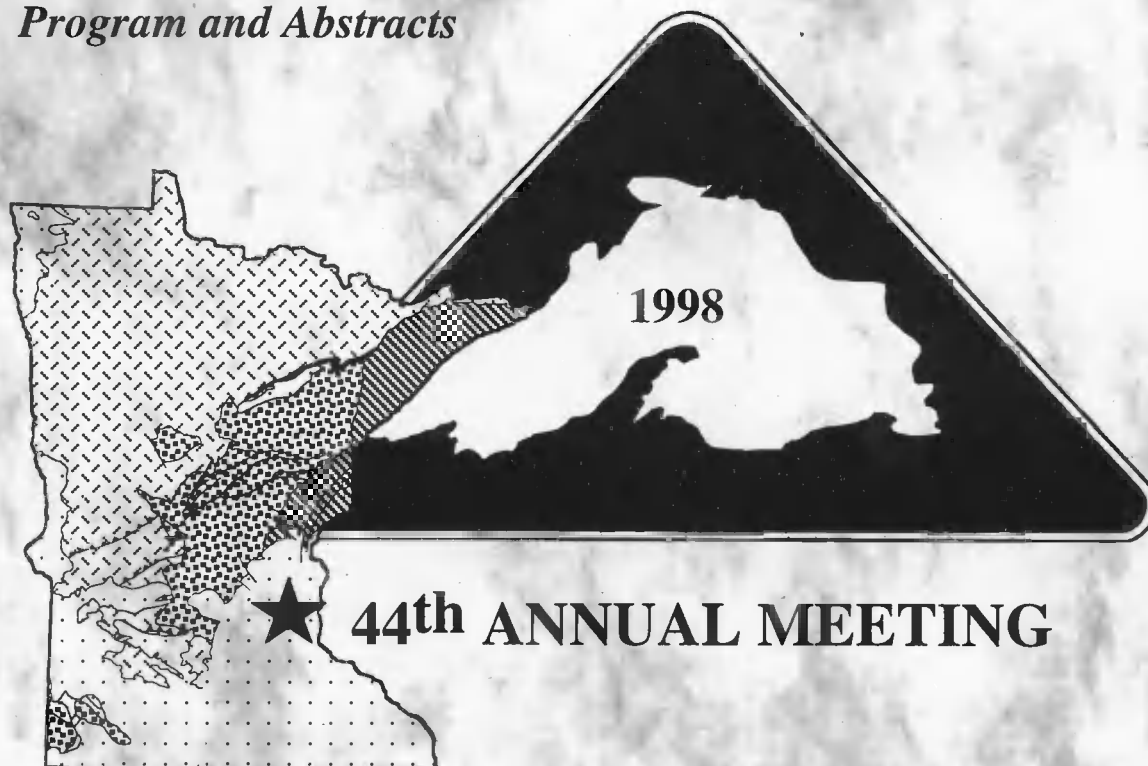


INSTITUTE ON LAKE SUPERIOR GEOLOGY

Program and Abstracts



**Minneapolis, Minnesota
May 6-10, 1998**

Organized by

**MINNESOTA GEOLOGICAL SURVEY
UNIVERSITY OF MINNESOTA**

**PROCEEDINGS VOLUME 44
Part 1—Program and Abstracts**

44th Annual Meeting INSTITUTE ON LAKE SUPERIOR GEOLOGY

Volume 44 contains the following parts:

Part 1: Program and Abstracts

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 Paleozoic rocks of southeastern Minnesota
- 5—Minnesota River Valley and vicinity, southwestern Minnesota

Reference to the material in this volume should follow the example below:

Sims, P.K., Neymark, L.A., Peterman, Z.E., and Kotov, A.B., 1998, Nd isotope evidence for Middle and Early Archean crust in the Wawa subprovince of the Superior Province, Michigan, U.S.A., [abstract]: Institute on Lake Superior Geology Proceedings, 44th Annual Meeting, Minneapolis, MN, 1998; v. 44, Part 1, p. .

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Mark Jirsa (term 1994-2000)
Minnesota Geological Survey
2642 University Avenue
St. Paul, MN USA 55114-1057
(612)-627-4780
email: jirsa001@tc.umn.edu
ILSG website http://www.geo.mtu.edu/great_lakes/ilsg/

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INSTITUTE ON LAKE SUPERIOR GEOLOGY



44th Annual Meeting
May 6-10, 1998
Minneapolis, Minnesota

Sponsored by:
Minnesota Geological Survey
University of Minnesota

PROCEEDINGS

Volume 44

Part 1—Program and Abstracts

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INSTITUTES ON LAKE SUPERIOR GEOLOGY, 1955-1998

#	DATE	PLACE	CHAIRS
1	1955	Minneapolis, Minnesota	C.E. Dutton
2	1956	Houghton, Michigan	A.K. Snelgrove
3	1957	East Lansing, Michigan	B.T. Sandefur
4	1958	Duluth, Minnesota	R.W. Marsden
5	1959	Minneapolis, Minnesota	G.M. Schwartz & C. Craddock
6	1960	Madison, Wisconsin	E.N. Cameron
7	1961	Port Arthur, Ontario	E.G. Pye
8	1962	Houghton, Michigan	A.K. Snelgrove
9	1963	Duluth, Minnesota	H. Lepp
10	1964	Ishpeming, Michigan	A.T. Broderick
11	1965	St. Paul, Minnesota	P.K. Sims & R.K. Hogberg
12	1966	Sault Ste. Marie, Michigan	R.W. White
13	1967	East Lansing, Michigan	W.J. Hinze
14	1968	Superior, Wisconsin	A.B. Dickas
15	1969	Oshkosh, Wisconsin	G.L. LaBerge
16	1970	Thunder Bay, Ontario	M.W. Bartley & E. Mercy
17	1971	Duluth, Minnesota	D.M. Davidson
18	1972	Houghton, Michigan	J. Kalliokoski
19	1973	Madison, Wisconsin	M.E. Ostrom
20	1974	Sault Ste. Marie, Ontario	P.E. Giblin
21	1975	Marquette, Michigan	J.D. Hughes
22	1976	St. Paul, Minnesota	M. Walton
23	1977	Thunder Bay, Ontario	M.M. Kehlenbeck
24	1978	Milwaukee, Wisconsin	G. Mursky
25	1979	Duluth, Minnesota	D.M. Davidson
26	1980	Eau Claire, Wisconsin	P.E. Myers
27	1981	East Lansing, Michigan	W.C. Cambray
28	1982	International Falls, Minnesota	D.L. Southwick
29	1983	Houghton, Michigan	T.J. Bornhorst
30	1984	Wausau, Wisconsin	G.L. LaBerge
31	1985	Kenora, Ontario	C.E. Blackburn
32	1986	Wisconsin Rapids, Wisconsin	J.K. Greenberg
33	1987	Wawa, Ontario	E.D. Frey & R.P. Sage
34	1988	Marquette, Michigan	J. S. Klasner
35	1989	Duluth, Minnesota	J.C. Green
36	1990	Thunder Bay, Ontario	M.M. Kehlenbeck
37	1991	Eau Claire, Wisconsin	P.E. Myers
38	1992	Hurley, Wisconsin	A.B. Dickas
39	1993	Eveleth, Minnesota	D.L. Southwick
40	1994	Houghton, Michigan	T.J. Bornhorst
41	1995	Marathon, Ontario	M.C. Smyk
42	1996	Cable, Wisconsin	L.G. Woodruff
43	1997	Sudbury, Ontario	R.P. Sage, W. Meyer
44	1998	Minneapolis, Minnesota	J.D. Miller, M.A. Jirsa

CONSTITUTION OF THE INSTITUTE ON LAKE SUPERIOR GEOLOGY

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

Article I Name

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

Article II Objectives

The objectives of this organization are:

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

Article III Status

No part of the income of the organization shall 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 within the past three years, and those who indicate interest in being a member according to guidelines approved by the Board of Directors.

Article V Meetings

The organization shall meet once a year, 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 Chairs; but if the board should at any time consist of fewer than five persons, by reason of unwillingness or inability of any of the above persons to serve as directors, the vacancies on the board may be filled by the Chair so as to bring the membership of the board to five members.

Article VII

Officers

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

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

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

Article VIII

Amendments

This constitution may be amended by a majority vote of the membership of the organization.

BY-LAWS OF THE INSTITUTE ON LAKE SUPERIOR GEOLOGY

I. Duties of the Officers and Directors

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

II. Duties and Expenses

- A. There shall be no regular membership dues.
- B. Registration fees for the annual meetings shall be determined by the Chair in consultation with the Board of Directors. The registration fees can include expenses to cover operations outside of the annual meeting as determined by the Board of Directors. It is strongly recommended that registration fees be kept at a minimum to encourage attendance of 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 of the membership of the organization; provided that such modifications shall not conflict with the constitution as presently adopted or subsequently amended.

GOLDICH MEDAL GUIDELINES

(Adopted by the Board of Directors, 1981; amended 1997)

Preamble

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

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

The first award was made by ILSG to Sam Goldich in 1979 for his many contributions to the geology of the region extending over about 50 years. Subsequent 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.

Nominating 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.

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 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

GOLDICH MEDAL COMMITTEE—1997-1998

(Committee membership through the meeting year shown)

Dan England (1998)

Eveleth Fee Office, Eveleth, Minnesota

John Klasner (1999)

Western Illinois University, Macomb, Illinois

Mark Smyk (2000)

Ontario Geological Survey, Thunder Bay

CITATION
Zell E. Peterman
1998 Goldich Medal Recipient

It's my personal pleasure to introduce Zell E. Peterman, this years Goldich medalist. Zell richly deserves this highest honor of the Institute on Lake Superior Geology because of his many outstanding contributions to Precambrian geology and geochronology of the Lake Superior region.

Zell received a Geologic Engineering degree from the Colorado School of Mines, a masters in Geology from the University of Minnesota, Minneapolis, and a Ph.D. in Geology in 1962 from the University of Alberta. At Minnesota, Zell was a student of Sam Goldich.

Zell has spent all of his career—except for the years since 1994—with the Geologic Division of the U.S. Geological Survey, and it was in this capacity that he carried out most of his geochronologic research that we acknowledge today.

Over a period of several years, working with field geologists, Zell has been mainly responsible for the isotopic time framework for the pre-Keweenawan that we accept today.

A major contribution was a study of Archean rocks across the Great Lakes tectonic zone in the Marenisco-Watersmeet area in Michigan. This study established that gneisses in the Minnesota River Valley subprovince are as old as 3,550 Ma and flanking metavolcanic-metasedimentary rocks in the Wawa subprovince (to the north) are in the range 2.6-2.8 Ga. This pattern has proved to be characteristic of Michigan-Wisconsin.

In the late 1980's, in an innovative study utilizing Rb-Sr ages of biotite, Zell outlined the uplift history of the Goodwin Swell in northeastern Wisconsin—a lithospheric flexure caused by crustal loading along the Midcontinent Rift System. This is the sort of thing that has been characteristic of Zell. More than most people, he has the ability to use various geochronologic techniques to solve problems most of us mortals don't know even exist.

Since 1994, Zell has been involved in DOE's Yucca Mountain Project, and some of the successful techniques used to solve projects just blow your mind.

I should mention Zell's administrative duties and skills. From 1971 to 1976, he was branch chief of the USGS's Branch of Isotope Geology, a time when the Isotope Branch was flourishing. Since 1994, he has assembled an isotope hydrology team under the Yucca Mountain Project that is doing many marvelous things, particularly using Rb-Sr tracers.

P.K. Sims

STUDENT TRAVEL AWARDS

The 1986 Board of Directors established the ILSG Student Travel Awards to support student participation at the annual meeting of the Institute. The awards will be made from a special fund set up for this purpose. These awards are intended to help defray some of the direct travel costs of attending Institute meetings, and include a waiver of registration fees, but exclude expenses for meals, lodging, and field trip registration. The number of awards and value are determined by the annual Chair in consultation with the Secretary-Treasurer. Recipients will be announced at the annual banquet.

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

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

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

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.

1998 STUDENT PAPER COMMITTEE

Nancy Nelson—Committee Chair

North Shore Technical Communications

Randy Van Schmus

University of Kansas

Peter Whelan

University of Minnesota—Morris

1998 BOARD OF DIRECTORS

(Board membership through the close of the meeting year shown)

James D. Miller, Jr., Co-chair (2001)

Mark A. Jirsa, Co-chair and Institute Secretary-Treasurer (2000)

Minnesota Geological Survey

Ronald P. Sage (2000)

Ontario Geological Survey—Sudbury, Ontario

Laurel G. Woodruff (1999)

U.S. Geological Survey—Mounds View, Minnesota

Mark C. Smyk (1998)

Ontario Geological Survey—Thunder Bay, Ontario

1998 LOCAL PLANNING COMMITTEE

James D. Miller, Jr.—Co-chair

Mark A. Jirsa—Co-chair and meeting Treasurer

Terrence J. Boerboom—Field Trip Coordinator

Lori Day—Meeting Coordinator

Assistance to the local Committee was provided by the following individuals from the Minnesota Geological Survey:

David L. Southwick

Director of host organization

G.B. Morey

Manuscript review

Alan Knaeble

Field and meeting preparation

Barb Lusardi

Manuscript preparation

1998 SESSION CHAIRS

(In order of appearance)

P.K. Sims

U.S. Geological Survey—Denver

G.B. Morey

Minnesota Geological Survey

Jim Lundy

Minnesota Pollution Control Agency

Laurel Woodruff

U.S. Geological Survey—Mounds View

Rod Johnson

Bitterroot Resources Ltd.

Mark Smyk

Ontario Geological Survey—Thunder Bay

John Green

University of Minnesota—Duluth

Paul Weiblen

University of Minnesota—Twin Cities

1998 BANQUET SPEAKER

Bevan French

Smithsonian Institution

*"When the sky falls: Large meteorite impacts and
the history of earth and other worlds"*

43rd ANNUAL INSTITUTE ON LAKE SUPERIOR GEOLOGY MEETING SUDBURY, ONTARIO

The 43rd annual meeting of the Institute on Lake Superior Geology was held on the campus of Laurentian University in Sudbury, Ontario from May 6, through May 11, 1997. The meeting was organized by the Precambrian Section and the Resident Geologists Office of the Ontario Geological Survey. Ron Sage, Precambrian Section, and Wilf Meyer, Resident Geologist, Sudbury, co-chaired the event. Mrs. Tracy Livingstone, Resident Geologist's Office, helped organize and coordinate all activities relating to the meeting. All the guidebooks and individual abstracts were reviewed by W. Meyer, R.P. Sage, and T. Livingstone.

The Proceedings of the 43rd ILSG were published in 7 parts:

- Part 1: Program and Abstracts* (edited by Ron Sage and Wilf Meyer);
- Part 2: The Huronian Supergroup between Sault Ste. Marie and Elliot Lake: Evidence for the Early Proterozoic atmosphere, climate, and tectonics* (G. Bennett, K.D. Card, and K.Y. Tomlinson);
- Part 3: New information on the Grenville Front near Sudbury* (A. Davidson);
- Part 4: The Sudbury Structure, with emphasis on the Whitewater Group* (S.F.M. Gibbins);
- Part 5: Magmatic ore deposits of the Sudbury Igneous Complex* (S.A. Prevec);
- Part 6: Alkalic rocks of the Sudbury region* (R.P. Sage); and
- Part 7: The greening of Sudbury* (K. Winterhalder).

A total of 101 people registered for the meeting in Sudbury and most of the field trips were well attended. There were 13 paid participants for the Huronian Supergroup field trip, 22 for the Grenville Front, 15 for the Sudbury Structure, 36 for the Magmatic ore deposits, 6 for the Alkalic rocks, and 3 for the greening of Sudbury field trip. Access to local mining sites was granted by INCO Limited and Falconbridge Limited. Coffee breaks were supported by Laurentian University, Falconbridge, and the Ministry of Northern Development and Mines.

The annual banquet was attended by 83 diners and held in the Cavern of Science North on Ramsey Lake. The Goldich Medal was awarded to Ron Sage of the Ontario Geological Survey for his contributions to geology in the Lake Superior region. The award was presented by Wilf Meyer, Resident Geologist, Sudbury, Ministry of Northern Development and Mines. The banquet address was given by Dr. Peter Lightfoot, INCO Limited. The title of the talk was "Origin of the Sudbury Structure and its mineral wealth".

The best Student Paper Award, consisting of \$270 (Can), was won by Craig Mancuso for his paper "Initial results of Ar/Ar mineral dating from the Peevy node area of northern Michigan and Dunbar dome area of northeastern Wisconsin". Zachary Naiman won \$150 for his poster "Petrogenesis of Chengwatana volcanics, Minnesota and Wisconsin". Three student travel awards of \$150 each were granted to Terry Arcuri, Zachary Naiman, and Dean Peterson.

The Board of Directors of the Institute on Lake Superior Geology met in Sudbury on May 8, 1997. Members of the Board in attendance were Mark Smyk, Jim Miller (representing Laurel Woodruff), Mark Jirsa (Secretary-Treasurer), Ted Bornhorst, Ron Sage, and Wilf Meyer. Invited guests were Tracy Livingstone and Gene LaBerge. Actions taken were:

- 1) Accepted the report of the Chair, 42nd ILSG, Laurel Woodruff, including the minutes of the last board meeting.
- 2) Approved an offer by the Minnesota Geological Survey to host the 1998 meeting. Jim Miller and Mark Jirsa will co-chair the meeting. The offer by Charles Blackburn to chair the meeting in Kenora in 1998 had to be withdrawn due to circumstances beyond his control. The 1998 meeting will be held in Minneapolis, Minnesota on May 6-10.
- 3) Approved the 1996-1997 financial report presented by Mark Jirsa.
- 4) Approved Ron Sage as the Goldich Medal winner for 1997.
- 5) Approved the Goldich Medal guidelines prepared by Ken Card.
- 6) Approved the replacement of Ken Card by Mark Smyk on the Goldich Medal Committee.
- 7) Discussed the ILSG newsletter and web site. The newsletter has been well received and will be continued. We may eliminate the annual publication of the Constitution and place a general preamble on the web site (http://www.geo.mtu.edu/great_lakes/ilsg). The web site includes information about the organization and its constitution, award guidelines, list of publications by the Institute and Goldich Medal recipients.
- 8) Approved the membership guidelines for the ILSG prepared by Mark Jirsa and Ted Bornhorst. Mailing list will be revised in an effort to reduce its size and lower mailing costs.
- 9) Discussed the Eisenbrey Fund and action on this fund was tabled for further review. A committee consisting of Gene LaBerge, Mark Jirsa, and Mark Smyk was formed to study and make recommendations on how the monies in the Eisenbrey Fund are to be used. Interest earned from this fund may be used to support student travel to the annual Institute meeting, and corporations and individuals may donate to the fund. Criteria to receive funding from the Eisenbrey Fund need to be established.
- 10) Discussed the ILSG mailing list. Mark Jirsa is to be in charge of the list.
- 11) Discussed US-Canada currency exchange. It was agreed that prices for Canadian meetings should always list a US currency price because many US participants have difficulty obtaining Canadian funds.

Budgeting for the 43rd ILSG was done with an attempt to keep cost down and not lose money. This was successful, in part, due to logistical support provided by the Ontario Geological Survey.

We enjoyed serving as Co-chairs of the 43rd Institute on Lake Superior Geology meeting. Organizing the meeting was a challenge, as the Ontario Geological Survey was going through a difficult period of reorganization, and two of the three individuals planning the meeting received surplusing notices at the height of the planning process. A special thanks is due to Wilf Meyer and Tracy Livingstone for staying with the planning and organization of the meeting while their lives were being upset due to reorganization. Without their efforts, the meeting could not have been organized.

Ronald P. Sage
 Wilf Meyer
 Co-chairs, 43rd ILSG
 Sudbury, Ontario



CALENDAR OF EVENTS AND PROGRAM

WEDNESDAY, MAY 6

0730-0800 **REGISTRATION/PRE-REGISTRATION PACKET PICK-UP**
Holiday Inn Pre-Function Area

0800-1800 **PRE-MEETING FIELD TRIPS**
Depart from: Holiday Inn Pre-Function Area

1) **EARLY PROTEROZOIC INTRUSIVE ROCKS OF EAST-CENTRAL MINNESOTA**

Leaders: Terry Boerboom, Mark Jirsa, and Daniel Holm

2) **GEOLOGY OF THE SOUTHEASTERN PORTION OF THE MIDCONTINENT RIFT SYSTEM, EASTERN MINNESOTA AND WESTERN WISCONSIN**

Leaders: Karl Wirth, Bill Cordua, Bill Kean, Mike Middleton, and Zach Naiman

3) **GLACIAL EXOTICA OF THE TWIN CITIES AREA**

Leaders: Howard Hobbs, Al Knaeble, and Gary Meyer

1600-2200 **REGISTRATION/PRE-REGISTRATION PACKET PICK-UP
PUBLICATIONS FOR SALE**
Holiday Inn Pre-Function Area

1700-2200 **POSTER SET-UP**
Holiday Inn Pre-Function Area

1800-2200 **WELCOMING RECEPTION/POSTER SESSION**
Free Beer and Hors d'oeuvres; Cash Bar
Holiday Inn Pre-Function Area / Aragon Ballroom A-B

THURSDAY, MAY 7

0730-1630 REGISTRATION/PRE-REGISTRATION PACKET PICK-UP
PUBLICATIONS FOR SALE

Holiday Inn Pre-Function Area

0730-0820 COFFEE AND TEA

Holiday Inn Pre-Function Area

SESSION I: GEOLOGICAL OVERVIEW OF THE LAKE SUPERIOR REGION

Aragon Ballroom D-E-F

Session Chairs: P.K. Sims (U.S. Geological Survey)
G.B. Morey (Minnesota Geological Survey)

0820-0830 WELCOME (Jim Miller—Meeting Co-chair, Minnesota Geological Survey)

0830-0900 **Card, Ken D.** (Card and Associates Geosearch)
Archean geology of the Great Lakes region of North America

0900-0930 **Ojakangas, Richard W.** (University of Minnesota—Duluth)
Generalized Early Proterozoic history, Lake Superior region

0930-1000 **Cannon, William F.** (U.S. Geological Survey)
Understanding the Middle Proterozoic history of the Lake Superior region:
What's new? What's next?

1000-1030 COFFEE BREAK AND POSTER SESSION (*Holiday Inn Pre-Function Area*)

1030-1100 **Runkel, Anthony C.** (Minnesota Geological Survey)
Paleozoic rocks in the northern part of the central midcontinent of North America

1100-1130 **Patterson, Carrie J.** (Minnesota Geological Survey)
Models for interpreting the Quaternary history of the Lake Superior region.

1130-1200 **Southwick, David L.** (Minnesota Geological Survey)
What's next for geology in the Lake Superior area?

1200-1400: LUNCH BREAK

ILSG BOARD MEETING (*Grill Room Restaurant, Holiday Inn*)
POSTERS (*Holiday Inn Pre-Function Area*)

SESSION II

Aragon Ballroom D-E-F

Session Chairs: Jim Lundy (Minnesota Pollution Control Agency)
 Laurel Woodruff (U.S. Geological Survey)

1400-1420 **Pfannkuch, H.O., and Paulson, Richard A.**
Improved geologic sensitivity and vulnerability assessments of groundwater pollution potential through application of fuzzy logic

1420-1440 **Campion, Moira**
Ground water recharge, discharge and residence time in Rice County, Minnesota: Implications for land use planning

1440-1500 **Cannon, W.F., Kolker, Alan, and Westjohn, D.B.**
The geological source of arsenic in ground water in southeastern Michigan

1500-1520 COFFEE BREAK AND POSTER SESSION (*Holiday Inn Pre-Function Area*)

1520-1540 **Fralick, P.W., and Kissin, S.A.**
The age and provenance of the Gunflint lapilli tuff

1540-1600 **Medaris, L.G., Jr., and Fournelle, J.H.**
Svanbergite in the Baraboo Quartzite: Significance for diagenetic processes and phosphorus flux in Precambrian oceans

1600-1620 **Medaris, L.G., Jr., Brown, P.B., and Bunge, R.J.**
Post-1.76 low-grade metamorphism of the Baraboo Quartzite

1620-1640 **Mudrey, M.G., Jr.**
Use of high-resolution aeromagnetic data for regional geology investigations, southeastern Wisconsin (Where's the kimberlite!)

1830-1900 **MIXER**(*Holiday Inn Pre-Function Area*)
Cash Bar

1900-2200 **ANNUAL BANQUET AND AWARDS PRESENTATION**
Aragon Ballroom D-E-F

- Announcement of 45th Annual Meeting location
- 1996 Goldich Award presentation to Zell Peterman
- Banquet speaker: **Bevan French**, Smithsonian Institution

"When the sky falls: Large meteorite impacts and the history of Earth and other worlds"

FRIDAY, MAY 8

0730-1200 REGISTRATION/PRE-REGISTRATION PACKET PICK-UP
PUBLICATIONS FOR SALE (coffee and tea 0730-0800)
Holiday Inn Pre-Function Area

SESSION III

Aragon Ballroom D-E-F

Session Chairs: Rod Johnson (Bitterroot Resources Ltd.)
Mark Smyk (Ontario Geological Survey)

- 0820-0840 **Jirsa, Mark A., Boerboom, Terrence J., and Chandler, Val W.**
Geologic setting of subeconomic gold deposits in the Virginia Horn,
northeastern Minnesota: A horn of plenty or a hornswoggle?
- 0840-0900 **Chandler, Val W., Jirsa, Mark A., and Lively, Richard L.**
Gravity and magnetic studies in the Virginia Horn area, northeastern
Minnesota
- 0900-0920 **Saini-Eidukat, Bernhardt, and Bernatchez, Raymond**
Preliminary ore mineralogy of the Herontrack silver-zinc-copper
occurrence, Lumby Lake area, Ontario, Canada
- 0920-0940 ***Salo, R.W., and Kissin, S.A.**
Alteration and metamorphism in an Archean lode gold deposit, Kremzar
mine, Goudreau-Lochalsh gold camp, Ontario
- 0940-1000 **Hudak, George J., Morton, Ron L., and Franklin, James M.**
The recognition of a lava dome complex and its relationship to the Archean
Sturgeon Lake caldera, northwestern Ontario

1000-1020 COFFEE BREAK/FINAL POSTER SESSION
Holiday Inn Pre-Function Area

- 1020-1040 **Sims, P.K., Neymark, L.A., and Peterman, Z.E.**
Nd isotope evidence for Middle and Early Archean crust in the Wawa
Subprovince of the Superior Province, Michigan, USA
- 1040-1100 **Schulz, Klaus J., and Ayuso, Robert A.**
Crustal recycling in the evolution of the Penokean Orogen: Isotopic
evidence for Archean contributions to crustal growth in the Pembine-
Wausau terrane, northern Wisconsin
- 1100-1120 **Holm, Daniel K., Schneider, David, and Coath, Chris D.**
Age and deformation of Early Proterozoic quartzites in the southern Lake
Superior region: Implications for extent of foreland deformation during final
assembly of Laurentia
- 1120-1140 ***Czeck, Dyanna M., and Hudleston, Peter J.**
Kinematic fabrics near Mine Centre, Ontario: Evidence for a modified
transpression model
- 1140-1200 **Corfu, F., and Easton, R.M.**
Extension of the Huronian magmatic suite inside the Grenville Province:
New zircon U-Pb evidence from the Grenville Front Tectonic Zone in Street
Township, Sudbury region, Ontario
- 1200-1400 LUNCH BREAK (posters to be removed; publication sales end)

SESSION IV

Aragon Ballroom D-E-F

Session Chairs: John C. Green (University of Minnesota—Duluth)
Paul W. Weiblen (University of Minnesota—Twin Cities)

1400-1420 **Nicholson, Suzanne W., and Woodruff, Laurel G.**
The Powder Mill Group revisited: Basal volcanic rocks of the Midcontinent Rift System on the south shore of Lake Superior

1420-1440 ***Naiman, Zachary J., and Wirth, Karl R.**
Composition and source(s) of Midcontinent Rift lavas (Chengwatana Volcanics) near Clam Falls, Wisconsin

1440-1500 ***Vislova, Tatiana**
The relevance of the geology of the mid-ocean ridges and ophiolites to the understanding of layered intrusions in the Midcontinent Rift: Part I. Geometry; Part II. Internal structure and petrology

1500-1520 ***Maki, John C., and Bornhorst, Theodore J.**
New field observations of the Clarksburg Volcanics, Upper Peninsula of Michigan

1520-1540 COFFEE BREAK(*Holiday Inn Pre-Function Area*)

1540-1600 **Tikoff, Basil, Bauer, Bob, Vignerese, Jean-Louis, and Haggeman, Nick**
A gravity, magnetic, and structural study of the Wakemup Bay Tonalite, Minnesota

1600-1620 **Myers, Paul E.**
Xenolithologies as indicators of intrusion mechanisms in the Wausau Syenite Complex, Wisconsin

1620-1640 **BEST STUDENT PAPER AWARDS
CLOSING**

1905 **BASEBALL: TWINS vs. YANKEES** (*HHH Metrodome*)

SATURDAY, MAY 9

0800-1800 **POST-MEETING FIELD TRIPS**
Depart from: Holiday Inn Pre-Function Area

4) **STRATIGRAPHY AND HYDROGEOLOGY OF PALEOZOIC ROCKS OF
SOUTHEASTERN MINNESOTA**

Leaders: Tony Runkel and Bob Tipping

5) **MINNESOTA RIVER VALLEY AND VICINITY, SOUTHWESTERN
MINNESOTA**

Leaders: Dave Southwick and Carrie Patterson

SUNDAY, MAY 10

0800-1800 **FIELD TRIP 5, DAY 2**
Returns to Holiday Inn Metrodome

POSTER PRESENTATIONS

1700 hrs. Wednesday, May 6 through 1400 hrs. Friday, May 8

***Abbott, Kathleen M., Thole, Jeffrey T., and Wirth, Karl R.**

Petrography and geochemistry of Midcontinent Rift rhyolite (Chengwatana Volcanics) near Clam Falls, Wisconsin

Bernatchez, Raymond A.

A preliminary detailed geological description of the new high grade silver-base metal discovery in the Lumby Lake metavolcanic belt northeast of Atikokan, Ontario, Canada

Boerboom, Terry, and Oberhelman, Matt

Dimension stone products of Minnesota

Chandler, V.W., Jirsa, M.A., Morey, G.B., and Lawler, T.

Mineral potential assesment of northern St. Louis County, southeastern Koochiching County, and northeastern Itasca County, Minnesota

Cannon, W.F., Laberge, G.L., Klasner, J.S., and Schulz, K.J.

Reinterpretation of the Penokean continental margin in part of northern Wisconsin and Michigan

Cannon, W.F., McRae, M.E., and Nicholson, S.W.

Geographic information system on the geology and copper deposits of the Keweenaw Peninsula

Daniels, D. L., Snyder, S. L., Nicholson, S. W., and Cannon, W.F.

New aeromagnetic surveys in Wisconsin by the U.S. Geological Survey

***Deangelis, M.T., Peck, W.H., and Valley, J.W.**

Polymetamorphism of skarns related to the Morin Anorthosite Complex, Grenville Province, Quebec

***Gramstad, Sally D.**

Pre-Wisconsinan gray till in the Mankato area of the Minnesota River Valley

Han, T.M.

A mineralographic study of magnetite in the Biwabik Iron Formation, Mesabi Range, Minnesota

***Hensel, Erin, *Joslin, Rick, and Lehrmann, Dan**

Facies and depositional environments of the Early Proterozoic Ironwood Iron Formation, Mt. Whittlesey, Wisconsin

Kjerland, Dean W., and Kjerland, Marc

Effects of electric-pulse disaggregation on microfossil-bearing argillaceous limestone of the Middle Ordovician Decorah Shale

- *Loofboro, Jeff, and Holm, Daniel**
Results of modeling Proterozoic thermal histories: Evaluating the possible effects of Wolf River Batholith reheating on thermochronologic data from northern Wisconsin
- Luther, Frank R.**
An Archean subaqueous heterolithic debris flow, Irwin, Pifher, and Meader Townships, Lake Nipigon region, Ontario
- McRae, M.E., Cannon, W.F., and Woodruff, L.G.**
Post-glacial shorelines of Isle Royale - Where are they now?
- McSwiggen, Peter L.**
Electron microprobe study of the Pt-Pd and related mineralization in the Minnamax/Babbitt Cu-Ni deposit
- *Peterson, Dean M., and Morton, Ronald L.**
GIS-based mineral potential analysis for lode-gold and massive sulfide deposits in an Archean terrane of northern Minnesota
- *Rausch, Deborah E., and Wattrus, Nigel J.**
Seismic evidence of pre-Nickerson Quaternary sediments in western Lake Superior
- *Schaper, D., *Suess, W., *Katzner, L., and Kean, W.**
Additional paleomagnetic results for a 1500 Ma mafic dike at Waterloo, Wisconsin
- Schmidt, Susanne Th., and Seifert, Karl**
Metamorphism, hydrothermal alteration, and lateritic weathering of drilled MRS volcanic rocks in Iowa
- Schulz, Klaus J., and Ayuso, Robert A.**
Crustal recycling in the evolution of the Penokean Orogen: isotopic evidence for Archean contributions to crustal growth in the Pembine-Wausau terrane, northern Wisconsin
- *Soofi, M.A., and King, S.D.**
A thin viscous sheet approach to investigate the post-rift evolution of the Midcontinent Rift System under the influence of Grenville Orogeny
- *Thomas, C., Kean, W., and Luther, F.**
Paleomagnetic studies of a Proterozoic porphyritic diabase dike, Pifher and Irwin Townships, Lake Nipigon district, Ontario
- Wirth, Karl R., and Gehrels, George E.**
Precise U-Pb zircon ages of Midcontinent Rift rhyolite (Chengwatana Volcanics), Clam Falls, WI



SPECIAL SESSION:

***Geological Overview
of the
Lake Superior Region***

The 1998 ILSG planning committee asked six leading geologists for a summary of their special subfields of Lake Superior geology, including what's new and what's next.

The following is their response.

ARCHEAN GEOLOGY OF THE GREAT LAKES REGION OF NORTH AMERICA

CARD, K.D., Card and Associates' Geosearch, Kanata, ON, K2K 1M1, email
culau2ag3@aol.com

Archean rocks of the southern Canadian Shield in the Great Lakes region form the world's largest (2 million sq. km.) Archean craton, the Superior Province. These ancient rocks were formed during several major cycles of volcanism, sedimentation, plutonism, and tectonism—mainly in the Lake Archean (2.5-2.8 Ga), but also in the Middle (2.8-3.4 Ga) and Early Archean (>3.4 Ga). Superior Province consists of northern and southern high-grade gneiss subprovinces and a broad central region of alternating granite-greenstone and sedimentary belts (Figure X). Some of the high-grade rocks represent exposures of lower crust of Superior Province uplifted in the Early Proterozoic; others, notably the Minnesota River Valley gneisses, are exotic blocks of Early Archean crust. The volcanic and related plutonic rocks are similar to those of modern island and continental arcs formed along convergent margins. The metasedimentary belts may mark Archean oceans. Middle Archean rocks, including plutonic gneisses approximately 3.0 Ga old are overlain unconformably by ca 2.8 Ga platformal sequences including quartzite, quartz pebble conglomerate and komatiitic volcanic rocks. In contrast, the Late Archean volcanic and sedimentary sequences are mainly juvenile, derived directly from the mantle or from crustal sources less than 200 million years older, and do not have stratigraphic bases; many greenstone belts may be allochthonous.

Superior Province is rich in minerals including copper, zinc, and nickel massive sulfide and lode gold deposits. Most of the mineral deposits occur in the granite-greenstone belts where they were formed in a period of 100 million years or less by processes related to the major volcanism, plutonism, and tectonism that marked the end of the Archean. These processes also led to the formation of a large, stable craton called Kenorland. Kenorland may have been part of a supercontinent—one of the first of Earth's supercontinents. It was broken up in the Early Proterozoic, parts of it migrating westward to Wyoming, and other parts going back to the old country to form the Baltic Shield.

Archean Earth was significantly different from modern Earth in many ways. The Archean atmosphere, for example, lacked free oxygen and was rich in ammonia, carbon dioxide, and methane. Meteorite impacts were much more frequent, and until about 4.0 Ga probably kept the crust well-stirred. This early period of Earth history is called the Hadean, probably with justification. Heat flow was also higher, resulting in a thicker mantle and a volcanically active crust. However, by the Late Archean, the rocks, mineral deposits, and structures being formed and preserved are remarkably similar to those of modern accretionary orogens, notably those around the Pacific Rim. Although currently the subject of debate, it would appear that the Archean Superior Province was formed by subduction-driven orogenic processes similar in most respects to those operating today.

Additional Reviews:

Card, K.D., A review of the Superior Province of the Canadian Shield, a product of Archean accretion: *Precambrian Research*, v. 48, p. 99-156.

Hamilton, W.B., Evolution of Archean mantle and crust, p. 597-614 in Reed, J.C. Jr., Ball, T.T., Farmer, G.L., and Hamilton, W.B., 1993, A broader view, in Reed, J.C.Jr., Bickford, M.E., Houston, R.S., Link, P.K., Ranking, D.W., Sims, P.K., and Van Schmus, W.R., eds., *Precambrian: Conterminous U.S.*, Geological Society of America, The Geology of North America, v. C-2, p.597-636.

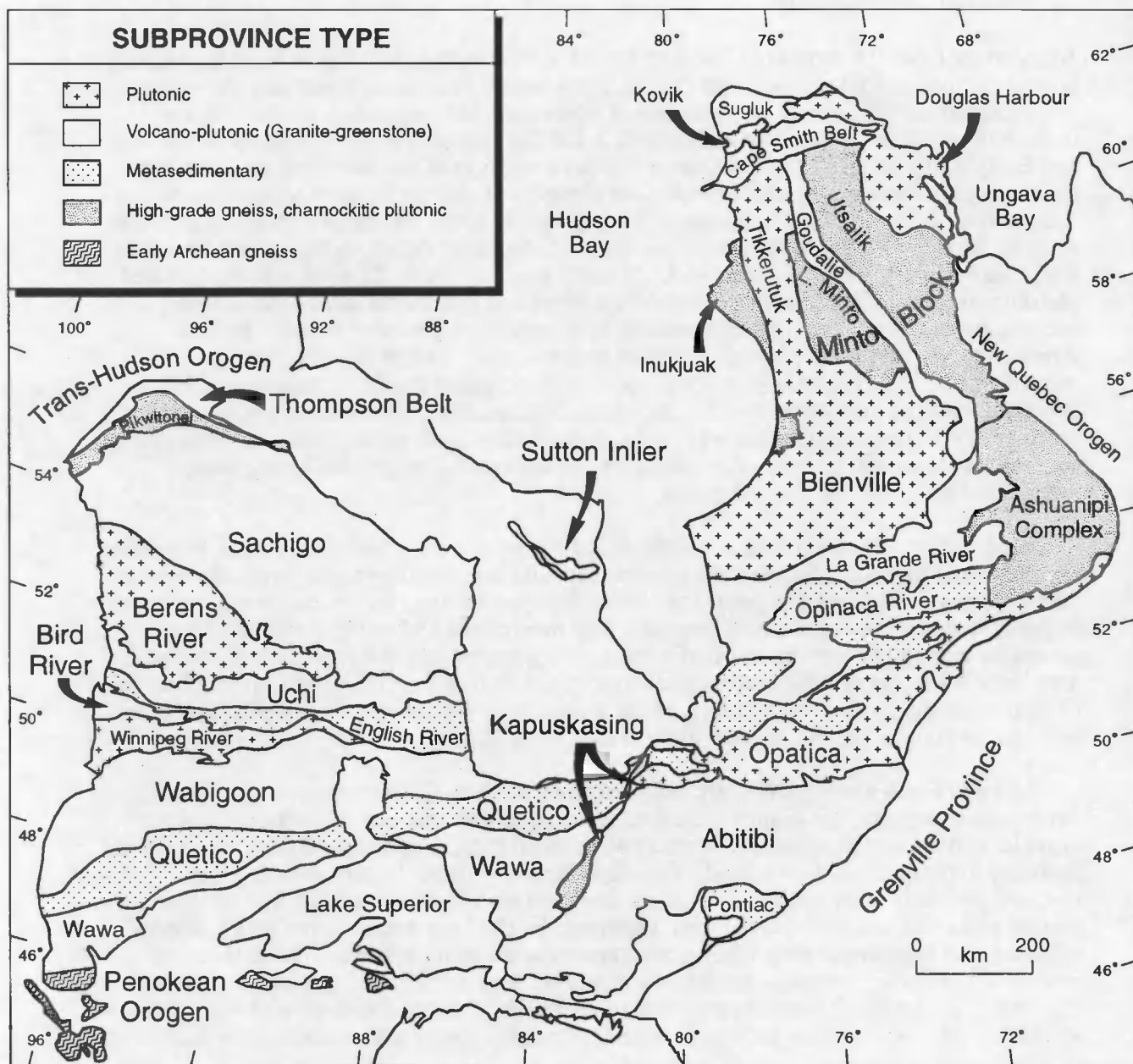


Figure x. Subprovinces of the Superior Province

GENERALIZED EARLY PROTEROZOIC HISTORY, LAKE SUPERIOR REGION

Ojakangas, Richard W., Department of Geology,
University of Minnesota-Duluth, Duluth, MN 55812
rojakang@d.umn.edu

INTRODUCTION

Over the last century, countless geologists have worked to decipher the fascinating Early Proterozoic geological history of this region. Unfortunately, it is impossible in a short review to acknowledge all the important works, but each cited reference contains a bibliography. Two compendiums are especially valuable and include more than 500 and 700 Precambrian references, respectively (Sims et al, 1993; Sims and Carter, 1996). As in any limited review, the bias of the reviewer will be present. The integration of plate tectonic theory permeates this history.

HURONIAN

After the supercontinent of Kenorland was assembled about 2.7 Ga (Card, 1990; Williams et al, 1991) during the Algoman (Keewatin) orogeny, a long period of weathering, erosion, and sedimentation occurred on this stable and thick crustal platform. The oldest sedimentary sequence, the Huronian Supergroup, was deposited between 2.45 Ga and 2.2 Ga, mainly north of Lake Huron. As thick as 12 km and thinning northward, this is a sequence quite unlike Archean sequences in that it contains "uncommon" glacial deposits, paleosols, carbonates, and abundant arkosic to quartzose sandstones. An upper part of this supergroup is a sequence, from the bottom up, of glaciogenic rocks, paleosol, quartz sandstone, and carbonate rocks with sabkha minerals (evaporites). A similar sequence is present as erosional remnants in the Upper Peninsula of Michigan, 200 km to the west (Chocolay Group, Marquette Range Supergroup). An even more complete similar sequence is found in southeastern Wyoming, the Snowy Pass Supergroup. The glacial units of these three sequences were first interpreted by Young (1970) as remnants of a major continental glaciation, and additional work (e.g., Ojakangas, 1984, 1985, 1988) further strengthens this idea. As an interesting aside, Williams and Schmidt (1997) stated that paleomagnetic data indicate that this Huronian glaciation occurred within 4-11° of the equator. Further evidence of the correlation of these three sequences was provided by Bekker and Karhu (1996) and Bekker (1998), who found similar high values of ¹³C-enrichment and ¹⁸O-depletion in carbonate units.

Supercontinent Kenorland began to undergo extension at 2.45 Ga, as indicated by mafic igneous rock units at the base of the Huronian Supergroup (e.g., Heaman, 1997; Cheney, 1998; Halls, 1998). Actual breakup occurred at 2.2 to 2.1 Ga with emplacement of Nipissing diabase sills and major dike swarms (Roscoe and Card, 1993). The Kenora-Kabetogama mafic dikes (2145 +/- 45 Ma) in northern Minnesota (Southwick and Day, 1983) that show up so well on aeromagnetic maps (Chandler, 1991; Chandler et al, 1984) appear to be products of this final extensional event. The breakup of

Kenorland has an even broader intercontinental significance; a similar sedimentary sequence with similar igneous activity is also present in Finland and adjacent Russia (Marmo and Ojakangas, 1984), and correlation seems likely (e.g., Ojakangas, 1984, 1988; Ojakangas, et al, 1991). In summary, Kenorland, which formed in the Late Archean, apparently broke up in the Early Proterozoic, with the Wyoming craton heading west and the Svecofennian craton heading east.

CORRELATION

Correlation of Early Proterozoic rock units of Michigan and Ontario has long been a problem. Glacial units have been used as marker units (e.g., Young, 1983; Ojakangas, 1988); on this basis, the lower portion of the Marquette Range Supergroup (the Chocolay Group) is correlated with the upper part of the Huronian Supergroup, including the Gowanda Formation and overlying units.

Correlation within the Lake Superior region itself has also long been controversial (Morey and Van Schmus, 1988; Morey, 1996). Correlations have long been made on lithostratigraphic grounds; for example, it had been assumed that the various iron-formations of the Lake Superior region were correlative, but this is now questioned. Correlations are complicated by deformation (both thin-and thick-skinned tectonics) and the lack of exposures because of extensive glacial cover. New approaches, such as C-isotopic studies of carbonate units, have been interpreted as evidence that not all of the carbonate units are correlative, as long assumed (Bekker and Karhu, 1996; Bekker, 1998). Unless the C-ratios have been affected by diagenesis/metamorphism, they indicate that the Kona Dolomite may be younger than the Bad River Dolomite (WI and MI), the Saunders Formation (MI), the Randville Dolomite (WI), and the Rabbit Lake (MN) units that have all been "correlative units". An excellent summary of the sedimentation and correlation of the continental margin assemblage is by Morey (1996).

IRON-FORMATION

Naturally enriched iron ores of the Lake Superior region made the U.S.A. an industrial giant, but only two of the many ranges, the Mesabi and the Marquette, are still producing iron ore (taconite pellets). "Lake Superior-type" siliceous iron-formation is known world-wide, and similar units have been described from other continents. For nearly a century, geologists had thought they were all about 2.0 Ga old. However, in recent years it has been suggested that there was more than one period of deposition. In Minnesota, there appear to be three ages ranging from about 2.2 Ga to 1.9 Ga (Southwick and Morey, 1991; Morey and Southwick, 1995); the oldest two are laminated and fine-grained (deposited below wave-base in extensional basins?), in contrast to the younger Biwabik Iron-formation that contains sand-sized grains of chert and iron minerals, is cross-bedded, and contains two stromatolite horizons indicative of deposition on a shallow shelf. In Michigan-Wisconsin, there may be two major periods of deposition (e.g., Ojakangas, 1994; Morey, 1996). The older Negaunee Iron-

formation of the Marquette district appears to have been deposited in deeper waters of a down-faulted graben (with the addition of terrigenous material by turbidity currents from the south side as noted by LaRue, 1981), whereas the Ironwood Iron-formation of the Gogebic range (Schmidt, 1980) and the Bijiki Iron-formation member of the Michigamme Formation appear to have been deposited on a stable marine shelf. Interesting spirally coiled, megascopic eukaryotic algae have been found in the Negaunee (Han and Runnegar, 1992).

The Biwabik Iron-formation (as thick as 225 m) on the Mesabi range (Morey, 1992) and the Ironwood Iron-formation on the Gogebic range appear to have a common origin; part of the evidence is found in the underlying Pokegama and Palms formations which have been interpreted as having formed in a tidal environment (Ojakangas, 1983; Ojakangas, G. W., 1996). These studies indicate that the iron-formations were deposited on a marine tidally-influenced shelf, seaward of the land-derived sand and muds of the Pokegama and Palms formations. Loughheed (1983) also proposed a tidal environment, with siderite-rich limestone the primary pre-diagenetic rock type. Deposition appears to have been related to a major marine transgression (Simonson and Hassler, 1996).

There are two oft-cited sources for the iron and the silica--hydrothermal activity associated with volcanism in the basin (e.g., Carrigan and Cameron, 1991; Isley, 1995) and weathering of the Archean craton (e.g., Lepp, 1987). The Ironwood Iron-formation on the Gogebic is interbedded with volcanics (Klasner et al, 1998), the Gunflint Iron-formation (once continuous with the Biwabik Iron-formation prior to intrusion of the 1.1 Ga Duluth Complex) contains tuff beds, and there is a prominent ashy bed in the Biwabik. Hoffman (1987) tied the iron-formations of the Lake Superior region to foredeep volcanism. C and O isotopes of the Gunflint indicate a hydrothermal source for the Fe^{+2} and the silica, with siderite being the primary iron mineral in a basinward facies (Winter and Knauth, 1992). The lower part of the overlying Virginia Formation contains numerous ash beds (Lucente and Morey, 1983). Thus there is a growing body of evidence indicating that volcanism was the main source of the iron and silica, but continental weathering may indeed have been another source (e.g., Drever, 1974). Biota have long been touted as important in the precipitation of the iron minerals (e.g., LaBerge, 1967; Loughheed, 1983; LaBerge et al, 1987).

When was the Biwabik Iron-formation, the largest and probably the youngest iron-formation in the region, deposited? Part of the evidence comes from the less-metamorphosed and correlative Gunflint Iron-formation that is on strike with and was once continuous with the Biwabik. Faure and Kovach (1969) reported a whole-rock Rb-Sr isochron age of 1.64 ± 0.2 Ga for the deposition or diagenesis of the Gunflint. A Sm-Nd isochron age on argillites in the Gunflint was determined at 2.08 ± 0.25 Ga (Stille and Clauer, 1986). A Sm-Nd whole-rock isochron of 2100 ± 52 Ma was reported for "slaty" portions of the Biwabik, but this

is probably a mixing age of Archean and Proterozoic components (Gerlach et al, 1988). Quartz veins in the underlying Pokegama were dated at 1930 $\pm$ 25 Ma (Hemming et al, 1990). Probably most indicative of the age is a new U-Pb date of 1876 $\pm$ 2 Ma on euhedral zircons from a reworked tuff bed in the lower Gunflint (Fralick and Kissen, 1998). This date has major tectonic implications, for it indicates that these two iron-formations were deposited on the peripheral foreland bulge of the Animikie foreland basin, rather than on the continental margin prior to the development of the foreland basin. In this scenario of a northward-migrating foreland basin, the terrigenous clastic Palms Formation and the Ironwood Iron-formation on the Gogebic range of Wisconsin-Michigan may be continuous with but older (i.e., diachronous) than the more northerly (by 100 km) terrigenous clastic Pokegama Formation and the Biwabik Iron-formation on the Mesabi range of Minnesota (Ojakangas, 1994).

PENOKEAN OROGEN

The Archean ended with the formation of a big supercontinent, Kenorland, the product of the amalgamation of volcanic arcs and granitic intrusive bodies, and history repeats itself. The Penokean (Hudsonian) orogeny occurred on the southern edge of the Superior craton, extending over a distance of 1100 km from the Grenville Front near Sudbury, ON, westward to the area just west of Lake Superior, deforming the sedimentary units deposited on the passive continental margin when volcanic arcs (the Wisconsin magmatic terranes) and microcontinents (that included Archean rocks) collided from the south with northward-directed thrusting over a southward-dipping subduction zone (e.g., Morey and Southwick, 1995; Sims, 1996).

The Penokean has long been an enigma for it seems to have been long-lived, lasting from at least 1982 Ma to 1770 Ma, with the earliest Proterozoic sedimentary units in Minnesota deposited about 2200 Ma (Morey and Southwick, 1995). Volcanic rocks of the orogen range in age from 1880-1840 Ma, plutonic rocks from 1980-1770 Ma, and deformation from 1982-1770 Ma (e.g., Southwick and Morey, 1991; Sims et al, 1993). Volcanogenic massive sulfide deposits and occurrences of Cu, Zn, and Pb, about 1860-1840 Ma, are abundant based on extensive exploration drilling of geophysical anomalies; more than 13 bodies have been identified (DeMatties, 1994), although only one (Flambeau) has been mined to date. Post-Penokean rhyolites and granites occur in Wisconsin (Sims et al, 1989) and post-orogenic metamorphism and coeval plutons in east-central Minnesota have been dated at 1770-1760 Ma with rapid cooling at 1760-1750 Ma (Holm et al, 1998). Two deformations in the southern portion of the Thomson Formation have been described, with F_1 isoclinal recumbent folds and F_2 upright folds that refolded the earlier folds (Holst, 1982, 1984). Excellent interpretations of Penokean deformation can be found, e.g., in Holst (1991), Klasner et al (1991), Klasner and Sims (1993), Gregg (1993), and Sims and Carter (1996).

By removing the 60 km-wide Middle Proterozoic Midcontinent Rift System from a regional geological map, thereby bringing Minnesota and Wisconsin-Michigan into juxtaposition, the fold-and-thrust belts of the two areas become one continuous zone. Southwick and Morey (1991) correlated the Niagara fault zone/suture (WI) and the Malmo discontinuity (MN). Similarly, the various turbidite-shale units (Thomson, Rove, Virginia, Tyler, Copps, and Michigamme Formations) then become one contiguous unit filling the Animikie Basin. This, however, does not imply that all of these formations are the same age, for the basin was migrating northward during deposition of these units; some sediment deposited in the earlier stages of basin development was likely cannibalized and redeposited.

The Animikie basin has been interpreted as a northward-migrating foreland basin that developed in front of (on the north side) of the fold-and-thrust belt due to the weighting down of the crust by this folded and thrust mountain range that then became a major source of sediment for the basin (e.g., Hoffman, 1987; Southwick et al, 1988; Barovich et al, 1989; Southwick and Morey, 1991; Ojakangas, 1994; Morey and Southwick, 1995).

Nd isotope data determined by Barovich et al (1989) indicate that some Michigamme samples had an Archean provenance to the north and some had an Early Proterozoic provenance to the south. Paleocurrent data for the Michigamme and the Tyler indicate a northward transport of sediment from the south side of the Animikie Basin and a southward transport of sediment from the north side of the basin as summarized in Ojakangas (1994). Hemming et al (1995), on geochemical and isotopic evidence, described the provenance of the Virginia Formation as a young differentiated volcanic arc to the south of the basin.

The Wisconsin magmatic terranes were located just to the south of the fold-and-thrust belt. The Pembine-Wausau terrane is comprised of older (1889-1860 Ma) magmatic rocks that formed in an island arc and/or back-arc basins above a south-dipping subduction zone (the Niagara fault zone or suture) and younger magmatic rocks (1845-1835 Ma) that formed above a north-dipping subduction zone, the Eau Pleine shear zone (Sims et al, 1989, 1993). Deep seismic profiling indicates that both the Niagara fault and the Eau Pleine shear zone may penetrate the entire crust (Cannon et al, 1991). An ophiolite sequence in the Quinnesec Formation of northeastern Wisconsin (Schulz, 1987) indicates the closure of an ocean basin. In the southerly Marshfield terrane, 1860 Ma rocks were deposited on Archean crust and amalgamation of the two terranes along the Eau Pleine suture occurred at about 1840 Ma (Sims et al, 1993). Three episodes of post-orogenic magmatism followed, dated at 1835 Ma, 1760 Ma, and the 1469+/- 28 Ma Wolf River batholith (Sims et al, 1989). Nd isotopic data of Barovich et al (1989) indicated the major growth of new crust from the mantle.

The Penokean (Hudsonian) Orogen was part of the reassembly (Hoffman, 1988) of a new supercontinent that Williams et al (1991)

dubbed Hudsonland. This supercontinent also included the Fennoscandian Shield (as did the Archean supercontinent of Kenorland). The Svecokarelian orogeny of that shield is comparable to the Penokean Orogen in many aspects.

QUARTZITES

The Penokean Orogen and adjacent rock units continued to be weathered (Southwick and Mossler, 1984) and eroded for about 100 Ma following the mountain-building culmination at about 1850 (?) Ma. Several quartzite units were deposited to the south of the orogen, including the Sioux Quartzite of Minnesota, South Dakota, and Iowa (e.g., Morey, 1984; Ojakangas and Weber, 1984; Southwick et al, 1986) and the Baraboo (Dott, 1983), Barron (Rozacky, 1987), Flambeau (Campbell, 1986), and McCaslin (Olson, 1984) Quartzites of Wisconsin. Their ages and correlation have long been a problem (e.g., Brown, 1986; LaBerge et al., 1991; Chandler and Morey, 1992; Ojakangas, 1993), especially because the Baraboo, Flambeau, and McCaslin are deformed whereas the Sioux and the Barron are relatively horizontal. These "Baraboo Interval" quartzites pose the "Proterozoic red quartzite enigma" of Dott (1983). Dott (1983) and Van Schmus et al (1993) suggested that a plate suture exists beneath the Paleozoic cover to the south, and that a southerly terrane collided with the then-passive margin of the continent over a southerly dipping subduction zone. Chandler and Morey (1992) interpreted paleomagnetic data to indicate that there are two ages of quartzite bodies, one late Penokean and the other post-1760 Ma. Recent U-Pb detrital zircon ages of 1730-1710 Ma for the Baraboo and the McCaslin and Pb/Pb ages on detrital zircons of 1730-1850 for the Sioux, 1745-1880 for the Flambeau, and 1750-1880 for the Barron (Schneider et al, 1998) and similar ages for detrital zircons in the Baraboo and McCaslin quartzites (Van Wyck, 1995; Dott et al, 1997) can be interpreted to indicate that these "Baraboo Interval" quartzites may be correlative. Holm et al (1997) have located a 1630 Ma thermal front in northwest Wisconsin based on cooling ages in Ar/Ar dates on mica; this front coincides with the deformational boundary between the Barron and the Flambeau.

If one assumes that the quartzites are erosional remnants of a larger sheet of quartz sand locally >1500 m thick and deposited on the continental margin, a tremendously large and deeply weathered quartz-bearing source terrane must be assumed. Even without the assumption of a single large basin, the volume of quartz is enormous. Whereas a fluvial origin is most likely for most of the quartzites (e.g., Southwick et al, 1986), a marine origin for the upper Sioux (Ojakangas and Weber, 1984) and for part of the Baraboo (Dott, 1983) has been proposed.

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UNDERSTANDING THE MIDDLE PROTEROZOIC HISTORY OF THE LAKE SUPERIOR REGION: WHAT'S NEW? WHAT'S NEXT?

W.F. Cannon, US Geological Survey, Reston, VA

Middle Proterozoic time encompasses 700 million years (1600-900 Ma) of geologic history. In the Lake Superior region only a small part of that time is recorded in the rock record. At about 1470 Ma large anorogenic granitic plutons were emplaced in northern Wisconsin. Between 1108 and about 1060 Ma the Midcontinent rift, a 2200 km-long volcanic and subsequent sedimentary basin, formed and was structurally modified. A brief summary of the current understanding of these two events is presented below emphasizing findings during the past 15 years. An extended list of references for the Midcontinent Rift presents some of the principal publications since the detailed papers in the 1982 Geological Society of America Memoir 156, "Geology and Tectonics of the Lake Superior Basin". For anorogenic plutons, references include original research from the 1970's and more recent summary papers.

Anorogenic plutons A suite of large granitic plutons was emplaced in a broad belt spanning most of the North American continent from Labrador to Arizona between about 1500 and 1450 Ma. The plutons intruded older continental crust during a period generally devoid of major orogeny, hence the name anorogenic plutons. That suite of plutons is represented in the Lake Superior region by the Wolf River batholith and Waussau and Stettin plutons in Wisconsin. These plutons were studied extensively in the 1970's but have received relatively little attention since, with the exception of being discussed in regional summary papers. The Wolf River batholith, with an exposed area of about 10,000 km², and the smaller plutons were emplaced at about 1470 Ma. The Wisconsin plutons share characteristics with the other members of the suite in being emplaced at shallow depths in Early Proterozoic crust and consisting of large volumes of granite with rapakivi affinities, and lesser volumes of more mafic rocks, largely mangerite and anorthosite. The granites of the suite are interpreted to have formed by relatively low percentage of partial melting (20±10%) of Proterozoic granitic rocks in the lower crust. Anorthosite may be derived from basaltic magma produced, in part, by partial melting of mantle lithosphere. Studies of the Wolf River batholith indicate that mangerite magma was derived at a depth of 21-32 km and a temperature of 950±90°C. Crystallization of the granite now exposed occurred at temperatures of 650-840°C and at shallow depths of 2-4 km. The cause of widespread melting of lower crust in a belt of continental dimensions remains obscure.

Midcontinent rift The Midcontinent rift extends in an arc from Kansas, through the Lake Superior basin, into southern Michigan. The physical character of the rift (rock types, geometry, structure, approximate age) have been well known for many decades. Research in the past 15 years has added critical information to allow the kinematic and dynamic aspects of evolution of the rift to be deciphered. Deep crustal seismic surveys, precise age determinations, petrochemical research, and experimental and theoretical studies of mantle and lithospheric processes can be integrated to understand the rift in the broad context of the evolution of the North American continent and global-scale processes.

Seismic surveys have shown that the rift is very deep, in places comprising the entire crustal thickness. Subaerial basalt flows form the lower part of the rift-fill and are as much as 20 km thick along the rift axis. Continental clastic sedimentary rocks overlie the basalt and are as much as 10 km thick. Basalt eruption and coeval rift subsidence was rapid and of relatively short duration. The volcanic phase of the rift lasted about 14 my (1108-1094 Ma). Rates of volcanism and subsidence were not entirely uniform and appear to have been greatest near the close of the volcanic phase. Subsidence of volcanic basins, as inferred from seismic profiles, appears to have been by a combination of normal faulting and broad flexure. Large volumes of mafic magma were also

emplaced both within the crust and as crustal underplating during this same period. Basalt eruption ceased rather abruptly at about 1094 Ma and subsidence rates declined correspondingly. Further filling of the rift was with continental sedimentary rocks, mostly red sandstone, and minor reduced lacustrine rocks. The duration of sedimentation is not well constrained but most likely continued, along with subsidence, at declining rates for at least several tens of millions of years. During sedimentation, inversion of the central portions of the rift took place along a set of major reverse faults. These events combined to form the present geometry of the rift. A central horst contains the originally deeper central parts of the rift, including thick sections of volcanic rocks. Flanking basins contain wedges of thinner volcanic sequences and overlying sedimentary rocks.

The great volume of basaltic rocks and related intrusive rocks in the rift, combined with limited amounts of lithospheric extension imply that the mantle was anomalously hot during rifting; probably about 200°C hotter than present day asthenosphere. Petrochemical studies indicate that much of the magma was generated by partial melting of primitive, enriched mantle. Together, these features point to the existence of a mantle plume beneath the rift, and more specifically, suggest that the rifting and volcanism was a consequence of the initiation of a new plume and the arrival of a plume head at the base of the lithosphere. Modelling and numeric simulation of plume behavior shows that when a new plume forms and rises from depth, it generates a large mushroom-shaped head of hot asthenosphere. The head grows as it rises slowly and is fed by its own narrower but faster rising stem. The arrival of a plume head at the base of the lithosphere and at depths where adiabatic partial melting occurs creates a short period of intense magma generation. Under suitable stress conditions in the lithosphere, the plume can also initiate extension and rifting. The arrival of a new mantle plume at the base of the lithosphere at about 1108 Ma provides the most coherent explanation for the origin of the rift and its great volume of igneous rocks.

Rift sedimentation occurred in basins somewhat broader than the volcanic basin. The sedimentary basins do not appear to be strongly controlled by faulting. Rather, they appear as smooth flexural depressions on seismic reflection sections. Subsidence was most likely a result of cooling of the lithosphere as the initial plume head spread and cooled conductively. Sediments were initially derived dominantly from volcanic rocks in the rift. As sedimentation progressed, however, more older terranes outside of the rift were tapped as a sediment source along with continued erosion of rift volcanic rocks.

Inversion of the central portion of the rift occurred during the later stages of sedimentation. A set of high angle reverse faults and thrusts, in part reactivated normal faults, produced displacements of as much as several tens of kilometers. The time of faulting is imprecisely known, but most movement must have been in the interval 1080-1040 Ma.

Viewed on a more regional scale, the Midcontinent rift has been historically somewhat of an enigma in that it is a major extensional feature which formed immediately west of the seemingly coeval Grenville orogen. In recent years, however, precise radiometric dating shows that the short interval (1108-1094 Ma) of extension in the Midcontinent rift appears to coincide with an interval of tectonic quiescence, or possibly extension, in the multi-phase Grenvillian orogeny. Thus, a mantle plume arriving at 1108 Ma could have begun a period of extension during this Grenvillian quiescent period. At about 1090 Ma compression in the Grenville Province was renewed and a period of northwest-directed thrusting, the Ottawa orogeny, continued for tens of millions of years. The onset of thrusting in the Grenville Province coincides remarkably closely with the end of extension in the Midcontinent rift and the onset of compressive deformation.

It appears then that development of the Midcontinent rift marks the arrival of a new plume head at the base in the lithosphere of the Lake Superior region at about 1108 Ma. Melting of the plume head and

stresses generated by lateral spread of the plume caused the intensely volcanic rift. Under some circumstances this event might have led to continental breakup. In this case, however, initiation of the Ottawa orogeny in the adjacent Grenville Province, transmitted northwest-southeast directed stresses into the Lake Superior region. This newly applied stress field not only terminated rift extension, but initiated a period of compressive deformation and rift inversion.

The processes that formed the rift were also important in forming the major mineral deposits for which the rift is well known. The vast new igneous rocks were fertile starting material for metal-concentrating processes. Some concentration occurred early, during fractional crystallization of magma. The very large Cu-Ni sulfide deposits of the Duluth complex and other intrusions formed at this stage, as did concentrations of platinum group elements. The rifting and related processes in the mantle also provided a large heat engine that drove hydrothermal circulation. Those hydrothermal systems formed the Keweenaw native copper district, the White Pine and related sediment-hosted copper deposits, and polymetallic vein deposits. The heat generated by the rift also caused regional metamorphism that converted Early Proterozoic iron-formations from non-magnetic to magnetic taconite in places such as the Mesabi Range and Gogebic Range.

Much progress has been made in the past 15 years in understanding fundamental causative factors of the Midcontinent rift. The data gathered in that period lay the foundation for continued refinements of knowledge of this important structure. Research continues on refining knowledge of the age of rifting events, internal stratigraphy of rift units, the nature of plume-lithosphere interaction, and patterns of regional metamorphism and alteration. Advances in the detail and precision of information on the geometry, age, and composition of the rift from recent and continuing research, combined with modern computational techniques, allows a new phase of quantitative numerical research on rift evolution to be undertaken. Examples of this new phase of research are current studies of the transient thermal history of the rift, and the paleohydrology of the rift as it related to formation of mineral deposits.

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PALEOZOIC ROCKS IN THE NORTHERN PART OF THE CENTRAL MIDCONTINENT OF NORTH AMERICA

RUNKEL, Anthony C., Minnesota Geological Survey, 2642 University Ave SE, St Paul, MN, 55114-1057

INTRODUCTION

Paleozoic strata in the central midcontinent region of North America consist of thin units of carbonate, sandstone, and shale distributed across tens of thousands of square kilometers. This overview focuses on the northernmost extent of lower Paleozoic strata which were deposited on the stable cratonic shelf northwest of the Illinois and Michigan basins (Figs. 1 and 2). They are exposed in a sinuous belt of outcrops in southern Minnesota, Wisconsin and northern Michigan, on the southern flanks of the Transcontinental arch and the Wisconsin dome and arch.

Deposition of Paleozoic sediments began in Middle to Late Cambrian time. Coarse siliciclastic sediments of the Mt Simon Sandstone covered the eroded Precambrian surface. Overlying strata were deposited in two broad, laterally equivalent facies belts across the central midcontinent region (Fig. 1 inset) (Palmer, 1960). An inner detrital belt was composed of shallow marine siliciclastics derived from subaerially exposed Precambrian shield areas on and to the north of the Wisconsin Dome. Thin, laterally extensive units dominated by either fine- to coarse-grained quartzose sandstone, very fine sandstone, or shale were deposited in the inner detrital belt. The middle carbonate belt consisted of subtidal to intertidal carbonate and shale deposits that accumulated to the south. The boundary between belts shifted, with inner detrital belt sedimentation dominant during Cambrian and part of Middle Ordovician time, and middle carbonate belt sedimentation dominant during the Early and Late Ordovician, as well as in Silurian and Devonian time (Fig. 2).

Early Paleozoic deposition occurred on a virtually horizontal, cratonic shelf with a very low subsidence rate. Late Cambrian subsidence averaged less than 10m/m.y. (Sloss, 1988), about one-fifth to one-tenth the rate in the contemporaneous Illinois Basin (Sargent, 1991) and orders of magnitude slower than that of better known, younger basins in North America. Maximum paleobathymetry was typically less than 100 m (e.g. Byers and Dott, 1995; Ludvigson and others, 1996) and the shelf had a low gradient slope of about 0.1m/km.

The Wisconsin arch and dome and Transcontinental arch were positive structural features that influenced early Paleozoic sedimentation patterns, and eventually controlled the distribution and configuration of gently folded and faulted Paleozoic strata today. In northern Iowa, southern Minnesota, and southwestern Wisconsin Paleozoic strata are preserved in what is known as the Hollandale Embayment, which is a broad syncline that lies between these two positive features. South and east of the Wisconsin arch and dome Paleozoic rocks dip less than 1 degree into the Illinois and Michigan basins.

DEPOSITIONAL MODELS

The depositional history of lower Paleozoic siliciclastic strata of this region remains poorly understood despite over 100 years of study. Many workers have lamented an apparent absence of modern or ancient depositional analogues. In addition, dozens of local studies have been conducted (e.g. Nelson, 1954; Haddox and Dott, 1990) but there are few regional-scale investigations that incorporate several lithofacies into a temporally constrained stratigraphic framework. Present-day understanding of early Paleozoic siliciclastic deposition is based mostly on work conducted since 1950, beginning with the predominantly stratigraphic investigations of Berg (1954), Nelson (1956), Berg and others (1956), Bell and others (1956), and Ostrom (1964, 1970). Subsequent work has been chiefly sedimentologic, focusing on the interpretations of near-shore marine facies (Fraser, 1976; Driese and others, 1981; Dott and others, 1986; Haddox and Dott, 1990; Barnes and

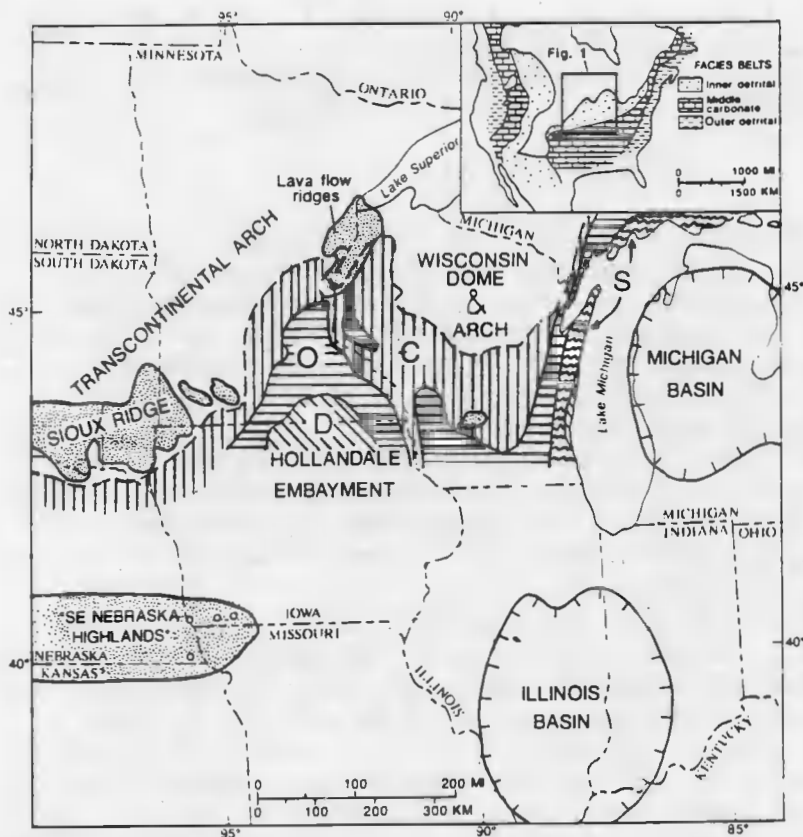


Figure 1. Location map showing early Paleozoic tectonic features, major paleotopographic highs of Precambrian rocks (stippled) and the approximate distribution of Cambrian (C), Ordovician (O), Silurian (S), and Devonian (D) strata in the northern part of the central midcontinent region. The inset shows the study area relative to the Late Cambrian inner (stipple) and outer (dashes) detrital belts and the middle carbonate belt (block pattern) of Palmer (1960). Modified from Runkel and others (1998)

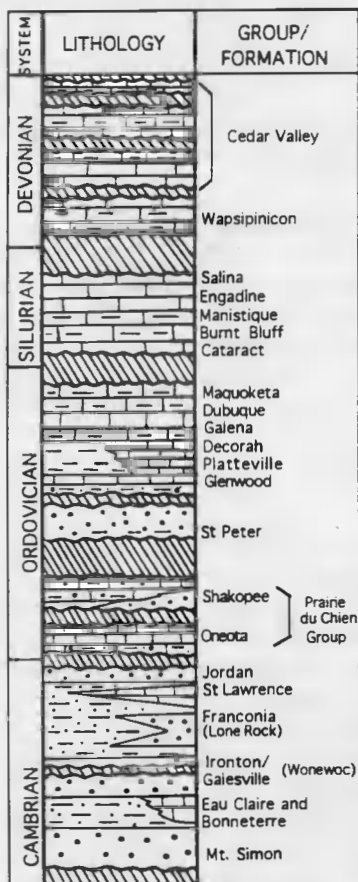


Figure 2. Generalized stratigraphic column (no scale) for lower Paleozoic rocks in the northern part of the central midcontinent region. The Cambrian and Ordovician nomenclature is that used in southeastern Minnesota and Wisconsin, the Silurian from eastern Wisconsin and northern Michigan, and the Devonian from southernmost Minnesota and northern Iowa.

others, 1992; Mossler, 1992; Runkel, 1994). In a very important and widely cited study Dott and others (1986) examined the transition from nonmarine to marine environments recorded in quartzose sandstones, and provided the first set of criteria for identification of nonmarine facies. They described an early Paleozoic terrestrial setting with broad braided streams and eolian sheet and erg systems that delivered sand to a shallow marine environment dominated by small three dimensional dunes. Dott and others (1986) stressed the *differences*, such as the lack of vegetation, between early Paleozoic depositional environments and those inferred for both younger rocks and modern settings. A depositional model of a simple, storm-dominated, texturally graded shelf was proposed by Runkel and others (1998), and is noteworthy in its *similarity* to models based on both younger rocks and modern systems. Their study was essentially a regional-scale outgrowth of the excellent outcrop work of Charlie Bell and his students from the University of Minnesota in the 1950's. Runkel and others (1998) suggested that early Paleozoic depositional processes and facies distribution are analogous to those depicted in well-known models of the Cretaceous interior seaway and the modern Bering Shelf. The thin widespread siliciclastic units characteristic of lower Paleozoic strata result from large lateral facies migrations which occurred in response to continental-scale changes in relative sea level.

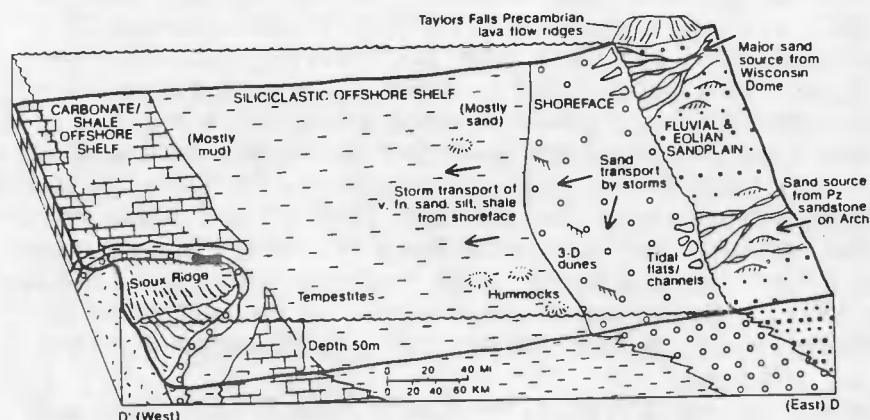


Figure 3. Conceptual depositional model of Late Cambrian storm-dominated, texturally graded shelf. Quartzose fine- to coarse-grained sand accumulated in nearshore terrestrial and shoreface environments. Finer grained, feldspathic siliciclastic sediments and subtidal carbonates accumulated in deeper water of the offshore shelf.

Carbonate rocks within the lower Paleozoic sequence have historically been regarded as more amenable to comparison with both modern and ancient facies models. Deposition occurred in environments that range from evaporitic, supratidal conditions for parts of the Prairie du Chien Group (Smith and others, 1993) to subtidal settings in depths of 100 m or more for parts of units such as the Decorah Shale (Ludvigson and others, 1996). Most investigations have been local in scope relative to the great lateral extent of these units and there are too many to cite them individually. Ordovician carbonate strata of the Hollandale embayment are the focus of a monograph edited by Sloan (1986). Silurian carbonates on the western flank of the Michigan Basin have recently been studied by Harris and Waldhuetter (1996). There are many excellent studies of Ordovician through Devonian age strata in northern Iowa, largely conducted by the Iowa Geological Survey; the results can often be extrapolated to Minnesota and Wisconsin (e.g. several papers in Witzke and others, 1996). Some regional scale studies have recently been completed; a stratigraphic framework has been developed for the Prairie du Chien Group from the Michigan basin to the Hollandale embayment (Smith and others, 1993, 1996; Barnes and others, 1996). Simo and others (1997) are currently constructing a large scale stratigraphic framework for Ordovician rocks of the central midcontinent in order to address long-standing problems such as identification of the controls responsible for the apparently synchronous regional-scale changes from "tropical" to "temperate" styles of carbonate deposition.

NOTABLE FEATURES AND LONGSTANDING PROBLEMS

Lower Paleozoic strata in the central midcontinent region are among the longest studied sedimentary rocks in North America. They are well known to geologists outside of the area for several enigmatic features (Dott and Byers, 1980). Most notable is the extreme textural and mineralogical maturity of the fine to coarse-grained sandstones, and the sheet-like geometry of these and other siliciclastic units. The overall dearth of shale has puzzled sedimentologists, and the fundamental controls on the episodic change from siliciclastic-dominated to carbonate-dominated sedimentation remain poorly understood. Lastly, the presence, position and magnitude of unconformities has been debated for decades. The remainder of this abstract summarizes the progress made in understanding these enigmatic features since the overview publication by Dott and Byers (1980) on lower Paleozoic strata.

Sheet geometry A long-standing question has been how sheet-like siliciclastic layers were initially deposited and then preserved across tens of thousands of square kilometers of the cratonic shelf. Most workers have attributed the formation of such sheets to depositional processes and environments that are markedly different from those described for most younger rocks and modern settings. Lochman-Balk (1970) inferred the presence of enormous tidal flats extending well over two hundred kilometers perpendicular to the shoreline. Dott and Byers (1980) suggested that quartzose sand aggraded more or less vertically into a sheet under high-energy conditions across a vast shallow sea. The most widely cited hypothesis is one which attributes the origin of quartzose sandstone sheets to fluvial and eolian processes that dispersed sand across a vegetation free landscape prior to marine reworking during a transgression (Dott and others 1986). Recent studies, however, have demonstrated that some quartzose sheets were deposited entirely within the marine realm under regressive conditions (e.g. Runkel, 1994, Hughes and Hesselbo, 1997, Runkel and others 1998), and that the depositional processes responsible for the dispersal of siliciclastic sediments were similar to those operating during the deposition of ancient sandstones that are *not* sheet-like.

The lateral persistence and sheet-like geometry of lower Paleozoic siliciclastic units probably reflect the roles of basin physiography and tectonics in controlling the lithostratigraphic architecture, rather than the existence of atypical sedimentary environments. Deposition was characterized by a continuous and abundant supply of sediment to a relatively stable, nearly flat basin with a slow, uniform rate of subsidence. Individual sheets of siliciclastic sediment were deposited when discrete facies (e.g. Fig. 3) migrated great distances during changes in sea level. Deep incision of the individual sheets during episodes of subaerial exposure did not occur, resulting in more or less uniform preservation.

Textural maturity of sandstones The extreme textural and mineralogical maturity of the fine- to coarse-grained sandstone units, such as the St Peter Sandstone, may be the best known and longest studied feature in the lower Paleozoic strata of the central midcontinent. The sandstones contain more than 98% quartz and most grains are moderately to well rounded. Such textural and compositional maturity could not have been achieved solely by fluvial and marine abrasion even over transport distances of hundreds of kilometers if the grains were derived directly from crystalline source rocks. Rare grains with abraded overgrowths are reworked from older sedimentary rocks, but the volumetric significance of such recycling is uncertain and a source of suitable sedimentary rock has never been identified. Odom (1975, 1978) conducted the most comprehensive mineralogical study of lower Paleozoic sandstones; he noted that the very fine grained fraction is feldspathic, whereas the fine to coarse-grained fraction contains more than 98% quartz (with the exception of some lower Mt Simon Sandstone beds). He suggested that a long history of abrasion in a marine setting

could account for both the maturity of the quartzose grains and the reduction in size of feldspar grains. Dott and others (1986) were the first to clearly identify the presence of substantial eolian deposits within some quartzose sandstones, and they suggested that eolian abrasion could contribute to the textural and mineralogic features described by Odom (1975, 1978). Lastly, chemical weathering in the source area must be taken into consideration (Morey, 1972). Odom (1975, 1978) noted that the very fine grained, feldspathic sandstones are rich in K-feldspar but have only a "trace" amount of plagioclase grains, even though plagioclase was presumably dominant in the source area of the Precambrian shield. Selective diagenetic leaching of plagioclase grains from the sandstone was discounted by Odom. Thus, chemical weathering probably preferentially dissolved plagioclase crystals and reduced the size and amount of other relatively unstable minerals prior to mechanical abrasion during transport to the shoreline.

While each of the processes described above could have been responsible in part for the mineralogic and textural attributes of lower Paleozoic sandstones, they do not entirely account for the compositional record that appears to indicate that virtually *all* fine- to coarse-grained sand was exceptionally mature when it arrived to the early Paleozoic shoreline. Fine- to coarse-grained immature sand would have almost certainly been deposited locally if the marine abrasion model of Odom (1975) were accurate. It is difficult to reconstruct a terrestrial setting in which *all* sand is subjected to prolonged eolian abrasion (Dott and others 1986) prior to deposition in a marine environment.

Dearth of Shale Lower Paleozoic rocks of the central midcontinent region are noted for a dearth of shale compared to other shallow marine deposits. Two very different hypotheses have been proposed to account for this dearth of shale. In a "marine bypassing" model, Pettijohn and others (1973) suggested that clay- and silt-sized particles were delivered to the shoreline, but subsequently carried in suspension by repeated storms across the shallow shelf before final burial in basinward areas. In contrast, Dalrymple and others (1985) suggested that strong winds blew clay and silt particles hundreds to thousands of kilometers offshore, to be ultimately deposited in the outer detrital belt (Fig 1).

Recent investigations of Upper Cambrian siliciclastic strata support the marine bypassing model of Pettijohn and others (1973), demonstrating that the well known dearth of shale is characteristic *only* of the outcrop belt on the flanks of the Wisconsin dome and arch (McKay, 1988, Runkel and others, 1998). Basinward of the Wisconsin arch, subsurface records from Minnesota and Iowa show that facies dominated by shale and siltstone are common. The shale and siltstone dominated facies are offshore equivalents to the shale-poor sandstone facies of the outcrop belt, and their geographic position changed through time in response to changes in the position of the storm-fairweather wave base. The outcrop belt has a dearth of shale simply because the depositional record is dominated by highstand shoreface facies deposited above fairweather wave base. This stratigraphic and sedimentologic attribute is not unique to the lower Paleozoic rocks of the central midcontinent region-it is common in many younger wave-dominated sequences along the landward margins of individual basins. The notion of a shale-free early Paleozoic epeiric sea is a deeply entrenched idea that simply reflects the bias of the outcrop belt. The dearth of shale in lower Paleozoic rocks should be removed from the list of enigmatic features unless the scarcity can be demonstrated to exist on a scale larger than that of the outcrop belt.

Siliciclastic-Carbonate cycles The fundamental controls on the transition from nearshore siliciclastic- to carbonate-dominated deposition have never been satisfactorily understood. For example, in Early Ordovician time carbonate deposition apparently dominated across the entire region even in the shallowest water conditions (Smith and others 1993). Both older (Jordan Sandstone) and younger (St Peter Sandstone) shallow marine environments were dominated by siliciclastics. Only speculative and vague hypotheses have been suggested to account for such fundamental changes. For example, Adams (1978) suggested that the Early Ordovician change in depositional styles may have been in response to drowning of the

siliciclastic source area by a shallow sea or the result of siliciclastics being "deflected" to another region. Early Paleozoic carbonate-dominated systems developed following extended periods of high sea level (Smith and others, 1993) which suggests that the siliciclastic source area may have been covered with a blanket of carbonate rocks. The spread of certain forms of terrestrial life such as bacterial encrustation, and later the development of vascular plants, may have also reduced siliciclastic input.

Cryptic unconformities Previous investigations of lower Paleozoic strata of the central midcontinent region have also been hindered by an inability to recognize unconformities. The unconformities bounding the major sequences of Sloss (1963) are fairly well established within the strata of the outcrop belt. The presence and position of "lesser" unconformities, especially within siliciclastic units, have been a matter of considerable debate. Stratigraphic relations and interpreted depositional histories indicate that such unconformities "should" be present. However, little or no evidence for regionally extensive subaerial erosion has been documented. Such sequence-bounding unconformities are difficult to recognize where they are contained within coarse siliciclastics because they separate quartzose sandstones that are texturally and mineralogically similar, and because they are relatively flat-reflecting erosion that occurred on a loose, sandy substrate along a low, uniform gradient, and in a nonvegetated terrestrial environment. Furthermore, the ultra mature mineral composition of the exposed substrate inhibits development of a distinctive weathering profile.

Recent work has shown some promise for identifying subtle subaerial surfaces of erosion. Recognition of cryptic unconformities requires interpretation of regional stratigraphic relations in conjunction with physical evidence collected at individual outcrops and high resolution biostratigraphic data. Smith and others (1993) interpreted local deposits of silica cement in uppermost Cambrian and Lower Ordovician strata as subaerially formed silcrete. Runkel and others (1998) suggested that cryptic unconformities within the Ironton and Galesville Sandstones and at the top of the Jordan Sandstone and can be identified only by overlying lag deposits. These lag deposits are the coarsest bed within nearshore sandstone successions; they separate a regionally traceable, decameter-scale, coarsening-upward interval below from a decameter-scale, fining-upward sequence above. Preliminary results of high resolution biostratigraphic dating using conodonts has verified the presence of an erosion surface on top of the Jordan Sandstone, and demonstrates promise for measuring the magnitude of such cryptic unconformities with detailed paleontologic work.

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MODELS FOR INTERPRETING THE QUATERNARY HISTORY OF THE LAKE SUPERIOR REGION

PATTERSON, Carrie J., Minnesota Geological Survey

The interpretation of the Quaternary glacial and interglacial history for the Lake Superior region is in the midst of change as a result of two new models. Firstly, oxygen isotope data have provided evidence leading to the development of a model that indicates a large number of glaciations occurred during the last two million years. Secondly, a new mechanical model for the dynamics of ice flow has been developed. In order to integrate the new models into our interpretations, a broad geographic perspective is required. Rather than provide a summary of the history of the investigations in the Lake Superior region, I will present relevant observations in the context of these new models. Even if the models are eventually replaced, they will have forced us to look beyond the confines of the Upper Midwest and the traditional glacial interpretations.

Number of glaciations

Evidence indicates that the number of Quaternary glaciations is significantly greater than the four-fold glacial chronology devised for North America around the turn of the century which included the Wisconsinan, Illinoian, Kansan and Nebraskan glaciations (Flint, 1957). The new precision is based on nonterrestrial records of global ice volume, including the oxygen-isotope record of ocean carbonates. During glaciation, ^{16}O is preferentially evaporated from the oceans and is stored in the ice sheets, enriching the glacial oceans in ^{18}O . Fluctuations in the amount of ^{16}O and ^{18}O can be measured in ocean sediments and ice cores (Shakleton and others, 1984) and used to determine global ice volume. Based on these calculations for global ice volumes, a series of oxygen-isotope stages has been identified. Even numbered oxygen-isotopes stages represent glaciations, and odd numbers represent interglacial periods. There were 40 glacial/interglacial oscillations involving moderate global ice volumes between 2.4 Ma and .9 Ma, and there were 22 oscillations involving greater ice volumes between .9 Ma and the present (Shackleton et al., 1984). For the most recent 11 glaciations, oxygen-isotope stages 2, 6, 12 and 16 show the greatest ice volumes, possibly corresponding to traditional four-fold record of terrestrial glaciations in North America.

Another feature of the traditional four-fold record of glaciations is that the most extensive glaciation formerly recognized, (the Nebraskan) was also interpreted to be the oldest. Successively less extensive glaciations, (the Kansan, Illinoian and Wisconsinan) were interpreted to be successively younger (Flint, 1957). This chronology is probably an artifact of the preservation of terrestrial glacial sediments. While there were clearly more than four glacial periods during the past 0.9 my, each glacial advance obscures, either by erosion or burial, the record of previous, less extensive advances. If, for example, there were ten successive glacial advances, each advancing some random distance, probability analysis suggests that only three glacial limits will survive at the surface and the oldest surviving advance will be the most extensive (Gibbons and others, 1984). It is therefore not surprising that of the 11 most recent glaciations we have historically recognized only four glacial limits at the surface.

The oxygen isotope record shows that glaciations in the first half of the Pleistocene did not have as great a global ice volume as those in the latter half (Shakleton and others, 1984). However, these early advances of ice were apparently extensive enough in North

America to reach Iowa and Nebraska (Hallberg, 1986) and the foothills of the Canadian Rockies (Klassen, 1989). The sediment of these early advances may be preserved in Minnesota (e.g. Meyer, 1997; Patterson, 1997) and in Canada in the subsurface (e.g. Klassen, 1989) in areas of net glacial deposition, but the record is discontinuous and localized in deep, preglacial valleys.

Discontinuous, subsurface glacial sediment is difficult to place in a stratigraphic framework because: (1) absolute dating of the units is difficult; (2) till of different glacial periods is lithologically and texturally similar if the source terrane traversed by the glacier is the same; (3) although till may change composition gradually with distance in the ice-flow direction, isolated exposures of till may be dissimilar enough to prevent correlation. Radiocarbon dating of organic remains is only useful for Wisconsinan-age deposits because of the limitations of the half life of ^{14}C . A few dates from scattered pre-Wisconsinan samples have been secured using vertebrate paleontology (e.g. Klassen, 1989), dating of volcanic ash present in the glacial sediment (summarized in Richmond and Fullerton, 1986), studies of remnant magnetization in till and lake sediment (e.g. Baker and others, 1983), and cosmogenic isotope age estimates of striated rock surfaces (Bierman and others, 1998).

Owing to the different substrates over which the ice flowed, it is possible to distinguish tills using matrix color, texture and mineralogy, and clast lithology. During the Late Wisconsinan, Minnesota was nearly equidistant from the two major ice accumulation centers of the Laurentide ice sheet and received ice from both (Dyke and Prest, 1986). Minnesota's unique position has facilitated provenance studies to determine ice-flow paths and source areas. The glacial stratigraphy of Canada and Minnesota (Fulton, 1989; Meyer, 1997) indicate that ice sheets had similar geometries throughout the Quaternary.

At least five ice lobes advanced into Minnesota during oxygen-isotope stage 2 (Late Wisconsinan). Many of these lobes had multiple readvances. During advance each lobe had the potential to erode older sediment and rock, and to deposit its own glacial sediment. Therefore, a single glacial period may be represented by ten's of compositionally and texturally different, incompletely preserved glacial units — each having several depositional facies.

Interpretation of the most recent advances is most straightforward because the deposits are continuous, and the associated landforms are well preserved. For this reason, research in Minnesota and neighboring states has historically focused on the activity of ice lobes during the Late Wisconsinan (for regional summaries see Wright, 1972; Clayton and Moran, 1982).

Dynamics of ice flow

During oxygen-isotope stage 2 (Late Wisconsinan), and probably during stages 6, 12 and 16 (all pre-Late Wisconsinan), Minnesota was marginal to an ice sheet that extended across most of Canada. Minnesota and the Great Lakes region were affected mainly by thin, dynamic ice lobes that advanced beyond the main body of the ice sheet. Much effort has been made to correlate the advances of these lobes (Clayton and Moran, 1982; Mickelson and others, 1983) but it has become apparent that they were not synchronous on a time scale of hundreds to thousands of years. Movement of the ice lobes is ultimately driven by the overall mass balance of the ice sheet, which is controlled by climate. Ice lobes, however, respond quickly to changes in mass balance and bed

conditions of their respective icesheds and may therefore appear to be out of phase with nearby lobes and regional climate.

Because the ice lobes were comparatively thin—decreasing from approximately 1 km where they left the ice sheet—existing structural and alluvial lowlands controlled the direction of ice flow. These lowlands were deepened even more owing to the enhanced glacial erosion resulting from fast, focused flow of the ice. The Great Lakes are well known examples of basins that controlled the flow of lobes; others include Great Bear Lake in the Northwest Territories, Great Slave Lake in the District of MacKenzie, Lake Athabasca, on the Alberta-Saskatchewan border, Reindeer Lake in Saskatchewan, and Lakes Winnipeg and Winnipegosis in Manitoba.

Evidence indicates that the development of ice lobes (or 'outlet lobes') may be the result of ice streams (Patterson, 1997). Ice flow hundreds of km up-ice from the outlet lobes may begin to converge into a narrow, fast-moving streams of ice (Dyke and Prest, 1986; Fulton, 1989; Thorliefsson and Kristjansson 1993; Fulton, 1995). The nature and distribution of glacial sediment and landforms implies that ice flow was much different in these narrow convergent zones. Till associated with ice streams is more distally derived, homogenous, traceable for hundreds of km, and typically has a level-to-streamlined surface expression. Tills deposited outside these narrow convergent zones are usually thin and locally derived.

Models for the mechanics of ice movement that are based on the study of modern ice sheets (Fowler and Johnson, 1995) predict that slow, uniform flow of ice is unstable and therefore unlikely. What is predicted and observed, by contrast, is a bimodal style of ice flow, with fast ice streams (km/yr) moving within slower ice (cm/yr). The location of ice streams appears to change over time, but is influenced by bed topography and hydrogeology. Ice streams and their outlet lobes are the major discharge areas for an ice sheet, and their development is largely a function of subglacial water. Ice streams draw down the ice mass in the ice accumulation centers. Ice-lobe advances therefore represent a redistribution of ice, and may actually signal the overall decay of the ice sheet rather than an increase in volume of the ice sheet.

The deglacial record of the Late Wisconsinan Laurentide ice sheet indicates that in the areas of continuous ice cover in Canada, ice streams developed within the ice sheet and fed the ice lobes that moved through the Great Lakes basins into the upper Midwest (Dyke and Prest, 1986; Hicock and Dreimanis, 1992; Thorleifson and Kristjansson, 1993). The ice streams were active throughout the retreat of the ice across Canada as documented in the pattern of moraines (Dyke and Prest, 1986; Fulton, 1995). It is unclear if ice streams were also important during ice-sheet growth because the effects of subglacial water are difficult to ascertain. This model of ice flow can be cautiously extended to earlier glaciations, bearing in mind that bed conditions could have been very different from those of more recent events.

The advantages of studying the geological record of Quaternary glaciations include: (1) the relatively excellent preservation, continuity and accessibility of the deposits; (2) the location of the deposits within a well established paleogeographic, paleomagnetic, and tectonic setting; (3) records for floral and faunal succession and pluvial lake-level histories that allow the construction of predictive global circulation models; (4) direct evidence of global ice volume from the ocean oxygen isotope record as well as the record of crustal rebound; and (5) fairly easy access to modern analogs (for example, the study

of Antarctic ice is relatively easy compared to the study of a deep magma chamber). These advantages also provide the greatest challenge to Quaternary researchers, who are required to integrate data across a wide range of disciplines and geographic areas. The ultimate goal is to provide a integrated picture of the geosphere, hydrosphere and biosphere for a specific period of earth's history, and to extend this understanding to more obscure glacial periods in the geologic record.

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WHAT'S NEXT FOR GEOLOGY IN THE LAKE SUPERIOR AREA?

SOUTHWICK, David L., Minnesota Geological Survey, 2642 University Ave. W., St. Paul, MN 55114-1057

Marvelous progress has been made in deciphering the complex, diverse geological framework of the Lake Superior region over the past twenty years. In particular, our comprehension of the Precambrian rock record has progressed remarkably through excellent programs of geologic mapping, regional geophysics, geochronology, and related topical research supported largely by government and justified on the premise that geologic understanding of Precambrian terranes will lead to discovery of economic mineral deposits. One hopes that this momentum can be sustained and that intellectual and technological progress toward the goal of finding and developing viable ore deposits will continue. Sustaining it will not be easy in the prevailing political climate, however.

Ultimately, albeit indirectly, the policies of democratic governments are determined by public opinion that is transmitted to elected representatives. At the present time the public is not particularly concerned about mineral commodities and therefore minerals issues do not have a high political profile. There are no pressing shortages, prices are moderate and stable, unemployment is generally low, and concerns for present-day "quality of life" issues greatly outweigh concerns for the long-term availability of mineral and energy resources in the minds of most people. As a consequence, elected representatives are being urged by their constituents to preserve and promote environmental quality, provide recreational opportunities in wilderness areas, improve urban infrastructure, combat crime, improve health care, extend educational opportunities, and reduce taxes. They are not being urged to provide for the well-being of a mining industry that we geologists know is vital to the long-term sustainability of the quality of life, because there is a powerful human tendency not to worry about future difficulties until circumstances absolutely demand it. Instead of mining, the plexus of environmental issues that immediately affect human health and happiness will be the primary driver of public resource policy and derivative geological investigations in the Lake Superior region over the next twenty years. Although metal mining and related industries surely will remain significant to local economies and will receive passive political support, they will not in themselves provide the rationale for increasing public expenditures on geological investigations.

The following will be growth areas for applied geologic thinking and research in the Lake Superior region. (1) Detailed characterization of unconsolidated materials within the uppermost 100 m of the geologic section. This work will involve collaboration among glacial geologists, stratigraphers, geophysicists, geochemists, hydrogeologists, and soil scientists and will have direct application to a number of societal concerns. It will also benefit mineral exploration, but it will not be justified on that basis. (2) The development and deployment of improved geophysical tools for obtaining information about the shallow subsurface. (3) Detailed geologic mapping of surficial deposits, especially in urban, urbanizing, and agricultural areas. Regional mapping to provide the stratigraphic framework of the Quaternary materials will be necessary as well, but the more pressing need will be for detail. (4) Hydrogeologic studies on a variety of scales, with particular emphasis on the geological controls of ground-water flow. Fractured-rock hydrogeology will be a developing area of research in which sedimentologists, petrologists, and structural geologists will become increasingly involved. (5) Low-temperature rock-water geochemistry, with applications to problems of surface-water and ground-water composition and the transport of dissolved chemical species. (6) The mapping and characterization of aggregate resources. (7) Characterization and control of mined land and mine waste, in which the full spectrum of hydrogeological and geochemical methodologies are brought to bear. (8) Geological and geophysical studies within Lake Superior itself that will be predicated on calibration of the paleoclimate record but will extend to investigations of lake-basin evolution.

As the geological profession becomes ever more dependent on government policies, our near-term research opportunities inevitably will reflect public priorities. This need not and will not mean the total demise of economic geology and the hard-rock disciplines that support it. However, traditional hard-rock work will diminish in favor of non-traditional investigations in which hard-rock thinking and skills can be applied. Flexibility of training and outlook will be critical to professional success.



GENERAL TECHNICAL SESSIONS

PETROGRAPHY AND GEOCHEMISTRY OF MIDCONTINENT RIFT RHYOLITE (CHENGWATANA VOLCANICS) NEAR CLAM FALLS, WISCONSIN

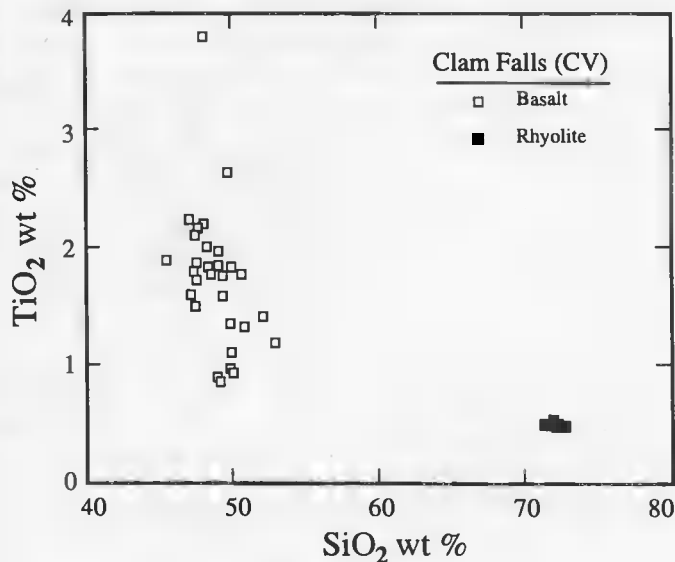
ABBOTT, Kathleen M., THOLE, Jeffrey T., WIRTH, Karl R., Geology Department, Macalester College, St. Paul MN, 55105; kabbott@macalester.edu; thole@macalester.edu; wirth@macalester.edu

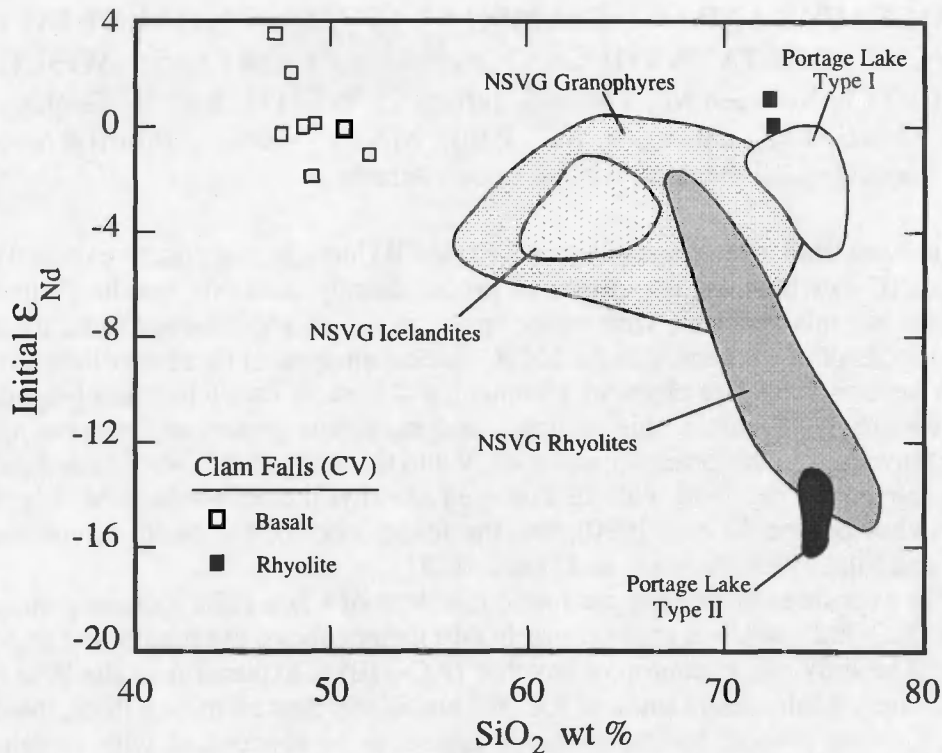
The southwest limb of the Midcontinent Rift (MCR) includes the poorly-exposed Chengwatana Volcanics (CV) which are comprised of predominantly tholeiitic basalts (Wirth et al., 1997, Naiman et al., this volume), with minor rhyolites which are believed to be the southernmost exposed rocks of this type within the MCR. Recent analysis of these rhyolites found near Clam Falls, Wisconsin, provides physical, chemical, and isotopic data which has helped constrain the timing (Wirth and Gehrels, this volume), and magmatic processes (Naiman and Wirth, this volume) involved in the generation of the CV and the southern MCR. These data are also used to compare the CV rhyolites with the Portage Lake rhyolites of northern Michigan (Nicholson, 1992, Nicholson and Shirey, 1990), and the felsic rocks of the North Shore Volcanic Group (Green and Fitz, 1993, Vervoort and Green, 1997).

Two exposures of rhyolite are found just west of Clam Falls including about 5 meters of rhyolite (KC-302) which is approximately 640 meters above the base of the exposed volcanic section. The only other outcrop of rhyolite (KC-310) is exposed near the base of the section approximately 3 kilometers south of KC-302 and is less than 10 meters thick. No flow contacts or foliations are present but the outcrops appear to be concordant with surrounding basalts which trend northeast and dip approximately 15 degrees to the northwest in this area. The base of the outcrop at KC-302 appears to be an intrusive contact with the underlying basalt and locally, the rhyolite contains subangular inclusions of ophitic basalt. The nature of emplacement of these rhyolite bodies is unclear.

The rhyolites are generally weakly (<5%) porphyritic containing small phenocrysts (~1mm) of euhedral to subhedral plagioclase (avg. $Ab_{94}An_2Or_4$) and trace amounts of subhedral Fe-Ti oxides. Quartz phenocrysts and albite glomerocrysts are present only locally. Amphiboles, partly replaced by chlorite/epidote/carbonate, are rare. The groundmass is commonly spherulitic (up to 2 - 3 mm) with phenocryst nuclei, containing tabular quartz (tridymite paramorphs), dusty, anhedral alkali feldspar (avg. $Ab_4An_1Or_{95}$), very fine-grained disseminated Fe-oxides, and local poikilitic anhedral quartz. Accessory zircon is present as minute euhedral prisms in most samples. The presence of minor epidote and carbonate within the groundmass is ubiquitous. Some samples contain minor diktytaxitic cavities. The presence of tridymite paramorphs indicate these rocks are similar to some rhyolites of the NSVG which are believed to have erupted at high temperatures (Green and Fitz, 1993). No apparent flow foliation or pyroclastic textures were observed in the exposures near Clam Falls.

Only basalt and rhyolite are present in the Clam Falls' section; no rocks of intermediate composition have been identified. Rocks of intermediate composi-





tions are found in both the NSVG and the Portage Lake Volcanics. Chengwatana basalt geochemistry is discussed by Naiman et al., this volume. The felsic Chengwatana rocks can be classified as tholeiitic rhyolites. The rocks are metaluminous and only one sample has normative corundum (0.16%). In general, the rhyolite chemistry is similar to both NSVG and Type I Portage Lake rhyolites. Notable variations from these two groups include slightly less SiO_2 (71-72%), higher total Fe (4.87 to 5.78 $Fe_2O_3\%$), higher Th (25-27 ppm), and significantly higher Zr (713-986 ppm).

Initial ϵ_{Nd} (1100 Ma) values on two Chengwatana rhyolites are 0.95 and -0.06. These values are similar to Chengwatana basalts of the Clam Falls region (-2 to +3.4). The Chengwatana rhyolite ϵ_{Nd} values are most similar to Portage Lake (Type I) rhyolites which range from -0.3 to -4.7 (Nicholson and Shirey, 1990) and are distinct from rhyolites of the NSVG which range from -2.3 to -14.8 (Vervoort and Green, 1997). NSVG granophyres and icelandites have ϵ_{Nd} values with a smaller range than NSVG rhyolites and these values are also lower than Chengwatana rhyolites. Large degrees of crustal melting are invoked as a major process in forming the NSVG rhyolites as indicated by the low ϵ_{Nd} values (Vervoort and Green, 1997). The Chengwatana rhyolites at Clam Falls lack the pronounced crustal Nd isotopic signature evident in the NSVG rhyolites and are believed to be fractionates of a primary basaltic magma derived from an enriched mantle source.

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A PRELIMINARY DETAILED GEOLOGICAL DESCRIPTION OF THE NEW HIGH GRADE SILVER-BASE METAL DISCOVERY IN THE LUMBY LAKE METAVOLCANIC BELT NORTHEAST OF ATIKOKAN, ONTARIO, CANADA

BERNATCHEZ, Raymond A., President & Consulting Geologist to Atikokan Resources Inc., P.O. Box 1376, 126 Willow Rd., Atikokan, Ontario, Canada, P0T 1C0. Tel. 807-597-4526, Fax 807-597-4636 (rbernatc@atikokan.lakeheadu.ca)

A high grade silver-zinc-lead mineral occurrence has been discovered within an east-west stratabound felsic volcanoclastic horizon at the southern edge of the Lumby Lake Metavolcanic Belt. Located north of the creek connecting Lumby and Herontrack Lakes, the discovery occurs at the southern margin of a 1.5 km thick east-west trending felsic volcanic package near the southern contact of the Lumby Lake Metavolcanic Belt with the Marmion Lake tonalite batholith to the south. The Lumby Lake volcanic belt is located 23 air miles northeast of Atikokan, Ontario, Canada and forms the northeasterly extension of the Steep Rock and Finlayson Lake volcanic stratigraphy. This discovery is contained within highly (hydrothermally) altered felsic volcanoclastic rocks having geological and geochemical features similar to other Archean massive sulphide deposits. However, the felsic volcanic rocks hosting this high grade silver-base metal occurrence have been dated at 3.0 Ga (Mesoarchean; Davis and Jackson, 1988), whereas all other base metal deposits found in the Archean in Ontario have been dated at 2.7 Ga. The occurrence contains unusually high silver content with some random grab samples assaying as high as 416 ounces/ton (14,265 gm/tonne) or 270 oz/ton over 1.1 meter (9292 gm/tonne).

The Lumby Lake greenstone belt is located within the Wabigoon subprovince, 30 km north of the Wabigoon-Quetico subprovince boundary and 37 air km northeast of Atikokan, Ontario. The Lumby Lake greenstone belt consists of a 60 km x 20 km synclinal supracrustal sequence of rocks composed of mafic (pillowed and massive), ultramafic (komatiitic), and felsic (tuff, lapilli tuff, tuff breccia, massive), metavolcanic rocks with lesser amounts of metasedimentary rocks (chert, argillite, arkose, conglomerate and iron formations). The metavolcanic-metasedimentary assemblage is in contact with the Marmion Lake Batholith to the south and the White Otter Batholith to the northwest. The belt has been intruded by two larger oval and heterogeneous monzodiorite-granite plutons, the Norway Lake and van Nostrand Lake Stock and smaller ones (the Bar Lake and Viking Lake stocks).

The Belt has been subjected to four major structural events: at least two folding events and two faulting-shearing events. The Belt has had a major synclinal folding event with its axis trending east-west through the central portion of the belt through Seahorse-Garnet Bay-Pinecone-Hematite Lakes system. The van Nostrand Lake stock intrudes this axis in the central part of the belt. A second folding event occurs within the interflow sedimentary units. The Redpaint Lake Fault truncates the Lumby Lake belt to the west. Two east-west deformation zones have been noted: the Bufo Lake - Spoon Lake Deformation Zone and the Garnet Bay-Viking Lake-Hematite Lake Deformation Zone.

The silver-base metal discovery is located in the western block of claims known as the Herontrack Lake Block and within the southwest portion of the Lumby Lake greenstone belt. A 130 km grid has been established in the central portion of this block from Lumby Lake to Hutt Lake. A detailed exploration program over this grid consisting of geological mapping, soil geochemical sampling, magnetic and partial VLF EM and IP surveys, lithochemical

sampling and overburden mechanical stripping has identified and exposed numerous sulphide bearing felsic volcanoclastic horizons containing economic to subeconomic values in zinc, copper, silver, lead and gold.

The detail geological mapping has identified five rock types: mafic volcanic, massive and pillowed; felsic volcanic, tuff, lapilli tuff, tuff breccia and coarse breccia, massive rhyolite as feldspar and/or quartz porphyries and cherty rhyolite; mafic to intermediate intrusive rocks (gabbro and diorite) as dykes and sills intruding the above; Marmion Lake batholith (tonalite) and finally felsic dikes intruding the felsic volcanic rocks.

The bulk of the mineralization is contained within stratabound interflow sediments. Pyrite, and in some interflow units, pyrrhotite make up the bulk of the sulfides. The high grade silver-zinc-lead discovery zone contains significant amounts of pyrite, sphalerite, galena, acanthite and native silver with minor chalcopyrite. This mineralization is contained within highly altered felsic volcanic rocks. The felsic rocks have been altered to sericite and chlorite in some locations. The sericite was previously interpreted as an altered and sheared quartz diorite; it now appears that this alteration was caused as the result of the footwall alteration associated with massive sulphide deposits. This has been partially confirmed by some limited lithogeochemical rock sampling.

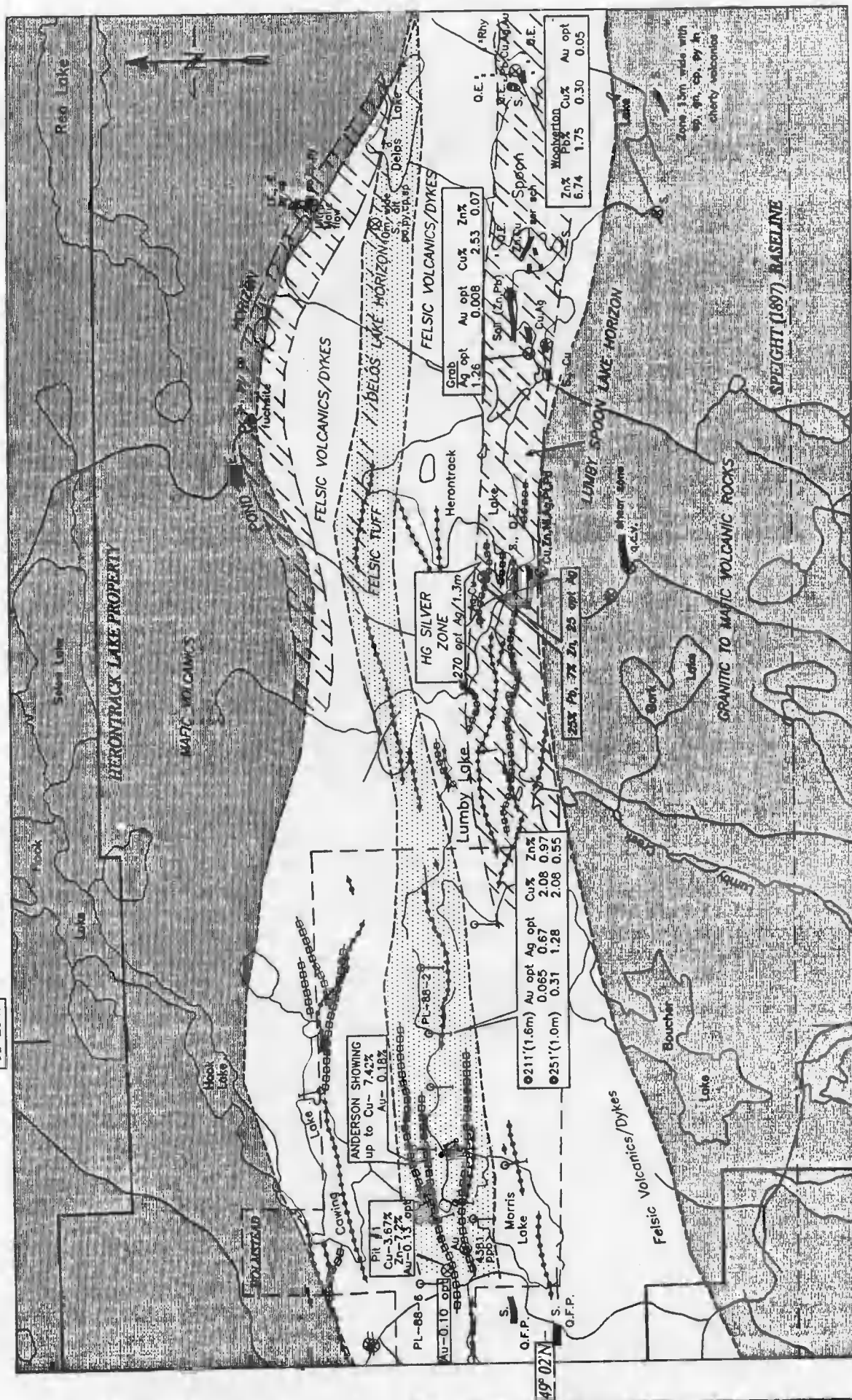
The exploration program carried out to date has identified three highly altered base metal mineralized horizons. The most economically significant horizon identified to date is the Lumby Lake-Spoon Lake Horizon which hosts the high grade silver discovery. Several other significant silver and base metal-bearing occurrences have been discovered along this 250 to 300 meter wide sulphide horizon that has now been traced for a strike length of about 6 km by mechanical stripping and geophysical surveys. Two additional altered sulphide base metal bearing felsic volcanic horizons (Delos Lake and Pond Lake Horizon) have been located a few hundred meters north of the silver discovery horizon.

The Questor Airborne Geophysical Survey carried out by the Ontario Geological Survey in 1980 did not identify any input anomalies along the Lumby Lake-Spoon Lake mineralized horizon. However, a broad magnetic low covers the area over the newly identified felsic strata. This magnetic low can be traced east-west along the southern volcanic-granite contact of the Lumby Lake greenstone belt for over 12 km from Bufo Lake to Hutt Lake. Other similar magnetic lows can be traced eastward to Old Man Lake a distance of over 13 km. Similar felsic volcanic rocks have been identified in these areas. A new copper-zinc-silver occurrence has been found along this magnetic low response near a series of airborne input anomalies at the west end of Old Man Lake. The OGS airborne geophysical survey has detected numerous other anomalies in the Lumby Lake greenstone belt, of which most have never been examined or tested. What other base metal discoveries will the Belt reveal?

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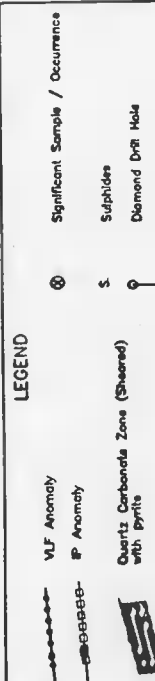
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ATIKOKAN RESOURCES INC.

HERONTRACK LAKE PROPERTY

WEST CLAIM GROUP



JAN 98 NTS: 52 G103

DIMENSION STONE PRODUCTS OF MINNESOTA

BOERBOOM, Terrence J., Minnesota Geological Survey, 2642 University Avenue, St. Paul, MN 55114; boerb001@tc.umn.edu; and OBERHELMAN, Matt, Minnesota Department of Natural Resources - Division of Minerals, 1525 E. 3rd Street, Hibbing, MN 55746-1461; matt.oberhelman@dnr.state.mn.us

The first dimension stone quarry was opened in 1868, to supply gray granite from the St. Cloud District for construction of the St. Paul Customs House and Post Office. Since then, the dimension stone industry in Minnesota has grown considerably. At present there are fourteen active dimension stone quarries in the state, and several others that are active on an intermittent basis. Dimension stone products from Minnesota are marketed worldwide, and are used for a variety of purposes that include interior tiling, counter tops, monuments and memorials, "surface plates" for precision machine mounts, acid-resistant industrial applications, decorative and structural exterior panels for major buildings, and grinding mill liners and balls.

The results of a recent Minnesota Department of Natural Resources' dimension stone inventory show that northern Minnesota offers excellent potential for further development of high quality dimension stone products. Field investigations have identified twenty-two prospect sites that exhibit potential for quarry development. Prospects have been identified in Middle Proterozoic rocks (ca. 1100 m.y.) of the Duluth Complex and Archean rocks (ca. 2700 m.y.) of the Vermilion Granitic Complex and other granitoid rock units. Prospects include black, green, pink, beige, and multi-colored stone with a variety of textures. Prospect evaluation included outcrop observations that considered joint spacing, color, texture, and deleterious materials. Results of the inventory are described in the following three MDNR reports: Dimension Stone Inventory of Northern Minnesota 1991, Report 289; Dimension Stone Inventory of Northern Minnesota 1993, Report 298; and Dimension Stone Inventory of Northern Minnesota 1995, Report 298-2.

Cold Spring Granite Co. is currently leasing three of the prospect sites identified by the dimension stone inventory study, and have opened quarries on two of these leases. Both utilize gabbroic anorthosite of the Duluth Complex; the stone from these sites is marketed under the names Mesabi Black and Lake Superior Green.

This poster display shows products from all of the currently active quarries in the state of Minnesota, along with samples of dimension stone prospects that were collected and prepared by the Minnesota DNR-Minerals Division (see below). The numbers on the samples refer to locations on the index map. The table on the following page summarizes the geologic aspects of the various dimension stone products of Minnesota.

ACKNOWLEDGMENTS

All of the quarry companies listed on the following table kindly contributed samples of their products to the Minnesota Geological Survey for this display.

Sample	Company	Trade Name	Geologic Unit	Age	Dominant Mineralogy	Texture
1	CSG	Mesabi Black	Duluth Complex	~1090 Ma	P, cpx, ilm	mgr, lam, lin, oph
2	CSG	Lake Superior Green	Duluth Complex	~1090 Ma	P, cpx, gp, ilm	very cgr, porph
3	CSG	Iridian	Isle Granite	1812 - 1770 Ma	K, P, Q, bi	m-cgr, porph
4	CSG	Charcoal Black	Reformatory granodiorite	1812±9 Ma ¹	P, K, Q, bi, hbl, sph	m-cgr, sl. porph.
5	CSG	Diamond Pink	Rockville Granite	1812±9 Ma ¹	K, P, Q, bi, hbl, sph	m-cgr, porph, rkv,
6	CSG	Rockville Beige	Rockville Granite	1812±9 Ma ¹	K, P, Q, bi, hbl, sph	cgr, porph, rkv,
7	CSG	Rockville White	Rockville Granite	1812±9 Ma ¹	K, P, Q, bi, hbl, sph	cgr, porph, rkv,
8	CSG	Agate	Unnamed	2618±1 Ma ²	K, P, Q, bi	cgr
9	DGC	Bellingham Granite	Unnamed	2618±1Ma ?	K, Q, P, bi	cgr
10	JSC		Sioux Quartzite	1700 - 1750 Ma	Q	recrystallized quartzite
11	CSG	Rainbow	Morton Gneiss	2600 - 3600 Ma	K, P, Q, bi, hbl	gneissic banded, gbl
12	MKS	Varieties of pink-gray	Oneota Dolomite	Earliest Ordovician	dolomite	bioturbated micro-xln.
13	VSC	Varieties of pink-gray	Oneota Dolomite	Earliest Ordovician	dolomite	bioturbated micro-xln.
14	BSC	Winona Dolomite	Oneota Dolomite	Earliest Ordovician	dolomite	bioturbated micro-xln.

Company abbreviations: **CSG** - Cold Spring Granite, **JSC** - Jasper Stone Company, **DGC** - Dakota Granite Company, **MKS** - Mankato-Kasota Stone, Inc., **VSC** - Vetter Stone Co., **BSC** - Biesanz Stone Co.

Mineral abbreviations: **P** - plagioclase, **K** - potassic feldspars, **Q** - quartz, **cpx** - clinopyroxene, **hbl** - hornblende, **bi** - biotite, **ilm** - ilmenite, **sph** - sphene, **gp** - granophyric quartz/feldspar, **xln** - crystalline

Texture abbreviations: **mgr** - medium-grained, **cgr** - coarse-grained, **lam** - igneous lamination (cumulus or trachytoid), **lin** - lineated, **rkv** - rapakivi, **gbl** - granoblastic, **oph** - ophitic, **porph** - porphyritic

¹U-Pb zircon date (Goldich pers. commun., as reported in Horan and others, 1987)

²U-Pb zircon date (Mark Schmitz, Massachussettes Institute of Technology, pers. comm., 1998)

GROUND WATER RECHARGE, DISCHARGE AND RESIDENCE TIME IN RICE COUNTY, MINNESOTA -- IMPLICATIONS FOR LAND USE PLANNING

CAMPION, Moira -- Minnesota Department of Natural Resources
e-mail -- moira.campion@dnr.state.mn.us

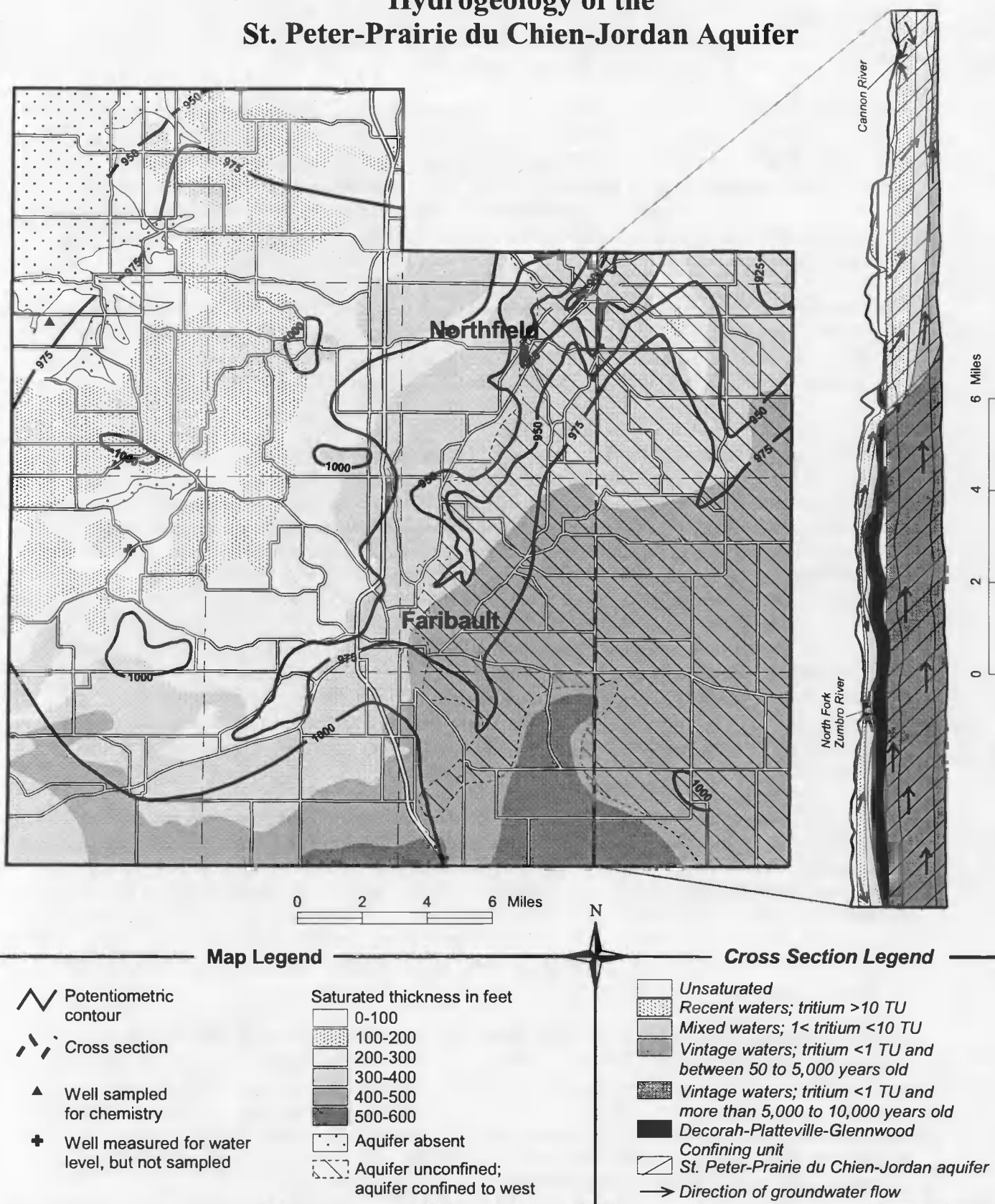
Rice county is located 40 miles south of the Minneapolis-St. Paul metropolitan area. The county contains urban, suburban, and rural areas and faces increasing development pressure for housing as well as for recreational and high intensity agricultural purposes. Water supply in the county is primarily from ground water and most of the 1600 wells in the county data base are completed in the St. Peter-Prairie du Chien-Jordan aquifer. This bedrock aquifer is confined throughout the western and southeastern portions of the county and is unconfined in the east-central and northeast. The potentiometric surface shows a regional high in southwest Rice County and lows in the central and northeast parts of the county where the aquifer discharges into local streams.

Throughout most of the county the aquifer is protected from direct surface recharge by various consolidated and unconsolidated low permeability materials, except in the northeast where the aquifer is exposed at or near the surface. The various low permeability deposits and their distribution result in different recharge conditions to the bedrock aquifer. In the northeast, where the aquifer is not protected by overlying material, recharge to the aquifer occurs directly through percolation from the land surface. In western Rice County, there are abundant lakes and wetlands in a hummocky terrain of thick supraglacial tills. Recharge to the bedrock aquifer occurs in complicated flowpaths through the lakes and tills in this part of the county. In the southeast, the Decorah-Platteville-Glenwood confining unit and some older tills cover the aquifer. Where this relatively thin package of shales and limestones is continuous, the St. Peter-Prairie du Chien-Jordan aquifer receives very little vertical recharge from the surface. Conversely, near the edge of this confining unit, recharge may be as much as 30 times greater than underneath this unit (Delin, 1991). Discharge from the aquifer occurs where ground water drains into the Cannon River, the Straight River, and Prairie Creek. Residence time of ground water was estimated using tritium and ^{14}C age-dating. These isotopic age estimates confirm the conceptual model of recharge in the county. Ground water is youngest in the northeast where low permeability cover is absent and oldest in the southeast under the Decorah-Platteville-Glenwood confining unit. Isotopic results in western Rice County show ages greater than tritium dating limits but less than a few centuries old.

Knowledge of these differing recharge conditions, coupled with geologic and hydrologic information, provides county planners with an important water resource management tool. This information allows county staff to decide where modification to current land use practices would minimize potential negative impacts on ground water quality. Basing land use planning decisions on resource management concepts rather than on politically based situations will increase the chance of resource protection.

RICE COUNTY, MINNESOTA

Hydrogeology of the St. Peter-Prairie du Chien-Jordan Aquifer



THE GEOLOGICAL SOURCE OF ARSENIC IN GROUND WATER IN SOUTHEASTERN MICHIGAN

W.F. Cannon and Alan Kolker, U.S. Geological Survey, Reston, VA

D.B. Westjohn, U.S. Geological Survey, Lansing, MI

The ground water in parts of nine counties in southeastern Michigan contains anomalous quantities of dissolved arsenic, presumably derived from a natural source. Many wells tested by the Michigan Department of Community Health and by the USGS exceed the U.S. Environmental Protection Agency's maximum contaminant level (MCL) of 50 $\mu\text{g/L}$ for drinking water. Extreme values are as high as 350 $\mu\text{g/L}$. In one county (Huron) about 30% of the tested wells exceeded the MCL for arsenic. Most wells with elevated arsenic were completed in the Mississippian Marshall Sandstone, but other units, particularly glacial aquifers, can also yield arsenic-contaminated water.

The nine affected counties have a combined population of more than 2 million people. The Marshall Sandstone is the principal bedrock aquifer in most of the affected counties and in some areas is the sole-source aquifer. These conditions combine to make knowledge of the natural source for arsenic a critical aspect in designing a strategy to provide a continued supply of safe drinking water for this region.

As part of a larger study of this problem, we have been examining the lithology, mineralogy, and chemistry of the Marshall Sandstone to better define the geographic, stratigraphic, and mineralogic distribution of arsenic in bedrock. In October 1997, a well was drilled and cored to collect a complete stratigraphic section of the Marshall Sandstone and immediately overlying and underlying units. The hole was drilled in Huron County, near one of the most contaminated wells known in the study area. Core from that hole and cuttings and core from other producing wells have formed the basis for this study.

The Marshall Sandstone is a fluvial to marginal marine sequence that is present at subcrop in a belt encircling the central part of the Michigan Basin. Arsenic-contaminated ground water is known only along the eastern flank of the basin. As seen in the Huron County core, the Marshall is a very heterogeneous unit of medium- to coarse-grained, gray to brown sandstone interbedded with massive to laminated gray and red siltstone and thin units of black to gray shale. Fossil plant debris is present and pyrite is common in accessory amounts in many units.

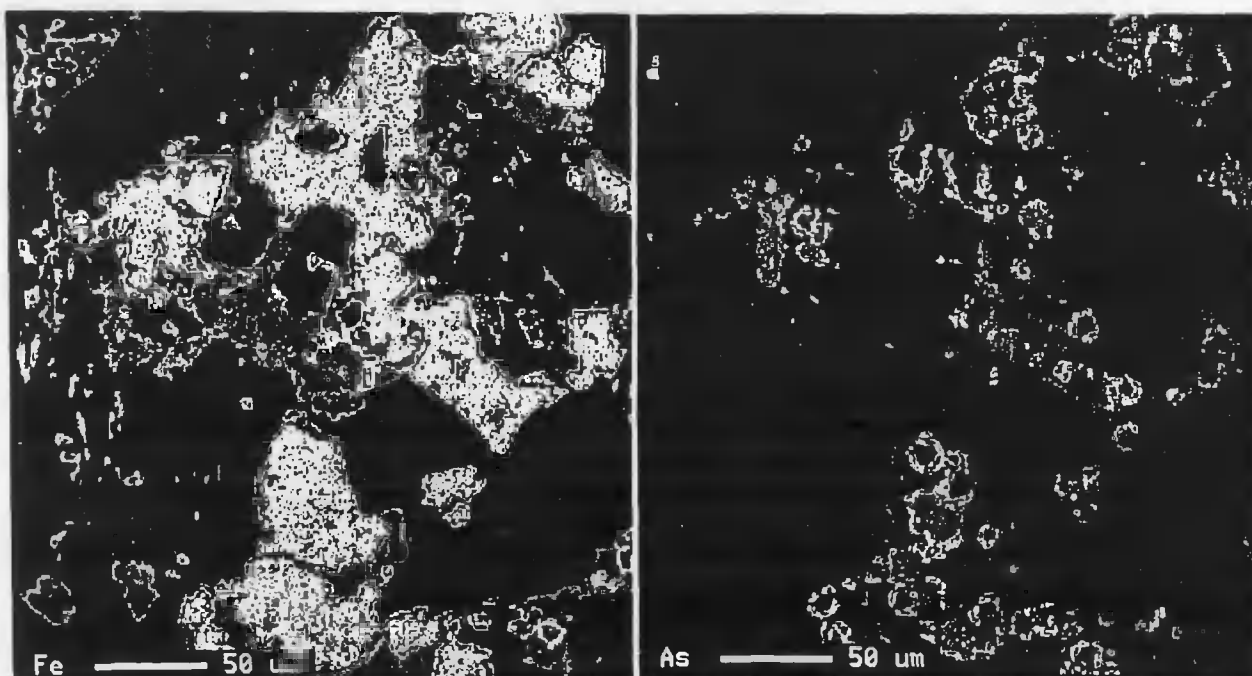
Arsenic is very unevenly distributed in the Marshall. Highest values in the Huron County core, up to 255 mg/kg, are in black shale units. Most sandstone and siltstone have an arsenic content below the analytically detectable limit (5 mg/kg), but some sandstone beds contain as much as 25 mg/kg arsenic. Average sandstones contain about 2 mg/kg arsenic, and so even these relatively low values are anomalous. Cuttings from wells in adjacent Lapeer County contain as much as 350 mg/kg arsenic. The strongly anomalous arsenic content of the Marshall Sandstone in the area of arsenic contaminated ground water lends strong support to the earlier belief that the source of arsenic is natural and within the Marshall aquifer.

Electron microprobe studies of well cuttings from Lapeer and Tuscola Counties show that essentially all arsenic is in pyrite. Pyrite is ubiquitous in the Marshall Sandstone, typically in trace concentrations, but locally constitutes from a few percent to as much as 20 percent of the rock, mostly as pore-occluding cement. Pyrite formed during several stages of diagenesis. Early diagenetic pyrite formed coatings on detrital grains. Framboidal pyrite formed in intermediate stages of diagenesis and precipitated on authigenic carbonate and chlorite or on authigenic quartz overgrowths. Late stage pyrite encapsulated framboids and in places formed displacive pyrite masses.

Arsenic is very unevenly distributed in pyrite at virtually all scales, even to the limit of resolution of the microprobe. Many pyrite grains have little or no arsenic at the limit of detection (about 0.01 mass percent), whereas nearby grains (within the same rock chip) may have extreme arsenic enrichment. Individual analyzed points contain as much as 6.5 mass percent arsenic. Arsenic shows a variety of modes of occurrence, but the most common is as strong enrichments in rims on individual framboids (see figure). It appears that a majority of arsenic was introduced during an intermediate stage of pyrite diagenetic growth, at the end of framboidal pyrite formation. Both framboid cores and later overgrown pyrite are not enriched in arsenic. Some other trace elements also show enrichment. Some arsenic-enriched pyrite contains as much as 0.7 mass % Ni and 0.5 mass % Co.

A critical remaining question is where and how arsenic is released from pyrite to contaminate ground water. In general, the oxidation of arsenic-bearing pyrite must be the fundamental control of arsenic release. Most arsenic seems to be contained in black shale units, which are not aquifers and have not been observed to be undergoing oxidation. It seems likely, therefore, that arsenic is introduced to ground water from smaller concentrations in the coarser sandstones that form the aquifers within the Marshall Sandstone. Observed arsenic content of coarse sandstone is as high as 25 mg/kg over several feet, or tens of feet, of section. The sandstones, therefore, have concentrations several hundred times greater than the MCL for drinking water and are able in quantitative terms to provide enough arsenic to contaminate a large volume of ground water. Results to date indicate that the potential for natural arsenic contamination of ground water is controlled by a variety of factors including total arsenic content of the rock and hydrologic characteristics of the rock, and by poorly known factors such as biological mediation of pyrite solution and variable redox conditions of ground water in both time and place.

Electron microprobe map showing framboids of arsenic-poor pyrite encased in arsenic-rich pyrite, in turn overgrown by arsenic-poor pyrite. Map of iron distribution (left) outlines large pyrite grains (lightest shade) that have grown in pore space between quartz clasts (black). Authigenic clay (intermediate gray) also fills pore space. Arsenic distribution is shown on the right, the same field of view as the iron map. Arsenic is concentrated on rims of pyrite framboids now completely enclosed within late stage pyrite.



REINTERPRETATION OF THE PENOKEAN CONTINENTAL MARGIN IN PART OF NORTHERN WISCONSIN AND MICHIGAN

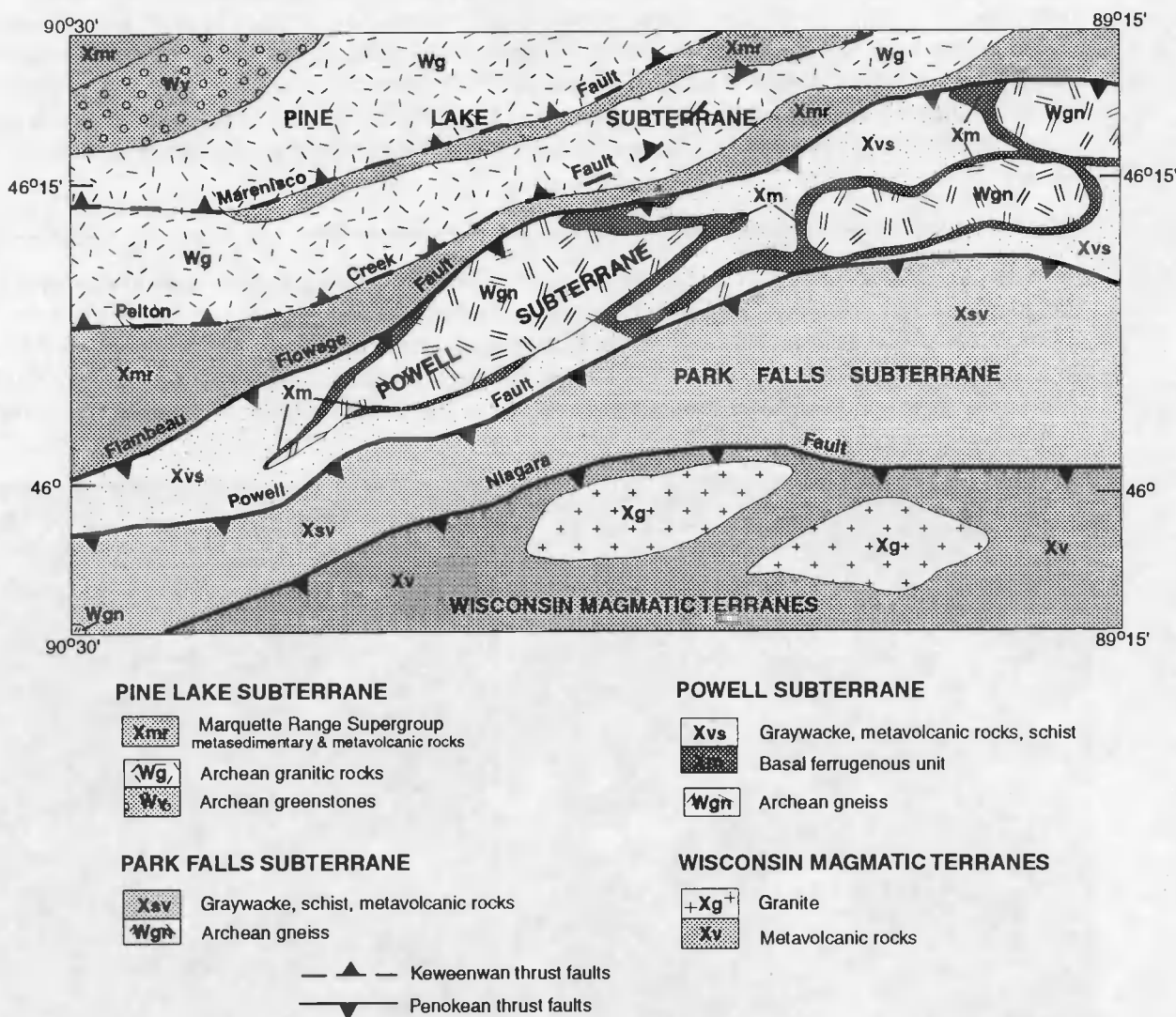
W.F. Cannon, U.S. Geological Survey, Reston, VA

G.L. Laberge, UW-Oshkosh, Oshkosh, WI

J.S. Klasner, Western Illinois University, Macomb, IL

K.J. Schulz, U.S. Geological Survey, Reston, VA

The depositional and tectonic history of part of the Penokean continental margin has been clarified by field studies, and examination of previously proprietary¹ magnetic, electromagnetic, and drill core data. A continental margin terrane, informally called the Marquette terrane, inasmuch as it is composed largely of rocks of the Marquette Range Supergroup and its Archean basement, consists of three subterrane, each with its own characteristic depositional and tectonic history (see figure). The subterrane are separated by major Penokean faults, each probably a northward-directed thrust.



¹We thank Cominco American Incorporated and Kerr-McGee Corporation for permission to publish detailed aeromagnetic and electromagnetic data for parts of our study area.

The Marquette terrane includes those areas where the Marquette Range Supergroup was deposited in a tectonically unstable environment for at least part of its depositional history and was subsequently significantly deformed and metamorphosed during the Penokean orogeny. The terrane is bounded on the north by areas where the Marquette Range Supergroup was deposited in a stable cratonic or foreland setting and was not appreciably deformed during the Penokean orogeny (central Gogebic Iron Range for instance), and on the south by the volcanic arcs of the Pembine-Wausau terrane. The essential characteristics of each subterrane are outlined below.

Pine Lake subterrane

- Basement is Late Archean granite, greenstone, and metagraywacke.
- Early Proterozoic has quartzite and dolomite of Chocoma Group at base.
- Menominee Group consists of Palms Formation, iron-formation including shallow-water oolitic jasper, and abundant volcanic rocks. Group was deposited in tectonically active region, probably in syndepositional grabens.
- Early Proterozoic rocks were strongly deformed, generally with increasing intensity of deformation to the south.
- Archean basement rocks were not deformed penetratively during the Penokean orogeny.
- Penokean granitic rocks are rare.
- Metamorphic grade ranges from chlorite to garnet (locally staurolite).

Powell subterrane

- Basement is Early and Late Archean gneiss.
- Early Proterozoic rocks include a widespread basal unit of ferruginous slate and lean iron-formation, quartzite, and black sulfidic slate and an overlying succession of metapelitic and lesser metavolcanic rocks. The rocks are probably broadly correlative with the Marquette Range Supergroup, but details of correlation are not known.
- Archean basement was penetratively deformed along with Early Proterozoic cover during the Penokean orogeny.
- Dikes and segregations of Penokean granitic rocks are widespread.
- High temperature and high pressure metamorphism occurs throughout. Pelitic assemblages are biotite-garnet-staurolite-kyanite.

Park Falls subterrane

- Basement is Archean gneiss.
- Early Proterozoic rocks are pelitic schist, carbonaceous sulfidic slate, and subordinate metavolcanic rocks. The rocks are probably broadly equivalent to the Marquette Range Supergroup but details of correlation are unknown.
- Rocks are intensely folded in multiple folding events.
- Dikes and segregations of Penokean granitic rocks are abundant.
- Metamorphism is moderate temperature and pressure. Pelitic assemblages are biotite-garnet-sillimanite.

The assemblage of subterrane hereby defined in Wisconsin and Michigan is similar to the assemblage known in analogous parts of the Penokean orogen in Minnesota. In particular, we suggest that the Flambeau Flowage Fault in Wisconsin and Michigan is the eastward extension of the Malmo discontinuity in Minnesota. Both structures thrust Archean gneiss and highly metamorphosed Early Proterozoic strata northward over less deformed and metamorphosed Early Proterozoic strata.

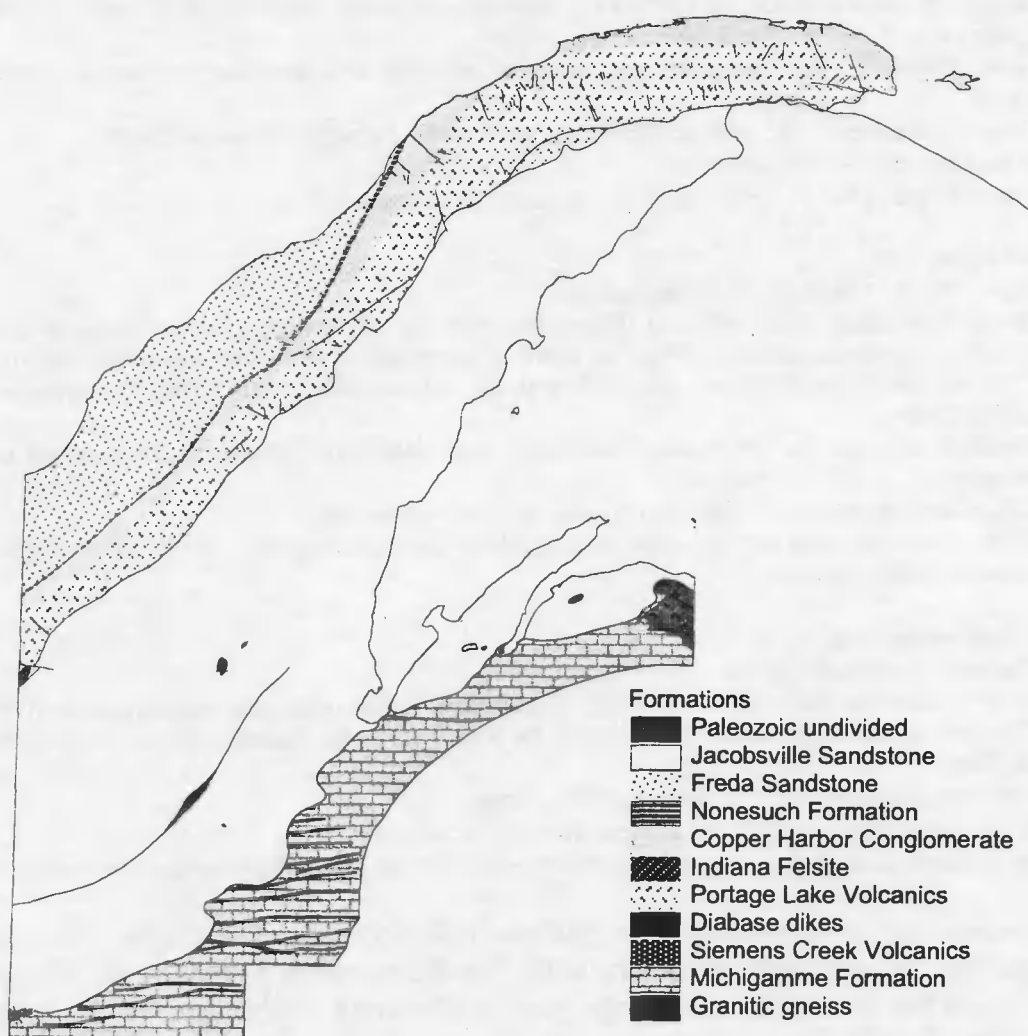
GEOGRAPHIC INFORMATION SYSTEM ON THE GEOLOGY AND COPPER DEPOSITS OF THE KEWEENAW PENINSULA

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

Michele E. McRae, Oak Ridge Associated Universities, Reston, VA

Suzanne W. Nicholson, U.S. Geological Survey, Reston, VA

Two new products on the geology and mineral deposits of the Keweenaw Peninsula and surrounding area have recently been developed: a traditional 1:100,000 scale U.S. Geological Survey geologic map (now in press) and a geographic information system (GIS) database. These products are based largely on detailed geologic maps, many at a scale of 1:24,000, published during the past 50 years. They present new data and interpretations in parts of the area. The paper product was compiled digitally and digital production techniques are being used to streamline the printing process.



Geology of the Keweenaw Peninsula and vicinity generalized by formation.

The data were developed using the Environmental System Resource Institute's ARC/INFO software and exported to ArcView. ArcView is a desktop mapping software package that provides a variety of tools for the display, query, analysis, and output of geographically referenced data sets. This particular GIS consists of coverages and tabular data on the geology, structure, mines, mineral deposits, hydrography, and transportation networks of the area. Most of the detail from the source maps has been incorporated into the database. Map views showing full detail can be constructed; however, the data have been structured to allow generalization by age, rock type, tectonic setting, or stratigraphic rank. The figure above was generated in ArcView, by generalizing the geologic units based on stratigraphic formation. ArcView also allows the user to access information either by interactively selecting features on a map view, or by performing logical selection on the data tables. For example, clicking on a mineral deposit with the 'identify' tool will open a window that provides tabular information on mines that worked the deposit, amount of production, years of production, and an estimate of the amount and grade of remaining identified resources. A logical search could be used to identify native copper lodes with greater than 1% Cu. Finally, this product will include geologic cross sections, a correlation chart, a description of map units, and interpretative text. The cross sections are dynamically linked to the cross sections lines on the map view.

GRAVITY AND MAGNETIC STUDIES IN THE VIRGINIA HORN AREA, NORTHEASTERN MINNESOTA

CHANDLER, Val W., JIRSA, Mark A., and LIVELY, Richard L. Minnesota
Geological Survey, 2642 University Ave., St. Paul, MN 55114
(chand004@maroon.tc.umn.edu)

Gravity and magnetic data were used to supplement geologic field mapping of Archean rocks of the Virginia Horn area of northeastern Minnesota. Although outcrop control is locally excellent, gravity and magnetic data assist to a minor degree in mapping areas covered by glacial deposits and mine dumps. More importantly, they provide additional information on geologic structure at depth. Preexisting subdivisions of the Archean and Paleoproterozoic rocks were used to guide mapping and geophysical work. Although the gross lithologic divisions have remained essentially unchanged, many details of their stratigraphic and structural relations are now much better known. Gravity data used in this study consist of preexisting stations in the state-wide database together with 203 new stations. The new gravity stations fill gaps in the previous coverage, and allow development of a 50 km northeast-southwest profile across the Archean rocks of the Virginia Horn area, together with five shorter (5-15 km) northwest-southeast profiles. The magnetic data are from the high resolution aeromagnetic survey of Minnesota; line spacing in the Virginia Horn area is 400 m. Subsurface structure was investigated using gravity and magnetic modeling on the long profile.

The gravity and magnetic data were interpreted using grid images of processed data. Unfiltered and derivative-enhanced versions of the gravity and aeromagnetic grids reveal many details of the bedrock geology. The northern part of the study area is underlain by Archean granitic rocks of the Giants Range Batholith. It is characterized by a strongly negative Bouguer gravity anomaly and a busy, moderate- to high-amplitude magnetic signature. The presence of intermediate to mafic phases within the batholith is indicated by more magnetic areas that are associated with highs in the derivative-enhanced gravity data. Derivative-enhanced magnetic data also delineate several previously unidentified northwest-striking faults that extend across the batholith. A discontinuous sliver of high-grade metavolcanic and metasedimentary rocks, the Minntac sequence, occurs along the southern margin of the batholith. A negative Bouguer gravity anomaly implies that the supracrustal rocks of the Minntac sequence are under-plated by granitic rocks at shallow depths. The Minntac sequence is separated from Archean rocks to the south by the east-west striking Laurentian fault. South of the Laurentian fault sub- to low-greenschist grade metavolcanic and metasedimentary rocks of the Archean Mud Lake and Midway sequences are characterized by a positive gravity anomaly and an extremely subdued magnetic signature. Rocks of the Mud Lake sequence form a broad southwest-plunging syncline. To the south and west, the supracrustal rocks of the Minntac, Midway and Mud Lake sequences are covered by the Paleoproterozoic Animikie Group. Regional gravity data indicate that the Archean rocks extend southwest as a major belt beneath the Animikie basin. The Biwabik Iron Formation of the lower Animikie Group is associated with complex, high-amplitude magnetic signatures; magnetic highs delineate oxide-rich taconites and magnetic lows delineate natural ores and faults.

Gravity and magnetic modeling was constrained by surface geologic mapping and rock properties determined from surface samples. The models indicate that most structures in the Archean rocks have near-vertical dips. The Giants Range Batholith and the low-grade supracrustal rocks of the Midway and Mud Lake sequences extend to about 5 km depth. The composition of the crust below 5 km remains uncertain, although the Minntac sequence (which we infer to have been uplifted along the Laurentian fault) may yield clues because it has been extensively invaded by tonalitic and other early phases of the Giants Range Batholith. Models clearly show that the low-grade sedimentary rocks of the Mud Lake sequence lie within a structural trough; low-density sediments as thick as 1 km are underlain

by moderately high-density rocks inferred to be largely basaltic. Thickness of the sedimentary rocks increases in stepwise fashion northwestward towards the center of the basin against northeast-striking faults. Sediment thickness is also interpreted to increase appreciably to the northeast. These results demonstrate that gravity and magnetic studies are valuable to a geologic mapping program, even in areas of abundant outcrop control.

ACKNOWLEDGMENTS

This study was supported by the Minnesota Legislature through the State Special Appropriation and an appropriation recommended by the Minnesota Minerals Coordinating Committee. The authors thank U. S. Steel Corporation, Inland Steel Mining Company, Cliffs Mining Services Company, LTV Mining Company, American Shield Company, the Duluth Mesabi and Iron Range Railway Company, and the Minnesota Power Company for access to their properties and for providing elevation data.

MINERAL POTENTIAL ASSESSMENT OF NORTHERN ST. LOUIS COUNTY, SOUTHEASTERN KOOCHICHING COUNTY, AND NORTHEASTERN ITASCA COUNTY, MINNESOTA

Val W. Chandler, M.A. Jirsa, and G.B. Morey, Minnesota Geological Survey
Presented by Tom Lawler, Department of Natural Resources, Division of Minerals

The Minnesota Geological Survey in a contract with the Department of Natural Resources, Division of Minerals produced a geologic map and mineral-potential assessment of a contiguous twenty-six township area in northern St. Louis, southeastern Koochiching, and northeastern Itasca Counties, Minnesota. Six tholeiitic to calc-alkaline volcanic sequences of the Archean Wawa subprovince are resolved that are usually separated by faults or metasedimentary belts, and are intruded by a variety of syn- to late tectonic granitoid plutons. Eight criteria are identified which indicate potential for twenty-two lode gold deposits; Six criteria identify potential for two iron-formation hosted replacement gold deposits; Seven criteria identify potential for four volcanic associated massive sulfide deposits; Seven criteria identify potential for mafic-ultramafic intrusion hosted Cu-Ni-PGE deposits; Six criteria identify potential for komatiite associated Ni-Cu-PGE deposits (although the criteria were developed only one area with PGE potential was identified); and Two criteria identify potential for two kimberlite hosted diamond deposits. All of these areas are to be regarded with appropriate caution and further evaluation would require detailed exploration including drilling.

The compilation of the bedrock geologic map (Plate 6), the magnetic and gravity model cross-sections (Plate 7) and the mineral potential assessment map (Plate 9) used available geologic data combined with gravity and airborne magnetic data. The interpretation used gridded forms of geophysical data that have been enhanced to emphasize near-surface geologic phenomena. Using the UTM based grid the aeromagnetic data were enhanced by reduction to vertical polarization and calculation of the second vertical derivative. These procedures shift anomalies more directly over their sources and eliminate interference from regional scale anomalies to help clarify the short wavelength signatures of shallow sources that lie at or near the Precambrian surface. With a similar procedure the gravity data were enhanced by the calculation of the second vertical derivative after smoothing by continuation to a level of two kilometers above surface to eliminate "noise" caused by variations in overburden thickness. Much of the quantitative analysis of this study are based on the Werner deconvolution method of inverse modeling using the approach and proprietary software developed by R.J. Ferderer (1988).

The contract resulted in a twenty-seven page open-file report 97-5: Chandler, V.W., Jirsa, M.A. and Morey, G.B., (1997) Mineral potential assessment of northern St. Louis County, southeastern Koochiching County, and northeastern Itasca County, Minnesota. The report includes a detailed account of analytical procedures and results, rock property data, six cross sectional studies using gravity and magnetic modeling, five tables and nine plates displaying results. This report and the plates are available in hard copy and digital format at the Minnesota Geological Survey, 2642 University Avenue, St. Paul, Minnesota, 55114-1057, Phone (612) 627-4780 also the Minnesota Department of Natural Resources, 1525 Third Avenue East, Hibbing, Minnesota 55746-1461, Phone (218) 262-6767.

EXTENSION OF THE HURONIAN MAGMATIC SUITE INSIDE THE GRENVILLE PROVINCE: NEW ZIRCON U-Pb EVIDENCE FROM THE GRENVILLE FRONT TECTONIC ZONE IN STREET TOWNSHIP, SUDBURY REGION, ONTARIO.

F. Corfu, Royal Ontario Museum, 100 Queen's Park, Toronto, ON M5S 2C6 and
R.M. Easton, Precambrian Geoscience Section, Ontario Geological Survey, 933
Ramsey Lake Road, Sudbury, ON P3E 6B5

The Sudbury region is characterized by very complex geological relationships due to the confluence and overlapping of multiple geological domains ranging in age from Archean to Neoproterozoic. Early Paleoproterozoic rifting of the Archean crust led to the deposition of extensive clastic sedimentary assemblages of the Huronian Supergroup and was initially accompanied by the emplacement of bimodal mafic and felsic, intrusive and extrusive rocks. Although the distribution and petrogenetic features of these magmatic rocks is well understood in the region west of Sudbury, the fate of the Huronian remains a matter of speculation farther to the east and south of the Grenville Front, the only exception being the previously dated River Valley gabbro-anorthosite. In conjunction with an Ontario Geological Survey mapping program along the Southern-Grenville Province boundary, we have examined two examples of metamorphosed granitic bodies and a metapyroxenite plug straddling the Grenville Front tectonic zone in Street Township, roughly 15 km east of Sudbury.

The metapyroxenite is part of a suite of small bodies, generally less than 500m in size, that occur within the Grenville Front tectonic zone between Coniston and River Valley. Mineralogically, these bodies consist of roughly equal amounts of orthopyroxene phenocrysts (0.5-5 cm in size) in an amphibole matrix; locally olivine phenocrysts are preserved. Metamorphic crystallization in these bodies increases with increasing distance from the Grenville Front, consequently, sampling was conducted on a body located only 250m southeast of the Grenville Front. The metapyroxenite contains highly resorbed, prismatic zircon yielding a U-Pb data array that points toward an upper intercept age of about 2490 Ma. The age corresponds approximately to that of the East-Bull Lake and Shakespeare-Dunlop (a.k.a. Agnew Lake) intrusions, emplaced in Archean crust at the margin of the Huronian basin east of Sudbury. On the basis of SEM examination, most of the zircon found in this sample is located within the orthopyroxene phenocrysts, in conjunction with Cr-spinel and chromite. In addition, the matrix of the metaproxenite is chemically differentiated. Thus, we are confident that the zircon fraction yielding the upper intercept age of 2490 Ma dates emplacement of these rocks. The metapyroxenite was metamorphosed and developed metamorphic zircon during an event at about 1700-1600 Ma, and was subsequently overprinted by Grenvillian-age metamorphism.

Two granitic bodies were sampled. The first was a foliated monzogranite located in an area south of the Ess Creek fault and north of the Grenville Front boundary fault as mapped by Lumbers

(1973). This fault-bounded region has been variously assigned to the Southern or Grenville provinces, and has been subjected to middle to upper amphibolite facies metamorphism. The second body is located about 15 km south of the first, and is one of several similar bodies located within the Grenville Province. Both sampled granites, as well as other bodies south of the Grenville Front, are chemically similar, suggesting they form part of a larger plutonic body or a suite of intrusions. In particular, they are characterized by SiO_2 66-72%, Al_2O_3 11.9-12.6%, $\text{FeO}^{\text{total}} > 3.5\%$, $\text{CaO} > 1.5\%$, $\text{Eu}/\text{Eu}^* .55-.70$, La/Yb 5-8, and Gd/Yb 1.2-1.65, and are identical in major and REE geochemistry with Stobie Formation dacites from both the Sudbury and Street Township areas. On various geochemical discrimination diagrams, they plot in the Within-Plate granite field. In contrast, felsic rocks of the Murray and Creighton granites and the Copper Cliff rhyolite have lower $\text{FeO}^{\text{total}}$ contents and higher SiO_2 and alkali contents. In addition, REE data, only available from the Copper Cliff rhyolites, have $\text{Eu}/\text{Eu}^* < .5$, $\text{La}/\text{Yb} < 5.5$ and $\text{Gd}/\text{Yb} < .75$. The foliated monzogranite defines a U-Pb zircon age of about 2460-2450 Ma, which overlaps the age of some of the youngest magmatic expressions of the Huronian rifting event such as the Copper Cliff rhyolite and the Hearst dyke swarm. The granite was overprinted by Grenvillian metamorphism that strongly, but not totally reset the titanite ages. The zircon data for the second granitic body display more pronounced effects of both a 1700-1600 Ma event and the Grenvillian orogeny at about 990-980 Ma, but are nevertheless consistent with a Huronian age and with the chemical similarities between these granitic intrusions.

The ages on the bodies reported here are consistent with field relations which show a close spatial relationship between the metapyroxenites, the granites, and mesocratic to anorthositic gabbros likely correlative with the ca. 2475 Ma River Valley gabbro-anorthosite. In addition, the foliated monzogranite is spatially associated with a thin sliver of mafic and felsic metavolcanic rocks that have been correlated with the Huronian Stobie Formation. The latter are the only Huronian volcanic rocks so far identified east of Sudbury. These field relationships, in conjunction with the geochronological results reported herein, suggest that the Huronian magmatic province is more extensive east of Sudbury than previously recognized. In addition, felsic magmatism of Huronian age is no longer confined to the vicinity of Copper Cliff, and indeed, could be more extensive than previously thought, particularly in the area of the little studied eastern Cobalt plate.

Reference:

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KINEMATIC FABRICS NEAR MINE CENTRE, ONTARIO: EVIDENCE FOR A MODIFIED TRANSPRESSION MODEL.

Czeck, D. M. and Hudleston, P. J., Department of Geology and Geophysics, University of Minnesota, 310 Pillsbury Dr. SE, Minneapolis, MN 55455

The boundary between the Quetico and Wabigoon subprovinces of the Archean Superior Province is characterized by ductily deformed Greenschist- Amphibolite facies rocks. The two subprovinces have been amalgamated through continental accretion processes. The working kinematic model to describe this area is transpression, which explains the dominant flattening fabric in the vertical plane and the evidence for noncoaxial strain noted in the horizontal plane. Theoretical work on classical transpression has shown that the long axis of the strain ellipsoid, and thus the mineral lineation, are necessarily either vertical or horizontal. Structural field work in this study has shown that the lineations along the Wabigoon-Quetico boundary plunge between 0-90° within the foliation plane. Therefore, a modification to the three-dimensional transpression model is necessary to adequately describe the deformation process. One possible modification to transpression which explains the oblique lineations is heterogeneous extrusion due to anastomosing shear zones.

New Aeromagnetic Surveys in Wisconsin by the U.S. Geological Survey

David L. Daniels, Stephen L. Snyder, Suzanne W. Nicholson, William F. Cannon, U.S. Geological Survey, MS 954 National Center, Reston, VA 20192

Aeromagnetic surveying in Wisconsin over the past 10 years by the U.S. Geological Survey (USGS) has added considerably to the coverage in the state and to the digital aeromagnetic database of the USGS Mineral Resources Program. Initial efforts were directed toward completing the coverage in the northern part of the state in which Precambrian bedrock is at the surface or covered by glacial deposits. The flight-lines were flown in a N-S direction because of the predominant easterly or northeasterly grain of the geology, were spaced ½-mile apart, and flown at 500 or 1000 ft above terrain. The surveys were designed to extend the large survey conducted by John Karl of the University of Wisconsin, Oshkosh (Karl, 1986; King, 1990), prior to 1977.

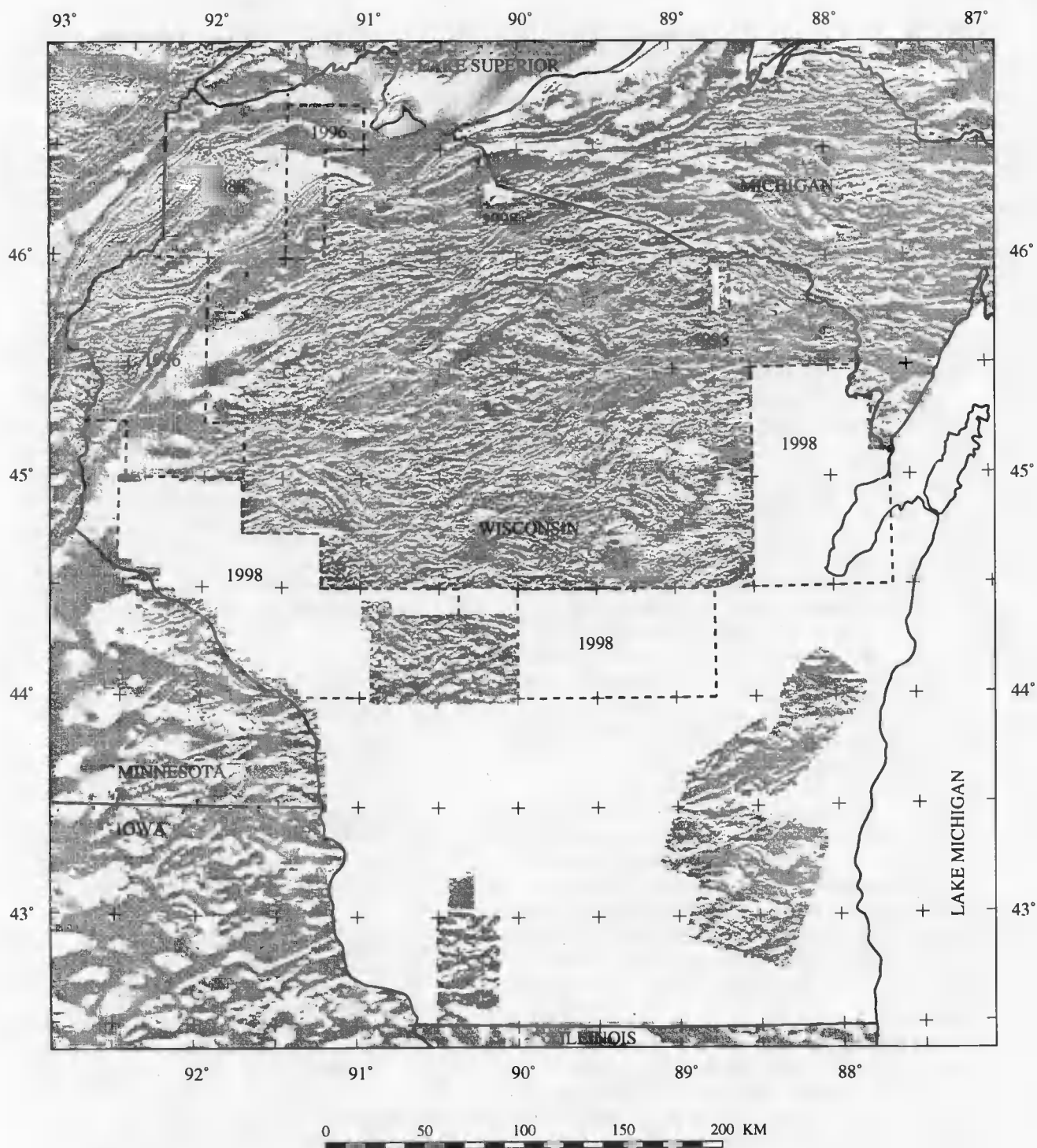
In 1988, the USGS flew a 3900 line-mile aeromagnetic survey in the northwestern corner of Wisconsin south of Lake Superior. In 1996, USGS surveying was continued in two areas adjacent to the 1988 survey (see index map) for an additional 6700 line-miles. These two surveys completed the coverage of the volcanic and sedimentary rocks in the Midcontinent rift system. These new data have led to new interpretations of structures in the highly magnetic Keweenaw basalt flows in the St. Croix horst (Cannon and others, 1997). In the most recent (10/97-3/98) survey, aeromagnetic data have been acquired in three blocks in a broad swath through the central part of the state, in the Marinette-Green Bay area, the Wisconsin Rapids area, and the Mississippi River area (about 16,000 line-miles). In addition, two small areas along the Wisconsin-Michigan border were filled in.

In much of the area covered by the most recent survey, a thin (<150m) veneer of magnetically transparent Cambrian sandstone overlies the more highly magnetic Early and Middle Proterozoic rocks; in the western part non-magnetic Middle Proterozoic sedimentary rocks form part of the basement. Thus, although this is an area of very little outcrop, the aeromagnetic data effectively delineate the structure and character of the buried basement rocks. The enhanced understanding of the basement geology provided by the aeromagnetic survey will allow better evaluation of the mineral potential of this region and aid in regional correlations of basement terranes in the region. Maps of the new aeromagnetic survey and the current aeromagnetic compilation of Wisconsin will be shown.

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Index of Recent Aeromagnetic Surveys in Wisconsin



POLYMETAMORPHISM OF SKARNS RELATED TO THE MORIN ANORTHOSITE COMPLEX, GRENVILLE PROVINCE, QUEBEC.

DEANGELIS¹, M. T., PECK, W. H., and VALLEY, J. W., Department of Geology and Geophysics, University of Wisconsin, Madison, Madison, WI, 53706, william@geology.wisc.edu. ¹student author

Skarn calc-silicate assemblages associated with the Morin Anorthosite Complex are exposed ~2 km west of the town of St. Jovite, Quebec, and display field relations and reaction textures which indicate a polymetamorphic origin. A set of ~25 small dioritic and monzonitic intrusive bodies, which are located between two mapped bodies of mangerite (Martignole and Corriveau, 1993) outcrop in a ~300 meter long series of four roadcuts in calcite marble along Highway 117. These bodies are rimmed by 10-20 cm thick skarns containing metasomatic banding of garnet, diopside, and wollastonite. This locality occurs adjacent to the western margin of the Morin Anorthosite Massif which was emplaced at 1155 ± 3 Ma (Doig, 1991). The anorthosite is associated with mangerite bodies that were emplaced 1135 ± 3 Ma (Doig, 1991). The area was metamorphosed under granulite facies conditions following emplacement of the anorthosite massif to pressures of 6-8 kb and temperatures of 650-775 °C (Indares and Martignole, 1989). This metamorphism has been dated at 1070-1100 Ma by Rb-Sr whole rock isochrons (see Doig, 1991).

Descriptions of skarns

Well developed skarns appear on both diorite and monzonite bodies. We interpret these bodies as intrusive because of cross-cutting relationships between different intrusions and relict igneous textures. On exposed surfaces, diorite bodies vary in both size and shape, but are typically circular to oval with diameters ranging from 1 to 10 meters. The diorite intrusives are composed primarily of plagioclase with minor amounts of clinopyroxene, amphibole, biotite, magnetite, pyrite, and sphene. Metamorphic minerals include calcite, garnet and clinozoisite. Surrounding the diorite intrusives are skarns which are made up of concentric garnet-, clinopyroxene-, and wollastonite-rich bands. Next to the diorite, garnet-rich bands are ~10 cm thick. Wollastonite-rich bands (in the middle of the skarn) are thinner (≤ 1 cm) and sometimes are not present. Clinopyroxene-rich bands are ~15 cm thick and gradually grade into the marble. The garnet-rich bands contain garnet, clinopyroxene, plagioclase, quartz, calcite, sphene, and small amounts of pyrite. The wollastonite-rich bands are composed of wollastonite, clinopyroxene, calcite, plagioclase, garnet, quartz, sphene, and small amounts of graphite and pyrite. The clinopyroxene-rich bands are made up of clinopyroxene, calcite, garnet, plagioclase, quartz, sphene, with minor amounts of graphite and pyrite.

The monzonite intrusives are composed of potassium feldspar and plagioclase with minor amounts of quartz, clinopyroxene, and sphene. Metamorphic minerals include calcite, garnet, and Fe-vesuvianite ($\text{Fe}/\text{Fe}+\text{Mg} \approx 0.65$ determined by electron microprobe). Fe-vesuvianite is visibly zoned in hand sample, with Fe-rich rims ($\text{Fe}/\text{Fe}+\text{Mg} \approx 0.67$) and less Fe-rich cores ($\text{Fe}/\text{Fe}+\text{Mg} \approx 0.61$). Fe-vesuvianite crystals can reach lengths of ~6 cm and are found within the monzonite and the inner most skarn band. Within one monzonite body, an unusual texture consisting of a cylinder of matrix minerals (potassium feldspar, plagioclase, garnet, and quartz) encased by a single crystal of elongate (~2-6 cm long, width ≤ 50 mm) clinopyroxene ($\text{En}_{26}\text{Fs}_{23}\text{Wo}_{50}\text{Ac}_1$) occurs. This gives these crystals a "hollow" appearance in thin section and on the outcrop. Monzonite occurs both as semi-circular bodies (1-10 m in diameter) as well as dikes which cross cut diorite. Skarns around the monzonite consist of small (3-5 cm) garnet- and clinopyroxene-rich bands. Garnet-rich bands contain garnet, clinopyroxene, calcite, potassium feldspar, plagioclase, Fe-vesuvianite, and sphene. Clinopyroxene-rich bands contain clinopyroxene, calcite, garnet, potassium feldspar, plagioclase, and sphene. Away from the igneous bodies, marble is composed of primarily equigranular calcite with small amounts of clinopyroxene, garnet, sphene, and feldspar. Trace amounts of graphite and pyrite are also observed. Bogoch et al (1997) report similar mineralogies of calcite, potassium feldspar, vesuvianite, quartz, clinopyroxene, plagioclase, wollastonite, graphite, and sphene in a body 2.5 m long and 50 cm wide in calcite marble approximately 12 km west of the field area.

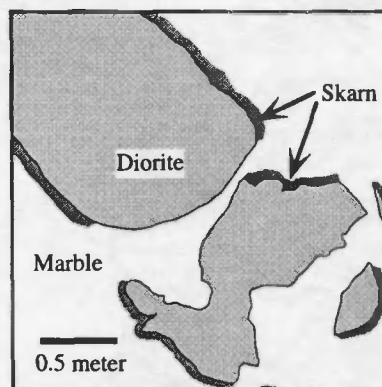


Figure 1. Fragmented diorite intrusion. Skarn is developed where hot diorite came into contact with marble. Brittle deformation of diorite and skarn post-dates intrusion.

Deformation and mineral reactions

The majority of the exposed skarns parallel the edge of the igneous bodies and maintain uniform thickness. However, some skarns and igneous rock are locally deformed. Some igneous bodies and their skarns are folded and boudined, 2-25 cm size skarn fragments are common away from igneous rock; some of which are variably folded. Skarn fragments and skarn minerals are observed being transported by ductile flow of the marble (e.g. into boudin necks and out of fold hinges). Some igneous bodies and their skarns show brittle deformation, breaking both skarn and intrusion into fragments (see Fig. 1). The lack of skarn development on some intrusion-marble contacts of dismembered igneous bodies indicates that brittle deformation (of igneous rock and skarn) occurred after igneous crystallization and skarn formation.

Mineral textures show that original skarn mineralogies have been modified by a later granulite-facies metamorphic event (see also Martignole and Schriver 1970). Garnet (Gr₉₂) rims surrounding calcite, wollastonite, and plagioclase indicate the reaction calcite + quartz + anorthite + wollastonite → grossular + CO₂ (see Fig. 2). Garnet-quartz intergrowths indicate the reaction anorthite + wollastonite → grossular + quartz. The univariant assemblage of garnet (Gr₉₅), plagioclase (An₁₉), quartz, wollastonite is observed as fine-grained intergrowths. Dilution of the anorthite component of plagioclase by albite moves the univariant assemblage to lower pressures and temperatures (Windom and Boettcher 1976), consistent with the estimates of regional metamorphism (Indares and Martignole 1990). The presence of wollastonite + vesuvianite, garnet + plagioclase + quartz + wollastonite, clinozoisite + plagioclase + quartz, and sphene indicate conditions of high X_{H₂O} if metamorphism was fluid saturated. These assemblages also consistent with estimates of low H₂O activity from granulite facies terrains if conditions are fluid absent or if non C-O-H fluid species are important (Valley et al., 1990).

Comparison to the Adirondacks

Economic wollastonite deposits in the Adirondack Highlands (~250 km to the south) are skarns associated with the Marcy Anorthosite Massif and related granitic rocks. Skarn formation adjacent to the Marcy anorthosite was due to the infiltration of oxidizing meteoric water into the high temperature contact zone of a shallow (<10km) anorthosite body. The Adirondacks underwent regional granulite facies metamorphism with high pressure, fluid-absent conditions ~100 Ma later (McLelland and Chiarenzelli, 1990), but wollastonite and other skarn minerals remained stable through this later metamorphism due to low f_{CO₂} "fluid-absent" conditions (Valley et al. 1990). Post-intrusion deformation and mineral textures in Morin Complex skarns suggest polymetamorphism, but published geochronology (i.e. dating of high temperature metamorphic minerals) at present does not allow a distinction between two separate metamorphic events, or a continuum of metamorphism under changing conditions following anorthosite intrusion or depth of intrusion.

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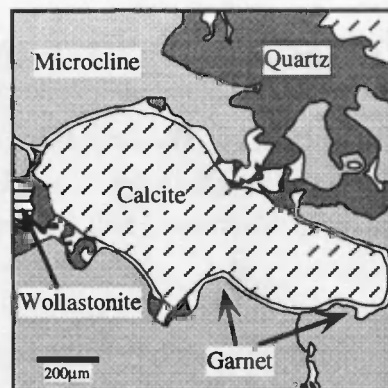


Figure 2. Calcite rimmed with garnet (Gr₉₂). This texture and garnet rimming wollastonite is evidence for the reaction calcite + quartz + anorthite + wollastonite → grossular + CO₂.

THE AGE AND PROVENANCE OF THE GUNFLINT LAPILLI TUFF

FRALICK, P.W. and KISSIN, S.A., Department of Geology, Lakehead University, Thunder Bay, Ontario, P7B 5E1, and **DAVIS, D.W.,** Royal Ontario Museum, 100 Queen's Park, Toronto, Ontario, M5S 2C6.

The Gunflint Formation forms the middle unit of the Animikie Group in northwestern Ontario, outcropping proximally to the western end of Lake Superior. It consists of an assemblage of chemical and fine-grained elastic sediments deposited in the strand-proximal zone of a south facing shelf as recently interpreted by Pufahl (1996).

Previous attempts at assigning an age to the Gunflint Formation (or the conformably overlying Rove Formation) and equivalents can be classified into three groups: (1) ages from 1.556 to 1.63 Ga based on whole-rock Rb/Sr or K/Ar techniques (Hurley et al., 1962; Peterman 1966; Faure & Kovach, 1969; and Franklin, 1978); (2) ages from 2.08 to 2.111 Ga based on whole-rock Nd/Sm techniques (Stille & Plauer, 1985; Gerlach et al, 1988); and (3) 1.86 and 1.99 Ga based on whole-rock Pb/Pb from the Virginia Formation (Hemmings et al; 1995).

Petrographic examination of a lapilli tuff unit present in the upper Gunflint at Kakabeka Falls identified euhedral zircons forming a small portion of the silt population together with large, monomineralic clasts of quartz and sanidine likely from an explosive, volcanic source. The stratigraphic section present here has a large algal bioherm complex at its lowest level (Figure 1). This is overlain by a thick sequence of parallel-laminated black shale with sporadic development of layer rip-ups caused by current activity. A series of what has been described as lapilli tuff beds occurs midway through this sequence (Shegelski, 1982). These are massive to cross-stratified and graded to disorganized bedded. Mudstone rip-ups are common. The lapilli consist of Fe-rich chlorite and are internally massive. The above strongly suggests that the lapilli are not accretionary volcanic-rainout debris, but rounded volcanoclastic mud rip-ups, which were eroded, abraded and transported by storm-induced currents. The black shale unit is correlated with a fine-grained, resedimented, volcanoclastic shale, which extends throughout upper Gunflint equivalents in the U.S.A. It may also be correlated with a small region containing basaltic flow rocks.

Approximately 100 zircons were recovered from the reworked tuffs, including altered, abraded and euhedral brown populations. Although the majority of the population analysed gave reset Archaean ages, a euhedral zircon gave a concordant age of 1878 ± 2 Ma BP (Figure 2). This most likely represents the age of volcanism that was penecontemporaneous with sedimentation.

Preliminary geochemical data for Gunflint basalts and volcanoclastic sediment indicates the possibility of a deep mantle source for the melts and rules out any involvement of subducting lithosphere. Similarities with the Emperor and Hemlock volcanics suggest a northward time-transgressive, extensional, intraplate eruptive event, which may in part overlap chronologically with the commencement of arc volcanism to the south.

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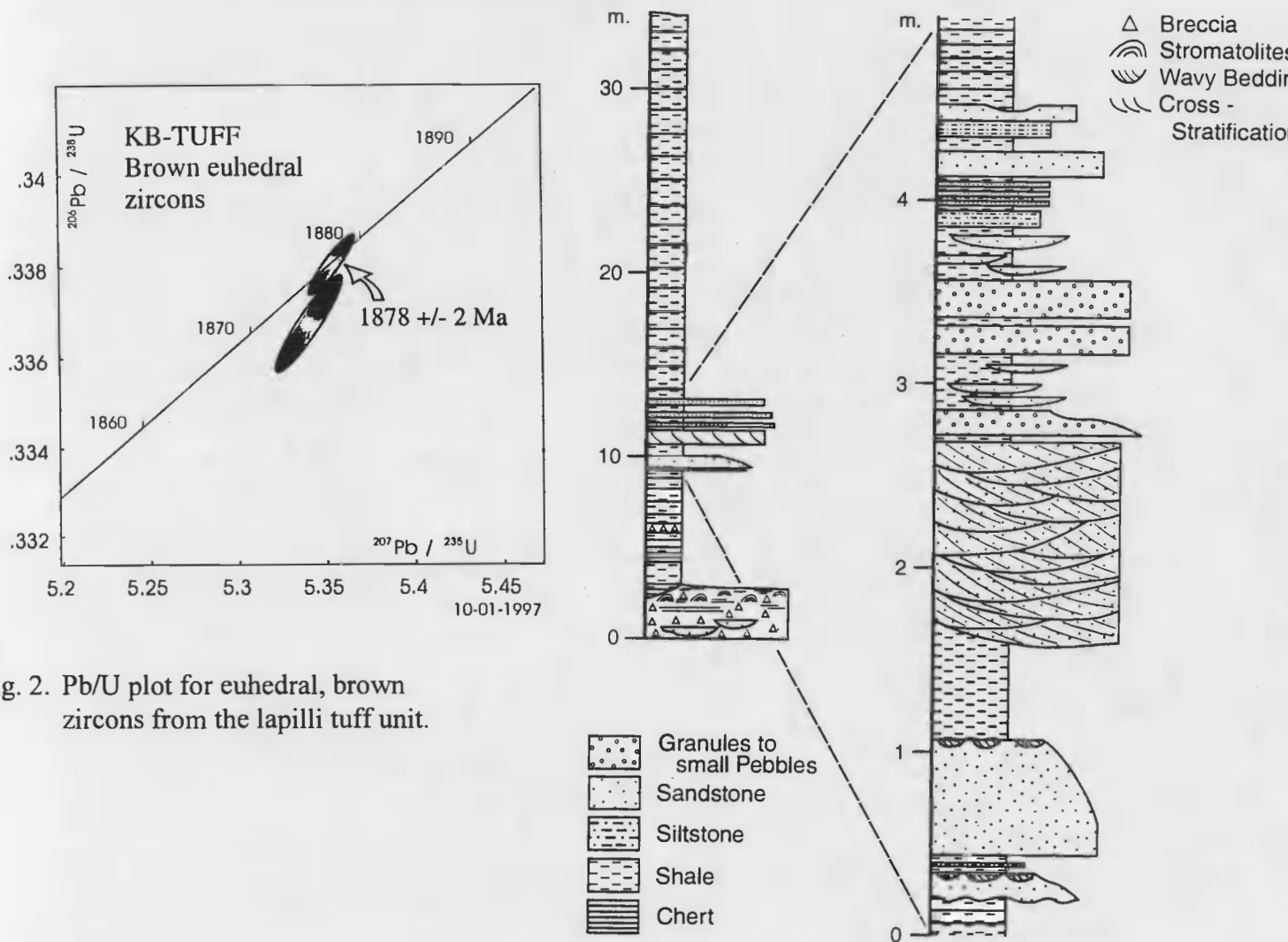


Fig. 2. Pb/U plot for euhedral, brown zircons from the lapilli tuff unit.

Fig. 1. Stratigraphic section of the upper Gunflint Formation containing lapilli tuff units in the Kakabeka Gorge.

PRE-WISCONSINAN GRAY TILL IN THE MANKATO AREA OF THE MINNESOTA RIVER VALLEY

GRAMSTAD, Sally D., student, Department of Geological and Atmospheric Sciences, Iowa State University, Ames, IA 50011, sgramsta@iastate.edu

Exposures of pre-Wisconsinan gray till in the Mankato area of the Minnesota River Valley show that this unit is up to 30 m thick and is somewhat continuous. Low shale content, moderate carbonate content, and NW-SE trending fabrics indicate a Winnipeg provenance. The texture and lithology of this unit are similar to those of other pre-Wisconsinan tills in the Midwest, including the Browerville and Elmdale tills in north-central and central Minnesota, and unit 1 at Salisbury Hill, which is twenty miles northeast of the study area.

The topography of the bedrock valley that is present in the Mankato area may have affected ice flow of the glacier that deposited the pre-Wisconsinan gray till unit. Influence of this bedrock valley may explain several anomalous fabrics, as well as the fact that the thick till unit is interrupted by sand and gravel layers at some sites and is completely undisturbed at others.

A MINERALOGRAPHIC STUDY OF MAGNETITE IN THE BIWABIK IRON-FORMATION, MESABI RANGE, MINNESOTA

T. M. Han, Senior Research Scientist (Retired), Cleveland-Cliffs' Research Laboratory

A substantial number of polished sections prepared from specimens collected from the Biwabik Iron-Formation were microscopically examined before and after an induced oxidation procedure. The Biwabik Iron-Formation is simply classified here as cherty and slaty members. It is considered a regionally metamorphosed sediment before the intrusion of the Duluth complex. Based on the nature and magnitude of the changes, the existing iron-formation may be divided into three metamorphosed sectors progressing from west to east, i.e. regionally, thermally, and pyrometasomatically. During regional metamorphism, hematite functioned as a "starting point" for the development of much of the magnetite through Fe^{++} diffusion. Thermal metamorphism involves mineralogical transformations of an isochemical nature, which may be subdivided into transitional, amphibole, and pyroxene zones. Pyrometasomatism process involved advanced recrystallization and replacement by gabbro adjacent to, and within, the intrusion.

This poster focuses on the genesis of magnetite in the regionally metamorphosed iron-formation and the textural and mineralogical changes caused by thermal metamorphism and pyrometasomatism. Most of the features observed during the course of study are photographically and photomicrographically shown. It covers:

A. Lithological characteristics from different metamorphic zones.

The irregularly and evenly banded macrostructures of the regionally metamorphosed iron-formation show little change, whereas the mineralogical composition and microstructures have experienced significant progressive elimination and transformation due to the thermal metamorphism and pyrometasomatism.

B. Hematite-Magnetite Relations in the Regional Metamorphosed Iron-Formation

1. Before Induced Oxidation. The hematite and magnetite occur either in separate layers or in intimate relations in the same layer. Hematite is almost always much finer and less abundant than magnetite. The replacement of hematite by magnetite is readily evident. The magnetite differs in external morphology, i.e. octahedral and pseudomorphs after other minerals.

2. After Induced Oxidation. The morphologies and arrangement of precursor hematite in existing magnetite vary significantly. In the evenly banded slaty lithology, the precursor hematite is almost exclusively lath-shaped and exhibits a decussate microstructure. In the irregularly banded lithology of both the slaty and cherty members, the precursor hematite exhibits a wide variety of morphologies. It is either randomly arranged or displays vuggy or microgeodic structures within magnetite that is present as irregular, coalesced crystals, granules, or pinch-and-swell layers. The external morphology of the present magnetite is governed by the precursor hematite. Some of the precursor hematite might have been enlarged by authigenesis before magnetite development. Magnetite with precursor hematite inclusions is present in nearly all the mineral assemblages of the iron-formation. The size and morphologies of precursor hematite in magnetite differs from the existing hematite, either coexisting with or playing host to the magnetite.

C. Effect of Thermal Metamorphism on Hematite and Magnetite

In the transitional zone, more than one stage of overgrowth on euhedral magnetite (with or without the precursor hematite inclusions) is frequently observed. Two to three external morphologies of magnetite were also seen in coexistence. The induced oxidation pattern progressively changes from grain boundary oxidation along the precursor hematite to cleavage oxidation along octahedral planes of the existing magnetite as the metamorphic grade increases. The hematite of the regionally metamorphosed iron-formation is progressively replaced by magnetite. The euhedral magnetite is progressively changed to subangular to nearly round grains. However, the outlines of the magnetite pseudomorphs and magnetite granules are still preserved. Magnetite porphyroblasts appear in the fine-grained coalesced subangular magnetite. Some siliceous magnetite blades or

cubic cavities are occasionally observed in magnetite distributed in the pyroxene zone. However, some hematite coexisting with magnetite has also been found in the pyroxene zone.

D. Effect of Pyrometasomatism on Hematite and Magnetite

1. Advanced Recrystallized Zone. The magnetite here is substantially coarser than in the regionally and thermally metamorphosed zones. The hematite, magnetite pseudomorphs, and magnetite granules no longer exist. Two generations of magnetite and the introduction of hercynite along magnetite cleavage planes are evident. The magnetite grains commonly have fine parallel to subparallel fractures, whereas the host does not. The fractured magnetite sometimes resembles specular hematite. Minute euhedral gangue inclusions are commonly present. Cleavage oxidation is typical. Magnetite inclusions within magnetite are either outlined by the effect of differential oxidation or by their grain boundaries.

2. Gabbroized Zone. The advanced recrystallized magnetite gradationally transforms to a titanomagnetite approaching the gabbroized zone. The latter contains minute inclusions of hercynite, ilmenite, and ulvöspinel, and an unidentified mineral. Most of these mineral phases are products of exsolution. Both magnetite and titanomagnetite may be observed in adjacent layers of the same specimen. Small octahedral inclusions of titanomagnetite are occasionally seen and exhibit essentially the same composition and texture as their titanomagnetite host. Some titanomagnetite contains apatite, pyroxene, and other gangue grains; some exhibits a myrmekitic intergrowth texture in pyroxene; and some appears to be replaced by ilmenite and sulfides.

Economically, regional metamorphism is the key contributor in generating magnetite for the present mining industry. Thermal metamorphism has a negative impact on magnetite size liberation but a positive effect on magnetite weight recovery. Advanced recrystallization has a positive effect on both size liberation and weight recovery, whereas the gabbroized iron-formation can no longer be considered iron ore.

The details relative to this study were reported in the following papers and abstracts.

T. M. Han (1978) "Microstructures of Magnetite as Guides to Its Origin in Some Precambrian Iron-Formations." *Fortschr. Mineral.* 56, 105-142

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FACIES AND DEPOSITIONAL ENVIRONMENTS OF THE EARLY PROTEROZOIC IRONWOOD IRON FORMATION, MT. WHITTLESEY WISCONSIN.

*Erin Hensel, *Rick Joslin, and Dan Lehrmann; *Dept. of Geology, University of Wisconsin-Oshkosh, Oshkosh, WI 54901*

There are numerous models of depositional environments of Early Proterozoic iron formation. The purpose of the study was to evaluate which of these models best fit the sedimentary facies and stratigraphic patterns in the Ironwood iron formation exposed at the Berkeshire Mine Ruins, at Mt. Whittlesey, in the Gogebic District, near Mellen Wisconsin. Soil and vegetation were stripped from this area by the abandoned mining effort. Approximately 100 meters of stratigraphic section was described bed by bed at a decimeter scale. An additional 150 meters was described in reconnaissance sections. Samples were collected, cut and described in detail to help understand depositional environments.

Five different facies were recognized from outcrop observation and sample descriptions. These are summarized as follows. 1) The *horizontal laminated facies* consists of continuous and discontinuous laminae of alternating magnetite and chert. Sedimentary structures include thin, graded laminae, scour marks, v-shaped cracks that probably resulted from differential compaction (possibly desiccation ?), and discontinuous lenses of granular facies. The lenses range from a few to 15 cm thick and commonly pinch out within a few meters laterally. 2) The *wavy laminated facies* consists of wavy laminae of magnetite and chert with few intraclasts of chert. Sedimentary structures include crinkley laminations that probably are horizontal stromatolites, convolute laminae, and lenticular layers. 3) The *intraclastic facies* consists of intraclasts of magnetite and chert derived from the wavy and granular facies. The clasts were cemented early by silica. Sedimentary structures include, planar cross beds, imbricated clasts, differential syn-sedimentary compaction, autoclastic breccia, and abundant v-shaped cracks penetrating the margins of intraclasts. These may be desiccation cracks. Some of the intraclasts are rounded and are concentrically coated with chert. 4) The *stromatolite facies* contains domal stromatolites composed of chert and magnetite. Intraclastic material, containing stromatolite fragments and clasts of granular facies, is interbedded with and occurs between the stromatolites. 5) The *granular facies* consists of coarse to fine sand and minor silt sized chert and magnetite grains. Most of these grains are peloids (featureless rounded grains), some are ooids. The granular facies appears to be winnowed with little fine grained matrix and locally contains ripple cross-lamination.

The most obvious stratigraphic pattern at Mt. Whittlesey is a meter- to decimeter-scale intercalation of the wavy, granular, and intraclastic facies (fig. 1). Careful observation reveals, however, that there is also a larger-scale change in facies associations in the outcrop that defines 3 lithologic cycles. These cycles are approximately 50 m thick. Within the cycles there is a preferential association in which the following facies more frequently occur together: 1) the granular and wavy laminated facies, 2) the intraclastic and stromatolitic facies, and 3) the horizontal laminated facies. The cycles consist of a repetition of the three facies associations above. Interestingly, the cycles are asymmetric in the sense that the intraclastic and stromatolitic facies association always occurs beneath the horizontally laminated facies and not above it (fig. 2).

Our data supports the interpretation that the iron formation was deposited in a shallow-marine, intertidal to subtidal shelf environment. This is similar to the environments that have been most widely interpreted for iron formations (cf. Simonson, 1985; Loughheed, 1983; LaBerge, 1987; Simonson and Hassler, 1996). Sedimentary features that support this interpretation include the stromatolites, ooids, ripple cross lamination, and cross bedding. We interpret that the iron formation formed as a biochemical precipitate of iron and silica minerals from sea-water. The similarity to Proterozoic or Early Paleozoic marine carbonate facies supports the idea that these are biochemical rocks. We found no evidence to support the interpretation that these were originally carbonate sediments that were diagenetically replaced by silica or for freshwater deposition that has been postulated by other authors (Hough, 1958; Eugster and Chou; and Trendall, 1973).

In our preferred depositional model, the wavy laminated facies formed on the tidal flats, the granular, intraclastic, stromatolite, facies formed progressively further seaward in shallow, wave agitated subtidal environments and the horizontally laminated facies formed in deeper environments between normal wave base and storm wave base (fig. 3). The horizontal laminations are interpreted to have formed in quiet waters below normal wave base. The abundant scour structures and discontinuous lenses of granular facies found in the horizontally laminated facies are interpreted to represent agitation and "spill over lobes" of granular material

washed seaward during storms (fig. 3). Originally we entertained the idea that the horizontally laminated facies formed landward of the oolite shoals in tidal flat ponds. If the v-shaped cracks were desiccation features, that would support such an interpretation. The v-shaped cracks are more commonly associated with syn-depositional deformation structures however, and the horizontally laminated facies is rarely associated with the wavy laminated facies. This, along with the asymmetrical pattern of the large-scale depositional cycles supports the deeper offshore environment. In this model, the cycles in facies associations would represent long term (~million year) asymmetric transgressions and regressions of the shelf. The stromatolites and intraclastic facies formed preferentially during initial transgressions, due to increased wave energy and increasing water depths. Maximum deepening is represented by the horizontally laminated facies and regression is represented by the shift back to the wavy laminated - granular facies association.

Previous studies have commonly interpreted the horizontally laminated facies as being a deep water deposit. In some cases it has been interpreted to be a very deep, pelagic and turbiditic facies. Our data suggests that, at Mt. Whittlesey at least, this is not the case. The granular units interbedded in the horizontal facies are far too discontinuous to represent distal turbidites and they lack Bouma sequences.

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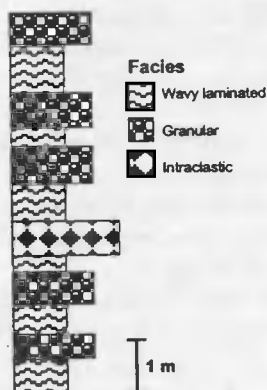


Figure 1



Figure 2

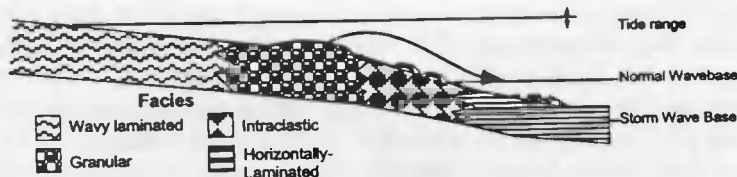


Figure 3: Depositional Model

AGE AND DEFORMATION OF EARLY PROTEROZOIC QUARTZITES IN THE SOUTHERN LAKE SUPERIOR REGION: IMPLICATIONS FOR EXTENT OF FORELAND DEFORMATION DURING FINAL ASSEMBLY OF LAURENTIA

Daniel Holm, Department of Geology, Kent State University, Kent, OH 44242

David Schneider, Dept. of Earth and Environmental Sciences, Lehigh University, Bethlehem, PA

Christopher D. Coath, Department of Earth and Space Sciences, UCLA, Los Angeles, CA 90095

Post-accretion stabilization in the Lake Superior region at 1770-1760 Ma resulted in deposition of locally thick successions of Early Proterozoic mature quartzites in Wisconsin and southern Minnesota. Their age of deposition and the age of the deformation which caused widespread folding of many of the quartzite units has long been a matter of considerable importance and controversy. We present new evidence for both the maximum and minimum age of these quartzites. Also, we document the spatial co-existence of a thermal front in Precambrian crystalline basement with a deformational front in the overlying quartzite units. The age of the front suggests that post-Penokean shortening of the Penokean province is likely related to the final stages of formation of the Laurentian supercontinent at ~1650 Ma.

The bulk of Laurentia formed by rapid aggregation of Archean continents at 1900-1800 Ma during the Trans-Hudson and Penokean orogenies (Hoffman, 1989). Subsequent accretion of juvenile crust along the southern margin of pre-1800 Ma Laurentia formed the Transcontinental Proterozoic provinces which consist broadly of a northern 1800-1700 Ma inner accretionary belt and a southern 1700-1600 Ma outer tectonic belt. The transition zone between the two tectonic belts of the TPP represents the region of known pre-1700 Ma rocks metamorphosed and deformed at ~1650 Ma during formation of the outer tectonic belt. The eastward continuation of this transition zone and of the outer tectonic belt from the central plains is problematic as no 1800-1600 Ma juvenile crust exists in the entire southern Great Lakes region (Van Schmus et al., 1993). However, on the basis of 1680-1640 Ma orogenic deformation and the existence of 1650 Ma batholithic intrusive rocks in Labrador, Van Schmus et al. (1993) have proposed that the outer tectonic belt was a single coherent continental arc extending from California to Labrador.

The Penokean orogeny involved island arc/microcontinent collision along the southern passive margin of the Superior Province at 1870-1830 Ma. In northern Wisconsin the south-dipping Niagara fault zone represents the main suture which separates uniformly metamorphosed (upper greenschist/lower amphibolite facies) island arc rocks of the Pembine-Wausau terrane from deformed continental margin rocks which exhibit a nodal metamorphic pattern imposed during collapse of the orogen (Schneider et al., 1996; Marshak et al., 1997). Abundant mica Ar/Ar cooling dates from central Minnesota and northernmost Wisconsin and Michigan indicate that collapse and orogenic unroofing occurred at 1750-1700 Ma shortly after an episode of widespread magmatism at 1770-1760 Ma (Holm and Lux, 1996; Schneider et al., 1996). In contrast, Rb-Sr whole rock isochron and biotite mineral dates in northern and central Wisconsin (Peterman and Sims, 1988) are mostly Middle Proterozoic (1600-1100 Ma) and reflect variable thermal resetting associated with a low-grade ~1630 Ma metamorphic event (Van Schmus and Woolsey, 1975; Van Schmus et al., 1975), intrusion of the 1470 Ma Wolf River batholith, and Keweenawan activity. Post-accretion rapid stabilization resulted in the accumulation of post-tectonic quartz arenites in the southern Lake Superior region (Van Schmus et al., 1993). Deformed quartzite units in central and southern Wisconsin yield post-Penokean detrital zircon Pb-Pb ages (Van Wyck, 1995). The folded Baraboo quartzite is depositional on a 1752 Ma granite (Medaris et al., 1996) and contains detrital zircons as young as 1712 Ma (Dott et al., 1997). The minimum age of these quartzite units is constrained only by the fact that some are intruded by the 1470 Ma Wolf River batholith, although Dott (1983) and Van Schmus et al. (1993) speculated that they may have been deformed during the 1630 Ma event.

The predominantly Middle Proterozoic mica mineral dates of central Wisconsin contrast sharply with the well-grouped 1750-1700 Ma mica dates obtained from central Minnesota, northernmost Wisconsin, and northern Michigan. The 1750-1700 Ma dates are the oldest mica dates obtained from the internal portions of the Penokean orogen and thus almost certainly reflect primary cooling through mica closure temperatures following Penokean metamorphism. Considering that primary cooling at 1750-1700 Ma was orogen wide, it is likely that the younger mica dates represent thermal resetting. An ~1630 Ma age contour thus separates basement with typical post-Penokean cooling ages to the north (and west, in Minnesota) from basement with thermally reset ages to the south. The eastward extent of the contour is not precisely located, however, north of the Flambeau quartzite in northwest Wisconsin the contour is sharply defined by Rb-Sr, K-Ar, and Ar-Ar mica dates.

Importantly, the Flambeau thermal front in northwest Wisconsin coincides spatially with an apparent deformational front in overlying post-Penokean quartzites. In Minnesota, the subhorizontal Sioux

quartzite lies just southwest of Penokean internal zone rocks which cooled rapidly through mica closure temperatures at ~1750 Ma. In northwest Wisconsin, the Barron quartzite is essentially flat-lying and is depositional on Precambrian basement with mica ages between 1730-1700 Ma. South of the thermal front, and only 25 km south of the Barron quartzite, are exposures of steeply-dipping Flambeau quartzite. Here the quartzite is folded into a moderately west-plunging synform (Myers, 1974) similar to the style of deformation exhibited by the Baraboo and McCaslin quartzites. The relatively undeformed Barron and Sioux Proterozoic quartzites must either lie outside the region of significant post-Penokean deformation (as seems suggested by the spatial coincidence of a thermal front with a deformational front) or be younger quartzite packages deposited after significant post-Penokean deformation. To test whether the subhorizontal quartzites are correlatable with the deformed quartzites we obtained single-grain, single-spot $^{207}\text{Pb}/^{206}\text{Pb}$ ages on detrital zircons separated from the Sioux, Barron, and Flambeau quartzites. Because we are mostly interested in constraining the maximum age of each quartzite we concentrated our efforts on dating euhedral or subhedral crystals wherever possible. All three quartzite bodies yielded Early Proterozoic and Late Archean detrital zircon dates comparable to dates obtained by Van Wyck (1995) for deformed quartzite bodies in Wisconsin. Many of the late Early Proterozoic (<2000 Ma) dates fall along a discordia with a lower intercept at or near the origin indicating recent lead loss attributed to upper crustal fluid circulation. Reliable $^{207}\text{Pb}/^{206}\text{Pb}$ Proterozoic ages are between 1730 and 1850 Ma for the Sioux (9 grains), between 1714 and 1880 Ma for the Flambeau (9 grains), and between 1750 and 1880 Ma for the Barron (6 grains). These data attest to the fact that all three quartzite bodies post-date the 1760 Ma magmatic event in the Lake Superior region. Thus far there is no evidence to suggest that the Barron and Sioux quartzites are younger than the deformed quartzites found throughout most of Wisconsin.

Abundant new thermochronologic data in the Lake Superior region allow us to make a simple but important first-order observation that provides the first direct structural evidence that the quartzites were deformed during the low-grade ~1630 Ma event in the Lake Superior region. We note that subhorizontal post-Penokean quartzites consistently overlie crystalline basement with primary post-Penokean cooling ages, whereas highly deformed quartzites everywhere overlie crystalline basement with secondary (thermally reset) cooling ages. We are fortunate that the proximity of the deformed Flambeau quartzite to the subhorizontal Barron quartzite in northwest Wisconsin allows us to precisely locate this deformational/thermal front. An age of 1650-1630 Ma for the deformation seems reasonable given that cooling ages south of the front probably post-date the deformation somewhat.

The thermal front extends eastward into northern Michigan, the geology of which is dominated by gneiss domes and classic nodal metamorphic isograds. No Early Proterozoic post-Penokean quartzites are known north of the McCaslin quartzite. However, it's interesting to note that the Republic metamorphic node located north of the thermal front is concentric whereas the Peavy metamorphic node located south of the thermal front is elongate east-west. It is tempting to speculate that the Penokean isograds of the Peavy metamorphic node have been shortened north-south and may therefore be yet another structural manifestation of the 1630 Ma deformational event. If our interpretations are correct, then the similar orientation of post-Penokean folds and Penokean-age folds (north of the front) requires that caution be used when attributing basement structures south of the front to Penokean deformation.

The low-grade ~1630 Ma metamorphism has been one of the most poorly understood events in the Lake Superior region. Although it has long been speculated upon that the quartzites may have been deformed during this event (Dott, 1983; Van Schmus et al., 1993), until now there has been no direct evidence of any intrusive or deformational event of that age. We believe that the data summarized here provides the missing structural link to that event. The timing and the strong approximately north-south shortening style of post-Penokean deformation together are consistent with it being the result of foreland deformation associated with emplacement of the outer tectonic belt onto the southernmost margin of Laurentia during the Mazatzal orogeny (Van Schmus et al., 1993). The rocks of the Transcontinental Proterozoic provinces were subjected to a major magmatic event during the Middle Proterozoic from 1500-1300 Ma. The undeformed Wolf River batholith in central Wisconsin is surrounded by and locally intrudes the deformed quartzite bodies, leading some to suggest that quartzite deformation was caused by Middle Proterozoic epeirogenic doming and igneous intrusion (Greenberg and Brown, 1984). However, the existence of the Flambeau deformational front (located over 100 km from exposures of the batholith) shows that the deformation does not wane away from the batholith. Rather, the abrupt nature of the front is characteristic of tectonic, not intrusion related, deformation. This study supports Dott's (1983) model which attributed post-Penokean deformation in Wisconsin to Early Proterozoic plate collision from the south and supports the hypothesis of Van Schmus et al. (1993) that the 1700-1600 Ma outer tectonic belt was a single coherent belt extending from California to Labrador.

References will be made available at the meeting or upon request (dholm@kent.edu).

THE RECOGNITION OF A LAVA DOME COMPLEX AND ITS RELATIONSHIP TO THE ARCHEAN STURGEON LAKE CALDERA, NORTHWESTERN ONTARIO

GEORGE J. HUDAK AND RONALD L. MORTON

*Economic Volcanology Research Lab, Geology Department, University of Minnesota – Duluth,
Duluth, Minnesota, USA 55812*

JAMES M. FRANKLIN

Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, Canada K1A 0E8

Detailed volcanic facies mapping has led to the recognition of the Archean Sturgeon Lake Caldera Complex in northwestern Ontario (Morton et al., 1991). This complex is up to 25 kilometers in strike length, contains up to 4500 meters of caldera fill material, and hosts six known volcanogenic massive sulfide (VMS) orebodies and numerous subeconomic massive sulfide lenses. The volcanic rocks within the complex have been divided into ten distinct stratigraphic successions based on the types of volcanic and sedimentary rocks present (Hudak, 1996).

The Lyon Creek Succession comprises the uppermost of these successions. Historically, these rocks were called the NBU rhyolite (Harvey and Hinzer, 1981; Severin, 1982), and were interpreted as rhyolite tuffs, lapilli tuffs, agglomerates, and graphite-rich sediments. However, our detailed field mapping, core logging, and petrographic investigations indicate that little or none of these rocks are pyroclastic in origin. Instead, this succession has been interpreted to represent a subaqueous lava dome complex.

A plagioclase-phyric dacite lava dome that is 2-3 km in strike length and up to 540 meters thick forms the base of the succession. This dome occurs within the caldera edifice approximately 1-2 km west of a major caldera margin fault. An absence of flow contacts, and an increase in the size of feldspar phenocrysts from the margins toward the core of the dome, suggests that the dome's growth was endogenous. A series of predominantly dome-derived clastic sediments overlies the dome. These include: a) matrix-supported breccia deposits which contain up to 75% dome fragments; b) arkosic greywacke deposits; c) very-fine grained tuffaceous sandstone and siltstone deposits; and d) graphite-rich shale deposits. The clastic sediments lack an abundance of pumice (rarely >3%) and cross-bedding is absent. Silica-, carbonate-, oxide-, and/or sulfide-facies iron formations and associated chert are interlayered with the clastic sediments and, locally, directly overlie the lava dome.

Detailed facies mapping indicates that the breccia deposits, the graphite-rich shales, and the iron formation were formed in restricted, fault-bounded basins within the top of the dome. The iron formation resulted from relatively low temperature hydrothermal activity that occurred proximal to the basin marginal faults. The lack of pumice, the absence of evidence suggestive of reworking by surface currents (e.g. cross-bedding), and the presence of graphitic shales suggests a relatively deep water (>500 meters), anoxic environment, although no absolute water depth estimate is possible.

Detailed studies on felsic volcanic centers indicate that the final two stages of caldera development involve major ring fracture volcanism and terminal hot spring and fumarolic activity (Smith and Bailey, 1968). The strata comprising the Lyon Creek Succession represent these final two evolutionary stages in the development of the Sturgeon Lake Caldera Complex.

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GEOLOGIC SETTING OF SUBECONOMIC GOLD DEPOSITS IN THE VIRGINIA HORN, NORTHEASTERN MINNESOTA: A HORN OF PLENTY OR A HORNSWOGGLE?

JIRSA, Mark A., BOERBOOM, Terrence J., and CHANDLER, Val W.—Minnesota Geological Survey (MGS), 2642 University Avenue, St. Paul, MN, 55114-1057 (jirsa001@tc.umn.edu)

Several significant—though, to date subeconomic—gold deposits occur within Archean bedrock in the area known as the Virginia Horn. Three prospects were worked to varying degrees by exploration companies in the late 1980's, and one of these, the "Viking prospect", was extensively drilled. The exploration focused on pervasively altered felsic porphyry intrusions having variably well developed deformation envelopes and associated carbonate-sericite alteration. Recent mapping by the MGS (Jirsa and others, 1998), together with geochemical work by the Natural Resources Research Institute (Englebert and Hauck, 1991; and work in progress) has provided further information on the lithological and structural framework, potential sources of Au, and relative timing of mineralization in these prospects and the surrounding area.

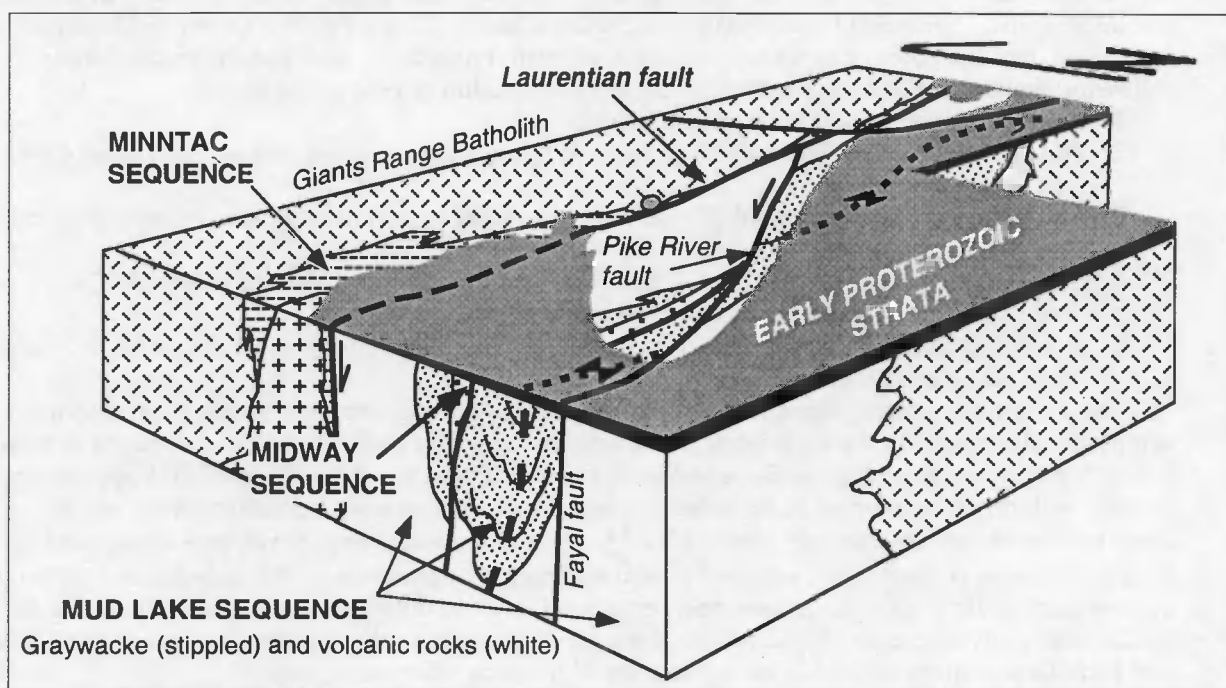


Figure 1—Schematic block diagram of the Virginia Horn. Map surface dimensions approximately 30X30 km.

The Archean rocks of the Virginia Horn lie within the Wawa subprovince of Superior Province. The rocks are subdivided into northern and southern panels on the basis of metamorphic grade and deformation style. The northern panel, immediately south of the Giants Range batholith, contains intensely lineated, amphibolite-grade schists having volcanic and clastic protoliths. The southern panel contains lithologically similar rocks that were metamorphosed to much lower grades, ranging from prehnite-pumpellyite to low greenschist. The two panels are separated by the east-trending, post-metamorphic, Laurentian fault (Figure 1). The metamorphic cleavage-forming event in both panels was the second (D₂) of 3 major deformations—the other two deformation events produced no discernible metamorphic affects. The first (D₁) involved upright folding, soft-sediment deformation, and complex faulting; the third (D₃) produced localized semi-brittle crenulation of D₁ and D₂ structures, brittle fractures, and selective reactivation of earlier-formed faults. Amphibolite grade rocks north of the Laurentian fault comprise the Minntac sequence; the low and sub-greenschist grade

strata south of the Laurentian fault are subdivided into Mud Lake and Midway sequences. The Minntac sequence contains strongly banded schists having geochemical and outcrop-scale characteristics of mafic to intermediate volcanic and volcanoclastic strata, subvolcanic mafic sills, and graywacke. Although the possibility of tight folding is great in rocks of the Minntac sequence, relict grading and bedding consistently indicate southward stratigraphic facing. In contrast, the Mud Lake sequence forms a broad, southwest-plunging, D₁ syncline that is cored by graywacke, slate, and minor felsic tuff; and has outer limbs of calc-alkalic and tholeiitic strata. The Mud Lake strata are cut by several variably porphyritic, quartzofeldspathic intrusions. The Mud Lake sequence and the intrusions are unconformably overlain by, and are locally in fault contact with, fluvial conglomerate and subaerially deposited trachyandesite flows and pyroclastic rocks that comprise the Midway sequence. The Midway has many attributes of Timiskaming-like strata in the Kirkland Lake and Shebandowan gold mining districts of Ontario. Like the Timiskaming rocks of Ontario, those in the Virginia Horn are inferred to have been deposited in a fault-bounded pull-apart basin that formed before the onset of D₂ deformation and metamorphism.

The Virginia Horn has a long history of gold "shows", dating back to the days of J.W. Gruner and F.F. Grout (Grout, 1937), and some visible gold can still be found locally in altered rocks in and adjacent to quartz veins. Sampling by exploration companies focused largely on the quartzofeldspathic intrusions, and the country rocks were rarely analyzed. From those data and the current study, the following generalizations can be made about the distribution of gold in the region:

1. Gold is most abundant in quartzofeldspathic dikes.
2. The greatest gold contents (as large as 50,000 ppb) occur in rocks that are pervasively altered and cut by quartz-rich veins.
3. Anomalous quantities of gold (50- 500 ppb) also exist in sedimentary and volcanic wall-rocks of the porphyritic intrusions.
4. Gold concentrations greater than a "mineable" cut-off of about 1000 ppb (0.029 OPT) are recorded exclusively from samples of quartzofeldspathic dikes.
5. In rocks uniformly affected by carbonate-sericite alteration, gold is most abundant in zones of anomalous arsenic content.

The carbonate-sericite alteration associated with gold mineralization varies from pervasive and not obviously related to the rock fabric, to having textures that imply strong involvement in shearing. Pyrite typically is associated with carbonate and sericite; and arsenopyrite and chalcopyrite occur locally. Alteration is inferred to have taken place during or just after D₂ deformation, as the alteration products are variably affected by S₂. That alteration is best developed along major fault zones, lithologic contacts, and adjacent to and within the quartzofeldspathic intrusions. Although the surface and shallow subsurface have been evaluated in some detail, comparisons with analog deposits in Canada imply that unexplored potential exists; 1) at depth in the low-grade rocks of the Midway and Mud Lake sequences; and 2) throughout the high-grade Minntac sequence.

ACKNOWLEDGMENTS

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EFFECT OF ELECTRIC PULSE DISAGGREGATION ON MICROFOSSIL-BEARING ARGILLACEOUS LIMESTONE OF THE MIDDLE ORDOVICIAN DECORAH SHALE

KJERLAND, Dean W., and KJERLAND, Marc P., amateur paleontologists,
8007 Xerxes Ave S, Bloomington, MN 55431 E-mail: 73563,3520@compuserv.com

The Middle Ordovician Decorah Shale is a fossiliferous shale with lenses and thin beds of coquinoïdal limestone and calcareous shale (Rice). The calcitic macrofossils and phosphatic conodont microfossils have been studied (Sloan, Webers). Though known from acid processing residues, other non-calcitic microfossils have not been documented.

We collected over 250 typical hand-sized samples of limestone from Decorah Shale beds disturbed during the reconstruction of Hwys 110, 55 & 13 at Mendota, Minnesota in 1993. Our selection criteria was the presence of phosphatic microfossils or fragments visible with a hand lens on either or both surfaces. Our photographic documentation of 200 of these surface microfossils using optical microscopy reveals a wide variety of microfossils including lithified mud internal casts of bryozoans (Cuffey), laminated plates, and gastropod steinkerns.

Separation of microfossils from the matrix is necessary for more efficient collection and documentation. Full viewing of specimens is useful for classification. Mechanical crushing is not an effective method for cleanly separating either macrofossils or microfossils from matrix. Acid processing yields clean microfossil specimens but artificially selects for either calcitic or phosphatic material. Both Ca and P, as well as Fe, S, Al, Si, and Mg, have been confirmed from our S.E.M. analyses of a sample of several dozen typical microfossils.

Saini-Eidukat and Weiblen reported the use of an Electric Pulse Disaggregator (EPD) for fossil extraction (see References). In our study we evaluated the potential of the EPD for separating visible microfossils from the surface 'fossil hash' of Decorah Shale limestone and also for sampling for microfossils buried in the matrix of this rock. We used the specialized, upgraded laboratory-scale version EPD at the University of Minnesota which is based on the electric-pulse facility in St. Petersburg, Russia (Saini-Eidukat and Weiblen).

A lenticular slab fragment, 16 cm long x 12.5 cm wide weighing about 1.2 kg, was quartered with a rock hammer and further fragmented/delaminated with a cold chisel to produce walnut-sized fragments for electric pulse disaggregation. The rock consisted of non-weathered, compact, dark blue-gray crystalline calcite with typical cemented calcitic microfossil fragment debris and gray interstitial surface clay on both sides and phosphatic microfossils and fragments visible on only one surface.

The slab pieces were hand fed in two batches into the hollow cathode of the EPD over a 6 mm integral sieve and subjected to approximately 200 pulses at approximately 100 kV. All material except the suspended fines was air dried and mechanically sorted through brass sieves (Table 1.) The material which passed through the 0.25 mm sieve was processed dry through a series of teflon meshes (Table 2.).

The aggregate produced by the EPD is fragmented crystalline calcite and yellow clay and mud-sized fines. Only a small fraction consists of whole calcite fossils or fragments and non-calcitic microfossils and fragments (either matrix-free or partly enclosed in calcite matrix).

Table 1: Grading criteria and results:

<u>Class</u>	<u>Sieve(in mm)</u>	<u>Weight(in g) and %</u>	
I	>6.0	31.2	2.5%
II	<6.0->4.0	297.8	24.0%
III	<4.0->2.0	397.3	32.1%
IV	<2.0->1.0	207.6	16.8%
V	<1.0->.701	65.6	5.3%
VI	<.701->.495	46.7	3.8%
VII	<.495->.250	62.9	5.1%
VIII	<.250	129.1	10.4%
	Total	1238.2	100.0%

Table 2. Grading of Class VIII Material

Note: The material which passed through the 0.25 mm brass sieve was re-graded using teflon meshes. Results are from top of mesh.

<u>Class</u>	<u>Mesh# (mm)</u>	<u>Weight(in g) and %</u>	
VIIIa	#60 (>.250)	6.4	5.0%
VIIIb	#80 (>.177)	15.9	12.3%;
VIIIc	#100(>.149)	13.0	10.1%;
VIIId	thru #100	93.8	72.6%.
	Total	129.1	100.0%

The Class VIIIa-d materials from the teflon meshes were not examined at this time. The Class I - VII materials were examined with an optical microscope and sampled for a). non-fossil crystalline calcite, b). fossil-bearing calcite, and c). non-calcitic fossils, fragments and unknowns. Based on subjective criteria (i.e. typical, interesting, unusual or trophy categories) 654 fossils, fragments and unknowns were collected. Specimen counts are: 11.8% calcitic fossils, 9.8% phosphatic fossils in crystalline calcite, 74.9% loose phosphatic fossils and fragments, and 3.5% unknown. Virtually all of the matrix-free non-calcitic fossils and fragments are from that portion of the aggregate (31%) recovered from the top of the sieves in the 2.0 mm - .250 mm sieve set (Class IV-VII).

Conclusion: The EPD provides a new method for disaggregating rocks for isolating microfossils in the size range from 2.0 mm to 0.25 mm. EPD processing effectively separates phosphatic, calcitic, and pyritic microfossils from their calcitic matrix and allows efficient testing of rocks for the presence of buried specimens. Although some specimens may break in processing or during sample preparation, many fossils preserved in shale are commonly fractured naturally in the matrix. We believe that EPD processing simply separates already damaged fragments or whole fossils along existing fractures.

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RESULTS OF MODELLING PROTEROZOIC THERMAL HISTORIES: EVALUATING THE POSSIBLE EFFECTS OF WOLF RIVER BATHOLITH REHEATING ON THERMOCHRONOLOGIC DATA FROM NORTHERN WISCONSIN

Jeff Loofboro (student) and Daniel Holm, Department of Geology, Kent State University,
Kent, OH 44242

Introduction. Mica Rb/Sr and Ar/Ar thermochronologic results across northern Wisconsin and northern Michigan (Peterman and Sims, 1988, Tectonics; Schneider and others, 1996, CJES; Holm and others, 1997, GSAA) reveal a 1630-1600 Ma chrontour which separates basement rock with primary cooling ages of 1760-1750 Ma to the north from <1630 Ma ages to the south. The chrontour coincides physically with an apparent deformational front in overlying, Early Proterozoic, post-Penokean quartzites leading Holm and others (1998, ILSG; and in review) to interpret the chrontour to represent complete thermal resetting of micas associated with foreland deformation related to accretion from the south. However, we note that the chrontour also appears to surround the known subsurface extent of the Middle Proterozoic Wolf River batholith (Fig. 1) raising the possibility that it might be an artifact of partial resetting. In this case, the 1630-1600 Ma chrontour may represent a collection of meaningless "mixed" dates resulting from partial resetting of the older primary 1760-1750 Ma dates at 1470 Ma when the batholith intruded. Using the MacArgon program (Lister and Baldwin, 1996, Tectonophysics) we have modelled various Proterozoic thermal histories in an attempt to evaluate the possible effects of Middle Proterozoic reheating on thermochronologic data from northern Wisconsin.

Initial conditions and model parameters. We initially consider a rock containing muscovite with a plateau Ar/Ar date of 1765 Ma and biotite with a plateau date of 1755 Ma. Precambrian basement rock north of the chrontour in northwest Wisconsin are near the Early Proterozoic nonconformity suggesting these rocks were at shallow crustal depths by ~1700 Ma. Considering this, we chose three different ambient temperatures (100°, 150°, and 200°) and imposed a thermal pulse at 1470 Ma to simulate intrusion of the batholith. We varied the peak temperature of the pulse between 200° and 450°C (using 50°C increments) and the duration of heating from instantaneous to 2 my (using 0.5 my increments). In all cases the duration of cooling back to ambient temperatures lasted 2 my and hence the total duration of the pulse varied in our models from 2-4 my. The duration of thermal effects of plutonism on country rock is normally shorter than this (Carslaw and Jaeger, 1959, Clarendon Press), but we chose such long durations in order to maximize the effects of partial resetting by the batholith. We assume no other thermal overprinting affects after intrusion of the Wolf River batholith, ending the thermal history with slow cooling from the chosen ambient temperature to 0°C at 600 Ma (Fig. 2). The variables in the modelling thus include the peak temperature obtained, the duration of the thermal pulse, and the initial ambient temperature. The affect of each of these parameters on argon diffusion in muscovite and biotite is described below.

Results of thermal modeling. As might be expected, the dominant factor influencing partial resetting is the peak temperature obtained by the rock during the imposed thermal pulse. Peak thermal pulses at or below the closure temperature of biotite (300°C) or muscovite (350°C) had little affect on the initial cooling age regardless of the duration of heating. Peak thermal pulses of 50°C above closure temperature resulted in considerable partial resetting. In this case the duration of the heating interval did have a moderate affect on the degree of resetting with 2 my heating intervals resulting in total gas ages which are ~50 my younger than in the case for instantaneous heating. Because of the difference in closure temperature between biotite and muscovite, the modelling reveals that large differences in the degree of partial resetting (and hence apparent ages obtained) are expected for 1470 Ma peak thermal pulses between 300 and 450°C. Temperatures 100°C above the mineral's nominal closure temperature resulted in nearly complete resetting of the isotopic systematics regardless of the duration of heating. Varying the initial ambient temperature between 100-200°C had little affect on the apparent ages obtained.

Implications. Existing thermochronologic data from northern Wisconsin show nearly concordant muscovite and biotite dates near the chrontour (with muscovite around 1620 Ma and biotite around 1600 Ma; Romano and others, 1997, GSAA). We are unable to obtain nearly concordant partially reset ages with any of our simulations and conclude that Middle Proterozoic intrusion of the Wolf River batholith was probably not responsible for generating the 1630-1600 Ma chrontour by partial resetting. This conclusion is indirectly supported by two independent lines of evidence. First, the degree of deformation of the Early Proterozoic quartzites in Wisconsin does not wane away from the Wolf River batholith as would be expected for intrusion related deformation. The sharp deformational front (which coincides with the 1630-1600 Ma chrontour) is more characteristic of tectonic-related deformation. Second,

thermal effects of the Duluth Complex on Archean country rock in northeastern Minnesota exist only to a map-view distance of 10 km away from the intrusion (Hanson and others, 1975, GCA). By comparison, the 1630-1600 Ma chrontour in northern Wisconsin is located more than 40 km away from the known subsurface extent of the Wolf River batholith (Fig. 1). Our results support the conclusion of Holm and others (1998, ILSG) that the 1630-1600 Ma chrontour represents complete thermal resetting of micas associated with latest Early Proterozoic tectonism.

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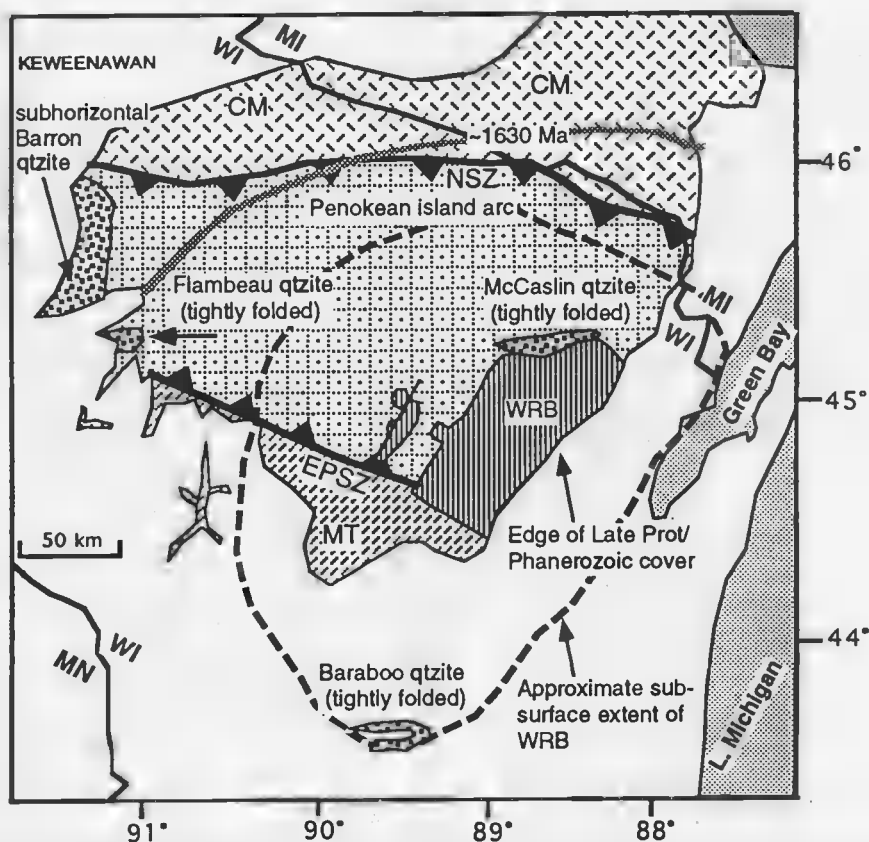


Figure 1. Simplified tectonic map of the central Penokean orogen, northern Wisconsin and Michigan, U.S.A. (after Sims, 1992; Holm and others, in review). CM = continental margin; EPSZ = Eau Claire shear zone; NSZ = Niagara suture zone; MT = Archean Marshfield terrane; WRB = Wolf River batholith.

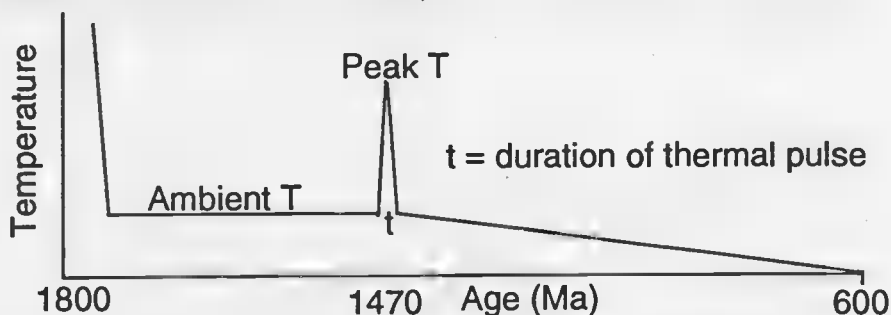


Figure 2. Temperature-time graph showing modelled parameters.

An Archean subaqueous heterolithic debris flow,
Irwin, Pifher, and Meader Townships,
Lake Nipigon Region, Ontario

Frank R. Luther, Geology Department, UW-Whitewater, Whitewater, WI 53190
lutherf@mail.uww.edu

This extensive body of volcanic breccia is located in northern Irwin, southeastern Meader, and a large part of southern and eastern Pifher Townships. It is 10-25 km east of Lake Nipigon and 17-28 km north-northeast of Beardmore.

Mapping by Mackasey (1975) and Kresz and Zayachivsky (1989) shows this rock to be enclosed in a thick sequence of typical greenstone assemblage rocks - pillowed and massive basalt flows, intermediate to felsic pyroclastics and flows, and lesser amount of spatially-associated volcanogenic sediments. It is cut by small granitic intrusions through most of its exposure area and by larger granitic intrusions in Pifher Twp to the northeast. Metamorphism increases to the northeast, perhaps caused by these intrusions. Keweenawan intrusions which cut the breccia include a large diabase sill which dips gently to the south and a small diabase dike, locally termed greenspar (Luther, 1997; Thomas, Kean, and Luther, in preparation).

The breccia contains rounded rock fragments ranging from <1 mm up to over 1 m in maximum dimension. Most fragments are disk-shaped to cigar-shaped in form although irregular on smaller scale; some smaller (5-20 cm) fragments are more competent and nearly spherical. Sorting and alignment of fragments is, in some locations, poorly-developed primary bedding while, in other locations, the sorting and alignment is a result of later strain. The smaller fragments vary in composition from that of the matrix to mafic or ultramafic to carbonate-rich. Larger fragments tend to be similar to the matrix in composition although minor differences in composition or consolidation cause the fragments to weather high or low.

The matrix of the breccia is composed of fine quartz grains (<0.05 mm), euhedral to broken crystals of plagioclase (now albite) ranging in size from <0.1 to 1 mm, a minor pelitic fraction (now muscovite), and, locally, fragments of quartz, pyroxene and/or hornblende (now chlorite) up to 0.5 mm. The primary texture is over-printed by a metamorphic assemblages of chlorite, epidote, actinolite, muscovite, and biotite. Representative whole rock analyses of the matrix and fragments are presented in Table 1. These analyses show the average (igneous rock equivalent) composition of the matrix to be dacitic while the fragments vary from dacitic to mafic.

In summary (1) the heterogeneity of the fragments, (2) the relative homogeneity of the matrix, (3) the shape, and rounding of the fragments, (4) the

great variability in size of the fragments, (5) the poorly sorted character of the whole body of rock, and (6) the spatial association with pillowed volcanics and bedded tuffs lead the author to conclude that this rock is the product of a subaqueous debris flow or flows off the side of a volcanic edifice. The slopes presumably consisted of poorly-consolidated volcanogenic debris including finely-crystalline quartz and clay which was transported from nearby weathered felsic-to-intermediate volcanics and an admixed quantity of pyroclastic debris.

Table 1. Whole rock analyses of the matrix and selected fragments of the volcanic breccia. (XRAL)

	matrix		fragments		
	<u>LN97-6-2</u>	<u>LN97-7-9-2</u>	<u>LN97-6-1B</u>	<u>LN97-6-2A</u>	<u>LN97-7-9A*</u>
SiO ₂	64.3	60.5	63.2	57.8	45.4
TiO ₂	0.49	0.53	0.51	0.51	0.36
Al ₂ O ₃	15.8	16.0	16.5	16.0	22.2
Fe ₂ O ₃	1.85	1.38	1.85	1.73	7.34
FeO	3.2	4.9	3.1	5.4	0.8
MnO	0.08	0.09	0.07	0.09	0.12
MgO	2.92	4.63	2.15	4.36	0.88
CaO	4.87	3.53	6.03	4.42	17.7
Na ₂ O	4.54	4.18	3.53	3.47	0.88
K ₂ O	1.05	1.15	1.49	2.18	0.30
P ₂ O ₅	0.10	0.12	0.11	0.11	0.08
LOI	0.55	2.4	0.85	1.45	2.0
=====					
TOTAL	99.75	99.41	99.39	97.52	98.06

* 95% epidote

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NEW FIELD OBSERVATIONS OF THE CLARKSBURG VOLCANICS, UPPER PENINSULA OF MICHIGAN

MAKI, John C. and Bornhorst, Theodore J., Department of Geological Engineering and Sciences, Michigan Technological University, Houghton, MI 49931

The Clarksburg Volcanics are a member of the Early Proterozoic Michigamme Formation, Baraga Group, Marquette Supergroup and crop out near US-41 between Champion and west Ishpeming, Marquette County, Upper Peninsula, Michigan (Cannon, 1974, 1975; Cannon and Klasner, 1977; Simmons, 1974). The Clarksburg Volcanics are stratigraphically above the Greenwood Iron-formation Member and below the Lower graywacke member of the Michigamme Formation and are laterally restricted over a 19 km strike length and only crop out on the southern limb of the Marquette trough.

These rocks dip about 60 degrees or more, hence the exposed section only provides data on stratigraphic and strike parallel variation. Despite metamorphism to the amphibolite facies in most exposures and greenschist facies in a few, primary textures are well preserved in the outcrops.

The Clarksburg Volcanics are composed mostly of volcanic rocks with lesser amounts of clastic sedimentary rocks and iron-formation. Field observations and available chemical data suggest that the volcanic rocks are dominantly basalt with less amounts of andesite. In general, the volcanic rocks are tuffs and agglomerates containing fragments 0.5 to 1.5 cm in diameter. Near the towns of Humboldt and Clarksburg, clast size is considerably larger than elsewhere, up to 30 cm in diameter. Laterally, the typical clast size is considerably finer in both the extreme eastern and western exposures with argillite being common in the west Ishpeming exposures. These observations suggest a proximal or near vent environment in the central exposures and a distal environment towards the east and west. Since mafic pyroclastic rocks often do not travel large distances from the volcanic vent, it is likely that the volcano was quite near the central exposures of the Clarksburg Volcanics.

Within the Clarksburg Volcanics there are several areas with interbedded banded iron-formation. The iron-formation is composed of mixed magnetite- and detrital-bearing layers (1 to 4 mm thick) and poorly defined chert layers (< 1 mm thick). Metamorphism has produced quartzite textures in the iron-formation. As the exposures of iron-formation are in the proximal section of the Clarksburg Volcanics, we suggest that the interbedded iron-formation has a volcanogenic origin.

Throughout the immediate region, diabase sills, dikes, and other shaped bodies are common. Cannon (1974) suggested that the diabase was approximately equivalent in age to the Clarksburg Volcanics. The major element chemical composition of the diabase and Clarksburg Volcanics are similar. Just south of the town of Clarksburg is a relatively large body of diabase with a surface exposure of approximately 1.5 by 1.5 km. This body of diabase cuts rocks stratigraphically older than the Clarksburg Volcanics and is spatially adjacent to the proximal section. We suggest this diabase is part of the subvolcanic roots of the Clarksburg volcanic system.

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POST-GLACIAL SHORELINES OF ISLE ROYALE – WHERE ARE THEY NOW?

M.E. McRae, Oak Ridge Associated Universities, Reston, VA

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

L.G. Woodruff, U.S. Geological Survey, Mounds View, MN

Well-developed shoreline features at elevations higher than the present day lake level are well documented in the Lake Superior basin. These shorelines formed approximately 10,000 to 4,500 years ago as the last glacier to occupy western Lake Superior receded to the northeast. Further, mapping of stranded shoreline features has demonstrated that these once flat-lying lake planes are now tilted from northeast to southwest as a consequence of differential isostatic rebound. Previous researchers have been able to construct isobases of rebound for several of the better-developed lake levels. These include Lakes Washburn and Beaver Bay (~9800 - 9700 B.P.), Lake Minong (~9500 B.P.), Lake Houghton (~8000 B.P.), and Lake Nipissing (~5500 - 4700 B.P.).

Beach ridges are common features on Isle Royale, particularly on the lower elevations of the southwest portion of the island where glacial debris is widespread. A few wave-cut features in bedrock have also been mapped in the northeastern half of the island. However, all of these features are scattered and discontinuous. Consequently, the exact positions of former shorelines are not precisely known from observable features for most of the island.

Using geographic information systems (GIS) software, we constructed a series of gridded surfaces representing lake level planes from the isobases of glacioisostatic rebound described above. Subtracting each gridded surface from the present-day digital elevation model (DEM) of Isle Royale yields a sequence of new DEM's showing the island's morphology at several different lake stages.

We then displayed the modeled shorelines with the known beach and wave-cut features. The two highest modeled shorelines, Lake Washburn and Lake Beaver Bay do not correlate with any of the mapped features. This may indicate that the island was not yet free of ice at these times. All mapped features fall either on or below the Lake Minong shoreline. Lengthy sections of mapped beach ridges lie on the modeled Minong shore. Evidence also seems to support the position of the modeled Nipissing shore. No features seem to correlate with the Houghton shoreline.

By overlaying the modeled shorelines on the modern digital elevation model, it is possible to determine the approximate elevation of the post-glacial shores around the island. This knowledge could serve as a guide to future mapping particularly if combined with information such as vegetation type, surficial material, abundance of outcrop, and accessibility to trails.

Lastly, prehistoric mining of native copper began about 5,000 years ago, and possibly earlier. We hypothesize that former lake levels influenced the prehistoric discovery and mining of copper. Copper would have been easily accessible and recognizable in wave-washed shoreline rock exposures, so discovery along prehistoric shorelines seems probable. Because wave-washed exposures remain largely barren of vegetative material for prolonged periods

after they are abandoned, they remained favorable points for discovery long after the lake levels had receded. Major prehistoric workings at the Minong Mine are in extensive bedrock exposures at or just above the projected Minong shore. During a brief reconnaissance in 1997 we observed prehistoric working in two other areas of extensive exposure at the Minong shore. Did early inhabitants of the Lake Superior region, such as the Plano Indians who inhabited the Minong shore near Thunder Bay, visit the island and discover copper during the Lake Minong stage, well before the generally accepted date of first mining? Or did barren rock exposures from the former Minong shore facilitate recognition of native copper thousands of years later? In either case, we suggest that the projected location of the Minong and younger shorelines can provide a guide to future archaeological studies.



Projected digital elevation model of Isle Royale during the time of Lake Minong.
Shoreline of the modern island is shown in white.

ELECTRON MICROPROBE STUDY OF THE Pt-Pd AND RELATED MINERALIZATION IN THE MINNAMAX/BABBITT Cu-Ni DEPOSIT

McSWIGGEN, Peter L., Minnesota Geological Survey, 2642 University Avenue, St. Paul, Minnesota 55114

The Minnamax deposit is one of several copper-nickel sulfide deposits that occur along the base of the Duluth Complex, which is a series of mafic intrusions that are part of the Keweenaw (1100 Ma) Midcontinent Rift system (Paces and Miller, 1993). The ore body consists of troctolitic and ultramafic rocks, as well as hornfelsic inclusions derived from Paleoproterozoic metasedimentary rocks, and unconformably overlying Mesoproterozoic volcanic rocks. The copper and nickel are contained predominantly in disseminated sulfides that make up between 1 and 5 percent of the rock. The sulfides consist largely of chalcopyrite, cubanite, pyrrhotite and pentlandite (Severson, 1991; Severson and Barnes, 1991). In addition to the copper and nickel, the deposit also contains significant concentrations of platinum (Pt), palladium (Pd), gold (Au), silver (Ag) and cobalt (Co). Sections of core ranging from 5 to 10 ft long have as much as 7.0 ppm Pd, 3.1 ppm Pt, and 13.1 ppm Au. As pointed out by Severson (1991), the high values for the platinum group elements (PGE's), other precious metals, and Co have been shown by others to be associated with the high-grade copper zones (Kuhns and others, 1990).

This electron microprobe study has shown that rocks at the Minnamax site contain at least two platinum group minerals (PGM's) -- froodite (PdBi_2) and cabriite (Pd_2SnCu). They are commonly associated with massive sulfide mineralization and are less common in samples consisting mostly of silicates. Of the 14 samples investigated in detail, 5 were found to contain either froodite or cabriite. Although the number of PGM grains is small, just a few of the 1-2 micron size grains could account for the reported whole rock values. Therefore there is no need to invoke PGE-sulfide phase solid solution to account for the PGE whole-rock values reported from these rocks.

Numerous examples of silver mineralization were found in these rocks. The silver is typically present either as solid solution in maucherite or as discrete grains of native silver. Significant gold was found in a few of the native silver grains. Values as high as 16 wt. percent Au were measured in 5 to 100 micron size grains of silver, but values were more typically in the 1 percent range. Cobalt was found at significant levels only in maucherite and pentlandite. Detailed inspections of these samples shows that they contain numerous rare phases including dienerite (Ni_3As), shadlunite $[(\text{Pb},\text{Cd})(\text{Fe},\text{Cu})_8\text{S}_8]$, altaite (PbTe), laurionite $[\text{PbCl}(\text{OH})]$ and cotunnite (PbCl_2).

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POST-1.76 Ga LOW-GRADE METAMORPHISM OF THE BARABOO QUARTZITE

MEDARIS, L.G., Jr., BROWN, P.B. and BUNGE, R.J., Dept. of Geology & Geophysics, Univ. of Wisconsin-Madison, Madison, WI 53706; medaris@geology.wisc.edu

It has long been recognized that the Baraboo Quartzite is folded and metamorphosed, and recent U-Pb dating of detrital zircons in the quartzite requires that deformation and recrystallization were post-1.76 Ga events. Although the structure of the Baraboo syncline has been well studied, little attention has been devoted to metamorphism in the Baraboo Range, other than identifying pyrophyllite in metapelite layers and recognizing that metamorphism was low-grade. We have undertaken a petrologic investigation of the Baraboo Quartzite and underlying granite and rhyolite to determine the conditions of post-1.76 Ga metamorphism.

Rock types, chemical compositions, and mineral assemblages A well-developed paleosol occurs in granite and rhyolite at the unconformable base of the Baraboo Quartzite. Intense chemical weathering and sedimentary processes combined to produce a marked geochemical differentiation among basement rocks, paleosol, and pelitic layers in the Baraboo Quartzite (Table 1). Ca, Na, and K were leached from granite and rhyolite, and Al and Fe were concentrated in the paleosol (saprolite and soil) and pelitic layers in the sedimentary section, which consisted originally of kaolinite and variable amounts of silt-size quartz grains. The most aluminous of three analysed pelites is listed in Table 1, and two other samples are equally low in Ca, Na, and K. During metamorphism, K was re-introduced into the paleosol by H₂O-rich fluids that were channeled along the sub-Baraboo unconformity; this K-metasomatism was accompanied by formation of thin diaspore-pyrophyllite-white mica veins in basal quartzites.

The compositions of Baraboo rocks are projected into the system, KASH, in Fig. 1, in which the positions of selected minerals are also plotted. The KASH equilibrium metamorphic assemblages for these rocks are: granite and rhyolite, quartz + microcline + muscovite; paleosol, quartz + muscovite; metapelite, quartz + pyrophyllite; and hydrothermal veins, pyrophyllite + muscovite + diaspore. Kaolinite is present in metapelite and hydrothermal veins, but only as a retrograde product. In addition to KASH minerals, granite and rhyolite contain albite, epidote, and chlorite. Hematite is abundant in these rocks, especially in paleosol and metapelite, and rutile is common in metapelite.

Table 1
Chemical Compositions, Baraboo Rocks

	rhyolite	avg granite	avg saprolite	avg soil	pelite
	(1)	(2)	(10)	(5)	(1)
wt%					
SiO ₂	72.80	69.25	70.51	56.41	59.70
TiO ₂	0.26	0.25	0.36	0.87	1.03
Al ₂ O ₃	13.30	15.15	17.18	20.89	25.40
Fe ₂ O ₃	2.99	3.46	2.82	10.18	8.04
MnO	0.07	0.09	0.00	0.00	0.01
MgO	0.14	0.89	0.07	0.38	0.04
CaO	1.16	1.55	0.14	0.09	0.03
Na ₂ O	4.93	4.40	0.34	0.32	0.04
K ₂ O	3.17	3.14	4.75	5.72	0.21
P ₂ O ₅	0.03	0.09	0.13	0.10	0.12
LOI	1.25	1.53	2.51	3.65	4.70
Sum	100.10	99.78	98.80	98.62	99.32

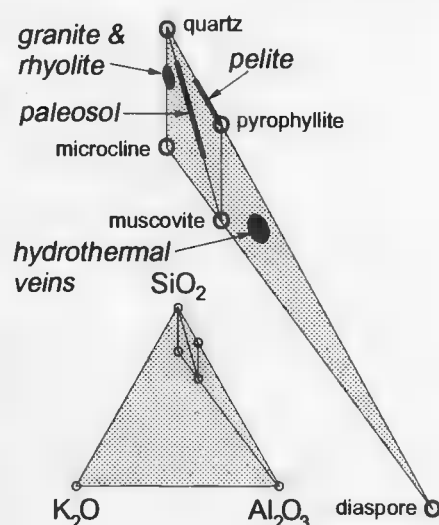


Fig. 1 Compositions of Baraboo rocks projected into the KAS plane of the system, KASH

Metamorphic conditions Mineral reactions and chemographic relations in the system, KASH (calculated for unit activity of H_2O), are summarized in Figure 1. Minimum temperatures of metamorphism are defined by the metapelite assemblage, quartz + pyrophyllite, which is stable above the reaction, $Kln + Qtz = Prl + V$, and by the absence of stable kaolinite from all observed T_{max} assemblages, indicating that temperatures were above the stability limit of kaolinite. Maximum temperatures are defined by the absence of kyanite from the assemblage, muscovite + pyrophyllite + diaspore, in hydrothermal veins, which is stable below the reaction, $Prl + Dsp = Ky + V$, and by the absence kyanite in metapelite, which indicates that temperatures did not exceed the stability limit of pyrophyllite.

Fluid inclusions were analysed from quartz in a folded quartz vein in metapelite. The quartz contains a single population of abundant aqueous inclusions that have final melting points of -15 to $-18^\circ C$, corresponding to 18 to 20 equivalent wt% NaCl. First melting below $-35^\circ C$ suggests the presence of divalent cations. Homogenization temperatures lie between 165 and $215^\circ C$ with a peak in the 175 - $185^\circ C$ range.

Intersection of the fluid inclusion isochore with the limiting mineral reactions constrains temperature-pressure conditions for the Baraboo Quartzite to lie between $\sim 320^\circ C$, 2.7 kbar and $\sim 385^\circ C$, 4.0 kbar. Such values correspond to a thermal gradient of 25 - $30^\circ C/km$, which is typical for Barrovian-type metamorphic terranes and is notably elevated over that for stable cratons ($\sim 17^\circ C/km$ at comparable depths).

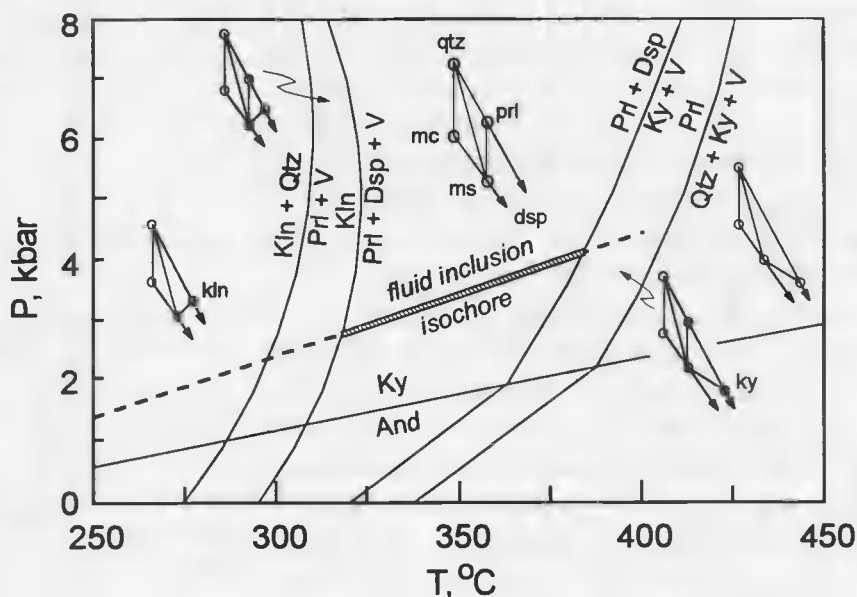


Fig. 2 Mineral assemblages and reactions in the system, KASH, a fluid inclusion isochore for quartz in a folded quartz vein, and metamorphic conditions for the Baraboo Quartzite

Conclusions Folding and metamorphism of the Baraboo Quartzite mark an important post-1.76 Ga tectonothermal event in the Lake Superior region. Although the age of this event remains uncertain, it could be related to an eastern extension of the Mazatzal belt at ~ 1.63 Ga. However, andalusite-bearing assemblages in the Waterloo Quartzite are probably due to contact metamorphism associated with Wolf River magmatism at ~ 1.43 Ga.

SVANBERGITE IN THE BARABOO QUARTZITE: SIGNIFICANCE FOR DIAGENETIC PROCESSES AND PHOSPHORUS FLUX IN PRECAMBRIAN OCEANS

MEDARIS, L.G., Jr. and FOURNELLE, J.H., Department of Geology & Geophysics,

University of Wisconsin-Madison, Madison, WI 53706; medaris@geology.wisc.edu

Authigenic minerals of the beudantite and crandallite groups have recently been recognized as widespread constituents of Archean to Cretaceous sedimentary rocks (Rasmussen, 1996).

Although the abundance of these aluminophosphate-sulfate minerals is small, on the order of 0.2 to 0.01 wt% in a given sample, they appear to be more abundant than authigenic apatite and play an important role in phosphorus balance in the oceans.

The beudantite and crandallite mineral groups The general formula for the beudantite group is $AB_3(XO_4)(SO_4)(OH)_6$, where $A = Ba, Ca, Ce, Pb, Sr$; $B = Al, Fe^{3+}$; and $X = As, P$; and for the crandallite group is $AB_3(XO_4)_2(OH,F)_{5,6}$, where $A = Ba, Bi, Ca, Ce, La, Nd, Sr, Th$; $B = Al, Fe^{3+}$; and $X = As, P, Si$. Electron microprobe analysis of Baraboo svanbergite demonstrates that its composition can be portrayed by a distorted pyramid (Fig. 1) in which members of the beudantite group lie along the front edge of the pyramid and members of the crandallite group lie in the far face (note that Ca and Ba have been combined for projection purposes).

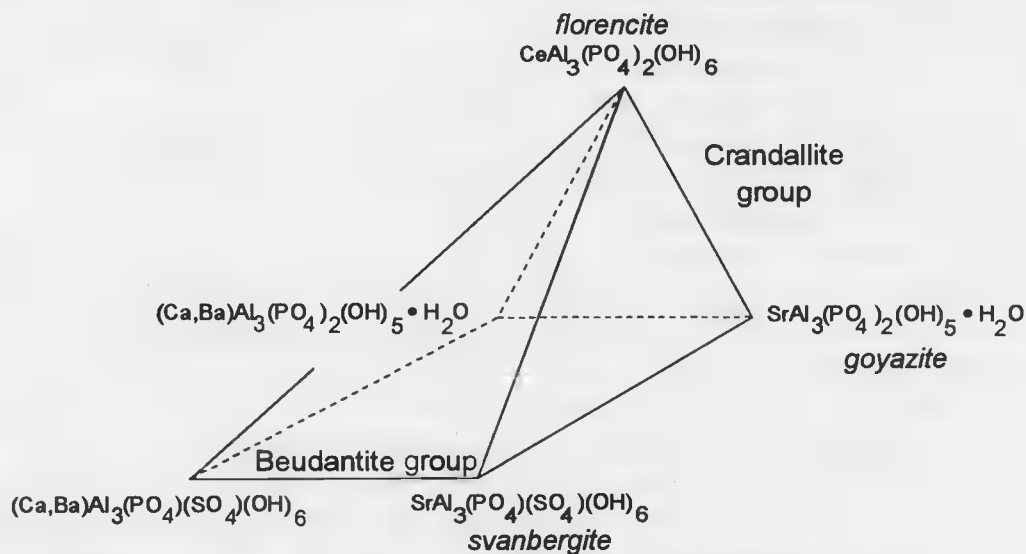


Fig. 1 Compositional space of Beudantite and Crandallite group minerals from Baraboo metapelite

Occurrence and chemical composition of Baraboo svanbergite Small amounts of svanbergite are widespread in metapelite layers in the Baraboo Quartzite, where it is associated with pyrophyllite, quartz, hematite, and rutile. Svanbergite grains are equant and have diameters of 10-20 microns, but despite their small size, are readily visible microscopically because of their marked difference in relief compared to associated pyrophyllite. Baraboo svanbergite contains < 2 wt% Fe_2O_3 , < 1 wt% As_2O_3 , and has negligible amounts of Bi, Pb, Th, Si, and F; its composition is a solid solution of $AAl_3(PO_4)(SO_4)(OH)_6$ - $AAl_3(PO_4)_2(OH)_5 \cdot H_2O$, where $A = Sr > Ca + Ba + REE$, which lies near the base of the pyramid in Fig. 1 between svanbergite and goyazite (Fig. 2).

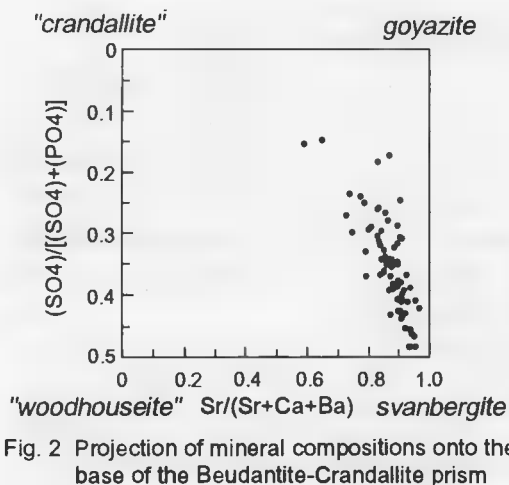


Fig. 2 Projection of mineral compositions onto the base of the Beudantite-Crandallite prism

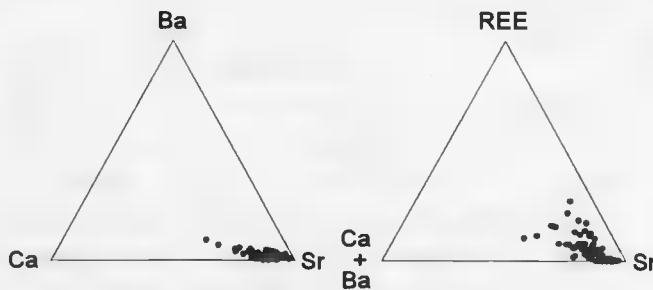


Fig. 3 Proportions of cations in the A-site of Baraboo svanbergite-goyazite

The Baraboo svanbergite solid solution ranges from almost pure svanbergite (beudantite group) to ~70% goyazite (crandallite group) with a concomitant decrease in $\text{Sr}/(\text{Sr}+\text{Ca}+\text{Ba})$ (Fig. 2), and A-site occupancy is dominated by Sr (Fig. 3). Many svanbergite grains are strongly zoned, with rims being enriched in crandallite component, in which the sum of La_2O_3 , Ce_2O_3 , and Nd_2O_3 reaches 5.3 wt %, amounting to ~27% occupancy of the A-site (Fig. 3). Although other RE elements may be present, they can't readily be determined by electron microprobe techniques due to their low abundances and spectral interferences. The light REE contents in svanbergite are ~5000 to 40,000 times greater than in chondrites, and La is enriched over Nd by a factor of 2 to 3 (Fig. 4). There is no marked Ce anomaly, although two samples may have a slight Ce enrichment with respect to La and Nd.

Geological significance of svanbergite Precipitation of authigenic aluminophosphate-sulfate minerals has been ascribed to bacterial decomposition of P-bearing organic matter in an Al-rich environment, such as shale, within the zone of sulfate reduction and methanogenesis (Rasmussen, 1996). If so, the occurrence of svanbergite-goyazite in Baraboo metapelites signifies that such a process may have been operative in mid-Proterozoic time.

The widespread occurrence of authigenic aluminophosphate-sulfate minerals represents a previously unrecognized repository for phosphorus in the oceans. Rasmussen has estimated that aluminophosphate precipitation accounts for a phosphorus burial flux of 7.6×10^{10} moles yr^{-1} , which is comparable to that resulting from authigenic phosphates and P-bearing carbonates ($2.2\text{--}9.1 \times 10^{10}$ moles yr^{-1}). However, Rasmussen used the composition of florencite (2 moles of P pfu) in his calculation, and using the compositional range of Baraboo svanbergite-goyazite (1.0–1.7 moles of P pfu) reduces the burial flux estimate by 15 to 50%. Regardless, aluminophosphate-sulfate minerals are an important factor in oceanic P-flux.

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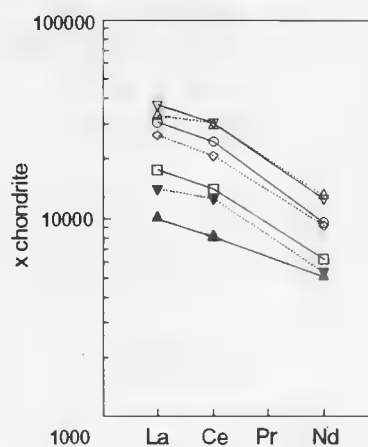


Fig. 4 Representative chondrite-normalized La, Ce, and Nd contents of Baraboo svanbergite-goyazite

USE OF HIGH-RESOLUTION AEROMAGNETIC DATA FOR REGIONAL GEOLOGY INVESTIGATIONS, SOUTHEASTERN WISCONSIN (WHERE'S THE KIMBERLITE!)

MUDREY, M.G., Jr., Wisconsin Geological and Natural History Survey, 3817 Mineral Point Road, Madison, WU 53705-5100, mgmudrey@facstaff.wisc.edu

Between 1876 and 1913, diamonds were found in at least seven localities in southern and central Wisconsin. All were found in Pleistocene gravel deposits or Holocene river gravel. The bedrock kimberlite source for these diamonds is unknown, but was presumed to be in northern Canada, the only area north of Wisconsin previously known to contain kimberlite. With the discovery of the Lake Ellen kimberlite in Iron County, Michigan, Cannon and Mudrey (1981) suggested the drift diamonds in Wisconsin may have come from a more local source.

Carlson and Adams (1997) described a kimberlite in southeastern Wisconsin about 280 m across. The preliminary identification was based on drilling small, highly magnetic anomaly identified from a little known aeromagnetic survey from the 1980s (800-meter flight-line spacing). Only recently have aeromagnetic surveys been sufficiently detailed to determine the presence or absence of kimberlite in southeastern Wisconsin. Prior to the most recent survey, limited flight-line spacing of 10-km precluded the identification of strong, small magnetic bodies at the shallow bedrock surface.

Analysis of the aeromagnetic survey indicates that flight-line spacing less than 800 m will be ineffective in the identification of small, highly magnetic kimberlite at the bedrock/surficial material surface in southeastern Wisconsin.

The identification of the kimberlite, and analysis of available aeromagnetic maps, indicate that other kimberlitic bodies may occur in southeastern Wisconsin and possibly northeastern Illinois and may be the source for the diamond discoveries in Wisconsin and Illinois. However, urbanization in the Milwaukee-Chicago corridor may discourage further geologic and geophysical analysis and competing land use may make further exploration and ultimate development difficult.

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Wisconsin, kimberlite, aeromagnetic data

XENOLITHOLOGIES AS INDICATORS OF INTRUSION MECHANISMS IN THE WAUSAU SYENITE COMPLEX, WISCONSIN

MYERS, Paul E., Geology Department, University of Wisconsin, Eau Claire, WI 54701

In the area west of Wausau, four alkaline subvolcanic plutons: (1) Stettin, (2) Wausau, (3) Rib Mountain, and (4) Ninemile (Figure), were intruded in a southeastward sequence into Lower Proterozoic metavolcanic, metasedimentary, and granitic intrusive rocks (Myers and others, 1984). Whereas the first three syenite plutons are concentrically zoned and pipelike in structure, the youngest, Ninemile pluton, although possessing an aplitic core rim, is a stock-like body which stopped its way to a shallow depth under the now-eroded volcanoes. This paper shows the connection between xenolithologies, magma emplacement, and wallrock alteration.

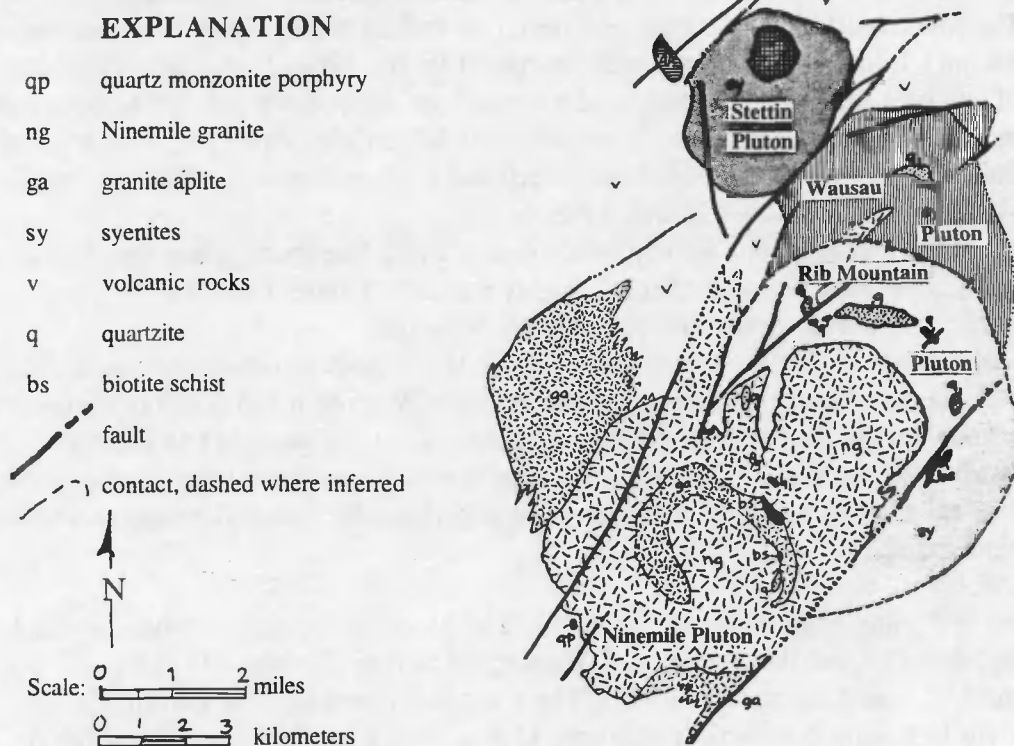


Figure -- Map of Wausau syenite plutons

The Stettin pluton, (Figure) which is the oldest, most alkaline intrusion of the Wausau syenite complex, is oval in plan with dimensions of 8.8 x 6.4 km, and has a concordant NE elongation. Its outer wall zone consists of strongly syenitized volcanic rocks and syenite aplite, which grade inward into concentric, sheet-like masses of gneissic nepheline and tabular syenites. The indistinctly bounded intermediate zone consists mainly of flow-lineated amphibole syenite, and the cylindrical core, with a diameter of 2 km has a rim of lineated nepheline syenite and an inner core of coarse, pyroxene syenite identical with that in the intermediate zone. The Stettin pluton is separated from the syenite bodies to the SE by a fault.

In the Wausau pluton, coarse, massive pyroxene and amphibole syenites form a partial outer rim on the north and east sides. A broad intermediate zone of lensoidal syenite and quartz syenite are crowded with lenticular xenoliths of mica schist, sillimanite-bearing

quartzite, and syenitized volcanic rocks. Xenolith volume locally exceeds the volume of the quartz syenite. As the contact between the Wausau and Rib Mountain plutons is obscured by a broad strip of Rib River alluvium, its core may not be visible in outcrop.

The Rib Mountain pluton produces a crescentic map pattern with an opening to the south where it is engulfed by younger Ninemile granite. The most striking feature of this concentric pluton is the 8km ring of very large, lenticular quartzite and mica schist xenoliths embedded in foliated quartz syenites in its intermediate zone.

The Ninemile Pluton, is an elliptical, stock-like body which was intruded at 1500 Ma. (Van Schmus and Bickford, 1981) into the core and south rim of the Wausau pluton. According to Anderson (1983) it is comagmatic with rapakivi granites of the Wolf River batholith. Although classed as a granite, the Ninemile pluton is mainly coarse biotite-amphibole monzonite containing up to 30 percent strained, polycrystalline quartzite grains usually accompanied by occasional mica schist and quartzite xenoliths. A crescentic mass of granite aplite defines the core rim of the larger southern lobe of the Ninemile pluton.

The Wausau plutons thus show a distinctive magmatic differentiation sequence, beginning with nepheline syenite in the Stettin pluton and ending with pegmatite dikes in the Ninemile pluton. As these dikes are shallow-dipping and contain miarolitic cavities with autoclasts of early crystalline phases, Falster (1985) concluded that they crystallized shallow enough for hydrothermal boiling. Several small porphyritic quartz monzonite plugs cut post-syenite faults outside the Wausau complex and probably represent the "last gasp" of the differentiated Ninemile magma.

Xenoliths in the Wausau, Rib Mountain and Ninemile plutons are unassimilated wallrock fragments carried up and down in the magmas during intrusion. Where there has been considerable vertical transport, as for instance along caldera walls, xenoliths show great diversity of protolithology and metamorphic grade. They include upper amphibolite-grade, sillimanite-bearing quartzite, mica schist, and amphibolite, metadiorite, andesitic metavolcanics and metasediments, and even cognate inclusions of earlier-phase syenites. Their shapes are most commonly lenticular and sheet-like with a preferential orientation parallel to cylindrical walls. Xenoliths are uncommon in the Stettin pluton.

In the Wisconsin River channel east of the power dam at Wausau, the relationships between xenoliths and flow structures in enclosing felsic and mafic quartz syenites are well displayed. Biotite amphibolite xenoliths with swirled lineation, give way southward in the outcrop to sheet-like masses of felsic and mafic rocks. The folded and fragmented mafic xenoliths are biotite-rimmed, showing advanced metasomatic replacement and deformation. The enclosing amphibole quartz syenite has highly discordant flow lineation with swirls and eddies suggesting considerable viscosity and turbulence. Late-stage syenite pegmatite veins with quartz cores probably represent residual liquid segregations along incipient thermal contraction fractures in quartz syenites containing incompletely assimilated quartzite xenoliths. The occurrence of several small xenoliths of unaltered, porphyritic trachyte in the north end of the outcrop suggest a downward movement of some of the clasts from the overlying volcanic pile. As elsewhere in the Wausau syenite complex, the considerable concentric heterogeneity of xenoliths suggests considerable vertical, somewhat laminar transport of xenoliths along caldera walls as a consequence changes in the level of magma in the conduit. Future field studies should include detailed, comprehensive mapping of xenolithologies.

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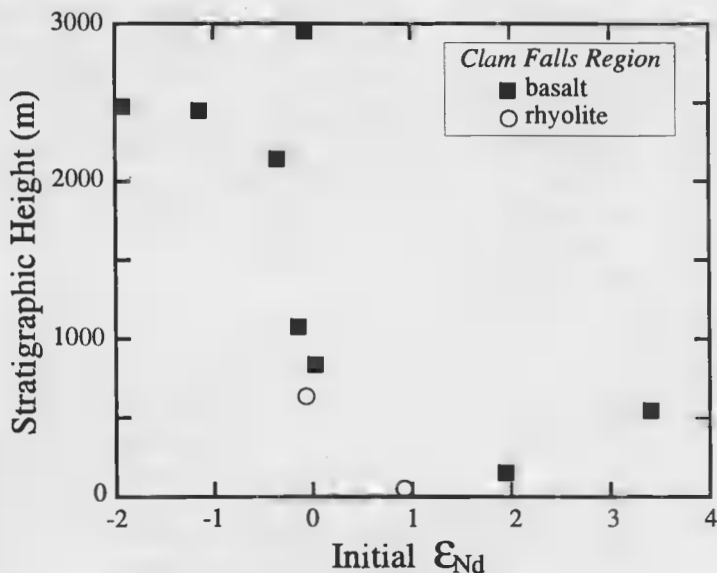
COMPOSITION AND SOURCE(S) OF MIDCONTINENT RIFT LAVAS (CHENGWATANA VOLCANICS) NEAR CLAM FALLS, WISCONSIN

NAIMAN, Zachary J., Department of Geosciences, University of Arizona, Tucson, Arizona, 85716, znaiman@geo.arizona.edu; WIRTH, Karl R., Geology Department, Macalester College, St. Paul, Minnesota, 55105, wirth@macalester.edu.

Most studies of the 1.1 Ga Midcontinent rift (MCR) have focused on the well-exposed volcanics in the Lake Superior region from the central part of the rift. Studies of the Chengwatana Volcanics (CV), the southernmost exposed volcanics of the MCR, provide information about variations in rift processes along the axis of the MCR. Here we report major element, trace element, and Nd isotopic data from mafic and felsic CV flows near Clam Falls, Wisconsin. Approximately 3000 meters of mafic volcanics, minor interflow sediment, and rare rhyolite are exposed in the Clam Falls area. The petrography and geochemistry of the rhyolite are discussed by Abbott et al. (this volume). New, precise U-Pb zircon ages ($1,102 \pm 5$ Ma) of rhyolite near Clam Falls (Wirth and Gehrels; this volume) provide a means for correlation of the Chengwatana Volcanics from Clam Falls and Taylors Falls with volcanics from other parts of the rift. Recent aeromagnetic data (USGS) suggest that Clam Falls flows are stratigraphically lower and therefore older than CV flows exposed in the Taylors Falls region.

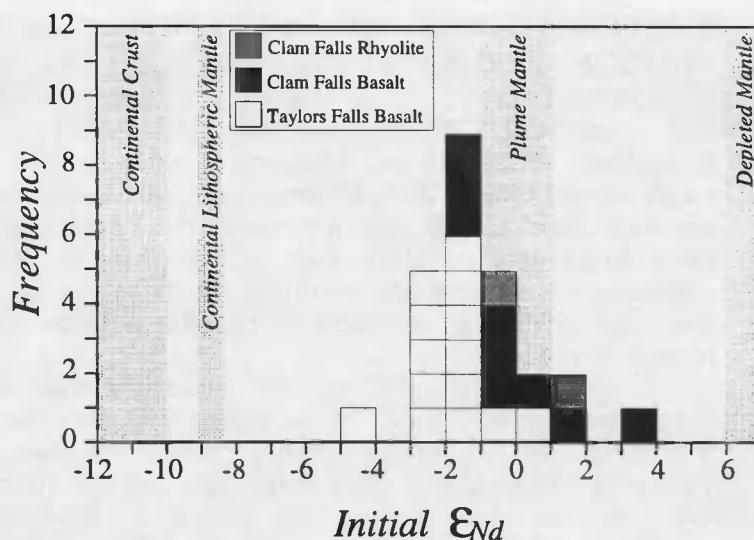
The mafic volcanics from the Clam Falls region are classified as basalt based on major and trace element abundances. The basalts are mostly olivine normative, but some flows contain small amounts of normative quartz. Most flows have moderately low Mg-numbers ($Mg\# = Mg/[Mg+Fe^{+2}] = 0.40 - 0.58$) and SiO_2 contents (45-53 wt. %) indicating that they have undergone significant fractionation, similar to flows from the Taylors Falls section of the Chengwatana Volcanics¹. Clam Falls basalts exhibit increasing incompatible element abundances (e.g., P, Ti, Y) with decreasing compatible element abundances (e.g., Mg, Ni, Cr) similar to those of the Taylors Falls region, and can be modelled by fractional crystallization processes². Clam Falls flows have TiO_2 concentrations which are similar to the low-Ti group (<2.3 wt. %) of basalts recognized in the Taylors Falls section¹.

Neodymium isotopic analysis of eight basalts and two rhyolites from the Clam Falls area yield initial $\epsilon_{Nd(1,100\text{ Ma})}$ values between -2.0 and +3.4. Initial ϵ_{Nd} values decrease with stratigraphic height (Figure 1), and all of the values are in general displaced toward more positive values relative to those of the overlying flows of the Taylors Falls section¹ (Figure 2). Although similarly high Nd values (initial $\epsilon_{Nd} \approx +2$) have been observed in other volcanic sequences in the Midcontinent rift (e.g., Group 6 and 7 flows of Mamainse Point³, Portage Lake Volcanics and "late basalts" of northern Wisconsin⁴), flows with initial ϵ_{Nd} values $> +2$ are rare in the early stages of rift evolution (time equivalent to upper Kallander Creek Formation or Group 5 lavas). Furthermore, Taylors Falls flows which overlie the Clam Falls basalts (and may be correlative with Portage Lake Volcanics and Group 6 flows) have epsilon Nd values that are generally more negative (initial $\epsilon_{Nd} = -4.5 - +0.1$) than has been observed in correlative main stage lavas (initial ϵ_{Nd}



= -1 - +4) elsewhere in the rift.

Most models of the magmatic evolution of the Midcontinent rift assume that the large volume of magmas were produced primarily from an enriched mantle plume with initial ϵ_{Nd} near zero^{3,4}. Lavas with negative ϵ_{Nd} values have been modelled by contamination of mantle plume melts with continental lithospheric mantle (ϵ_{Nd} near -9) or with continental crust ($\epsilon_{Nd} < -10$). In contrast, lavas with positive ϵ_{Nd} values has been modelled by a combination of enriched mantle plume and depleted asthenospheric mantle ($\epsilon_{Nd} > 6$) that may have been entrained in the plume head⁵. Following this model, the initial ϵ_{Nd} values of Chengwatana basalts suggest a progression of mantle sources from enriched mantle plume+depleted asthenospheric mantle (flows with $\epsilon_{Nd} > 1$ near the base of the Clam Falls section) to enriched mantle plume that has been variably contaminated with lithosphere (the remainder of the Clam Falls section and the overlying Taylors Falls section). The inferred progression of mantle sources observed in the Chengwatana Volcanics (plume+asthenosphere → plume +/- continental lithosphere) occurs at a time when mantle sources elsewhere in the rift are inferred to be changing from plume+continental lithosphere to plume+asthenosphere. If the depleted mantle component of early Clam Falls flows originated from material that was entrained in the plume head, as has been suggested by several for other parts of the rift^{3,4,5} then the proportion of melts produced from entrained asthenospheric mantle in the plume varied in space and time throughout the rift. Alternatively, the depleted mantle component may have been differentially incorporated into plume-generated melts as they traveled through the asthenosphere before reaching the continental lithosphere. The relatively low initial ϵ_{Nd} values observed in flows of the Taylors Falls and upper Clam Falls sections indicate greater involvement of a continental lithosphere (crust and/or mantle) component than has previously been recognized during the early part of "Main Stage" volcanism in the rift. In all of these cases, the observed isotopic differences between the Chengwatana Volcanics and other volcanic sequences of the MCR might be related to the "off-axis" position of the Chengwatana Volcanics relative to the location of the inferred plume head.



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THE POWDER MILL GROUP REVISITED: BASAL VOLCANIC ROCKS OF THE MIDCONTINENT RIFT SYSTEM ON THE SOUTH SHORE OF LAKE SUPERIOR

NICHOLSON, Suzanne W. USGS, National Center, MS 954, Reston, VA 20192

and WOODRUFF, Laurel G., USGS, 2280 Woodale Drive, Mounds View MN 55112

In northern Wisconsin and Michigan the Powder Mill Group comprises the oldest volcanic rocks related to the 1.1 Ga Midcontinent rift system (MRS). In the more than twenty years since Hubbard (1975) first separated the Powder Mill Group from the overlying Portage Lake Volcanics, an abundance of geophysical, structural, geochemical, isotopic, and chronological data for Midcontinent rift rocks has become available. This report integrates new and existing information to provide a better understanding of the early magmatic history of the MRS.

The Powder Mill Group consists of the basal Bessemer Quartzite, and the reversely magnetized igneous rocks of the Siemens Creek Volcanics and overlying Kallander Creek Volcanics. The outcrop distribution extends for more than 180 km along strike, from just west of the Lake Owen fault near Cable, WI discontinuously eastward to Silver Mountain, MI. The true extent of the group is unknown because it is either structurally truncated or unconformably overlain by younger rocks. However, seismic reflection profiles suggest that the Powder Mill volcanic rocks extend laterally beneath Lake Superior.

The Siemens Creek Volcanics is subdivided informally into upper and lower members based on field, geochemical, and isotopic characteristics. The lower member of the Siemens Creek Volcanics is dominantly basalt, but includes recently recognized basal high-MgO picritic flows. The lower member is thin (<50 m thick), has limited regional extent, and is distinctive because some flows contain augite phenocrysts, uncommon among younger MRS basalts. Pillows formed in the basal few basalt flows that directly overlie the Bessemer Quartzite. Basalt with minor basaltic andesite and andesite dominates the upper member, which is more widespread and thicker (up to 1.5 km) than the lower member. No ages have been determined for the Siemens Creek Volcanics, but by correlation with the basal units of the Osler Group in Ontario and the Nipigon sills, volcanism probably was initiated about 1108 Ma.

High-MgO (picritic) rocks related to the Midcontinent rift magmatism are now known to occur near the base of the section in three areas: 1) in the Nipigon area in Ontario associated with dikes and sills (Sutcliffe, 1987); 2) at Mamainse Point in the basal 500 m of the MRS section (Berg and Klewin, 1988); and 3) in the Club Lake, WI area west of the Mineral Lake intrusion as recently identified picritic flows near the base of the Siemens Creek. The high-MgO flows in the Siemens Creek Volcanics are strongly altered to serpentine, chlorite and talc: no primary mineralogy is present. An average of three analyses of these high-MgO flows ($\text{TiO}_2 = 1.95 \text{ wt } \%$; $\text{Al}_2\text{O}_3 = 8.89 \text{ wt } \%$; $\text{MgO} = 16.09 \text{ wt } \%$) is chemically most similar to an analysis of a Nipigon picritic dike ($\text{TiO}_2 = 1.88 \text{ wt } \%$; $\text{Al}_2\text{O}_3 = 7.72 \text{ wt } \%$; $\text{MgO} = 17.1 \text{ wt } \%$) in having higher TiO_2 and lower Al_2O_3 and MgO than a picritic average reported from Mamainse Point ($\text{TiO}_2 = 0.90 \text{ wt } \%$; $\text{Al}_2\text{O}_3 = 9.79 \text{ wt } \%$; $\text{MgO} = 19.89 \text{ wt } \%$; Berg and Klewin, 1988). Picritic flows in the Siemens Creek Volcanics show steep REE-element patterns ($\text{Ce}_N/\text{Yb}_N = 18.6$), consistent with derivation from partial melting of an enriched mantle source at a depth of more than about 80 km.

Basalts from the lower Siemens Creek Volcanics show moderate TiO_2 , lower Al_2O_3 and higher MgO than basalts from the upper Siemens Creek. REE patterns are steeper ($\text{Ce}_N/\text{Yb}_N = 14.2$), for the lower Siemens Creek than for overlying units. In addition, the two members of the Siemens Creek Volcanics can be distinguished on the basis of Nd isotopic composition: lower Siemens Creek basalts have initial $\epsilon_{\text{Nd}} = -1$ whereas the upper Siemens Creek basalts have initial $\epsilon_{\text{Nd}} = -3.6$.

The Kallander Creek Volcanics overlies the Siemens Creek Volcanics, and also has been informally divided into upper and lower members. Both members range from basalt to andesite and rhyolite. The lowermost 1.5 km of the Kallander Creek consists of flood basalt typically containing plagioclase phenocrysts, which locally, form large radiating clusters. A

rhyolite flow near the top of the lower Kallander Creek gives an age of 1107.3 ± 1.6 Ma (Davis and Green, 1997). The upper member (about 2 km thick) is dominated by andesite and is considered to represent the extrusive products of a localized magmatic system, the Mellen complex (Cannon et al. 1993). A thick laterally extensive rhyolite at the top of the upper member of the Kallander Creek gives an age of 1099.0 ± 2.6 Ma (Zartman et al. 1997).

Basalts of the lower member of the Kallander Creek Volcanics are characterized by their high TiO_2 and low MgO , Cr and Ni, suggesting strong fractionation. Although the REE patterns for this group are similar to those for the lower Siemens Creek basalts, the elemental REE abundances are substantially higher for this group. In addition, not only are incompatible trace element ratios such as Ce_N/Yb_N and Ta/Th similar for both lower members of the Kallander Creek and Siemens Creek Volcanics, their Nd isotopic compositions are similar as well (initial $\epsilon_{\text{Nd}} = -1$). In contrast, basalts of the upper Kallander Creek show lower incompatible trace element ratios and much less steep REE patterns than the lower Kallander Creek member, despite the fact that their major element compositions are similar. The Nd isotopic composition of the upper Kallander Creek yields an initial $\epsilon_{\text{Nd}} = -1.5$, slightly lower than the lower member.

The Siemens Creek and Kallander Creek Volcanics represent the initiation of a continental rifting event that has been attributed to the upwelling of a mantle plume beneath the Lake Superior region. The diversity of basalt compositions, including picrites, that are representative of the first several million years of rifting are characteristic of other continental rift settings in which mantle plumes play a dominant role. Based on the geochemical and isotopic characteristics, both the lower Siemens Creek and lower Kallander Creek units are probably the products of varying degrees of partial melting of an enriched source (mantle plume) at great depth with the lower Kallander Creek having undergone significant fractionation. The upper Siemens Creek member probably represents larger degrees of partial melting of a plume source at shallower depths, producing melts that may have interacted with lithosphere and undergone limited fractionation. The upper Kallander Creek appears to have undergone significant fractionation probably in shallow crustal magma chambers now seen as layered intrusions.

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GIS BASED MINERAL POTENTIAL ANALYSIS FOR LODGE-GOLD AND MASSIVE SULFIDE DEPOSITS IN AN ARCHEAN TERRANE OF NORTHERN MINNESOTA

DEAN M. PETERSON and DR. RONALD L. MORTON

*Economic Volcanology Research Lab, Geology Department, University of Minnesota - Duluth,
Duluth, Minnesota, USA 55812*

The last decade has been a period of worldwide political and economic change. The globalization of the world's economy has created new challenges and opportunities for the mining and mineral exploration industry. Many areas, which previously were strictly the domain of nationalist enterprises (Southeast Asia, South America, and the former Soviet Union), are now open to mineral exploration by companies from North America and Europe. Many exploration companies are focusing large portions of their resources away from North America and into these recently opened countries. This switch in regional area selection has had a negative impact on the amount of mineral exploration conducted in the Archean terranes of Minnesota. Aside from the changes in global economics, other specific reasons for the lack of recent mineral exploration in the Archean terranes of Minnesota include the following:

- no local prospectors are “*beating the bush*” and discovering prospects in Minnesota
- misconception that mine permitting would be as cumbersome as with Wisconsin VMS deposits
- absence of success in previous gold and massive sulfide exploration programs
- most mineral industry geologists have little knowledge of the geology of Minnesota, and
- the identification of specific exploration target areas are normally not included in geological reports and maps

The discovery of economic lode-gold and massive sulfide deposits will only occur following prolonged exploration in the Archean terranes of Minnesota by the mineral industry. To increase exploration activity, state agencies in Minnesota have completed extensive geological and geophysical mapping, completed several mineral potential studies, and currently are promoting Minnesota's geology and mineral potential to the mineral industry. However, because of extensive glacial cover, an absence of producing mines, and the aforementioned reasons, the mineral industry requires additional geological incentives in order to start exploration programs in the Archean terranes of Minnesota. These incentives could include detailed descriptions of known prospects, detailed mineral potential studies, and specific targets and geologic criteria upon which to base exploration programs.

This study is an attempt to generate specific lode-gold and massive sulfide target areas that the mineral industry can use as a premise to begin exploration programs in the state. Current ore deposit models have been integrated into GIS databases of important Canadian mining camps (Timmins, Kirkland Lake, Hemlo, and Sturgeon Lake (Figure 1)), and lode-gold and massive sulfide exploration models developed from detailed spatial analysis. Exploration target areas in the Minnesota study area have been generated from the integration of these models into a detailed GIS of a large Archean terrane of northern Minnesota (Figure 2).

The methods developed to complete this study comprise five separate, but related themes:

- Thorough research on the theory and methods of ore deposit modeling, and the geological setting of Archean lode-gold and massive sulfide deposits.

- Standardized geological compilations of four analog mining camps from the Superior Province of Ontario, Canada. These compilations are integrated with Ontario Geologic Survey (OGS) drill hole, geochemical and mineral deposit inventory databases and have been converted into GIS format.
- Standardized geological, geophysical, and geochemical compilation of the Minnesota study area, and the conversion of this compilation into GIS format.
- Development of mineral exploration models and targeting criteria generated from knowledge-based queries of the analog GIS datasets. These models integrate Archean lode-gold and massive sulfide deposit models with spatial features in the analog GIS databases. Specific geological criteria have been developed that define the location of the lode-gold and massive sulfide deposits within the analog GIS datasets.
- Thorough mineral potential evaluation for lode-gold and massive sulfide deposits in the Minnesota study area. This evaluation is based upon spatial analysis of the Minnesota GIS database using targeting criteria developed from the exploration models generated from queries of the analog GIS databases.

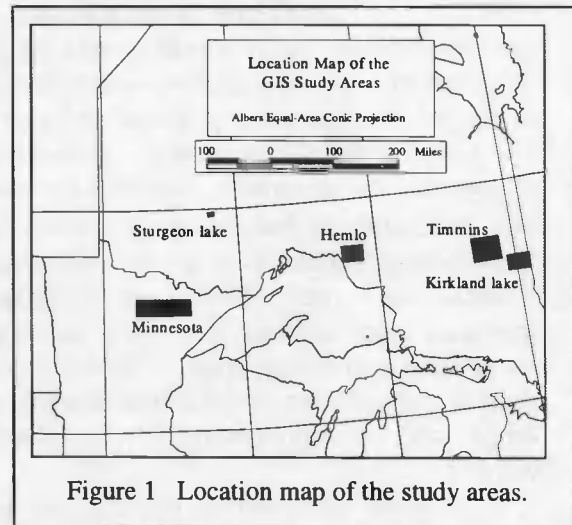


Figure 1 Location map of the study areas.

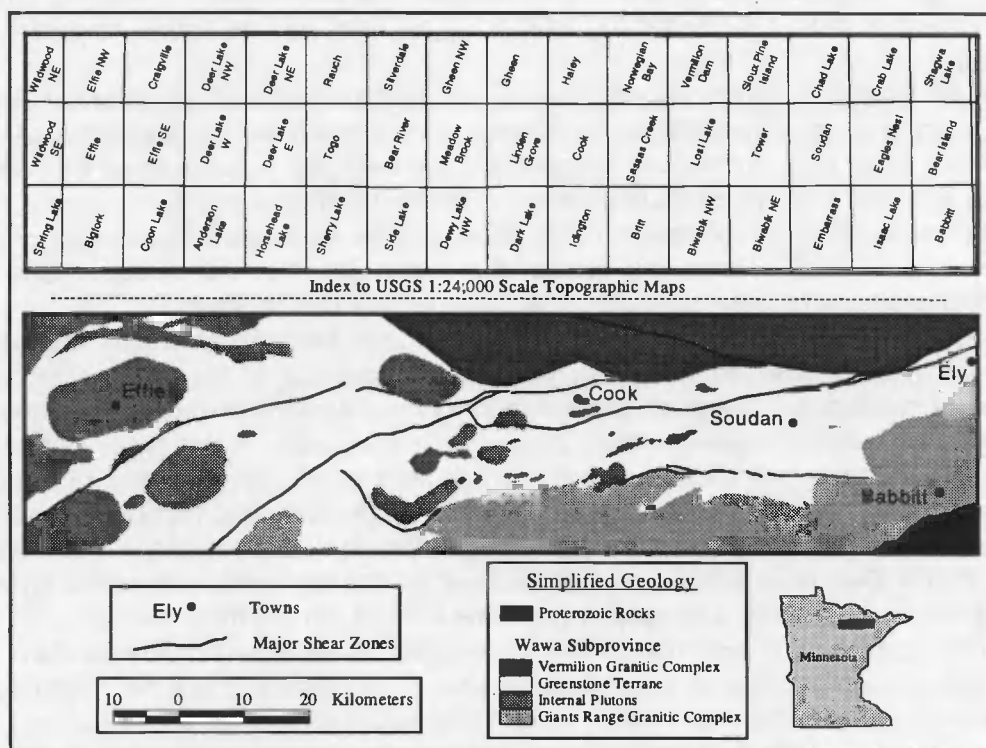


Figure 2 Simplified geology and location of USGS 1:24,000 scale quadrangle maps of the Minnesota study area.

IMPROVED GEOLOGIC SENSITIVITY AND VULNERABILITY ASSESSMENTS OF GROUNDWATER POLLUTION POTENTIAL THROUGH APPLICATION OF FUZZY LOGIC

PFANNKUCH, H.O., and PAULSON, Richard, A., Department of Geology and Geophysics,
University of Minnesota, 310 Pillsbury Drive S.E. Minneapolis, MN 55455

Vulnerability/sensitivity assessments belong to the general problem class of suitability assessments. In general, these are management tools to evaluate the feasibility, reliability or risk of using a given physical entity or process. In the environmental or geologic context it is a decision aid in a resource protection, or management plan.

In general, the procedure has three components: a physical model that describes the process in a risk analysis framework, and a methodology to aggregate individual partial vulnerability indices to a global vulnerability index. In the context of a vulnerability assessment to groundwater contamination the physical model simulates contaminant transport along pathways from the land surface to the groundwater body. The pathway is subdivided into a sequence of zones in which different transport processes and parameters predominate. These compartments are surface parcel, soil zone, vadose zone, capillary fringe, and the groundwater flow zone which may be further subdivided if more detail is wanted.

In a perfectly deterministic world where all transport processes can be described as mathematically exact, where flow boundary geometry, boundary conditions and physico-chemical parameters are known everywhere in the domain of interest, the transport process can be modeled exactly along continuous pathways, given appropriate computational power. Then, concentration of the contaminant everywhere in space and time is known. Its residence time in the system and its exposure to and impact of exposure on the target can be quantified. From this, choices about protection of the resource, the environment, or human targets can be made. This is all that is needed for solving the problem, and no further steps are necessary.

Alas, the world is not isotropic, homogeneous and perfect, and mathematical simulation models even less so. Therefore, severely restrictive approximations and simplifying assumptions have to be introduced to represent the transport process in an half-way adequate manner. The approximations concern the mathematical description of the process, limited by insufficient and infrequent information, and by inadequate knowledge of impacts. The greater the simplifications, the greater the uncertainty that the model results reflect reality and produce reliable predictions or vulnerability designations.

This uncertainty traditionally has been handled by a risk analysis approach. The likelihood of a contaminant particle reaching the groundwater target and its likelihood to produce unwanted consequences has been expressed in terms of conditional probabilities and statistical estimates as confidence limits or ranges. Inadequacies in the geologic database have been handled by statistical methods such as Monte-Carlo approaches or kriging. A groundwater system is extensive, three dimensional, dynamic and non-homogeneous. Its properties and states must be spatially referenced for most efficient analysis and map representation. Georeferencing is best carried out by a Geographic Information System (GIS) which also performs aggregation functions able to handle map overlay-index procedures using built in algorithms. The information for each hydrogeologic flow compartment is represented as an information layer in the GIS, and can be combined into an aggregate or monothematic layer such as a global vulnerability map layer.

Traditional methods of groundwater sensitivity assessment translate the protection afforded by various elements of the geological conditions and materials between the surface and the groundwater body into vulnerability indices, from which, pollution potential can be

estimated. One such methodology is USEPA's DRASTIC. Many of these procedures lack internal consistency, and give no explicit rationale for assigning rating indices, range intervals and thresholds, weights to the various factors, and leave the choice of an additive aggregation model unexplained.

The Minnesota Department of Natural Resources' (MN DNR) guidelines stand on a much firmer conceptual basis. They link geologic sensitivity to travel time of a conservative tracer from the surface to the groundwater. Long travel times are equated to low sensitivities, and short travel times to high sensitivity. In order to take into account the availability of information for mappable factors it makes some sweeping simplifications. It uses three factors: depth to water, geologic material in the vadose zone and material at the water table and obtains the aggregate index through a binary decision tree procedure. Because of these simplifications the degree of uncertainty and the confidence limits are large. Introduction of a fuzzy set methodology will lead to a greater internal consistency of the rating process and facilitate the use of vague and descriptive data in a more appropriate way.

Fuzzy logic is a branch of set theory that allows objects degrees of belonging to a set rather than a binary yes or no description. Fuzzy numbers are defined by membership functions that describe their degree of belonging to one set or another, and thereby are able to deal with verbal descriptors or linguistic variables, and to take into account the natural vagueness and uncertainty inherent in geologic data. Fuzzy methodology provides the algorithms to operate on vague rating classes in a consistent way. Fuzzy methodology will also give more realistic boundary definitions between rating categories and classes. This research casts the definition of the MN DNR rating factors into a fuzzy context. This approach is capable of: (1) more adequate representation of linguistic variables such as lithologic descriptions from well log information into manipulable index numbers, (2) combining of layer information in a GIS through fuzzy rule based instructions, and (3) to extend the number of factors that go into the overall evaluation to geohydrologic and land use layers.

Fuzzy methodology application: The technique for performing a Level 2 geologic sensitivity analysis as set forth by the MN DNR is relatively simple and straightforward. The techniques were intentionally designed so that water resource managers (or others) who may not have training on, or access to, a geographic information system (GIS), would still be able to implement a hand-performed overlay analysis. This can be a very time consuming and tedious task for the analyst. In an effort to speed up and simplify especially the preliminary assessment or project stage, an *Excel* spreadsheet based program is being developed using *Microsoft Visual Basic*. It accepts the various MN DNR specified vadose zone parameters under consideration as input. The input data layers include: depth to water table below the land surface, aquifer matrix material type at the water table, cumulative thickness of any low and moderate permeability units in the vadose zone. A second version of the program incorporates the principles of fuzzy methodology into the analysis. The sensitivity ratings produced by the "fuzzy" version are compared to those produced using the present MN DNR technique.

SEISMIC EVIDENCE OF PRE-NICKERSON SEDIMENTS IN WESTERN LAKE SUPERIOR

Deborah E. Rausch and Nigel J. Watrus
Large Lakes Observatory, University of Minnesota
Duluth, MN 55812

email: nwattrus@d.umn.edu

The Superior lobe of the Laurentide Ice Sheet advanced and retreated out of the western basin of Lake Superior several times during the Wisconsin glaciation. Wright et al. (1973) recognized four separate phases of ice advance out of the Lake Superior basin, they are (in order of decreasing age): the St. Croix; Automba; Split Rock and Nickerson phases. The tills of the last two phases show an enrichment in clay, which represents the incorporation of proglacial lacustrine sediments with each advance. As the ice retreated during the Nickerson phase, a series of proglacial lakes formed against the edge of the retreating ice. The position of ice margins bordering these lakes have been determined by correlating subaerial moraines on either side of western Lake Superior (Farrand, 1969; Saarnisto, 1974) and Isle Royale (Huber, 1973). A series of subaqueous recessional moraines, presumably associated with this sequence of proglacial lakes, have been described in the western arm of Lake Superior near Isle Royale (Landmesser et al., 1982).

The sediment record contained in western Lake Superior is intimately related to the retreat of the Laurentide Ice Sheet. An idealized soft sediment section for western Lake Superior based upon coring (Farrand, 1963; Dell, 1971; Thomas and Dell, 1978) and high resolution seismic surveying (Johnson, 1980; Scholz, 1985; Anderson, 1997), consists of till overlain by a glaciolacustrine clay sequence followed by a thin post-glacial Holocene clay. Recent data collected by the Large Lake Observatory (LLO) suggests the presence of a relict sediment section below the till, presumably from earlier advances into the Lake Superior basin.

Since 1996, the Large Lakes Observatory (LLO) has collected over 2500 km of high resolution single channel seismic reflection data in western Lake Superior. The surveyed area extends from Duluth to Isle Royale and southeast to Houghton, Michigan. Most of this new data was collected with a ORE Geopulse system. The firing rate was 0.5 seconds and the average vessel speed was 6.5 knots. The data were digitally recorded at rate of 0.5 milliseconds/sample for later post-survey processing. Positioning information was derived from the ships GPS navigation system.

Images of the recently acquired data show most of the soft sediment section and bedrock-soft sediment interface (acoustic basement). In water depths of less than 100 meters, the development/preservation of the glacial/post-glacial and Holocene clays above the till is negligible due to current action on the lake floor. In the deeper portions of the lake, the near surface reflections are associated with the post-glacial Holocene clays, glaciolacustrine clays and a thin basal till (less than six meters thick). Presumably, this glacial/post-glacial sequence is associated with the last advance/retreat in the Lake Superior basin (Nickerson/post-Nickerson deposition). Many of recent seismic lines, especially those in the western portion of the survey area, exhibit buried channels containing thick sequences of pre-Nickerson deposits (Figure 1). There is often a well defined unconformity separating the pre-Nickerson sediments from the overlying younger section. The unconformity clearly represents a period of erosion, perhaps associated with the last advance of ice across the basin.

Seismic facies analysis suggests that the pre-Nickerson material is composed of a sequence of glacial tills and glaciolacustrine sediments. Presumably these represent relict sediments preserved from earlier advances of the Superior Lobe in western Lake Superior. Very few of the cores collected in Lake Superior penetrated sediment below the glaciolacustrine varved clays. One long core collected of Split Rock on the Minnesota North Shore, however, recorded over 190 meters of glacial and glaciolacustrine sediments (Zumberge and Gast, 1961).

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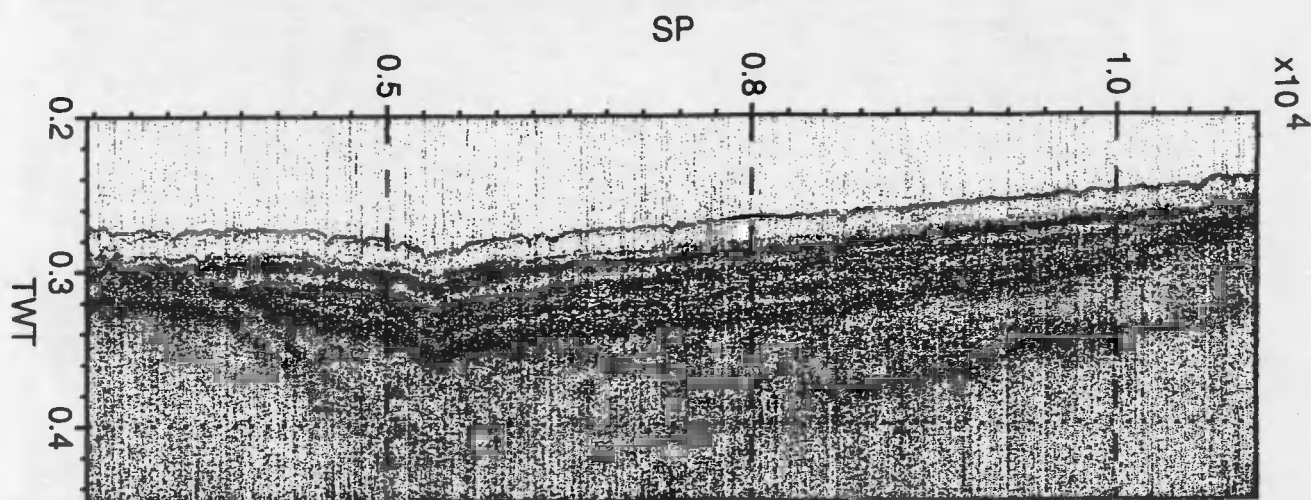


Figure 1. Geopulse seismic reflection data collected off the Minnesota North Shore southwest of Grand Marais, Minnesota. Relict sediments are clearly preserved in a broad channel and are unconformably overlain by younger till and glaciolacustrine sediments of the Nickerson phase.

PRELIMINARY ORE MINERALOGY OF THE HERONTRACK SILVER-ZINC-COPPER OCCURRENCE, LUMBY LAKE AREA, ONTARIO, CANADA

SAINI-EIDUKAT, Bernhardt, Department of Geosciences, North Dakota State University, Fargo, ND 58105-5517 USA (sainieid@badlands.nodak.edu).
BERNATCHEZ, Raymond, Atikokan Resources, Inc., Box 1376, 126 Willow Road, Atikokan, Ontario, Canada (rbernate@atikokan.lakeheadu.ca)

The Herontrack silver-zinc-copper occurrence occurs near Herontrack Lake in the Lumby Lake greenstone belt. It lies in the southwestern part of the Archean Superior Province, near Atikokan, Ontario. Recently discovered in the region of the famous Steep Rock iron mine, the Herontrack occurrence contains numerous stratiform mineralized horizons, some of which contain significant Ag mineralization.

The Lumby Lake greenstone belt occurs in the Wabigoon subprovince, near its border with the Quetico subprovince (Fig. 1, from Davis and Jackson, 1988). It comprises a 60 km x 20 km synclinal supracrustal assemblage of mafic, ultramafic (komatiitic) and felsic metavolcanic packages with subordinate metasedimentary units (Jackson and Chevalier, 1985). It contacts the older Marmion Lake tonalite batholith to the south, and is intruded by the younger Norway Lake granite to the north, and by mafic dikes. Felsic units include lapilli tuffs, quartz porphyries, and rhyolite flow breccias. To the west of the Lumby Lake area, the northeasterly trending Red Paint Lake fault zone truncates the assemblage.

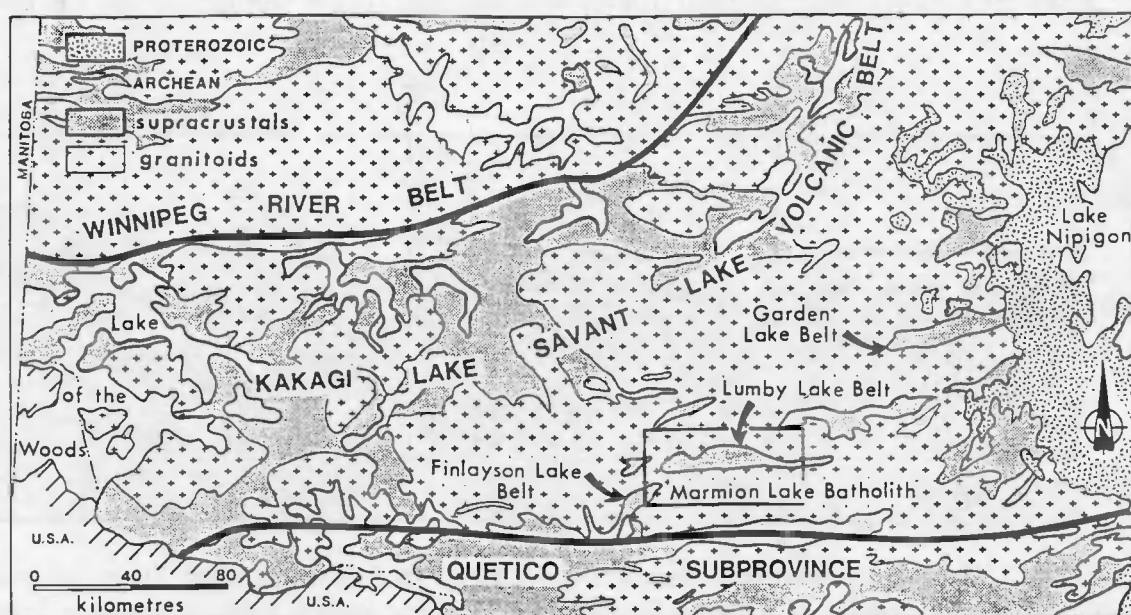


Figure 1. Geologic map of the western Wabigoon subprovince, showing the location of the Lumby Lake area. From Davis and Jackson, 1988.

The lack of a metamorphic aureole in the supracrustal sequence against the Marmion Lake tonalite indicates that the batholith was a basement unit upon which the Lumby Lake, and possibly the Steep Rock Lake group, were deposited (Davis and Jackson, 1988). Davis and Jackson (1988) dated felsic samples from the Lumby Lake area and the Marmion Lake batholith to approximately 3 Ga, an age older than most greenstone belts.

During the mid 1990's, Atikokan Resources, Inc. prospected the Lumby Lake area and discovered a high-grade silver occurrence on the west side of Herontrack lake. The occurrence is hosted in a 1.5 km thick east-west trending intermediate to felsic volcanic sequence in the area between Herontrack and Lumby Lakes (Staargaard, 1997). This sequence thins to the east and west, indicating it might be an eruptive center. The felsic units are fragmental, often containing quartz eyes, and can contain significant cherty units. Chip samples (over one meter) indicate greater than 40 g/tonne Ag.

Thin and polished block sections of ore horizon samples are being investigated using transmitted and reflected light microscopy analysis to determine the host rock and ore mineralogy and genesis. The relationship between fold structures recognizable on both outcrop and thin-section scales and mineralization indicates that the silver mineralization may be locally remobilized. These fold structures, however, may be related to mafic dike intrusion and not to regional shear. Mineralization occurs in chert units as disseminated sphalerite, galena, native silver, acanthite, chalcopyrite and pyrite. Native silver and acanthite occur as isolated grains 10 to 30 μm in diameter and as veinlets 10 – 20 μm wide. No Au was detected in the Ag or the acanthite using EDS analysis. Electron microprobe analyses are being undertaken to determine the amount of Ag contained in galena and trace element composition of sphalerite. Continued mapping may show that the Herontrack silver occurrence represents a locally remobilized silver-rich distal portion of a larger massive sulfide system.

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ALTERATION AND METAMORPHISM IN AN ARCHEAN LODGE GOLD DEPOSIT, KREMZAR MINE, GOUDREAU-LOCHALSH GOLD CAMP, ONTARIO

SALO, R.W.* and KISSIN, S.A., Department of Geology, Lakehead University, Thunder Bay, Ontario, P7B 5E1

The Kremzar Mine is located 45km northeast of Wawa, Ontario in the Michipicoten Greenstone Belt. The Kremzar is one of several former gold-producing mines in the vicinity including the Magino and Edwards Mines, as well as a number of smaller properties. The mine was most recently operated by Canamax Resources Inc. in the late 1980s, with a total production of 46 798 oz Au (Domville, 1998). The present study was undertaken while the property is under redevelopment as the Island Gold Project of Patricia Mines Inc.

The No.2 Zone, a gold-bearing vein system well exposed on the surface, was channel-sampled in order to study the alteration associated with the quartz-carbonate vein. Petrographic studies were carried out on 25 samples collected at 0.5m intervals; 13 of these were selected for whole-rock analyses of major, minor and trace elements by XRF and NAA, respectively.

The vein system cuts metavolcanic rocks of intermediate composition, which contain the chlorite zone mineral assemblage chlorite-sericite-albite. Alteration is marked by intense carbonate and quartz flooding, as well as a number of changes in accessory mineralogy. Primary ilmenite is progressively replaced by sphene, and allanite occurs only within the alteration zone. Zoisite, not present in the country rock, is abundant in the altered zone. Weakly pleochroic, fine-grained biotite is closely associated with quartz veining and flooding.

Among major components, CaO increases inward toward the vein system, whereas normally mobile components Na₂O and K₂O show little variation. TiO₂ decreases slightly, although it usually immobile. Among trace elements, W shows a marked increase. Although REE are considered to be immobile in gold vein systems (McCuaig & Kerrich, 1994), the light REEs, La and Ce, are markedly enriched in the alteration zone.

The presence of euhedral zoisite, minor wollastonite and prehnite and abundant calcite produce an assemblage resembling that of a low-grade skarn. The skarnoid assemblage is the result of regional metamorphism subsequent to formation of the vein system, which has operated on the compositionally modified and carbonate-enriched alteration zone. Multiple metamorphic events are consistent with three deformational regimes documented by Arias & Helmstaedt (1989).

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*student author

ADDITIONAL PALEOMAGNETIC RESULTS FOR A 1500 Ma MAFIC DIKE AT WATERLOO WISCONSIN

Schaper*, D., Suess*, W., Katzer*, L., and Kean, W. Department of Geosciences, University of Wisconsin-Milwaukee P.O. Box 413, Milwaukee, Wi. 53201 (* student authors)

Recent expansion of the Michels Materials Quartzite Quarry (Gillen Quarry) at Waterloo Wi. has exposed additional outcrops of a near vertical mafic dike which cuts the quartzite in a North-South direction. The new exposure is approximately 1.5 meters wide and about 50 meters long located on the NE top surface of the quarry. The other exposure previously reported by Kean(1994) is on a vertical wall in the Southwest corner of the quarry (Luther,1997). The two exposures are on line and appear to be the same dike. The age of the dike is assumed to be 1500 Ma, which is the age of mafic material from a drill core in the nearby Portland Quarry (Aldrich et.al., 1959) and similar to the age of a pegmatite (1440 Ma, Aldrich 1959) in the area. Luther(personal communication, 1994) identified the dike as basalt which has been metamorphosed to possibly greenschist facies.

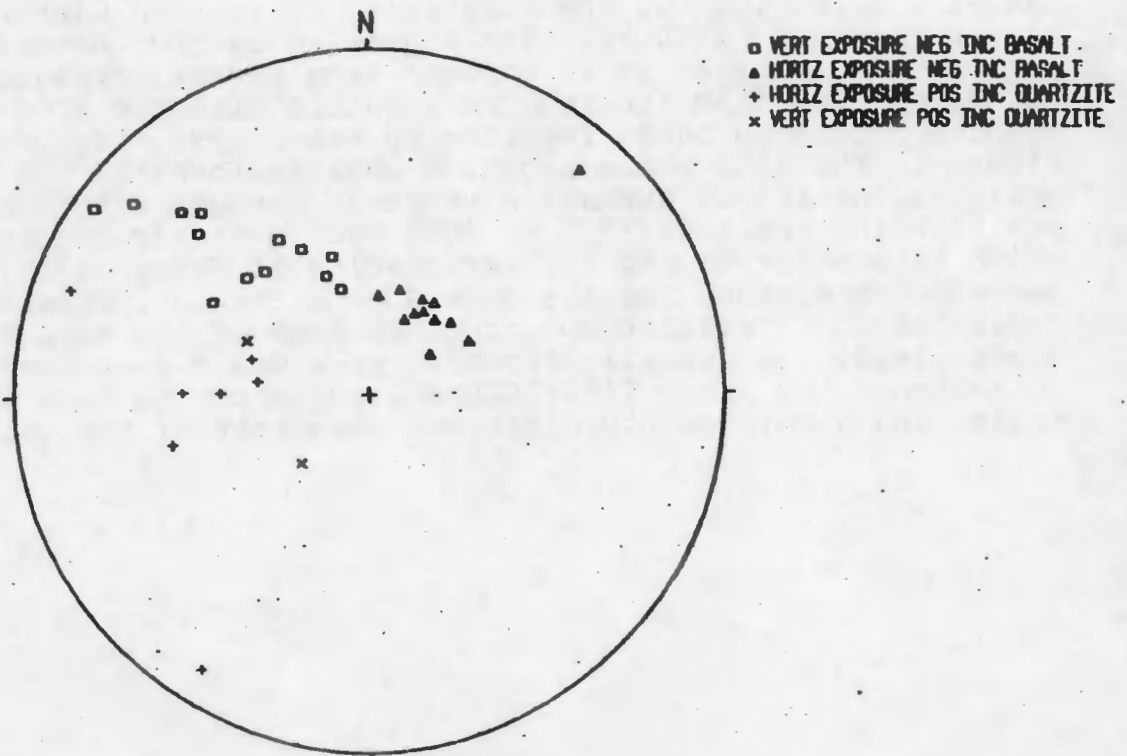
Thirty six cores were collected from both locations, as well as from the surrounding quartzite. The edges of the dike show evidence of weathering and mineral alteration, so the majority of the mafic samples were collected from the center of the dike. Cores from all sites were subjected to detailed thermal demagnetization to either 600° or 750° C. Several dike samples were also A.F. demagnetized to 100mT. The demagnetization characteristics and the Saturation Isothermal Remanent Magnetization characteristics (SIRM) indicate that magnetite is the primarily carrier of the magnetism. There is one primary magnetic direction for the dike which is removed with thermal demagnetization to 600°C. The magnetism of the quartzite is carried by hematite, as is evident from thermal demagnetization to 750°C., and SIRM studies. The magnetic directions of all samples including those reported by Kean, 1994, are presented in Figure 1. The dike shows negative inclinations(-30° to -50°) and declinations in the NNW-NNE direction. The quartzites have positive inclinations (30° to 40°) and westerly declinations, which is similar to the earlier results of Mercer(1984). The magnetic directions for the dike show streaking, which may represent an alteration component in some of the samples. Nonetheless, the overall direction provides a pole position consistent with other 1400-1600 Ma. rocks in the Lake Superior region, and significantly different than that of the quartzite.

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FIGURE 1

MAGNETIC DIRECTIONS FOR WATERLOO BASALTIC DIKE AND WATERLOO QUARTZITE. DIKE MATERIAL HAS NEGATIVE INCLINATIONS AND NORTHERLY DECLINATIONS. THE QUARTZITE HAS POSITIVE INCLINATIONS AND WESTERLY DECLINATIONS. THE DATA REPRESENTS TWO DIFFERENT EXPOSURES IN THE SAME QUARRY



METAMORPHISM, HYDROTHERMAL ALTERATION AND LATERITIC WEATHERING OF DRILLED MRS VOLCANIC ROCKS IN IOWA

SCHMIDT, Susanne Th., Mineralogisch-Petrographisches Institut,
Bernoullistr. 30, CH 4056 Basel, Switzerland,
schmidts@ubaclu.unibas.ch; SEIFERT, Karl, Departement of Geological
& Atmospheric Sciences, Iowa State University, Ames, IA 50011,
kseifert@pop-2.iastate.edu.

Well cores and cuttings from deep wells into the Precambrian igneous rocks of the buried Midcontinent Rift System in Iowa (Iowa horst, Anderson, 1990) were studied to identify primary and secondary mineral assemblages and the bulk geochemical composition was determined by instrumental neutron activation analysis (INAA) for trace elements and by inductively coupled plasma (ICP) analysis for major elements. The results indicate a complex alteration history with metamorphic and hydrothermal stages, followed by lateritic weathering on the Precambrian erosion surface. Minerals were analyzed by electron microprobe analysis, clay minerals by X-ray diffraction (air-dried and glycolated), and the isotopic composition of calcite was determined.

The large majority of these Midcontinent Rift samples were originally basalts or diabases (Seifert & Anderson, 1996) compositionally similar to intermediate olivine tholeiites as described by Brannon (1984) from the Midcontinent Rift or North Shore Volcanic Goup (NSVG) exposed north of Duluth in Minnesota. Although alteration has greatly modified the primary composition and texture of most samples, relicts of the original magmatic mineral assemblage can still be observed in some samples. Based on amygdale frequency and degree of alteration it is possible to differentiate between the various morphological flow units. Flow tops with a large number of amygdules and highest degree of alteration can be distinguished from massive flow interiors without any amygdules and a less intensive alteration. In some flow tops no primary igneous texture is visible. Massive flow interiors show various degrees of alteration but the primary texture is often preserved.

A relatively homogenous regional metamorphic alteration pattern is observed based on the highly amygdaloidal flow tops and amygdale minerals. In addition, some massive flow interiors have preserved part of the early alteration history. The assemblage epidote-Fe-rich-chlorite-albite-quartz±pumpellyite±sericite is characteristic for all studied drill sites of the Iowa horst and indicates conditions of the beginning greenschist facies. The same facies is also observed in the lowermost part of the ca 8 km thick NSVG in Minnesota near Duluth which is interpreted to be the result of burial metamorphism (Schmidt, 1990; 1993).

The Sharp #1 core documents the complex alteration history that affected at least part of the Midcontinent Rift System in Iowa. A sequence of secondary alteration stages can be established. In the massive flow interior of Sharp #1 (sample 2206.4), an early Fe-poor, Si-rich phyllosilicate replaces pyroxene along grain boundaries. Fe-poor, Si-rich phyllosilicates (smectites) are also reported from massive flow interiors of the NSVG indicating an earlier alteration stage under lower temperatures (Schmidt & Robinson, 1997). The Fe-poor, Si-rich phyllosilicate is in turn replaced by a late Fe-rich chlorite which also occurs in veinlets. This Fe-rich chlorite also forms part of the epidote-Fe-rich-chlorite-albite-quartz $\pm$ pumpellyite $\pm$ sericite assemblage in the amygdaloidal flow tops. In samples, a late potassic alteration is present with K-feldspar as a frequent overgrowth not only of silicates (albite and pyroxene), but also of chalcopyrite.

All samples which were derived directly from the original Precambrian erosion surface are partly intensively altered to kaolinite which is attributed to a tropical lateritic weathering (Seifert & Anderson, 1996). This correlates well with the suggested position of Iowa near the equator at the end of the Precambrian time. No kaolinite is present deeper in the drill cores.

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CRUSTAL RECYCLING IN THE EVOLUTION OF THE PENOKEAN OROGEN: ISOTOPIC EVIDENCE FOR ARCHEAN CONTRIBUTIONS TO CRUSTAL GROWTH IN THE PEMBINE-WAUSAU TERRANE, NORTHERN WISCONSIN

Schulz, Klaus J. and Ayuso, Robert A., U.S. Geological Survey, 954 National Center, Reston, VA 20192 (kschulz@usgs.gov)

Continental growth models depend on information regarding the age of basement in orogenic belts and on estimates of the amount of crustal recycling involved in their evolution. The distribution and role of Archean basement in the Early Proterozoic Penokean orogen in the Lake Superior region has long been a topic of debate and speculation. Early workers viewed the Early Proterozoic history of the region in terms of intracratonic deposition and reactivation of Archean crust of the Superior Province (e.g., Sims, 1976). More recently there has been a general consensus that the Early Proterozoic rocks evolved through plate tectonic processes including continental rifting and subduction, with formation of significant volumes of juvenile crust that was accreted to the Archean craton (Hoffman, 1988; Sims and others, 1989). However, isotopic studies on rocks from the Wisconsin magmatic terranes have again raised questions about the distribution and role of Archean crust in the Penokean orogen (Barovich and others, 1989; Van Wyck and Johnson, 1997). In particular, Van Wyck and Johnson (1997) proposed that the Penokean orogen evolved through back-arc rifting of the southern Superior Province, followed by collision of a continental arc terrane (the Marshfield terrane) from the south.

One of the primary lines of evidence used by Van Wyck and Johnson (1997) to support a model of continental back-arc rifting for the Pembine-Wausau terrane was an inferred correlation between the degree of crustal contamination and distance from the northern margin of the terrane, the Niagara fault zone, in which contamination decreased southward (i.e., $\epsilon_{Nd}(T)$ values become more positive southwards). To test this model for the Pembine-Wausau terrane and further refine estimates for the involvement of older crust, 14 volcanic rocks and 14 granitic rocks from across the Pembine-Wausau terrane in northern Wisconsin were analyzed for Nd and/or Pb isotopes. These samples, collected from the three principal outcrop areas in northern Wisconsin—the Dunbar-Pembine area located in northeastern Wisconsin just south of the Niagara fault zone, the Monico area located about 45 km south of the Niagara fault zone in northcentral Wisconsin, and the Marathon County area located at the southern margin of the Pembine-Wausau terrane in central Wisconsin—significantly expand the sampling density in these three areas and for the first time provide isotope data for several volcanic units within the Pembine-Wausau terrane. Results are summarized in the table below.

The analyzed mafic volcanic rocks from the Monico and Marathon County areas are light REE-enriched but have positive $\epsilon_{Nd}(T)$ from +1.3 to +3 and relatively primitive μ values. These Nd isotope data are slightly more enriched than the Nd isotope results of Beck and Murthy (1991) for the Quinnebec basalts ($\epsilon_{Nd}(T) \sim +4.2$) from the Pembine area and suggest derivation from depleted Early Proterozoic mantle with possibly a small ($\leq 10\%$) addition of older crustal components. In contrast to the mafic volcanic rocks, the felsic volcanic rocks from throughout the Pembine-Wausau terrane have $\epsilon_{Nd}(T)$ values ranging from ~ 0 to -4 and relatively high μ values >10 suggesting variable but significant input of older, probably Archean crustal components. Surprisingly, the felsic volcanic rocks from the Monico area show the greatest crustal contamination. The granitic rocks, like the felsic volcanic rocks, also have mostly negative $\epsilon_{Nd}(T)$ values but show a greater range from ~ 0 to -7.4 , and relatively high μ values >10 ; younger granites tend to have the most negative $\epsilon_{Nd}(T)$ and highest μ values in both the Dunbar-Pembine and Marathon County areas. The isotope data lie along mixing lines between depleted Early Proterozoic mantle and Archean Superior Province crust; mixing models suggest from 20 to $>70\%$ Archean crustal contamination for felsic volcanic and granitic rocks.

Areas	$\epsilon_{\text{Nd}}(\text{T})$	T_{DM} (in Ga)	μ ($^{238}\text{U}/^{204}\text{Pb}$)
Dunbar-Pembine (North)			
• Pemene Rhyolite (2)	$\sim +0.35$	2.3	~ 12
• Dunbar Dome (5)	-0.9 to -4.2	2.2 to 2.9	~ 10.4
• Bush Lake Granite (1)	-7.4	2.9	11.5
• Twelve Foot Falls (1)	-3.2	2.8	-
Quartz Diorite			
Monico			
• Basalt (2)	+2.1	2.1	~ 9.8
• Dacite/Rhyolite (3)	-3.1	~ 2.6	~ 11
• Quartz Porphyry (1)	-4.7	2.5	9.4
Marathon County (South)			
• Basalt/Andesite (4)	+3 to +1.3	2.0 to 2.2	~ 9.8
• Dacite/Rhyolite (3)	-0.8 to -2.0	2.2 to 2.3	~ 10.6
• Pre/Syn-Tectonic Granite (3)	~ -1.0	~ 2.3	~ 10.9
• Syn/Post-Tectonic Granite (3)	~ -4.2	~ 2.8	~ 13.2

The new data presented here do not support a correlation of increasing ϵ_{Nd} with distance from the Niagara fault zone. The felsic volcanic rocks from throughout the terrane show isotopic evidence for crustal contamination with the greatest crustal component in rhyolites from the Monico area. The granitic rocks from throughout the terrane also show isotopic evidence for significant crustal contamination. However, the isotope data do suggest that crustal contamination was greatest for syn- to post-tectonic granites emplaced near the northern and southern margins of the Pembine-Wausau terrane.

The new isotope data for the Pembine-Wausau terrane suggest that: (1) input of Archean crustal components to Penokean crust formation was greater and more widely distributed than previously recognized; (2) there is no clear correlation between ϵ_{Nd} and distance from the northern (Niagara) suture zone, although contamination appears to have been greatest for syn- to post-tectonic granites emplaced near the margins of the terrane; and (3) the high levels of crustal components shown by the felsic igneous rocks probably result from crustal assimilation and mixing and not from contamination of a depleted mantle source by subduction of Archean derived sediments.

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ND ISOTOPE EVIDENCE FOR MIDDLE AND EARLY ARCHEAN CRUST IN THE WAWA SUBPROVINCE OF THE SUPERIOR PROVINCE, MICHIGAN, U.S.A.

Sims, P.K., Neymark, L.A., and Peterman, Z.E., U.S. Geological Survey;
Kotov, A.B., Institute of Precambrian Geology and Geochronology, St. Petersburg, Russia

New Sm-Nd isotopic data on Late Archean granitic rocks from the Wawa subprovince (a granite-greenstone terrane) of the Superior province, northern Michigan, indicate a Middle to Early Archean crustal source for the rocks. At 2.7 Ga ϵ_{Nd} values vary from -6.4 to +3.3, which correspond to depleted mantle model ages between 2.7 and 3.6 Ga (see table). Previous Nd-isotope studies in granite-greenstone terranes in the southern part of the Superior province have indicated that most granitoid rocks are juvenile, i.e. mantle derived, with little identifiable participation from older crust or recycled material.

Samples were taken from the Puritan batholith (Fig. 1), which lies astride the Michigan - Wisconsin border, and the northern complex of the Marquette district (Fig. 2); both igneous bodies have crystallization ages of ~2.7 Ga.

Candidates for the source of the Middle and Early Archean rocks in the Michigan segment of the Wawa subprovince have not been identified, but these rocks mainly constitute ancient continental crust, perhaps a proto-craton block like that in the Sachigo and Minto subprovinces (Percival and other, 1994) to the north.

Not unexpectedly, high-grade gneisses from the adjacent Minnesota River Valley subprovince, to the south, which contains the oldest rocks in the Superior province, have comparable old Nd-depleted mantle model ages (see table), ranging from 2.9 to 3.3 Ga.

Table. Sm-Nd isotope data for granites from Wawa Subprovince and felsic gneisses and granites from Minnesota River Valley Subprovince.

Sample	T(Ga)	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/$ ^{144}Nd	$^{143}\text{Nd}/^{144}\text{Nd}$ ^{*)}	$\epsilon_{Nd}(t)$	$\epsilon_{Nd}(0)$	T_{DM}	T_{DM1} ^{**)}
<i>Wawa Subprovince (Granite-Greenstone Terrane)</i>									
182B	2.7	8.88	40.9	0.0980	0.510695 (13)	-3.7	-37.9	3202	3319
183B	2.7	19.7	98.2	0.1214	0.511072 (5)	-4.5	-30.5	3394	3384
198	2.7	5.70	32.2	0.1074	0.510842 (8)	-4.1	-35.0	3276	3352
215B	2.7	2.76	17.0	0.0982	0.510672 (13)	-4.2	-38.4	3237	3361
0919-1-89	2.7	4.06	30.2	0.0815	0.510594 (12)	0.1	-39.9	2922	3012
0919-3-89	2.7	8.08	57.7	0.0925	0.510707 (6)	-1.5	-37.7	3044	3144
0920-4-89	2.7	3.56	17.9	0.1205	0.511397 (10)	2.3	-24.2	2840	2839
136R	2.7	0.79	3.11	0.1545	0.511781 (9)	-2.1	-16.7	3478	3193
M169	2.7	1.60	11.5	0.0848	0.510708 (10)	1.2	-37.6	2863	2924
M170	2.7	2.98	17.4	0.1041	0.511040 (10)	1.0	-31.2	2908	2943
177	2.7	2.53	13.8	0.1107	0.510912 (10)	-3.8	-33.7	3277	3334
179	2.7	1.01	4.67	0.1315	0.511415 (9)	-1.2	-23.9	3182	3123
D1044	2.7	4.10	16.7	0.1486	0.511572 (7)	-4.1	-20.8	3646	3358
D1731	2.7	2.08	10.5	0.1200	0.511070 (7)	-4.0	-30.6	3347	3347
D2493	2.7	1.26	6.48	0.1176	0.511266 (7)	0.7	-26.8	2959	2966
D2494	2.7	5.06	33.6	0.0913	0.510928 (7)	3.3	-33.4	2744	2758
D2495	2.7	5.60	33.6	0.1012	0.510792 (4)	-2.9	-36.0	3163	3256
<i>Minnesota River Valley Subprovince (Gneiss Terrane)</i>									
34-90	2.8	6.22	44.9	0.0841	0.510600 (8)	0.8	-39.8	2971	3037
161-B	2.8	2.35	12.8	0.1117	0.510993 (11)	-1.5	-32.1	3192	3226
211	2.8	7.36	38.2	0.1170	0.511027 (10)	-2.7	-31.4	3309	3325
213	2.8	3.80	21.2	0.1089	0.511018 (8)	0.0	-31.6	3072	3104
<i>Tilden Granite</i>									
3-90	2.6	10.5	59.2	0.1078	0.510791 (8)	-6.4	-36.0	3358	3456
<i>Gwinn Granite</i>									
226-89	2.6	5.65	31.6	0.1082	0.511006 (10)	-2.3	-31.8	3068	3127

*) Data corrected to La Jolla $^{143}\text{Nd}/^{144}\text{Nd}=0.511860$, 2σ within-run errors are given in parentheses.

**) Two-stage Nd-model age assuming $^{147}\text{Sm}/^{144}\text{Nd}=0.12$ in the source of rocks before T Ga ago.

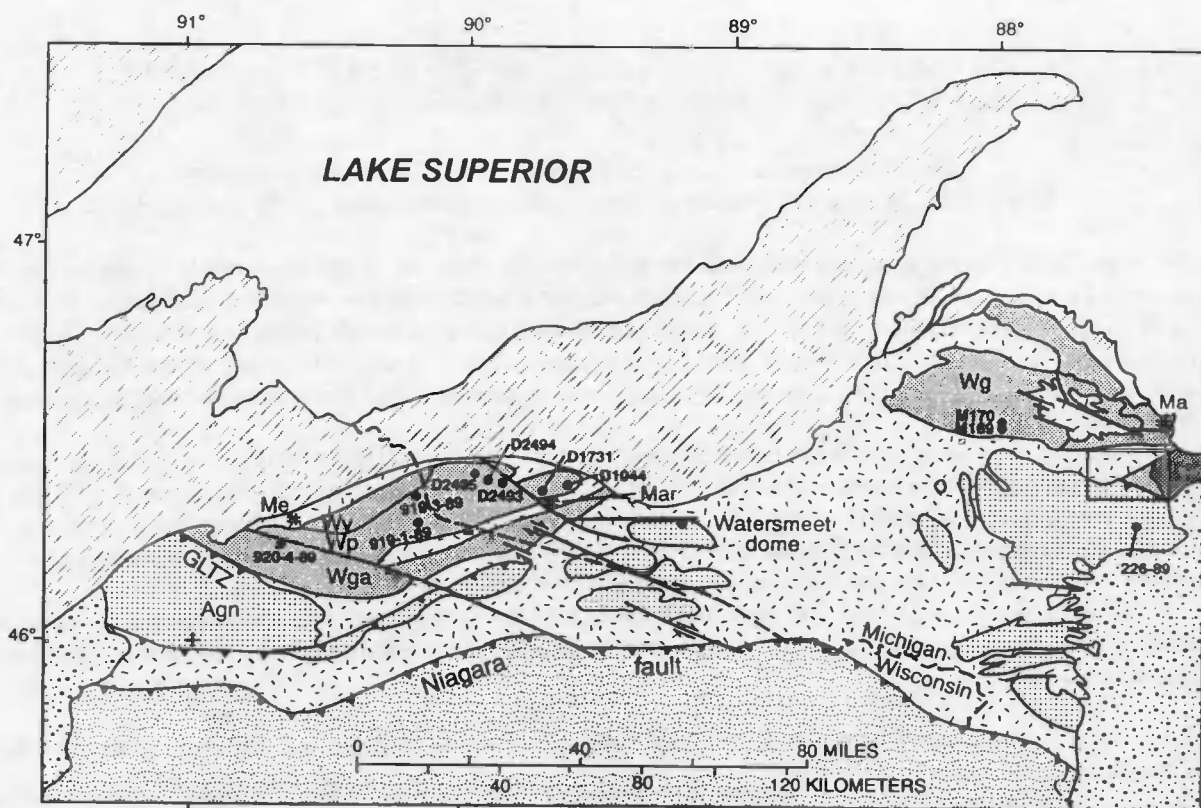


Figure 1. Geologic map of Precambrian rocks in northern Michigan and adjacent Wisconsin, showing localities of Sm-Nd samples. Figure 2 is an enlargement of area outlined south of Marquette.

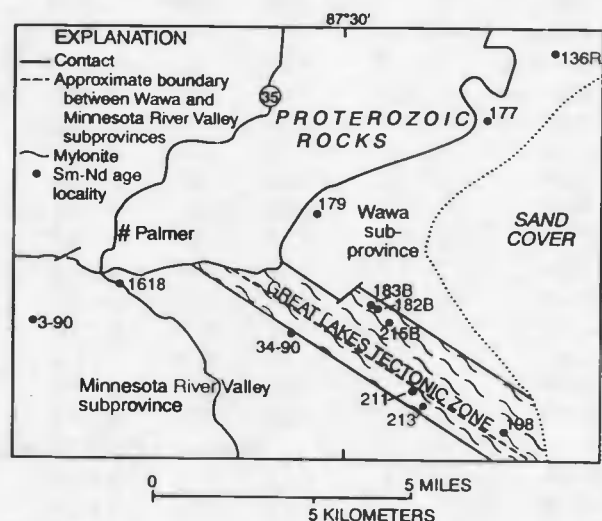
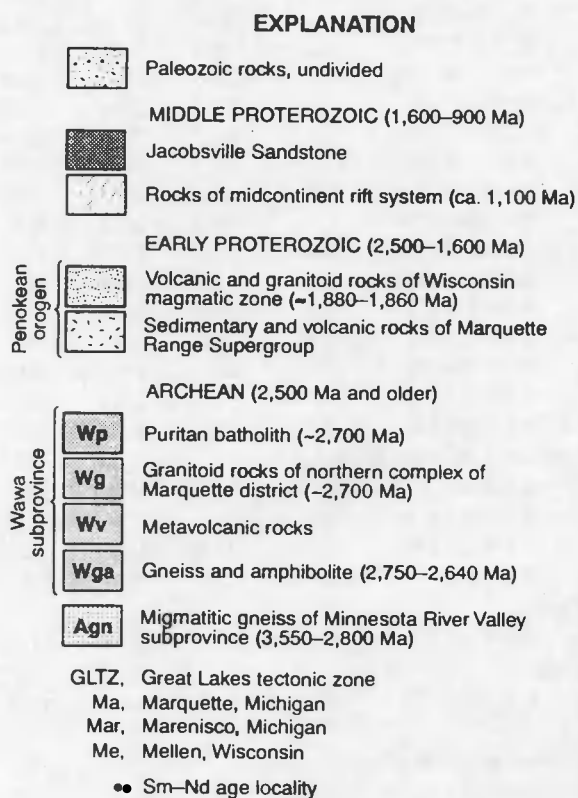


Figure 2. Geologic sketch map of Precambrian rocks in an area south of Marquette, showing localities of Sm-Nd samples. The Great Lakes tectonic zone separates granite-greenstone terrane (Wawa subprovince) from gneiss terrane (Minnesota River Valley subprovince).

A THIN VISCOUS SHEET APPROACH TO INVESTIGATE THE POST RIFT EVOLUTION OF THE MIDCONTINENT RIFT SYSTEM UNDER THE INFLUENCE OF GRENVILLE OROGENY

Soofi, M. A., and King, S. D., Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, Indiana 47907

The cause of the termination of rifting along the Midcontinent Rift system (MCR) and the presence of reverse faults along the rift margins are still troublesome for the investigators of the MCR. Suggestions for the cause of rifting range from a passive mechanism, where processes at plate boundaries were responsible (e.g. Hinze et al., 1982), to an active mechanism, where a mantle plume ascended and initiated rifting (e.g. Cannon and Hinze, 1992). Similarly, the formation of reverse faults has been suggested to be a consequence of plate flexure under the loading due to rift related rocks (e.g. Nyquist, 1986), or an effect of compressive stresses from the plate boundaries, which not only terminated the rifting but also caused thrusting along the original rift bounding normal faults (e.g. Cannon, 1994).

This study focuses on the evolution of the MCR under the influence of plate boundary forces, particularly the compressive forces from the Grenville Orogeny. We are using the thin viscous sheet model (TVS) of England and McKenzie (1983) which is implemented in a finite element code by Houseman and England (1986). This model has been used in the study of India-Asia collision (England and Houseman, 1986) and Arabia-Eurasia convergence (Sobouti and Arkani-Hamed, 1996), where it has successfully reproduced the topography and deformation observed in the overriding Eurasian plate. The model uses incompressible, vertically averaged, power-law rheology for the lithosphere.

For a given geometry, boundary conditions, stress-strain exponent (n) and Argand Number (Ar) values, the model calculates crustal thickness, stresses, strain rates and rotation. These can then be correlated with topography and deformation in the overriding plate. A continuous medium is assumed such that there is no discontinuity in the velocity field. Fault planes cannot be defined explicitly but, information on the type of faulting can be inferred from the stress and strain rate distribution.

Our results indicate that even in the case of a very weak lithosphere (i.e. $n=10$) stresses from the Grenville Front (GF) can be transmitted inland to interact with the processes that were occurring along the MCR. Also, depending on the size of the colliding microcontinents (i.e. indenters) and their position along the GF it is possible that the MCR was subjected to different magnitude of stresses along its length and it evolved through the superposition of these stresses. The varying degree of thrust faulting observed along the MCR could be a manifestation of such a collision style. The models also predict significant thickening of crust next to the indenter, the thickening decreases away from the collision boundary. For a comparatively rigid lithosphere ($n=1, Ar=1$) crustal thickening is as much as 2 km where as for a weak lithosphere ($n=10, Ar=1$) crustal thickening is as much as 19 km. Assuming crustal density of 2700 kg/m³ and mantle density of 3300 kg/m³ and assuming the surface of the 35 km thick crust to be at the sea level the change in crustal elevation is 0.36 km for rigid lithosphere and 3.4 km for the relatively weak lithosphere. The high elevations predicted by the TVS can initiate local extension, as suggested by England and McKenzie (1982) for the Tibetan plateau. Such a mechanism may have been responsible for the late stage extension reported for the Grenville Orogeny (e.g. Easton, 1992).

We are also studying the effect of oblique convergence along the GF on the evolution of the MCR. For fixed boundary conditions and rheology, the length scale of deformation decreases with increasing obliquity. As discussed for the normal convergence, microcontinents of various sizes converging obliquely along the GF can produce stresses of different magnitudes along the MCR. Oblique convergence produces same pattern of crustal thickening as observed for normal convergence except that it is not symmetric. One significant difference between oblique and normal convergence is the significant area of crustal thinning next to the colliding microcontinent (indenter). This thinning represent extension in the over riding plate. For normal convergence the thinning is very localised and produced in a very small area that does not changes significantly with rheology. For oblique convergence this area of extension increases for weaker rheology (increasing n value). We hypothesize that oblique convergence, together with a weak lithosphere (due to thermal anomaly resulting from subduction), may had helped, if not initiated, the rifting process.

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PALEOMAGNETIC STUDIES OF A PROTEROZOIC PORPHYRITIC DIABASE
DIKE, PIFHER AND IRWIN TOWNSHIPS, LAKE NIPIGON DISTRICT,
ONTARIO

Thomas*, C., Kean, W., Department of Geosciences,
University of Wisconsin-Milwaukee, Milwaukee, WI 53201
and Luther, F., Geology Department, UW-Whitewater,
Whitewater, WI 53190 (* student author)

This approximately 50 m wide porphyritic diabase dike, outcropping in western Irwin and Pifher Townships in the Nipigon district, is locally known as greenspar. The dike has a characteristic greenish mottled appearance in outcrop as a result of saussaritized plagioclase glomerophenocrysts in a diabase groundmass (Luther, 1997). The dike strikes due north and dips vertically, and is found as segments, off-set by east-west faulting (Mackasey, 1975). There are no radiometric dates on this rock or associated rocks, although, it is cut by a large middle or late Proterozoic sill in Irwin Township (Mackasey, 1975).

Paleomagnetic studies were completed on 2-3 cores from each of 5 locations. Each location represents one dike segment. Samples from each location were subjected to both alternating field (A.F.) and thermal demagnetization studies. The samples show one primary magnetic direction which is removed at demagnetization temperatures of 570° C. or by A.F. fields of 60 mT. All but one location shows normal polarity with northwesterly declinations (200°-300°) and inclinations of 40°-80°. The northern most section of the dike which we sampled is reversally magnetized with declinations of about 90°-100° and inclinations of -75°. These magnetic directions are consistent with Keweenaw age paleomagnetic directions in the Lake Superior Region.

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A GRAVITY, MAGNETIC, AND STRUCTURAL STUDY OF THE WAKEMUP BAY TONALITE, MINNESOTA

TIKOFF, Basil, Department of Geology and Geophysics, Rice University, Houston, TX 77005-1892, USA, BAUER, Robert Department of Geological Sciences, University of Missouri, Columbia, MO, 65211, USA, VIGNERESSE, Jean-Louis Vignerresse, CREGU, 54501 Vandoeuvre, Nancy Cedex, France, and HAGGEMAN, Nick, Department of Geology and Geophysics, University of Minnesota, Minneapolis, MN 55455, USA

The Wakemup Bay tonalite is a small intrusive body that intrudes amphibolite-grade biotite schist on the extreme southern edge of the Quetico sub-province in the western part of Lake Vermilion in Minnesota. The tonalite is part of the Wakemup Bay block, which is bounded by the Vermilion fault to the north and the Haley fault to the south. The Haley fault has a dip-slip component that separates amphibolite-grade rocks of the Quetico sub-province to the north from greenschist-grade rocks of the Wawa sub-province to the south. The primary purpose of our investigation was to evaluate the mechanism of emplacement of the Wakemup Bay pluton and its relationship to local doming by determining its 3D shape and internal magnetic fabric. We conducted a gravity survey over the pluton, and use the gravity inversion to evaluate the pluton shape. We collected anisotropy of magnetic susceptibility (AMS) data to evaluate the magnetic fabric of the pluton.

Bauer (1985, 1986) reports previous structural analysis and mapping of the Wakemup Bay pluton. The pluton comprises a medium-grained biotite tonalite, with sphene, apatite, magnetite, and zircon as accessory minerals. The tonalite typically has a layered appearance, and the microstructures throughout the pluton, particularly at the pluton margin, indicate solid-state deformation. Foliation dips outward (20-60°) from the middle of the pluton, in a concentric pattern. Biotite schist - consisting dominantly of plagioclase, quartz, and biotite - surrounds the tonalite on all sides, and has foliation that also dips away from the center of the pluton on all sides. On a more regional scale, the foliations of the schist defines a doubly plunging, EW-trending anticline with moderately dipping limbs. The tonalite is spatially associated with the hinge area of this fold, which Bauer (1985, 1986) interpreted as an F3 fold in the local deformation sequence. A hornblende diorite unit that intruded the biotite schist outcrops on both the north and south sides of the tonalite. The center of the pluton is capped by a roof of wallrock that extends ~40 m above the tonalite contact. The roof consists of both the biotite schist and a relatively flat-lying layer of the hornblende diorite.

The Anisotropy of Magnetic Susceptibility (AMS) is a technique that is widely used in the study of granitic fabrics. The magnetic susceptibility is defined by $M = K \times H$, where M is the induced magnetization and H is the inducing magnetic field. The variation of this magnetic susceptibility with the sample placed in different orientations produces an AMS ellipsoid, similar to the finite strain ellipsoid. The principle AMS axes are $k_{max} > k_{int} > k_{min}$, which may be interpreted in terms of a magnetic foliation ($k_{max} - k_{int}$ plane) or magnetic lineation (k_{max} orientation). The bulk susceptibility values varied widely in the Wakemup Bay tonalite (5×10^{-4} to 10^{-1} SI), interpreted as representing the presence or absence of magnetite. The AMS foliation essentially parallels the measured field foliation. The major insight from the AMS study comes from the orientation of the magnetic lineation. Throughout the Wakemup Bay tonalite, the magnetic lineation is oriented dominantly EW, plunges shallowly, and is generally parallel to the long direction of the Wakemup Bay pluton and parallel to the trace of the F3 fold hinge. This observation has significance with respect to emplacement mechanism.

We selected the Wakemup tonalite for our detailed gravity study because: 1) It had previous structural mapping (Bauer, 1985); 2) It has a single surrounding lithology with a significant and consistent density contrast (2.67 ± 0.04 for the tonalite and 2.75 ± 0.04 for the surrounding schists); and 3) A wallrock roof exists over the center of the pluton, despite the relatively low relief of the area (< 40 m). Thus, the depth recorded by the gravity inversion represents the true depth of the pluton, within the limitations of the gravity inversion technique (e.g., method of Vignerresse, 1995). To achieve resolution obtained in structural measurements, 142 gravity stations were collected on the Wakemup pluton and immediate

surroundings using a Lacoste & Romberg, model G gravitimeter. Laser theodolite from existing benchmarks and the controlled-elevation shoreline Of Lake Vermilion provided the critical elevation controls. A map of the Bouguer anomalies is provided (Fig. 1a). Using a gravimetric three-dimensional iterative technique, resulted in a good first-order picture of the pluton (Fig. 1b). Most of the pluton is very thin, less than 0.5 km thick. There are two root zones, both of which indicate depths of up to 4.0 km, using the calculated densities. The depth anomaly in the southwest part of the pluton has a linear, NW trend and is approximately 5 km long. It lies adjacent to the SW part of the pluton and is thus adjacent to the Haley fault. The depth anomaly in the center of the pluton is slightly less deep (~3 km). It also contains a NW trend, although the depth is clearly at a maximum in the SE part of the NW-SE oriented trend. It is interesting to note that the deepest portion of the tonalite does not sit under the present exposure of the pluton.

As a result of the structural geology, magnetic analysis, and gravity measurements, the Wakemup Bay pluton is interpreted as intruding a broad anticlinal hinge, during the folding event (F3). This was one of the possibilities suggested by Bauer (1986) and consistent with the very thin nature of the pluton (<0.5 km). The wallrock preservation in the roof represents the anticlinal hinge. The hornblende diorite unit on the north side, south side, and above the pluton is a good indication of this situation. The two NW-root zones were presumably were feeder zones for the magma, although given the very high exposure level this claim is impossible to support by geological or magnetic measurements. The feeder zones may have initiated on NW oriented fractures. This type of cross-faulting is commonly seen in folds, particularly those with a component of hinge-parallel extension. The large southern root zone may have affected the subsequent movement of the Wakemup block, between the Haley and Vermilion faults.

The Haley fault occurs just south of the deep southern root zone, and the root of the tonalite may have acted as a strong heterogeneity in the schist. The Haley fault shows indications of some dextral strike-slip faulting, which is inferred to have occurred after its earlier normal movement (e.g., Bauer, 1986). This type of small rigid block moving between major fault systems is inferred in other orogenic belts.

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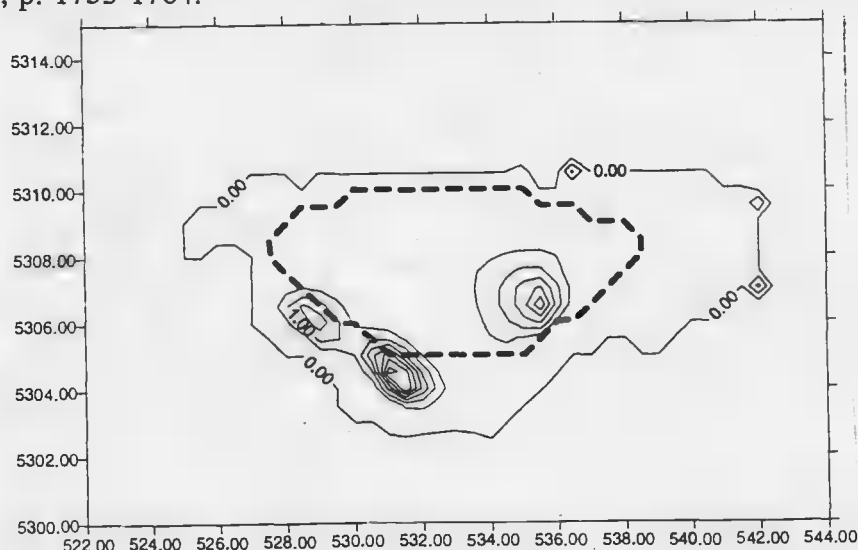


Fig. 1. Gravity inversion model for Wakemup Bay tonalite. Heavy dashed line represents current outcropping of the pluton. Light lines are inferred depth of the pluton, contoured for 0.5 km. The tonalite is generally a thin sheet (<0.5 km), with two deep root zones.

THE RELEVANCE OF THE GEOLOGY OF MID-OCEAN RIDGES AND OPHIOLITES TO THE UNDERSTANDING OF LAYERED INTRUSIONS IN THE MIDCONTINENT RIFT: PART I. GEOMETRY; PART II. INTERNAL STRUCTURE AND PETROLOGY

Tatiana Vislova, Department of Geology and Geophysics, University of Minnesota, USA

Part I. Insights from current research on mid-ocean ridges and ophiolites remain to be applied to studies of intracontinental rift systems. Dynamic magma chambers where fractional crystallization and formation of layered cumulates occur simultaneously with spreading are being defined by seismic data for ocean island and mid-ocean ridge systems. But layered intrusions in continental crust are still generally studied from the point of view of fixed geometry. However, if we accept the conclusion that the Duluth Complex and associated intrusions such as the Sonju Lake and the Bald Eagle intrusions formed in an intracontinental rift system, the concept of dynamic magma chambers during crystallization of layered gabbro must be considered.

There is a growing database on the geometry and dynamic processes of crystallization and the formation of layered gabbro based on seismic studies along the fast spreading (>10 cm/yr.) East Pacific Rise (Sinton, 1992; Wang, 1996; Barth, 1996) and the slow-spreading (<5 cm/yr.) Mohns Ridge (Geli, 1994) and Mid-Atlantic Ridge (Rommevaux, 1994). These studies demonstrate that active magma chambers: 1) are segmented and centered under topographic highs and active vents along the ridge axes (McKenzie, 1997 and Wright, 1995), 2) pinch and swell in plan view with typical widths and along-axis lengths of 5 – 15 km (Geli, 1994), and 3) are found at depths of 1.5 – 2.5 km below the seafloor. These features are best developed along slow spreading rifts such as the Mohns Ridge (Geli, 1994).

Because ophiolites are fragments of oceanic crust, they provide an opportunity to study the processes that occur along ridge axes. Recent detailed mapping and interpretation of the Oman ophiolite generally confirm the segmental structure of ridge magma chambers as described above (Nicolas, 1996 and references therein).

The geophysical expressions of present-day oceanic ridges and the 1.1 Ga Midcontinent Rift in North America show the same segmented bulls-eye structure on a scale of 100-1000 km. On a scale of 1 – 100 km, the geophysical data on active magma chambers along ridge axes and the first derivative of the aeromagnetic data on the Bald Eagle Intrusion have a similar pinch and swell geometry. These similarities on large and small scales imply that our current understanding of the processes responsible for the structure and petrologic features of ridge magma chambers and layered gabbro in ophiolites can be used to explain the origin of similar features in layered intrusions in intracontinental rifts. The geometries of intrusions formed in dynamic or static magma chambers are related to spreading rates and continuity of spreading. With fast, continuous spreading rates it is possible to produce layered gabbro at a lateral scale of many kilometers from a relatively narrow, growing magma chamber which is never more than 1-2 km wide at any given time (e.g., Nicolas, 1996, p.17,842). On the other hand, with slow, episodic spreading rates the lateral extent of layered gabbro could be restricted to the dimensions of the active magma chambers. Thus the Sonju Lake intrusion, with its sill-like geometry (Miller, 1996), could have formed in a static magma chamber; whereas the Bald Eagle intrusion, with its funnel shape, could have formed in a more dynamic environment.

Part II. The funnel-shaped layering in the Bald Eagle intrusion contrasts remarkably with near-horizontal layering of the other intrusions in the Duluth Complex and in the Oman ophiolite. Unfortunately the current interpretations of the layering in ophiolites do not provide

a ready explanation for the layering in the Bald Eagle intrusion. There is an active debate in the literature concerning the processes that would lead from the isotropic crystal mushes of active ocean-ridge magma chambers to the near-horizontal layering in gabbro of the ocean floor and in ophiolites (Quick, 1993, and Nicolas, 1996). In essence Quick's analysis implies that the layering and the igneous lamination are post-crystallization phenomena, produced when crystal mush is carried away from the active magma chamber. If this idea is applicable to the Duluth Complex, the Bald Eagle intrusion could be a frozen active chamber thus far not observed in ophiolites. Layered gabbro of adjacent South Kawishiwi intrusion could be the equivalent of layered gabbro in ophiolite produced during spreading away from a ridge axis.

One might expect that the cryptic, compositional variations of cumulus minerals formed in static chambers might differ from those formed in dynamic chambers. A suggestion of such differences can be seen in Figure 1. All three data sets lie on a common trend. Gabbro in the Oman ophiolite and rocks in the Bald Eagle intrusion show more restricted ranges of differentiation than rocks in the Sonju Lake intrusion, and the Oman magma is the most primitive. Additional electron microprobe mineral and minor- and trace- element rock analyses of the Bald Eagle intrusion are planned to evaluate the suggestion that the chemical variations produced in dynamic chambers are definitively distinct from those established for static chambers.

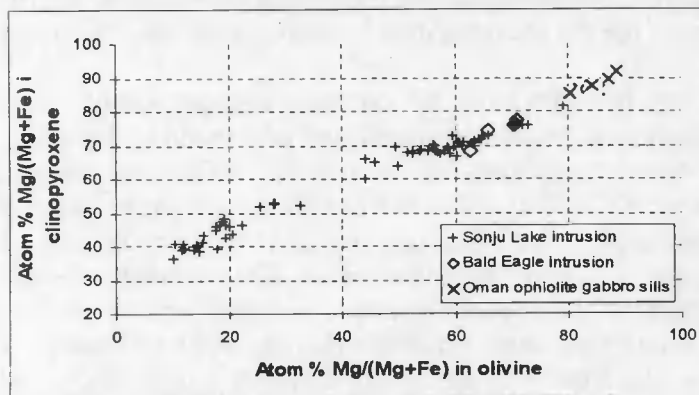


Fig. 1. Mg/(Mg+Fe) variation in pyroxene and olivine. All the data are electron microprobe analyses. Sonju Lake intrusion (Miller, 1996); Bald Eagle intrusion – data points are averages of over 200 analyses of representative samples of troctolite, olivine and oxide gabbros; Oman ophiolite – data from gabbro sills (Korenaga, 1997).

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PRECISE U-Pb ZIRCON AGES OF MIDCONTINENT RIFT RHYOLITE (CHENGWATANA VOLCANICS), CLAM FALLS, WI

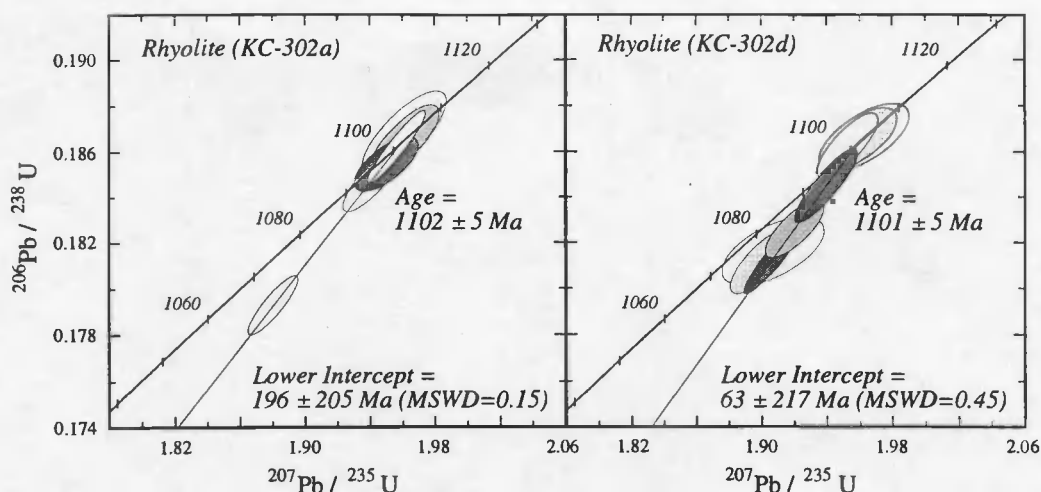
WIRTH, Karl R., Geology Department, Macalester College, St. Paul, MN 55105, wirth@macalester.edu; and GEHRELS, George, E., Department of Geosciences, University of Arizona, Tucson, AZ 85721, gehrels@geo.arizona.edu.

Recent studies of the southwestern segment of the Keweenaw Midcontinent rift along the St. Croix River have focused on the structural (Leslie et al., 1994), paleomagnetic (Kean et al., 1997), and magmatic (Wirth et al., 1997) evolution of the poorly-exposed Chengwatana Volcanics (Minnesota and Wisconsin). Comparison of Chengwatana Volcanics from this segment of the rift with the those of the better-studied portions of the rift in the Lake Superior region (e.g., Nicholson et al., 1997) have been hindered by the lack of well-constrained ages for the Chengwatana Volcanics. The only previous geochronologic study of these volcanics (Zartman et al., 1997) resulted in an age of 1094.6 ± 2.1 Ma for rhyolite exposed in the Ashland syncline in northern Wisconsin; rhyolite from drill core in Hudson-Afton Horst (SE of Minneapolis) yielded an anomalously old (1130 Ma) age. Here we report precise U-Pb zircon ages (1102 ± 5 Ma) for rhyolites exposed in the lower part of the volcanic section along the Lake Owen Fault, which bounds the eastern margin of the rift. Petrographic and geochemical studies of the rhyolitic and basaltic flows of this segment of the rift are described by Abbott et al. and Naiman et al. (both this volume).

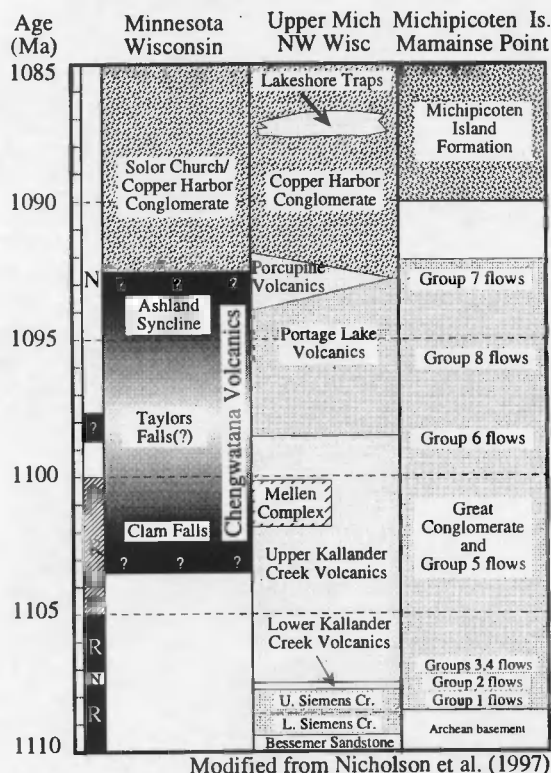
Rhyolite exposed one kilometer east of Clam Falls, WI contains phenocrysts of plagioclase and rare quartz in a spherulitic groundmass of tabular quartz and potassium feldspar. The rhyolite is typically fine- to medium-grained and massive (sample KC-302a), but becomes more coarse-grained near its base (sample KC-302d) and contains subangular clasts of basalt. Flow structures are not apparent, but the rhyolites are otherwise similar to the large rhyolites of the North Shore Volcanic Group. Rhyolite is rare in this portion of the Midcontinent rift and is estimated to compose less than one percent of the exposed volcanic and sedimentary sections.

Zircons from both samples have relatively simple prismatic (length:width ratios = 2:1 to 8:1) forms, are translucent, and vary in color from reddish-brown, to honey brown, and to pale pink. Dark grains typically contain abundant inclusions and were not selected for analysis. Analyses were conducted by conventional isotope dilution-thermal ionization mass spectrometry, as described by Gehrels et al. (1991). Six euhedral crystals (175-250 μm in length) from KC-302a were abraded to 75% their original size and were analyzed as individual grains. Three of the grains yielded concordant ages with mean $^{206}\text{Pb}^*/^{238}\text{U}$ and $^{207}\text{Pb}^*/^{206}\text{Pb}^*$ ages of 1102 Ma; an uncertainty of ± 5 Ma (2σ) is assigned to this age on the basis of the errors of the individual determinations, rather than the error of the mean of the three concordant analyses. Three additional grains are slightly discordant, presumably due to small amounts of lead loss. A discordia through these points, projected from 1102 Ma, yields a lower intercept of 196 ± 205 Ma (MSWD = 0.15). Analyses of KC-302d were conducted on two multigrain fractions, one unabraded single grain, and five abraded single grains. The single grains were all ~ 200 μm in length originally, and the multigrain fractions consisted of: 1) seven grains measuring ~ 125 μm in length, and 2) thirty grains ~ 80 μm in length. The three abraded grains are analytically concordant and yield mean $^{206}\text{Pb}^*/^{238}\text{U}$ and $^{207}\text{Pb}^*/^{206}\text{Pb}^*$ ages of $1101 \text{ Ma} \pm 5 \text{ Ma}$. Three additional grains and the two multigrain fractions are slightly discordant; a discordia through these points, projected from 1101 Ma, yields a lower intercept of 63 ± 217 Ma (MSWD = 0.45). Given the uncertainties of ± 5 Ma on each of the ages, the 1 Ma age difference between the two samples is probably not significant.

Analyses of the Chengwatana rhyolites near Clam Falls indicate that magmatism began by at least 1102 Ma in this portion of the rift, considerably earlier than the age reported by Zartman et al. (1997) for rhyolite (1094.6 ± 2.1 Ma) exposed near the base of the Chengwatana



section in the southeastern limb of the Ashland syncline. This implies that flows exposed near Clam Falls likely formed contemporaneously with the Upper Kallander Creek Volcanics and the Mellen Complex of Northern Wisconsin, and the Group 5 flows and Great Conglomerate of Mamainse Point. The 1102 ± 5 Ma age of Chengwatana Volcanics in the Clam Falls region implies that the Clam Falls flows may have “reversed” paleomagnetic directions since they are coeval with the time of the reverse-to-normal magnetic polarity change (1105–1100 Ma) that has been widely observed throughout the Lake Superior region. New aeromagnetic data (USGS) suggest that Chengwatana Volcanic flows exposed near Taylors Falls, MN, are younger than those near Clam Falls. Flows near Taylors Falls have predominantly “normal” paleomagnetic directions (Kean et al., 1997) and are likely younger than the regionally documented reverse-to-normal polarity shift; these flows may be correlative with Portage Lake Volcanics (northern WI) and Group 6 flows (Mamainse Point). A few Taylors Falls flows have “reversed” paleomagnetic directions (Kean et al., 1997) and record a reversal event that is younger than the regionally observed reverse-to-normal magnetic polarity change.



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