

Institute on Lake Superior Geology



Proceedings

**40th Annual Meeting
May 11-14, 1994**

Michigan Technological University
Houghton, Michigan

Volume 40
Part 1—Program and abstracts

Editors: Theodore J. Bornhorst and S. Douglas McDowell

40TH ANNUAL MEETING INSTITUTE ON LAKE SUPERIOR GEOLOGY

Volume 40 consists of

Part 1: Program and Abstracts

Part 2: Self-guided geological field trip to the Keweenaw Peninsula, Michigan

Part 3: Volcanic geology of eastern Isle Royale, Michigan

Part 4: Michigan kimberlites and diamond exploration techniques

Part 5: Lessons from mining case histories: West Menominee Range, Michigan

Reference to material in Volume 40, Part 1 should follow the example below:

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Part 1—Program and abstracts

Editors: Theodore J. Bornhorst and S. Douglas McDowell
Department of Geological Engineering, Geology, and Geophysics
Michigan Technological University, Houghton, Michigan 49931-1295

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INSTITUTE ON LAKE SUPERIOR GEOLOGY

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

CONSTITUTION OF INSTITUTE ON LAKE SUPERIOR GEOLOGY

Article I Name

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

Article II Objectives

The objectives of this organization are:

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

Article III Status

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

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

Minn. Stat. Anno. 290.01, subd. 4

Minn. Stat. Anno. 290.05(9)

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

Article IV Membership

The membership of the organization shall consist of the board of directors. Any geologist interested shall be permitted to attend and participate in and vote at the annual meetings.

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 Chairman, Secretary-Treasurer, and the last three past Chairman; 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 annual meeting so as to bring the membership of the board up to five members.

Article VII Officers

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

- A. The Chairman 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 term of office as Chairman will terminate at the close of the annual meeting over which he presides or when his successor shall have been appointed. He 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 term of office shall be two years or until his successor shall have been appointed.

Article VIII Amendments

This constitution may be amended by a majority vote of those persons who are personally present at, participating in, and voting at any annual meeting of the organization.

BY-LAWS

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 presides.

B. It shall be the duty of the Secretary-Treasurer to:

1. Keep accurate attendance records of all annual meetings.
2. Keep accurate records of all meetings of, and correspondence between, the board of directors.
3. Hold all funds that may accrue as profits from annual meetings or field trips and to make these funds available for the organization and operation of future meetings as required.

C. It shall be the duty of the board of directors to plan locations of annual meetings and to advise on the organization and financing of all meetings.

II. Duties and Expenses

1. There shall be no regular membership dues.
2. Registration fees for the annual meetings shall be determined by the Chairman in consultation with the board of directors. It is strongly recommended that these 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 those persons who are personally present at, participating in, and voting at any annual meeting of the organization; provided that such modifications shall not conflict with the constitution as presently adopted or subsequently amended.

Award Guidelines SAM GOLDICH MEDAL

Preamble

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

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

The exemplary award was made by I.L.S.G. to Sam Goldich in 1979 for his many contributions to the geology of the region extending over about 50 years.

Award Guidelines

- 1) The medal shall be awarded annually by the I.L.S.G. Board of Directors to a geologist whose name is associated with a substantial interest in, or a major contribution to, the geology of the Lake Superior region.
- 2) The Board of Directors, I.L.S.G. shall appoint the Nominating Committee. The initial appointment will be of three members, one to serve for three years, one for two, and one for one year, the member with the briefest incumbency to be chairman. After the first year the Board of Directors shall appoint at each spring meeting one new member who will serve for three years. In the third year this member shall be the chairman. The Committee membership should reflect the main fields of interest and geographic distribution of I.L.S.G. membership.
- 3) By November 1, the Goldich Medal Nominating Committee shall make its recommendation to the Chairman 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.

April 4, 1981

J. Kalliokoski, Chairman
Bill Cannon
Fred Kehlenbeck
G.B. Morey
Greg Mursky

GOLDICH MEDAL COMMITTEE 1993-94

- R.D. Sage** (1994)
Ontario Geological Survey, Sudbury, Ontario
- Glen Adams** (1995)
Crystal Exploration Inc., Crystal Falls, Michigan
- P.C. Morton** (1996)
Department of Geology, University of Minnesota Duluth, Duluth, Minnesota

GOLDICH MEDALISTS

- | | |
|---------------------------|------------------------|
| 1979 Samuel S. Goldich | 1987 Henry H. Halls |
| 1980 <i>not awarded</i> | 1988 Walter S. White |
| 1981 Carl E. Dutton, Jr. | 1989 Jorma Kalliokoski |
| 1982 Ralph W. Marsden | 1990 Kenneth C. Card |
| 1983 Burton Boyum | 1991 William J. Hinze |
| 1984 Richard W. Ojakangas | 1992 William F. Cannon |
| 1985 Paul K. Sims | 1993 Donald W. Davis |
| 1986 G.B. Morey | 1994 Cedric Iverson |

1994 Goldich Medal Recipient

Cedric Iverson

BANQUET SPEAKER

Geoffrey S. Plumlee, U.S. Geological Survey, Denver, Colorado
The Crucial (but underutilized) Role of the Economic Geologist in Predicting
and Remediating the Environmental Effects of Mineral Resource
Development.

STUDENT TRAVEL AWARD

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

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

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

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

INSTITUTE ON LAKE SUPERIOR GEOLOGY	
<i>Student Travel Award Application</i>	
Please print:	
Student Name: _____	Date: _____
Address: _____	
I certify that the above named person is an active resident student.	
_____ Department Head - Typed	
_____ Department Head - Signature	_____ Date
Educational Status: _____	
Are you the Senior Author of an oral or poster paper? Yes _____ No _____	
Will any other students will be traveling with you? _____ How many? _____	
Statement of Need: (If you need more room, please use the back of the page.)	
Other Significant Details:	

Please return to:	

BOARD OF DIRECTORS

- 1994 **Theodore J. Bornhorst, Chairman**
Michigan Technological University, Houghton, Michigan 49931
- 1993 **David L. Southwick**
Minnesota Geological Survey, St. Paul, Minnesota 55114
- 1992 **Albert B. Dickas**
University of Wisconsin-Superior, Superior, Wisconsin 54880
- 1991 **Paul E. Meyers**
Department of Geology, University of Wisconsin, Eau Claire, Wisconsin 54701

Secretary-Treasurer

M.G. Mudrey, Jr.

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

LOCAL COMMITTEES

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S. Douglas McDowell

Department of Geological Engineering, Geology and Geophysics, Michigan Technological University, Houghton, Michigan 49931

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Theodore J. Bornhorst

Department of Geological Engineering, Geology and Geophysics, Michigan Technological University, Houghton, Michigan 49931

Milton A. Gere, Jr.

Geological Survey Division, Michigan Department of Natural Resources, Marquette, Michigan 49855

LOCAL COMMITTEES

continued

STUDENT PAPER COMMITTEE

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S. Beske-Diehl

Department of Geological Engineering, Geology and Geophysics, Michigan Technological University, Houghton, Michigan 49931

J.S. Klasner

Department of Geology, Western Illinois University, Macomb, Illinois 61455

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Cliffs Mining Services Company, Ishpeming, Michigan 49849

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Geological Survey Division, Michigan Department of Natural Resources, Lansing, Michigan 48909

L.G. Woodruff

U.S. Geological Survey, St. Paul, Minnesota 55112

39th Annual Institute on Lake Superior Geology Eveleth, Minnesota

The 39th Annual Institute on Lake Superior Geology was held May 5-8, 1993 in Eveleth, Minnesota, under nearly perfect weather conditions. Co-hosts for the meeting were the Minnesota Geological Survey, the Minnesota Department of Natural Resources - Minerals Division, and the Mesabi Range Geological Society. David L. Southwick was the General Chairman, Jane Cleland coordinated the technical sessions as Program Chair, and Mark Jirsa organized the four bus and bag-lunch events as Field Trip Chairman. Proceedings of the 39th Institute were published in two parts: Volume 39, Part 1 contains the program and abstract of papers given in the technical sessions on May 6 and 7; Part 2 contains the field guides for the field trips conducted May 5, 6, and 8.

The technical sessions and the annual banquet were held in the Holiday Inn, Eveleth, Minnesota. A total of 182 people registered for the meeting and 104 attended the banquet. The technical program consisted of 31 oral presentations and 21 posters. Field trips 1 through 4 (see below) attracted 77, 60, 51, and 41 participants, respectively, demonstrating once again that the field trips are the major inducement for people to attend ILSG.

A highlight of the annual banquet was the presentation of the Goldich Medal to Donald W. Davis of the Royal Ontario Museum, Toronto, in recognition of his outstanding contributions to high-precision radiometric dating of Precambrian rocks and events in the Lake Superior area. The citation for Don was read by Ken Card, who also presented the medal on behalf of the Institute. The banquet address was given by Robert Zierenberg of the U.S. Geological Survey, who was a JOI/USSAC Distinguished Lecturer in 1993. His topic was "Implications for massive sulfide genesis from ODP leg 139 drilling in Middle Valley, northern Juan de Fuca Ridge".

Because field trips are so central to the success and survival of the Institute, the trips associated with the 39th ILSG and their leaders are here specifically acknowledged.

Trip 1, May 5, 1993: Geology and taconite mines of the Mesabi range. Leaders Ronald G. Graber, R.W. Ojakangas, Robert J. Waidler, and G.B. Morey.

Trip 2, May 6, 1993: DNR Core Library open house and core display. Leaders G.B. Morey, Mark J. Severson, Dennis P. Martin, Dale F. Cartwright, and Gary N. Meyer.

Trip 3, May 8, 1993: Geology of Archean greenstone - granite terrane in the Cook to Side Lake area. Leaders Mark Jirsa, Terry Boerboom, and Peter McSwiggen.

Trip 4, May 8, 1993: The Duluth Complex at Duluth. Leaders James D. Miller, Jr., John C. Green, and Val W. Chandler.

Travel awards totalling \$1,120 were made to students Zaira Arias, Sidney Hemming, Nick Van Wyck, and Hristo Stoyanov to facilitate their participation in the Institute. Awards of \$150 each were made to Zaira Arias of Queens University and Michael Handke of Lawrence University for best student oral presentation and best student poster, respectively.

The Board of Directors of the Institute on Lake Superior Geology met in Eveleth, Minnesota on May 6, 1993. In attendance were M. M. Kehlenbeck, A.B. Dickas, D.L. Southwick, T.J. Bornhorst, M.G. Mudrey, Jr., and J.M. Robertson. Principal actions taken were:

1. An offer from Michigan Technological University to host the 40th Annual Institute in Houghton, Michigan in 1994 was accepted with thanks. T.J. Bornhorst will be Chairman.

2. The Chairman (Southwick) agreed to explore with upper management of the Ontario Geological Survey the possibility of the OGS hosting ILSG in Marathon, Ontario, or elsewhere in the Province, in 1995. [Subsequent conversations and correspondence with John Wood, OGS Director, lead us to believe that a 1995 meeting in Marathon is likely).

3. It was decided that a mid-year conference-call meeting of the ILSG Board (in October or November) could provide useful guidance for the chairman of the next annual meeting, and should become normal practice henceforth. The Secretary-Treasurer (Mudrey) was instructed to work with the 1994 chairman (Bornhorst) to arrange such a conference call in the fall of 1993.

4. The annual report of the Treasurer was received and approved. The central ILSG accounts (investments and checking account) showed a net positive balance of \$13,678.43 as of May 6, 1993. Details of the accounts may be obtained from the Secretary-Treasurer upon request.

POST-MEETING NOTE:

The on-site account for the 39th ILSG at Eveleth, managed by the Minnesota Geological Survey through the Professional Development and Conference Services Office of the University of Minnesota, closed in September 1993 with an operating loss of \$1,991.27 for the meeting. The deficit was covered from the central ILSG treasury. As General Chairman of the Eveleth meeting, I am deeply chagrined by this financial mismanagement and accept full responsibility for it. I have thoroughly investigated the matter, identified the sources of unanticipated costs, and informed the Secretary-Treasurer and next year's Chairman of my findings. I am sure Ted Bornhorst will profit from my errors and run a meeting in Houghton that finishes in the black.

Respectfully submitted,

David L. Southwick
General Chairman, 39th ILSG

PROGRAM

CALENDAR OF EVENTS AND PROGRAM

Wednesday, May 11

8:00 a.m. - 5:00 p.m. **Field Trips 1 and 2**

1. **Underground geology of the White Pine and Caledonia Mines, Ontonagon County, Michigan. Leaders: Staff White Pine Mine, R. Whiteman, R.W. Seator and T.J. Bornhorst.**
2. **Lessons from mining case histories: West Menominee Range, Michigan. Leader: A.M. Johnson**

5:00 p.m. - 8:00 p.m. **Registration - Second Floor, Memorial Union Building on the campus of Michigan Technological University.**

7:00 p.m. - 10:00 p.m. **Poster Session and cash bar in Ballroom B, Memorial Union Building (Authors at posters 7:30 p.m. - 9:00 p.m.).**

Thursday, May 12

All technical sessions are in Ballroom A, Memorial Union Building on the campus of Michigan Technological University

7:15 a.m. - 4:30 p.m. **Registration - Second Floor, Memorial Union Building on the campus of Michigan Technological University.**

Technical Session I - Resources Session Chairs: J.M. Robertson and G.W. Scott

8:10 a.m. **Opening - 40th Annual Institute on Lake Superior Geology
T.J. Bornhorst, General Chairman**

8:15 a.m. **Welcome Address - President Curtis J. Tompkins, Michigan Technological University**

8:30 a.m. **Bornhorst, T.J.
*Forty years of Institutes on Lake Superior Geology***

8:50 a.m. **Lavigne, M.J.
*Archean rifts and gold: Examples from the central Shebandowan greenstone belt***

9:10 a.m. **Lehmann, E.K. and Beck, J.W.
*The Birch Lake prospect - A major PGM prospect in the Duluth Complex***

9:30 a.m. **Melcher, F.H., Morey, G.B., McSwiggen, P.L. and Cleland, J.M.
*On the origin of manganese oxides in iron-formation of the Cuyuna North Range, East-central Minnesota - New evidence from the U.S. Bureau of Mines Gloria drill site***

9:50 a.m. **Coffee Break**

- 9:50 a.m. **Coffee Break**
- 10:20 a.m. Han, T.M.
Genesis of hematite and magnetite in Precambrian magnetite iron-formation of low metamorphic grade, Lake Superior District, USA - A microscopic observation
- 10:40 a.m. Pasteris, J.D., Harris, T.N., and Sassani, D.C.
Dual immiscibility of dominantly aqueous fluids in rocks of the southwestern footwall of the Duluth Complex, NE Minnesota
- 11:00 a.m. Pufahl, P. and Fralick, P.
Depositional controls on shallow water iron formation accumulation, Gogebic Range, Wisconsin
- 11:20 a.m. Miner, G.C.
A possible metasomatic origin for the Longnose oxide-rich ultramafic body
- 11:40 a.m. Woodruff, L.G., Cannon, W.F. and Back, J.M.
Chalcocite mineralization in the Portage Lake Volcanics, Keweenaw Peninsula, Michigan
- 12:00 noon - 1:40 p.m. Optional Luncheon, Room 105A and B, Memorial Union Building
Speaker: Larry Lankton "The stuff of life: Provisioning the early miners"
- 12:00 noon - 1:40 p.m. Board of Directors Meeting, Room 100, Memorial Union Building
(by invitation only)

Technical Session II - Fluids and Environment Session Chairs -
A.R. Blaske and P.C. Morton

- 1:40 p.m. Person, M.
Hydrologic models of sediment - hosted ore formation within continental rift basins
- 2:00 p.m. White, R.B. and Suchoski, T.J.
Use of runoff- and sediment-control models in the design of mine hydrologic controls
- 2:20 p.m. Lapakko, K.A. and Wessels, J.N.
Release of acid and trace metals from quartz-carbonate hosted gold mine tailings
- 2:40 p.m. Loukola-Ruskeeniemi, K.
Environmental geochemistry of Proterozoic black shales in eastern Finland: a pilot study
- 3:00 p.m. **Coffee Break**
- 3:20 p.m. Eger, P.
Wetland treatment of mine drainage - an alternative to conventional treatment or voodoo treatment?

- 3:40 p.m. Davis, S.R.
Metallic mineral resources and ecosystem management at Voyageurs National Park, Minnesota
- 4:00 p.m. Johnson, A.M.
Geotechnical solutions for mining related problems
- 4:30 p.m. - 5:00 p.m. *IGCP Organizational Meeting - Room 105 A and B, Memorial Union Building*
- 6:00 p.m. - 7:00 p.m. Social - Seaman Mineral Museum, Fifth Floor, Electrical Energy Resources Center
- 6:30 p.m. - 7:30 p.m. Cash bar, Ballrooms A and B, Memorial Union Building
- 7:30 p.m. - 9:30 p.m. Annual Banquet, Ballroom A, Memorial Union Building
Speaker: Geoffrey S. Plumlee "The crucial (but underutilized) role of the economic geologists in predicting and remediating the environmental effects of mineral resource development"

Friday, May 13

Technical Session III - Regional Geology Session Chairs: J.D. Pasteris and D.M. Rossell

- 8:30 a.m. Kissin, S.A. and Fralick, P.W.
Granitoid rocks of the Elliot Lake area, Ontario and their relationship to U-Th-REE bearing pegmatites
- 8:50 a.m. LaBerge, G.L. and Klasner, J.S.
Tectonic implications of Early Proterozoic lithostratigraphy on the eastern Gogebic Range, Northern Michigan
- 9:10 a.m. Klasner, J.S. and LaBerge, G.L.
Structural evolution of the eastern Gogebic Range, Northern Michigan
- 9:30 a.m. VanWyck, N., Johnson, C. and Gross, S.
Archean crust in the Wausau-Pembine Terrane; continental underthrusting, or island arc basement?
- 9:50 a.m. **Coffee Break**
- 10:20 a.m. Uribe, R.D.
Petrography and diagenesis of the Upper Cambrian Mt. Simon Sandstone, SE Minnesota
- 10:40 a.m. Kissin, S.A. and Fralick, P.W.
Early Proterozoic volcanics of the Animike Group, Ontario and Michigan, and their tectonic significance
- 11:00 a.m. Bennett, G., Born, P. and Hatfield, K.G.
The stratigraphic significance of a dolostone unit near Sault Ste. Marie, Ontario

- 11:20 a.m. VanWyck N., Medaris, Jr., L.G. and Johnson, C.M.
The Wolf River A-type magmatic event in Wisconsin: U/Pb and Sm/Nd constraints on timing and petrogenesis
- 11:40 a.m. Smyk, M.C. and Schnieders, B.R.
A geological Marathon: The rocks of the North Shore of Lake Superior
- 12:00 p.m. - 1:30 p.m. Optional Luncheon, Room 105 A and B, Memorial Union Building
Speaker: Stanley Dyl "Minerals and decorative arts in Russia"

Technical Session IV - Midcontinental Rift System Session Chairs: L.G. Woodruff and P. Sundeen

- 1:30 p.m. Allen, D.J., Hinze, W.J., Dickas, A.B., and Mudrey, M.G., Jr.
Geophysical investigations of the Midcontinent rift system: A new model for western Lake Superior and northern Wisconsin
- 1:50 p.m. Palacas, J.G. and Burruss, R.C.
Preliminary source-rock and maturity evaluation of the Precambrian Nonesuch Formation in the Terra Patrick #7-22 borehole, Midcontinent rift system, Bayfield County, Wisconsin
- 2:10 p.m. Waggoner, T.D.
Echo Lake Gabbro, Houghton County, Michigan
- 3:00 p.m. Boerboom, T.J.
Archean crustal xenoliths in a Keweenaw hypabyssal sill, northeastern Minnesota. White was right!
- 3:20 p.m. **END OF TECHNICAL SESSIONS**

Saturday, May 14

8:00 a.m. - 5:00 p.m. **Field Trips 3 and 4**

3. Michigan kimberlites and diamond exploration techniques. Leaders: S.M. Carlson and W. Floodstrand
4. Geology of the Keweenaw Peninsula, Michigan.
 Leader: T.J. Bornhorst

Friday, May 13 to Thursday, May 19

Field Trip 5 - Volcanic geology of Eastern Isle Royale, Michigan. Leader: W.I. Rose

Poster Session

7:00 p.m. Wednesday, May 11 to 12:00 noon Friday, May 13

Session Chair: M.A. Gere, Jr.

Chenier, F.

Inventory of the Michigan Geological Survey Division's Upper Peninsula significant water well cuttings library at Escanaba.

Frey, B.A.

Minnesota drill core examination and assay

Kean, W.

Paleomagnetism of a 1500 MA mafic dike at Waterloo, Wisconsin

Kropf, E.P., Wirth, K.R. and Craddock, J.P.

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Minnesota Department of Natural Resources, Minerals Division

A compendium of mineral resource information, east-central Minnesota

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Geochemical characteristics of granitoids from the Michipicoten Greenstone Belt, Wawa Subprovince, Superior Province: Implications for source regions and tectonic evolution

ABSTRACTS

GEOPHYSICAL INVESTIGATIONS OF THE MIDCONTINENT RIFT SYSTEM: A NEW MODEL FOR WESTERN LAKE SUPERIOR AND NORTHERN WISCONSIN

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Seismic reflection data are of enormous value for investigating the 1100 Ma Midcontinent Rift System. Recently released eight-second profiles from Lake Superior, together with proprietary data from northwestern Wisconsin, have resulted in a better understanding of the western Lake Superior and Wisconsin segments of the rift system. Combined interpretation of these seismic profiles with gravity data reveals several interesting structural and stratigraphic features, including two pre-Keweenawan ridges within the rift interior, the termination of major reverse faults, a flanking sedimentary basin located east of the St. Croix Horst, and, possibly, an Archean batholith buried beneath the rift.

Along the Lake Superior syncline (Fig. 1), seismic data image up to 9 km of sedimentary rocks (the majority of which are likely Oronto Group strata) and up to 18 km of volcanic flows. Along the Ashland syncline in Wisconsin (Fig. 1), the Oronto Group is as thick as 4 km, and the underlying volcanic flows have a maximum thickness of 14 km. The Ashland and Lake Superior synclines, however, are separated by a prominent ridge that was first hypothesized by White (1966) on the basis of gravity and magnetic data. Along White's Ridge, the volcanic strata are very thin (<2 km) and pinch out in northern Wisconsin, placing Oronto strata directly on top of the pre-rift basement (Fig. 1). Southeast of Grand Marais, Minnesota, the Lake Superior syncline is deflected around the southern end of a similar ridge (Fig. 1). Stratigraphic relations indicate that White's Ridge and the Grand Marais Ridge remained topographically positive as the adjacent volcanic basins subsided. The volcanic flows pinch out gradually onto the ridges, with no evidence for substantial normal faulting.

As the Douglas Fault (Fig. 1) approaches Lake Superior, it bends east and follows the southern margin of White's Ridge. Displacement across the fault gradually decreases to the east until the fault is replaced by a fold near the eastern margin of White's Ridge. The seismic data also indicate that the Isle Royale Fault gradually terminates ~40 km southwest of the Isle. Between the terminations of the Douglas and Isle Royale Faults, late-stage rift compressional forces resulted in folding rather than development of major reverse faulting.

East of the Hastings Fault (Fig. 1), seismic data image up to 6 km of sedimentary strata within an asymmetric basin which is spatially associated with the Paleozoic River Falls syncline. This basin is characterized by a pronounced negative gravity anomaly that achieves its lowest values near Emerald, Wisconsin. Gravity modeling indicates that strata within the Emerald Basin have a low density and are probably correlated with the Bayfield Group of Wisconsin and the Fond du Lac and Hinckley sandstones of Minnesota. Interestingly, the northern margin of the Emerald Basin corresponds to the northern termination of the Hastings Fault and the southern termination of the Lake Owen Fault (Fig. 1). Although the exact relation between the Hastings and Lake Owen Faults is unclear, local gravity and magnetic characteristics are consistent with ~10 km of left-lateral offset along a cross-fault.

In western Lake Superior, the rift's igneous and sedimentary rocks cannot fully account for the observed gravity signature. A northeast-striking, ~30 mGal negative anomaly persists after the effect of the rift rocks is removed from the observed gravity field. The trend, amplitude, and gradients of this anomaly suggest that it may be produced by a buried granite belt within the Archean greenstone-granite terrane that lies beneath the rift (Allen et al., 1993). As shown in Figure 1, the Douglas and Isle Royale Faults terminate as they approach the proposed granite belt, both pre-Keweenawan ridges occur above this structure, and the St. Croix Horst terminates at the southern margin of this feature. Therefore, this Archean batholith might have acted as a buttress throughout the history of development of the rift, redirecting both the early tensional stresses and the late compressional stresses.

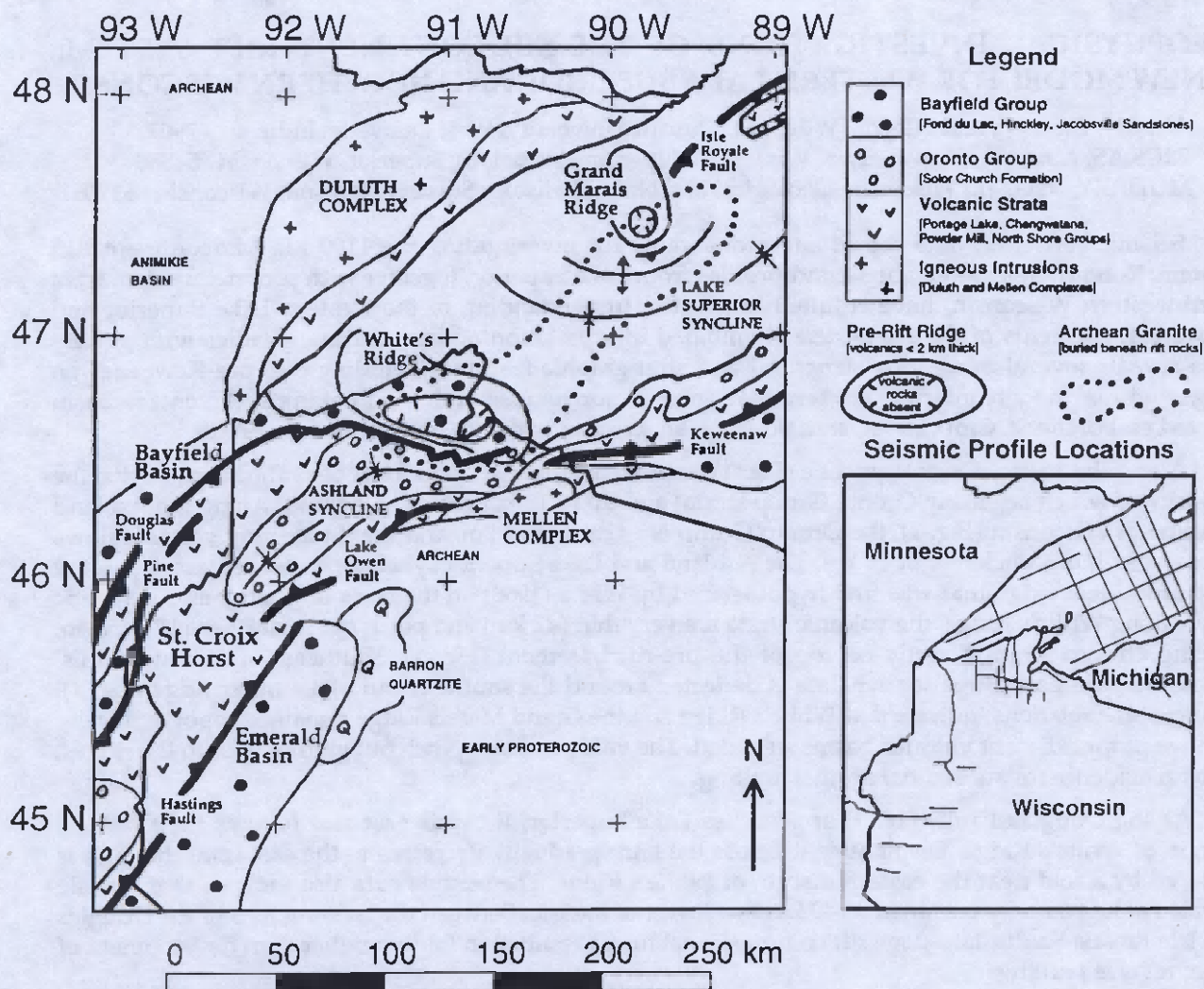


Figure 1: Geologic map of the western Lake Superior region based on interpretation of seismic reflection and gravity data. Insert shows the locations of the seismic profiles used in this study (e.g., McGinnis and Mudrey, 1991; also refer to acknowledgments).

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Acknowledgments

Seismic profiles in Wisconsin were provided to the authors courtesy of Texaco Exploration and Production, Inc. of Denver, Colorado and Amoco Production Company of Houston, Texas.

THE STRATIGRAPHIC SIGNIFICANCE OF A DOLOSTONE UNIT NEAR SAULT STE. MARIE, ONTARIO.

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While undertaking geological mapping in Fenwick Township near Sault Ste. Marie Ontario in 1986, Peter Born of the Ontario Geological Survey, identified a 30 meter thick dolostone-chert unit, lithologically distinct from known carbonate units in Ontario (Born et al., 1987). The dolostone-chert sequence directly overlies fractured and sheared, green and maroon siltstone and is overlain by red to maroon laminated siltstone and sandstone. The basal one third of the dolostone unit consists mainly of intercalated dolostone with minor recrystallized chert. Much of the upper portion of the unit is a clastic dolostone made up largely of medium to coarse sand-sized grains of dolostone and quartz. Oolitic dolostone is locally present. Barite occurs as a few irregular replacement bodies about midway in the dolostone-chert sequence.

The dolostone-chert-siltstone assemblage forms an approximately 400 meter wide southeastward trending, steeply dipping, fault-bounded block between (Huronian) Lorrain Formation to the south and Archean metavolcanics to the north. An altered mafic (diabase) dike intrudes the dolostone. (Bennett et al. 1989; Bennett et al. 1993),

The authors conclude that the dolostone-chert assemblage represents a carbonate facies of the Gordon Lake Formation of the Huronian Supergroup for the following reasons: (a) The red or maroon colored rocks are generally lacking below the Cobalt Group of the Huronian Supergroup (b) The metamorphic grade of the assemblage is higher than that of the Keweenawan rocks on the east shore of Lake Superior. (c) Jackson et al. (1992) have reported the presence of dolostone in the Gordon Lake Formation about 60 km southeast of Fenwick Township. (d) The previously proposed depositional environment of the Gordon Lake Formation is consistent with features in the Fenwick Township dolostone-siltstone assemblage (Wood, 1973).

The dolostone of Fenwick Township closely resembles in terms of lithology and stratigraphic association, the Kona Dolomite of the Marquette Range Supergroup of northern Michigan. The dolostone of Fenwick Township provides additional evidence for the previously proposed correlation of Cobalt Group of the Huronian Supergroup and the Choccolay Group of the Marquette Range Supergroup (Young, 1983)

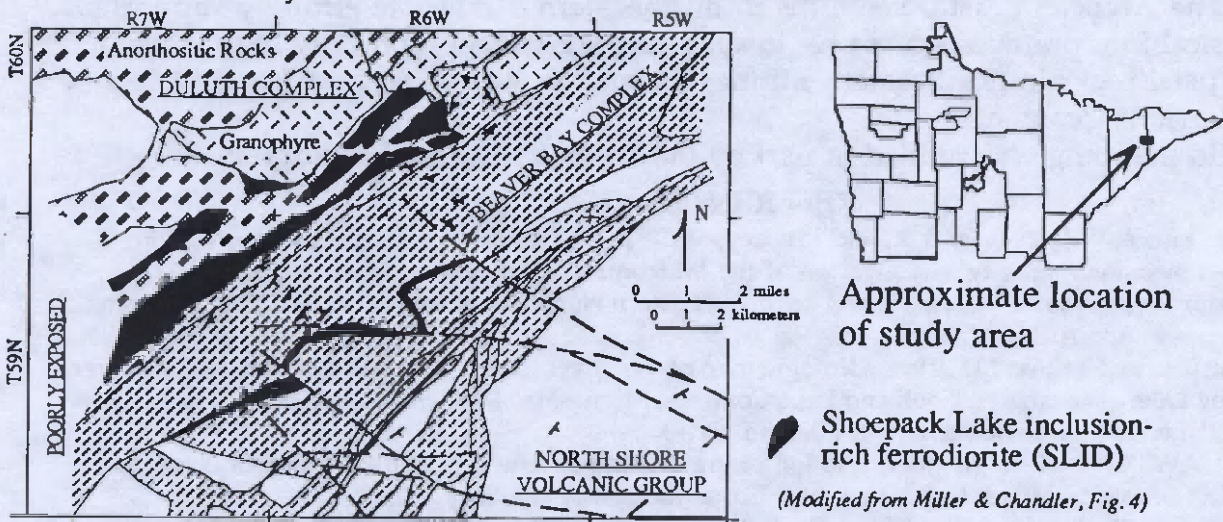
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ARCHEAN CRUSTAL XENOLITHS IN A KEWEENAWAN HYPABYSSAL SILL, NORTHEASTERN MINNESOTA. WHITE WAS RIGHT!

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Recent field studies have identified abundant xenoliths of Archean crust in the earliest of several intrusions along the northeast-trending transition zone between the upper portion of the Duluth Complex and the Beaver Bay Complex in northeastern Minnesota (Boerboom and Miller, 1994). This inclusion-rich, highly contaminated, mafic hypabyssal intrusive unit, informally termed the Shoepack Lake inclusion-rich ferrodiorite (SLID), has been widely redistributed by intrusion of granophyric and anorthositic components of the Duluth Complex, and by later NE-trending mafic dikes and sills related to both the Duluth and Beaver Bay Complexes. Most outcrops of SLID contain abundant xenoliths of Keweenawan felsic to mafic volcanic rocks, but at its northern extent nearly all xenoliths are Archean crust. Similar but unrelated contaminated diabase containing abundant Keweenawan inclusions has been mapped to the south, and is interpreted as the first magma pulse of the Beaver River Diabase dike and sill complex of the Beaver Bay Complex (Miller and others, 1989). Although the SLID is clearly older than the Beaver River Diabase, it similarly represents an initial pulse of magma related to incipient conduit opening. These early, inclusion-rich phases are inferred to have 'cleaned the pipes' and cleared the way for later inclusion-free dikes and sills.



Archean xenoliths in the SLID range from single disaggregated quartz crystals to outcrops as large as 50 m across, but most are between 0.3 and 1 meter in size. Compositions include biotite schist locally cut by folded dikelets of granite pegmatite, volcanogenic graywacke having graded bedding, pink granite, pegmatite, and granitic gneiss, and granodiorite to monzodiorite with locally abundant lamprophyre inclusions—all components typical of Archean rocks west of the Midcontinent rift system. Frozen amoeboid stringers of felsic material, trails of granular quartz grains, and small rock fragments in various states of assimilation commonly emanate from

felsic inclusions. The ferrodiorite host rock ranges from dense black to pinkish gray due to variably assimilated xenoliths.

The part of the SLID that contains Archean xenoliths overlies a northwest-trending gravity low, first recognized by White (1966), who postulated a sub-Keweenawan ridge of Archean basement extending northwestward from the shoreline of Lake Superior. Geophysical modeling of this area by others supports White's interpretation of the negative gravity anomaly (Ferderer, 1982; Chandler, 1990; Allen and others, 1993).

Geologic evidence other than Archean crustal xenoliths also supports White's interpretation. Multiple northeast-trending intrusive components of the Beaver Bay Complex form thick stacks of sheeted intrusions both northeast and southwest of the gravity low, but over the gravity low are pinched into narrow dike-like bodies (Miller and Chandler, in prep). This configuration suggests a buried control on their shapes. In addition, Jirsa's (1984) study of interflow sedimentary strata in the North Shore Volcanic Group has defined two sub-basins separated by a paleotopographic high that roughly corresponds to "White's basement high," and also to the necked zone of magmatic emplacement of the Beaver Bay Complex. Such a paleotopographic high implies that relative basement uplift occurred before or during deposition of the flow/interflow sequences. Other areas of shallow crustal basement inferred from geophysical modeling underlie the Bayfield Peninsula in Wisconsin and an area southwest of Isle Royale (White, 1966; Allen and others, 1993). The Archean crustal xenoliths in northeastern Minnesota strongly support geophysical interpretations of a pre- to syn-magmatic, topographically high block of older crustal rocks in northeastern Minnesota, and by inference, near Isle Royale and in northern Wisconsin.

Field mapping was funded in part by the USGS-COGEOMAP program.

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FORTY YEARS OF INSTITUTES ON LAKE SUPERIOR GEOLOGY

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The Institute on Lake Superior Geology (ILSG) began in 1955 with annual meetings held in April or May of each year, at locations throughout the Lake Superior region. Meetings have been held at 18 different locations, with 9 locations repeating (repeat interval around 11 years). More diversity with time in meeting locations is indicated by 6 single locations occurring in the last 10 years. Over the 40 years of ILSG, there have been 30 chairmen; 9 have been chairman twice (repeat interval around 11) and 21, once. For the 5 years from 1990 to 1994, all chairmen have been repeats from previous years, indicating less diversity with time in annual chairmen.

The ILSG was founded to bring together geologists from academia, government surveys, and industry to discuss the geology of areas related geographically to Lake Superior (see the Sam Goldich Medal Award Guidelines). The attendance over the 40 years of ILSG, estimated to be in excess of 6000, clearly indicates that the ILSG has met its objectives. Data on attendance is known for the years 1966 to 1969, and 1982 to present, and suggest a cyclical pattern.

The number of abstracts published in proceedings volumes provides another quantitative measure of the success of the ILSG in bringing together geologists. The total number of abstracts over the 40 years is approximately 1450. For annual meetings, the number of abstracts ranges from 12 to 60, with a median of 31. Overall, the number of abstracts gradually increased from 1955 to 1983, and then dramatically increased in 1984 and has stayed higher than in earlier years, although slightly declining from 1985 to 1994. The total number of authors on abstracts over the 40 years is approximately 2450. For annual meetings, the number of authors ranges from 14 to 126, with a median of 49. Both the number of abstracts and number of authors, documents a significant volume of discussion on the geology of the Lake Superior area.

The only available means of analyzing the mix of academia, government surveys, and industry is through the abstracts. For every abstract, over the 40 years of ILSG, the senior author and every other author was categorized as affiliated with either academia (includes students), government surveys, or industry (includes consultants). The proportion and temporal patterns are nearly identical, using affiliation of either: senior author only, or all authors. Published contributions by academic geologists have dominated most of the 40 year history of the ILSG, with a median of about 65 % of contributions each year. The overall pattern in the proportion of academic contributions is one of a gradual increase from around 40 % in 1955, to 80 % in 1975, followed by a decrease to about 45 % in 1994. Government survey contributions have gradually increased over the 40 years of ILSG from around 20 % to around 35 %, with a median of about 25 %. Published contributions by industry geologists were much greater in the first 6 years of the ILSG, around 25 %. The proportion of industry contributions fell to a low around 1975 of near 0, while at the same time academic contributions peaked, and has since

increased to around 10 %. The median proportion of industry contributions over the 40 years of ILSG is 6 %. The ILSG has succeeded at bringing together a mix of geologists from academia, government survey, and industry. While published contributions from industry are low, an analysis of attendees, which is not possible, may indicate higher industry geologist participation in ILSG.

The ILSG has had a focus on Precambrian geology and mineral resources throughout its 40 year history. Every abstract was categorized as related to either resources, basic geology, geophysics, glacial/environmental, or other. Basic geology topics have dominated ILSG abstracts, with a median contribution of about 60 % over the 40 years. Basic geology contributions gradually increased from 1955 to 1972, and have since fallen to around 45 %. The proportion of resource related papers was greatest in the first 5 years of the ILSG, at around 50 %, and since then it has remained variable at about 30 % (overall median of about 30 %). Geophysics abstracts have remained consistent with a median of 8 % contribution. Glacial/environmental topics have a median of 2 % contribution. As the 1994 Chairman, I was directed by the Board of Directors to increase the proportion of glacial/environmental contributions. Solicitations, with the help of M. A. Gere, Jr., resulted in a dramatic increase of glacial/environmental abstracts to about 20 % for 1994 (by far the 40 year high).

What is the future of the ILSG? The role of geologists in North America today is much different than it was in 1955. The ILSG has changed over its 40 year history. It is important that the ILSG look to its future. The Board of Directors had a lengthy discussion on the future of ILSG at the annual board meeting in 1993, and will continue the discussion in 1994. Can or should the ILSG maintain its focus on Precambrian/resource geology? Should the ILSG expand into all areas of geology of the Lake Superior region? The critical question is, what changes must the ILSG undergo to insure 40 more years of success?

I thank Mary L. Larson for the hours of compilation from proceedings volumes in the Michigan Technological University Library Archives.

INVENTORY OF THE MICHIGAN GEOLOGICAL SURVEY DIVISION'S UPPER
PENINSULA SIGNIFICANT WATER WELL CUTTINGS LIBRARY AT ESCANABA

Frank Chenier, District Geologist; Michigan Department of Natural
Resources; Geological Survey Division; Escanaba, Michigan

Drill cuttings from approximately 570 selected water wells
representing the geology of the Upper Peninsula are maintained by
the Geological Survey Division of the Michigan Department of
Natural Resources office at Escanaba. The collection includes
rocks of precambrian and paleozoic age and overburden samples.
Environmental and groundwater conditions as well as potential
mineral resources can be assessed by the investigation of some of
these cuttings. In addition, the office maintains a library of
available water well logs for the entire U.P. All of the above
are available for study and review. For more information contact
Frank Chenier at (906)786-2351.

METALLIC MINERAL RESOURCES AND ECOSYSTEM MANAGEMENT AT VOYAGEURS NATIONAL PARK, MINNESOTA

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Under a Memorandum of Understanding with the National Park Service, the Intermountain Field Operations Center of the U.S. Bureau of Mines recently completed a hardrock mineral study on the Voyageurs National Park area of north central Minnesota. The study was prompted by proposed changes in the State's Metallic Minerals Leasing Rules aimed at encouraging mineral exploration and development. The announcement prompted a great deal of uncertainty by the Park's management staff as to what a likely mineral development might encompass, and what ramifications it might have on Park resources and operations.

The USBM study includes a comprehensive analysis of the region's historical mining activities and apparent mineral potential, as well as descriptive models of known mines in similar geologic terranes. The final documents, a Mineral Land Assessment and Executive Summary, include socioeconomic impact analyses of a typical mine development, and an applicable environmental management plan incorporating an ecosystem-sensitive approach. Included in the data package is a series of resource management maps in both hard copy and GIS (digital) form, allowing for site specific project and proposal analysis and management.

This project is an opportunity to impart a better understanding of what potential metallic mineral resources exist in the area, and the likely development scenario that might occur if these resources are identified and developed. The report also details the environmental concerns related to mineral developments and current state-of-the-art mitigation technologies. The project should therefore impart a better understanding of mineral development on the part of the Park Service personnel, and alleviate some of the concerns relative to disruptions of regional ecosystem integrity and balance. Objective and comprehensive studies such as these, tailored to the specific issues and management needs of the National Parks involved, should prove valuable to the Park Service, and at the same time achieve primary Bureau of Mines goals of continuing resource evaluation and increased mineral awareness.

Wetland Treatment of Mine Drainage -
an Alternative to Conventional Treatment or Voodoo Treatment?

Paul Eger

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Although wetlands have been used to treat mine drainage the application of this technology has not always been successful. The type and size of wetland that is needed is a function of the input drainage quality, the effluent requirements and the length of time treatment is required.

Results from both pilot and full scale tests have demonstrated that from 50 - 90% of the influent copper, nickel, cobalt and zinc can be removed from neutral mine drainage in free water surface wetlands. Acid mine drainage has been treated in a pilot system representing a subsurface wetland. The pH of the drainage has generally been increased from influent values between 4 and 5 to effluent values between 6.5 and 7. Over 90% of the influent copper, nickel, cobalt and zinc have been removed.

Although wetland treatment systems will require much less maintenance than conventional technology, plans for maintenance and replacement must be included for successful long term treatment.

MINNESOTA DRILL CORE EXAMINATION AND ASSAY

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Current work includes the new logging of 100 drill core samples and assaying of 212 new samples of existing DNR Drill Core Library samples for most of which no modern descriptive logs and little chemical data are available. Samples are from Central Minnesota, where rocks associated with the Penokean Orogen dominate and there are few outcrops. Drill cores were laid out and logged in a qualitative manner and then sampled in order to determine alteration, mineralization, and protoliths. The descriptive logs were entered into a digital database for future GIS application. The fields and current codes are listed elsewhere on the poster. An example of the database printouts from the most recent logging is also shown.

Logging for this project has verified or expanded the knowledge of this Proterozoic terrane. Three interesting features observed in this geologic setting are the presence of tourmaline, granitic intrusive relationships, and the presence of ultramafic rocks. Grain mounts taken while core logging have identified vein or stratiform tourmaline from several additional core samples. Amounts of tourmaline are generally small. Where stratiform, the tourmaline is generally found with oxide, chert, silicate, or sulfide chemical sediment. Granitic intrusives and veinlets have been found in several places. They have intruded phyllitic schists, metagabbro, and magnetite chert iron formation. Some (within phyllitic schist) may be sweated out from surrounding rocks while others are good intrusives. The intrusives and veins may help to explain the recrystallized nature common with the quartz rich portions of these iron formations. In places, this granite is relatively fresh with assimilated magnetite, or it may be extremely altered with carbonate, epidote, and chlorite to create epidotites. Even when fresh, it appears to be tectonized, with carbonate having a spatial association. Four drill cores with ultramafic rocks were logged. Chemistry subdivides these based on relative abundances of V versus Cr, Ni, and MgO contents, and logging by differences in mineralogy and degree of alteration. The more magnesian rocks are more pervasively and destructively altered compared to the vanadium rich rocks.

The rocks of the area also underwent a period(s) of pre-Pleistocene weathering before being glacially scoured. These effects have been superimposed on the original rock types. Weathering effects include limonitic, red hematitic, and goethitic alteration, although some goethitic alteration may be hydrothermal in nature.

There are numerous observed ore-mineral occurrences and alteration. Carbonate is regionally abundant within altered volcanics, as an iron formation component, as marble, and as minerals associated with most veins. Some veins have associated skarn and mineralogy. In association to this, preliminary examination of thin sections indicated the unexpected local occurrence of bright blue-violet pleochroic sodic amphiboles associated with carbonate, epidote, zoisite alteration.

Stratiform sulfides occur in numerous DDH's, as does graphitic argillite-phyllite which is often associated with the stratiform sulfides. These sulfides are typically pyrrhotite or pyrite, but lesser chalcopyrite or sphalerite is sometimes found. Seven DDH's also had trace amounts of bornite.

Possible visible sphalerite from the latest logging occurred in K-1, BM-2, MLCH-7, MLCH-5, MLCH-11, BM-1, CW-1, MLCH-9, T-665, MLCH-2, and C4 (see analytical results). Drill core K-1 had the most visible sphalerite, with the chemical data verifying the sphalerite. Reddish-orange siderite is also present and looks similar to sphalerite.

Analytical results for 212 new samples have been received from our contractor, Bondar-Clegg & Company Ltd. of Ottawa, Ontario. Forty nine samples were analyzed using a 52 element package with 163 samples analyzed using a 21 element package including Au, Pt, and Pd. Some of these analyses were from drill core logged during the previous biennium.

From the standpoint of economic geology, there are many significant assay results. The highest

Zn values to date have come from the recent analyses. A 5 foot sample from DDH K-1 had a Zn assay > 20000 ppm. A sample from DDH H12 had a Zn value of 683 ppm. Beside Zn, these samples had anomalous Ag, Pb, Cu, Au, Pt, Pd, Cd, Mo, F, Sb, Hg; and separately, other elements. The new analyses had several Cu values over 600 ppm from DDH's H6, K-1, and B1-117. Drill cores from several different areas had anomalous As (to 234 ppm), Cd (to 134 ppm), F (to 14,075 ppm), and Hg (to 428 ppb).

The highest Pb values (to 762 ppm) came from the unusual association of MgO rich (to 24.54%) altered ultramafics in DDH TC-101 and TC-102. These samples were also high in Cr, Ni, and Hg.

The data indicates that hydrothermal processes were active in many places within Central Minnesota, and that there may be a high probability for undiscovered economic mineralization.

GENESIS OF HEMATITE AND MAGNETITE IN PRECAMBRIAN MAGNETITE IRON-FORMATION OF LOW METAMORPHIC GRADE, LAKE SUPERIOR DISTRICT, USA - A MICROSCOPIC OBSERVATION

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The low metamorphic grade Precambrian magnetite iron-formations of the Lake Superior District examined in this study were the Biwabik of the Mesabi Range, the Ironwood of the Gogebic Range, and the Negaunee of the Marquette Range. The Biwabik and Ironwood iron-formations consist of both an evenly banded type and an irregularly wavy banded type. The Negaunee iron-formation is exclusively the evenly banded type which consists of two dominant subtypes, i. e. carbonate-chert and silicate-carbonate-chert. The magnetite in the wavy banded iron-formation coexists with hematite, iron carbonates, layered iron-silicates and chert. The evenly banded iron-formation has essentially the same mineral assemblage but is generally free of hematite.

The study was done by microscopic examination of a substantial number of polished sections prepared from specimens collected from these iron-formations, before and after an induced oxidation procedure is employed. The results indicated that: (a) The origin of both the hematite and the magnetite in these iron-formations is far more complicated than previously believed. (b) Some of the hematite is probably a product of primary sedimentation, or developed shortly after deposition; and some of it may be a result of authigenic growth generated from the migration and precipitation of Fe^{++} from acidic pore fluids during diagenesis. (c) The various hematites functioned as "starting points" responsible for the development of most of the magnetite present in the iron-formations. (d) The magnetite development apparently proceeds concurrently by replacing the hematite on one hand and overgrowing into the host of the hematite on the other. (e) More than one stage of overgrowth is evident on some magnetite. (f) A progressive morphological change of magnetite in some of the carbonate-chert subtype, i.e. it changes from clusters of lath-shaped pseudomorphs to aggregates of anhedral grains and finally to coalesced octahedra. (g) The newly formed magnetite is believed to be a product resulting from the solid diffusion of Fe^{++} toward the hematites. The Fe^{++} is generated from the reaction between hematite and carbonaceous matter in the iron-formation during low grade metamorphism.

As a result, both the primary and diagenetic hematites became a minor ore mineral while magnetite became a major ore mineral in the Precambrian iron-formation of the Lake Superior District. Much of the magnetite in the iron-formation currently processed for blast furnace feed on the Mesabi and Marquette ranges was enriched through such a process. Much of the hematite previously and currently mined on the Mesabi, Gogebic and Marquette ranges is of postmetamorphic origin and represents an oxidation product of the magnetite, iron carbonates and layered iron-silicates.

These interpretations are based on: (a) the morphological character and the mineral association of the magnetite; and (b) the morphologies, microstructures, impurities and microtextural relationships of preexisting hematite inclusions in the existing magnetite. Many of these features are revealed after induced oxidation.

GEOTECHNICAL SOLUTIONS FOR MINING RELATED PROBLEMS

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ABSTRACT

Mining practices of the 19th and early 20th centuries have sometimes resulted in problems of current concern. These problems include unsightly or unsafe conditions at the mines and, in some instances, environmental damage to varying degrees.

Examples of problems of these types can be found in all of the older iron ore and copper mining districts in Michigan. More than 20 years of studies of problems on the West Menominee Iron Range in Iron County have identified problems of the following types:

- 1) inadequately capped and sealed mine shafts and raises;
- 2) the threat of surface subsidence above shallow mine stopes;
- 3) presently unacceptable disposal of mining waste rock; and
- 4) mineralized and acid mine drainage.

These studies with solutions to problems of these types have been reported in the literature and in published reports. One of these studies addressed a serious acid drainage problem at the Dober Mine complex in the Iron River Valley.

Here acid waters (pH 2) with high levels of dissolved metals (iron and aluminum) flowed into the Iron River. Neutralization of the acid by the river waters caused insoluble Fe and Al hydroxides (yellow boy) to precipitate, turning the waters yellow brown. This highly visible pollution affected the Iron River some seven miles to its confluence with the Brule River, which marks its border with Wisconsin to the south. Residents of both states were affected.

To address this problem, a study was done to quantify the extent and nature of the acid drainage. It was determined that a huge reservoir of acid water was present in the underground mine complex. It was also learned that acid waters flowed from the Dober Mine in response to groundwater inflow into the elevated western part of the mine complex. Calculations showed that the acid waters, which flowed at an average rate of 50 gpm, would continue to impact the river system for at least 50 years, at which time the mine would have been sufficiently flushed of the acid.

Bench and pilot scale tests of methods to neutralize the acid led to a conceptual design whereby controlled amounts of river water would be diverted into the mine to mix with and neutralize the acid. This treated drainage from the mine was to be diverted through a series

of downstream ponds adjacent to the river in which settling would remove the metal precipitates. From there a clear effluent would be returned to the river. The test results were promising and an engineering and economic assessment indicated the concept to be feasible.

The plan was accepted and supported by the local communities and the Michigan Department of Natural Resources. Ultimately it was funded through Act 307 (Michigan's "Superfund"), as the first cleanup under the Act. The system was built and became operational in 1988. It is working as designed, with significant improvement to the Iron and Brule River system.

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PALEOMAGNETISM OF A 1500 MA MAFIC DIKE AT WATERLOO
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A recently opened quarry of Waterloo Quartzite exposes a 1.5 meter thick mafic dike that cuts almost vertically through the quartzite. The dike is assumed to be the same age as a mafic dike found in drill core from the nearby Portland Quarry, and dated at 1450-1500 Ma by Ar/Ar dating. The dike was studied for paleomagnetic analysis to aid in determining a more reliable paleopole position for the 1500 Ma time frame for central North America.

Twelve 2.54 cm diameter cores were drilled from the site and subjected to alternating field demagnetization to 100mT., and saturation isothermal remanent magnetism studies. Magnetite appears to be the dominant magnetic mineral. The characteristic direction of Dec=308 deg., Inc=-18.82 deg. yields a paleomagnetic pole of 146 deg.E, 18.66 deg.N and an alpha 95 of 11 deg. The dike seems to cut across the folds in the quartzite so no structural corrections have been made.

Studies of the Wolf River Batholith (Hershberg, 1976), and the Wausau Syenite Complex (Zich, Chan, and Myers 1986) which are both dated at about 1500 Ma indicate possible remagnetization at about 1100 Ma but show a component similar to the results presented here. Also the magnetic directions from the dike are significantly different from those in the surrounding quartzite (Mercer 1984).

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EARLY PROTEROZOIC VOLCANICS OF THE ANIMIKE GROUP, ONTARIO AND MICHIGAN, AND THEIR TECTONIC SIGNIFICANCE

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Although volcanic ash components are found in the Early Proterozoic Animike Group throughout the Lake Superior region, volcanic units are rare. The Gunflint Volcanics of Ontario and the Emporer Volcanics of Michigan have been little studied in comparison to associated iron formations, the Gunflint Formation and the Ironwood Iron Formation, respectively. We report here the initial results of petrographic and geochemical work on these units, together with data on the lapilli tuffs of the Gunflint Formation.

The Gunflint-Lavas occur conformably within the Gunflint sedimentary rocks near Mink Mountain, Jean Township, Ontario. The very limited outcrop consists of thin bedded, massive, aphanetic basalt. Pillowed structures enveloped in chert were described by Goodwin (1960). The basalts are very fine-grained, with few microscopically distinguished features apart from plagioclase. Some units contain spherulites of microcrystalline quartz and K-feldspar that may be absorbed and recrystallized felsic lapilli.

The Emporer Volcanics are exposed in the Wakefield and Marenisco Quadrangles, Gogebic County, Michigan. They have been described most recently by LaBerge (1992), who documented a suite of mafic sills, massive and pillowed flows, hyaloclastites, and pillow breccias associated with felsic hyaloclastites, tuffs, and breccias. The volcanics have been known to be interbedded with iron formation since the work of Irving and Van Hise (1892).

Whole rock geochemistry reveals that in spite of a range in major element chemistry, the Gunflint Volcanics and mafic Emporer Volcanics have indistinguishable chondrite-normalized REE plots. The felsic Emporer Volcanics are somewhat depleted in REEs, but the plot indicates their probable close genetic relationship to the mafic units (Fig. 1).

The classification of the basalts according to the trace element content of Pearce and Cann (1973) was applied to samples fulfilling the criterion of $12 < \text{CaO} + \text{MgO} < 20$ wt %, as well as to the Gunflint Volcanics, which are obviously basaltic but with low CaO + MgO. These samples plot in the fields of alkaline ocean-floor basalts. These affinities suggest that Gunflint Volcanics and Mafic Emporer Volcanics may have formed in a back-arc spreading environment when the Penokean island arcs, sutured to the craton at 1860 ma (Sims *et al.*, 1989), were still at some distance to the south.

The Gunflint lapilli tuff beds are thickest and most numerous in the Kaministiquia River gorge near the apparent depositional edge of the unit. At this locality the lapilli tuff beds are interbedded with carbonaceous shales. The lapilli are mostly calcite-cemented and show evidence of sedimentary reworking (Shegelski, 1982). Although a graded air-fall bed is present, the remaining beds may have been accumulated by sedimentation shed from the adjacent Archean Shield. The lapilli contain sanidine and quartz xenocrysts up to 2-3 mm in diameter, likely derived from explosive rhyolitic volcanism. The Gunflint Volcanics clearly are not viable sources for these constituents, and the Emporer Volcanics are unlikely. The most likely source is a distal island arc, now highly metamorphosed in Penokean orogenic terrane.

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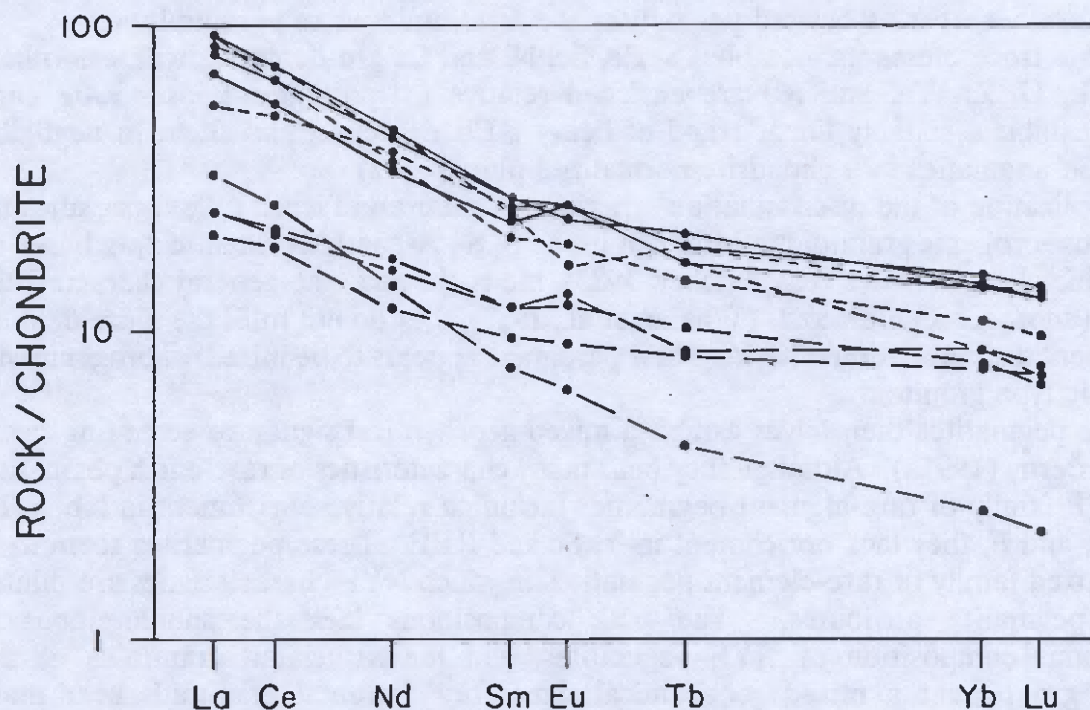


Fig. 1. Chondrite-normalized rare earth element plot for Animike Group volcanics. Solid lines - Gunflint Volcanics; short dashed lines - mafic Emporor Volcanics; long dashed lines - felsic Emporor Volcanics.

GRANITOID ROCKS OF THE ELLIOT LAKE AREA, ONTARIO AND THEIR RELATIONSHIP TO U-Th-REE BEARING PEGMATITES

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Archean granitoid rocks intrusive into metavolcanic terrane form the footwall of the Huronian Supergroup in the Quirke Syncline of the Elliot Lake area, Ontario. These granitoids have never been studied in detail, attracting little interest in relation to U-Th-REE deposits of the Elliot Lake area because of their low levels of radioactivity (Robertson, 1981; Charbonneau, 1982). Recent discovery of U-Th-REE bearing pegmatites (Kissin and Fralick, 1991) in the north footwall of Quirke Syncline indicate that the granitoids merit investigation as parental bodies to the pegmatites.

The granitoid body at the Huronian footwall has been informally named the Kindiogami River Batholith (Breaks, 1991). It consists of pink to brick red, equigranular biotite granite. The granite is uniformly coarse-grained, with books and clots of biotite as the main mafic mineral ($CI < 10$), with lesser muscovite and accessory hornblende, sphene, and zircon.

Analyses of seven granite samples and one associated aplite yield high SiO_2 (70-77 wt %), high Al_2O_3 (12-14 wt %) and low MgO , CaO , and TiO_2 (most < 1 wt %). Total iron as Fe_2O_3 is variable (1-4 wt %), but H_2O (generally < 1 wt %) is low. The K_2O is usually greater than Na_2O . In a Shand diagram (Fig. 1), the granites are subaluminous to slightly peraluminous, whereas associated pegmatites are metaluminous to peraluminous.

Some trace elements, notably Cs, Be, Sc, Ni and Cr are depleted, whereas others, notably Th, U, Zr, Ta, and Nb are enriched relative to most granitoids. Rare earth elements exhibit a roughly linear trend of heavy REE depletion and slight to negligible negative Eu anomalies in a chondrite-normalized plot (Fig. 2).

Application of the discrimination criteria of Maniar and Piccoli (1989) classifies the rocks as post-orogenic granitoids. Although in the I-, S-, A-, and M- classification based on petrographic characteristics (e.g., Pitcher, 1983), the rocks have the general characteristics of A-type (anorogenic) granitoids (Whelan et al., 1987), they do not fulfil the more detailed trace element discrimination criteria. Their parentage appears to be mixed, anorogenic with an orogenic type granitoid.

The pegmatites themselves exhibit a mixed geochemical signature according to the criteria of Černý (1991a). Although they bear many characteristics of rare-earth pegmatites of the NYF family of rare-element pegmatites including relative enrichment in $Nb > Ta$, Zr, U, Th, and F, they lack enrichment in Y, Sc and REE. These pegmatites seem to fit into the mixed family of rare-element pegmatites in which NYF characteristics are diluted by LCT pegmatite attributes. The bulk compositions lack the subaluminous to metaluminous composition of NYF pegmatites, and the associated granitoids of this pegmatite group bear a mixed geochemical signature. Parental granitoids bear many characteristics of anorogenic granites, as in the case of Kindiogami River Batholith, they appear transitional to other types. Černý (1991b) has suggested that such mixed pegmatites may arise from: 1) anatectic granites derived from partially depleted crust; 2) anatexis of

both depleted and undepleted crust, or 3) an NYF magma becoming contaminated by assimilation of undepleted material.

Whatever the ultimate source of the granites of the Kindiogami Batholith, they and their associated pegmatites are distinctive and provide a plausible proximal source for detrital U, Th, and REE deposits in the Huronian Supergroup. The pegmatite field associated with roof and proximal regions may have been largely removed by the effects of erosion. Similar pegmatitic deposits in the Arabian Shield have been found to be both large and of high grade (Jackson *et al.*, 1985).

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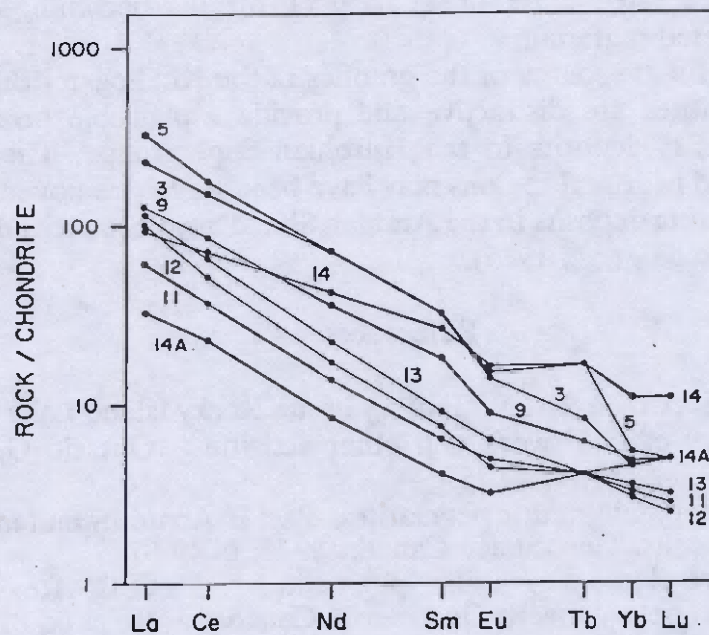


Fig. 1. Chondrite-normalized rare earth element plot for granites of the Kindiogami River Batholith of the Elliot Lake area.

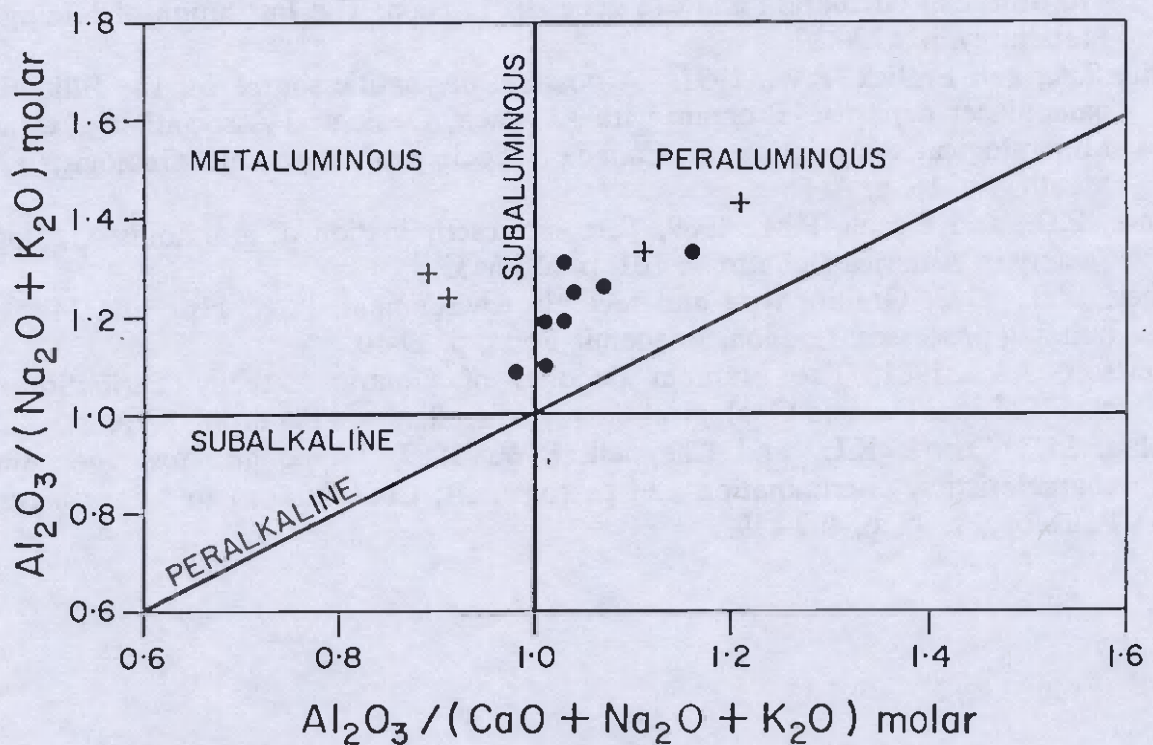


Fig. 2. Shand diagram for granites (circles) and pegmatites (crosses) of the Elliot Lake area.

STRUCTURAL EVOLUTION OF THE EASTERN GOGEBIC RANGE NORTHERN MICHIGAN

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The eastern Gogebic range is an area of outcropping, iron-bearing rocks that extends some 100 km from northern Wisconsin to northern Michigan. Lithostratigraphic relationships (LaBerge and Klasner, this volume) indicate that Early Proterozoic (EP) volcanic and sedimentary rocks of the Menominee Group were deposited in a developing, fault-bounded trough in this region, much like the Marquette trough some 180 km to the east. Following this extensional event, EP strata of the Copps formation were deposited in a compressional foreland basin. All EP strata were then subjected to at least two penetrative, thin-skinned, compressional events, and subsequently to a series of thick-skinned fault events that affected both Archean and EP strata. Much later, these deformed strata were tilted northward during the formation of the Middle Proterozoic (MP) Midcontinent Rift (Cannon and others, 1993).

COMPRESSIONAL EVENTS

D₁ - During this initial event most EP strata were detached from underlying Archean basement, creating northeast-trending folds and north-verging, bedding-parallel shears in the supracrustal sequence.

D₂ - Both the bedding-parallel shears and **D₁** folds in the EP strata were further deformed into a series of gently northeast-plunging folds that also appear to be detached from Archean basement inasmuch as **D₁** and **D₂** structures have not been found in the basement rocks.

D₃ - Folds of a third event, overprinting **D₁** and **D₂**, were observed in a few places. These folds may be related to later faulting associated with the Presque Isle set (see below).

The Copps formation was deposited in angular unconformity on underlying EP strata, (see LaBerge and Klasner, this volume). Basal conglomerates in the Copps contain clasts that indicate Menominee and Chocoma Groups were the source. This source evidence implies that, prior to deposition of the Copps, there must have been some uplift of pre-Copps strata, possibly as a forearc bulge. Because the Copps strata and the underlying EP strata all possess the same structural pattern (northeast-trending folds and axial planar foliation), we suggest that the structural evolution of the whole EP stratigraphic sequence is the result of a continuum of coaxial, thin-skinned, north-verging deformation that occurred after deposition of Copps strata.

FAULT EVENTS

Other manifestations of deformation in the eastern Gogebic iron range are found in three fault sets -- the Little Presque Isle set, the Presque Isle set, and the Sunday Lake set.

Little Presque Isle fault set -- Faults of this north-northeast-trending set, especially the Little Presque Isle fault, formed early as extensional growth faults, but they were later reactivated in Middle Proterozoic (MP) time. This continued movement resulted in truncation and juxtaposition of EP strata in the northeast-trending Wolf Mountain anticline against Archean rocks. The juxtaposition occurs in an en echelon pattern along the southwest extension of the Little Presque Isle fault. This interpretation is supported by magnetic data. Faults of the Little Presque Isle set cut the unconformable contact between MP Keweenaw and underlying EP and Archean strata, also indicating late MP movement on them.

Presque Isle fault set - The south-side-up, east-northeast-trending Presque Isle fault marks the southern edge of the Menominee Group depositional trough. We suggest that, like the Little Presque Isle fault, the Presque Isle fault was a growth fault. Other parallel faults of the Presque Isle set cross cut and offset the Little Presque Isle fault near the core of the Wolf Mountain anticline, giving the Little Presque Isle fault its en echelon pattern in this region.

Sunday Lake fault set - The south-side-up, left-lateral Sunday Lake fault truncates the Presque Isle fault. Several parallel faults of this set occur to the north, one at the Copps Mine exploration prospect where conspicuous shearing and associated mineralization is found.

Formation of the Midcontinent Rift resulted in northward tilting (up to 70 degrees) of the Archean, EP and MP strata along an easterly trending axis. The northeast-trending depositional trough was also rotated so that the map pattern is a view looking down the original keel of the trough -- the Little Presque Isle fault forming the northern edge of the trough and the Presque Isle fault forming the southern edge. During MP rotation, faults of the Little Presque Isle set were reactivated, offsetting the EP-MP unconformity.

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NEW ARCHEAN-HOSTED PSEUDOTACHYLITE OCCURRENCES, WESTERN LAKE SUPERIOR REGION

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Pseudotachylite occurrences were recently discovered in the western Lake Superior region hosted in a variety of Archean rocks: 1) Granite Falls, MN (Minnesota River Valley terrane), 2) Deer Lake complex, MN (Wawa terrane), 3) Rosspport, ONT (Wawa terrane). All of these pseudotachylites are adjacent and parallel to mafic dike swarms, in contrast to the pseudotachylite dated and described by Peterman and Day (1989) along the Rainy Lake fault in the Wabigoon terrane in western Ontario.

Granite Falls, MN

Pseudotachylite has been discovered crosscutting folded Archean amphibolite-grade host rocks of the Minnesota River Valley terrane (Himmelberg, 1968; Bauer, 1980) near Granite Falls, MN. The pseudotachylite is parallel to the regional foliation (N70°E, 75° N), is < 2 cm in width, can be traced in outcrop for ~50 m, and contains "amygdules" of calcite (diameter: .5 cm; Fig. 1), calcite-quartz mixes, and plagioclase inclusions in calcite. Mafic dikes, which cross-cut the Kenora-Kabetogama swarm (~2.2 Ga), are also parallel to the pseudotachylite and are a number of calcite veins. The outcrop is located 70 km to the south of the boundary between the Wawa (north) and Minnesota River Valley (south) terranes. The pseudotachylite is compositionally layered along its margins and preserves some relict flow foliation swirls defined by inclusions (Fig. 2) and "amygdules" of calcite. Dextral winged porphyroclasts are present and preserve the opposite kinematic displacement sense of S-C structures in the country rock. The amygdule calcite is mechanically twinned and preserves a horizontal shortening axis (magnitude: -0.74%) that is parallel to the strike of the pseudotachylite. Two phases of calcite veins are present, one set preserves twinning strains (shortening magnitude: -2.5%) identical to those in the pseudotachylite calcite amygdules. The second vein set contains a horizontal, vein-perpendicular shortening strain (magnitude: -2.4%). Inferred differential stresses for the different twinning strains are 66 MPa (pseudotachylite) and 200 MPa (calcite veins).

Deer Lake Complex, MN

This Archean ultramafic complex is composed of interlayered gabbro, peridotite and pyroxenites (Jirsa, 1990) in Itasca county. The Kenora-Kabetogama mafic dikes (strike: N45°W) crosscut the complex and, parallel to the dikes, are a number of thin (1-5 mm), regularly-spaced cataclastic zones which are locally mylonitic and contain some pseudotachylite material.

Rosspport, ONT

Archean granites and granodiorites along Lake Superior are crosscut by 2 thin pseudotachylites (5 mm wide) which were locally injected in the country rock. Mafic dikes of unknown age are adjacent and parallel to the pseudotachylite veins (strike: N-S).

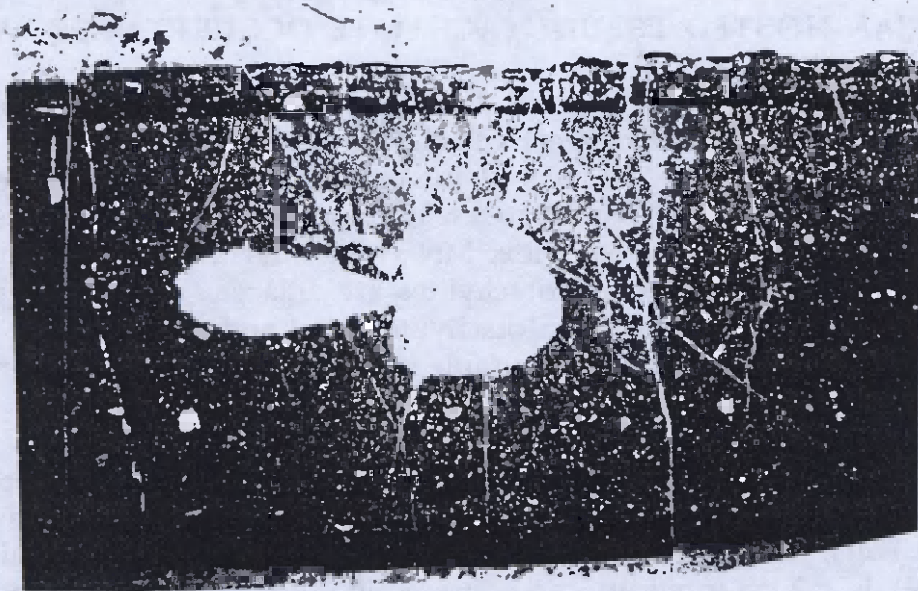


Figure 1: Foliated Granite Falls pseudotachylite (width=2cm) with calcite amygdules.

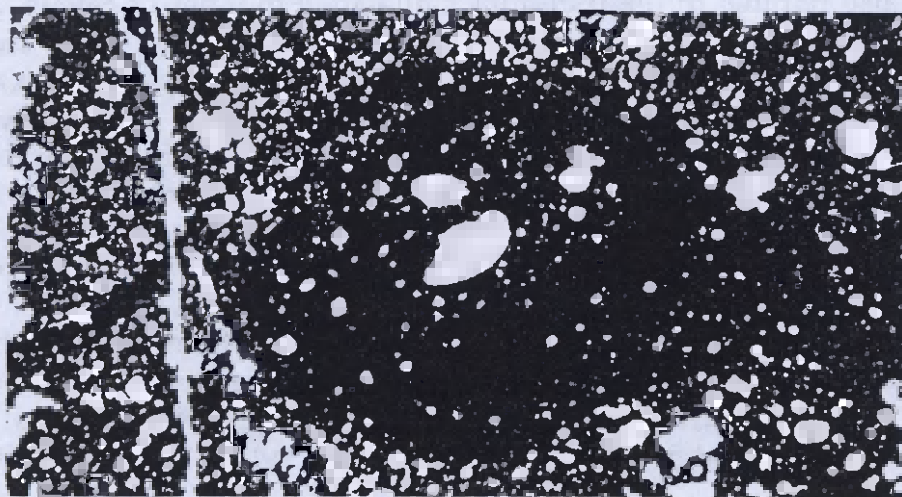


Figure 2: Close-up of swirled porphyroblast from Fig. 1. View is 3.5X2.2 mm.

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TECTONIC IMPLICATIONS OF EARLY PROTEROZOIC LITHOSTRATIGRAPHY ON THE EASTERN GOGEBIC RANGE, NORTHERN MICHIGAN

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Our recent mapping on the eastern Gogebic range reveals abrupt changes in stratigraphy and structure that occur mainly at the newly discovered Little Presque Isle fault east of Wakefield, Michigan. These changes have an important bearing on interpretations on depositional history and tectonic evolution of this part of the Penokean orogen.

In the western part of the map area (Figure 1), the Palms Formation and underlying Chocolay Group form a north-dipping stratigraphic sequence. These strata are not exposed immediately east of the Little Presque Isle fault, although the Palms Formation reappears 10 km to the east. Similarity in lithology of the Palms in the two areas suggests that it was deposited as a continuous stratigraphic unit. Its absence in the 10 km interval is probably a consequence of faulting (Klasner and LaBerge, this volume).

The Ironwood Iron-formation, which overlies the Palms Formation, shows abrupt changes within the map area. For nearly 100 km to the west, it consists of alternating units of granular and laminated iron-formation with relatively uniform thickness. However, east of the Little Presque Isle fault the Ironwood appears to be much thicker, and is composed mainly of laminated iron-formation.

There is also an abrupt change in the Emperor Volcanic Complex, which is interbedded with the iron formation, across the Little Presque Isle fault. To the west, the Emperor is mainly basalt flows and diabase sills. To the east, the volcanic rocks are mainly mafic pillow breccias and felsic hyaloclastites of rift-related tholeiites. The combined thickness of iron-formation and volcanic rocks changes abruptly across the Little Presque Isle fault. West of the fault, the thickness is about 250-300 meters. East of the fault, the thickness is much greater but cannot be accurately measured because of structural complexities.

We interpret these relationships to indicate that the Little Presque Isle fault was active during deposition of the iron-formation. The area east of the Little Presque Isle fault appears to be a remnant of a graben-like structure bounded by the Little Presque Isle and Presque Isle faults. The change from granular to laminated facies of iron-formation suggests a change from shallow-water deposition in the west to deeper water deposition in a developing trough to the east. The increase in volcanic rocks within the postulated graben suggests that bounding faults may have served as channelways for the magmas. These relationships are interpreted to indicate that rifting occurred during iron-formation deposition.

Older geological literature refers to a number of "ranges" south of the Gogebic district that contain Early Proterozoic iron-formation. These include the Marenisco, Turtle, Manitowish, Vieux Desert, and Conover "ranges" of Allen and Barrett, (1915). They, and Dutton and Bradley (1970), and Prinz (1981) showed that these areas contain iron-formations and other sedimentary rocks interbedded with volcanic rocks. We suggest that these "ranges" may represent graben-like environments similar to that on the eastern Gogebic range. If so, these various "ranges" may represent a series of grabens formed on the rifted continental margin that were intensely deformed during later convergent tectonism.

In the eastern Gogebic range the Copps Formation of the Baraga Group overlies the iron-formation and other rocks with marked unconformity (Figure 1). A basal conglomerate with cobbles of iron-formation, volcanic rocks similar to the Emperor, and Archean granitoids, as well as complete removal of the Menominee and Chocoyay Group rocks demonstrate the unconformable relationships. We interpret the Copps to represent a sequence of turbidites deposited in a foreland basin on eroded remnants of rocks deposited earlier on a rifted passive margin.

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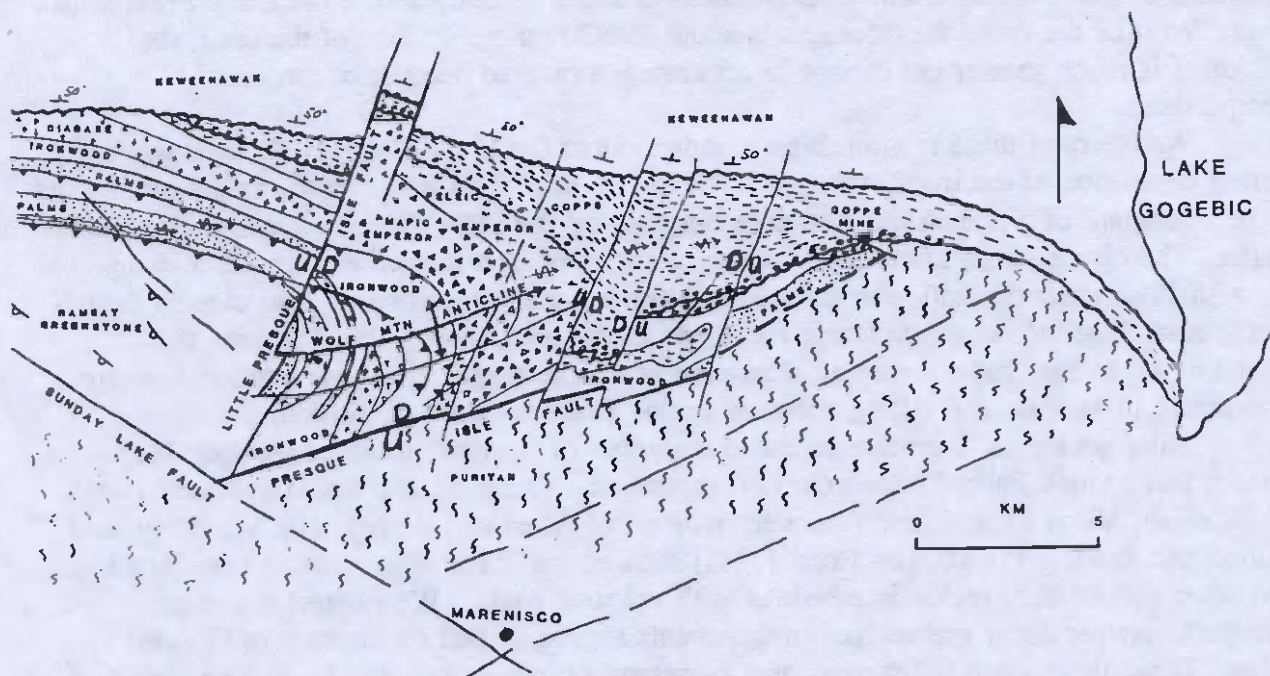


Figure 1. Sketch map of the geology of the eastern Gogebic range showing the major lithologic units and structural features. (Modified from Trent, 1973, and Prinz, 1981.)

RELEASE OF ACID AND TRACE METALS FROM QUARTZ-CARBONATE HOSTED GOLD MINE TAILINGS

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Exploration for gold (and other non-ferrous minerals) is presently occurring in Minnesota. Prior to mineral resource development, the potential mine wastes must be characterized and the quantity and quality of drainage projected. This information will be used to identify the types of mine waste management and drainage control required to protect the water resources of the state. Little information has been compiled on the characteristics of, or drainage quality from, such mining wastes. The lack of such information will inhibit the effectiveness and efficiency of drainage quality prediction and delay development of techniques to mitigate the problems identified. The objective of this project was to characterize and determine release of acid and trace metals from tailings which are representative of potential mining wastes from Minnesota.

Ten tailings samples were collected from operating North American gold mines. These samples provide the best presently available approximation of tailings which might be generated if present exploration led to development of a greenstone belt exploration site in Minnesota. The geologic settings, hydrothermal quartz-carbonate hosted deposits, from which the gold mine tailings were collected are similar to a majority of those presently under exploration in Minnesota. The gold tailings were characterized and subjected to dissolution testing for 151 weeks to examine the relationship between the solid-phase characteristics and release of acid and trace metals.

The samples were quite fine, with 47% to 97% of each sample occurring in the minus 270 mesh fraction and 26% to 91% in the minus 500 mesh fraction. The total sulfur contents, an indicator of acid production potential, ranged from 0.1% to 7.63%. The carbon dioxide content, an indicator of neutralization potential, ranged from 0.61% to 21.85%.

Most of the sulfur was associated with pyrite and pyrrhotite, with iron sulfide minerals constituting 0.58% to 13.6% by weight of each sample. Total calcium carbonate plus magnesium carbonate mineral content varied from 1.4% to 21%. Siderite was present in appreciable amounts (14% and 31% by weight) in two samples and in minor amounts (0.1% to 1.9%) in seven samples. Three samples contained ankerite (Lapakko, 1992). The major rock forming minerals were quartz (16%-44%), feldspar (1%-37%), mica (4%-24%), and chlorite (2%-21%).

A wet-dry cycle dissolution test was conducted on the tailings (Lapakko, 1994). The 75-g samples (as received) were placed into reactors in a controlled temperature and humidity room, and rinsed weekly with 200 mL of distilled water. The pH of drainage from one sample (T9) was neutral for 120 weeks, dropped below 6.0 after 122 weeks of dissolution, and reached 3.45 after 151 weeks.

Nine samples produced alkaline drainage (generally at or above pH 8) throughout the experiment. Based on the composition of three of these samples and their rates of iron sulfide and calcium plus magnesium carbonate mineral dissolution (as indicated by the rates of sulfate, calcium, and magnesium release in drainage), their drainage could become acidic after six to fourteen years. Based on similar data analysis it was concluded that the six remaining samples, terminated after 57 weeks of dissolution, would continue to produce alkaline to neutral drainage. For the estimates on these nine samples, assumptions were required which lend uncertainty to the predictions. More accurate estimation requires additional information on the formation of coatings on the surfaces of sulfide and carbonate minerals present in the mine waste.

A relationship between sulfate release rates and solid-phase sulfur content of the samples was determined by regression analysis. Samples which were inconsistent with the relationship defined, as well as some "typical" samples, were analyzed for specific surface area (BET) and surface morphology (SEM). The anomalous sulfate release rates were apparently due to differences in pyrite specific surface area

resulting from variations in pyrite particle size and morphology. There was no apparent evidence suggesting that something other than the pyrite surface area was controlling the rates of pyrite oxidation.

Elevated arsenic concentrations (maximum concentrations of 140 to 4900 $\mu\text{g/L}$) were observed in drainage from solids T7, T8, and T9, which had solid-phase arsenic contents greater than 1000 ppm. A fourth sample (T6) had a solid-phase arsenic content of 1200 ppm, but no arsenic was detected in the laboratory drainage. Elevated antimony concentrations (250 to 2800 $\mu\text{g/L}$) were observed in drainage from T7, T8, and T9, with solid-phase antimony contents of 20 ppm, 40 ppm, and 290 ppm, respectively. A maximum molybdenum concentration in excess of 700 $\mu\text{g/L}$ was observed in drainage from T9, which had a solid-phase molybdenum content of 1100 ppm. Concentrations of barium, copper, nickel, and zinc were also occasionally detected in drainage from some samples. The concentrations of As, Cd, Cu, Mo, Ni, Pb, Sb, and Zn in the laboratory were in qualitative agreement with that in the field. In fourteen of twenty-five cases available, field concentrations were 1 to 5 times those in the laboratory. It was concluded that trace metal concentration in laboratory drainage was better suited as an indicator of potential elevation in the field, but not as a quantitative measure.

In summary, one of the tailings from quartz-carbonate hosted gold mines produced acid drainage, while three yielded the potential for acid drainage in six to fourteen years of dissolution. The remaining six samples tested were predicted to remain neutral. Trace metal release from the tailings was variable, with arsenic, antimony, and molybdenum having the highest concentrations in drainage. The trace metal release was in qualitative agreement with field concentration data.

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ARCHEAN RIFTS AND GOLD: EXAMPLES FROM THE CENTRAL SHEBANDOWAN
GREENSTONE BELT

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The discovery of 41 gold occurrences in the central Shebandowan Greenstone Belt in the last 10 years has led to the realization of a new gold belt. The gold mineralization is spatially (and in some cases demonstrably), temporally and genetically related to "Timiskaming" type assemblages. These assemblages occur as long (75 km) narrow linear belts. These belts contain conglomerate, greywacke, iron formation, shoshonitic pyroclastic and alkalic intrusive rocks. One area, particularly rich in iron formation and gold, was known as the Matawin Iron Range and from this, the term Matawin Gold Belt was dubbed. At the Stewart property, gold occurs within the intrusive breccia of a syenite stock. The mineralization is characterized by disseminated pyrite and hematite alteration. Gold in the Matawin Iron Range area consists of single ladder veins to more complex vein arrangements in granodiorite dykes. At Gold Creek South, the gold occurs as disseminated sulfides in felsic volcanics. The delineation of late Archean rifts serves as a "first step" exploration criteria.

MINERAL POTENTIAL EVALUATION, CENTRAL MINNESOTA, PHASE I BASIC DATA

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The Minnesota Department of Natural Resources, Minerals Division, has completed a program using contemporary methods to begin to evaluate the mineral potential of a large part of Central Minnesota. This project is oriented toward identifying nonferrous metallic mineralization, associated alteration or lithologic units and structures permissive of such mineralization. The purposes are: 1. To serve land use planning within the D.N.R.; 2. To encourage private exploration through better data access, and; 3. To serve government agency planning of future programs.

Creating an improved regional mineral potential evaluation was done by: 1. Defining mineral occurrences, or lithologic units and structures permissive of mineral deposits. 2. Defining basic bedrock lithologic locations from existing drill core. 3. Creating 1:62,500 scale inferred geologic maps, which display interpreted mineral potential, using available geophysical and geologic data supplemented by some field work. and; 4. Re-evaluating existing geochemical surveys using contemporaneous statistical analytical methods.

A contract was completed by Dr. Don L. Shettel Jr. and Dr. Patrick O'Hara to interpret three existing ground water and lake sediment geochemical data sets using state of the art statistical and geochemical modeling methods. From these models Drs. Shettel and O'Hara constructed anomaly maps for gold, base metals, iron and uranium.

Contracts were also completed by Dr. Allan Spector to make an inferred geologic map of the twenty township Shephard Area at a scale of 1:62,500 and a second twelve township map extending this area to the northeast. Dr. Spector's maps display structurally deformed, folded and faulted, greenstones with associated metasedimentary units and intrusives. An important aspect of this contract was construction of 1:62,500 scale maps displaying several high mineral potential areas as modeled from geophysical characteristics of known mines located in similar Precambrian terrains. These models are primarily based on Dr. Spector's experience with such features. Some of these areas of high mineral potential are coincident with anomalous geochemical results defined by Drs. Shettel and O'Hara.

Geophysical measurements of density and magnetic susceptibility were made on selected logged samples for computer modeling of geologic features. Detailed magnetic ground traverses were completed along roads using an A.T.V. or golf cart for transportation.

In summary significant results include: Improved definition of geologic features; Lithologic units and features permissive of economic ore deposits; Detailed inferred geologic maps with definition of areas having high mineral potential; Multi element geochemical anomalies with significant pathfinder element anomalies coincident with favorable inferred geologic features. To test the inferred geology, in cooperation with the M.G.S., six vertical holes were drilled through glacial overburden and into bedrock far enough to obtain hard bedrock samples. Hand lens examination of the core confirms inferred geologic bedrock maps in most of the drill holes and provides encouraging indications of mineral potential.

The Birch Lake Prospect - A Major PGM Prospect
in the Duluth Complex

by

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ABSTRACT

The Birch Lake Platinum Group Metals (PGM) Prospect is located within the Duluth Complex on the St. Louis/Lake County border just east of the Dunka Taconite Mine of LTV Steel and about 10 miles south of Ely, Minnesota. The surface of the area is marked by a humocky terrane developed on the surface of the Complex and covered with a thin ground moraine.

The area was originally explored for copper-nickel in the 1950's and 60's including drilling by Duval. These drill holes encountered copper-nickel mineralization but were not analyzed for PGMS. Resampling of the drill core in the early 1980's by state agencies revealed ore and near ore concentrations of PGMS in two holes. This work coincided with a program of PGM exploration being carried out by the Beaver Bay Joint Venture and its partners. Subsequent drilling in 1988 through 1991 was carried out by the venture.

The PGM prospect at Birch Lake occurs within the South Kawishiwi intrusive, a part of the Duluth Complex. Mineralization is confined to a unit near the base of the intrusive which consists of a copper-nickel sulphide rich olivine troctolite zone and is associated with iron oxide rich troctolites. These units dip at shallow angles to the east. The area drilled is on the south flank of a strong oval magnetic anomaly which is believed to be the same depth as the mineralized zone; the rocks above the mineralized zone typically have a low magnetic susceptibility. This magnetic anomaly may indicate increased sulphide and/or iron oxide content at its center, giving a strong suggestion of better potential for economic mineralization on this as yet untested target.

The mineralized zone is characterized by serpentization and saussuritization and the occurrence of a high chlorine content which causes a unique rusting of the rocks on exposure to air. The PGM values are associated with copper and nickel.

Ratios of Pt:Pd are in the range of 1:1 to 1:2, rather than ratios of 1:3 to 1:4 characteristic of the Minnamax, Inco and Dunka Road copper-nickel deposits which contain only accessory amounts of PGMs. The mineralogy of the PGMs at Birch Lake is poorly known though complex platinum-palladium-bismuth-telluride sulphosalts have been identified. The deposit is believed to have formed in a trough in the base of the complex, perhaps caused by faulting which permitted chlorine rich solutions to deposit and enrich PGMs in the zone of pre-existing copper-nickel sulphide mineralization.

Considering the substantial thickness of the mineralized zone and its possible major areal extent, the potential exists for a world class PGM deposit mineable by large scale highly mechanized methods. Initial investigations suggest the possibility of making a bulk sulphide concentrate for sale to existing smelters in Canada or Europe. Preliminary economic analysis suggests that at least one drill hole contains mineralization of economic grade at current prices under such a scenario. Further drilling of the deposit is planned to test its economic potential.

PETROGRAPHY AND STRUCTURE OF THE KEWEENAW CHENGWATANA VOLCANICS NEAR DRESSER, WISCONSIN

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The Dresser Trap Rock quarry provides a unique look at 6 flows of the Chengwatana volcanic group (Age: ~1.1 Ga) which range in thickness from 10 to 70+ meters. The flows are basaltic diabases whose primary mineralogy consists mainly of unzoned plagioclase (An 45-50) and augite with lesser amounts of illmenite and hornblende. No modal olivine or olivine alteration products exist in these samples, but previous chemical analysis indicates that the flows are olivine normative (Cavaleri et al., 1987). The flows strike NNE and dip 13-20°W. Flow bottoms tend to be aphyric and rapidly coarsen into subophitic or intergranular textures. The centers of the flows are understandably more coarse, with the coarseness in proportion to the thickness of the flow. Flow centers contained in the quarry exhibit two textures. The most common texture is an ophitic pyroxene-plag. intergrowth termed "luster-mottled" due to the spotted appearance of the rocks on exposed faces. A few flow centers exhibit a plagioclase-phyric texture often with 1-2 cm plagioclase laths in a medium-grained groundmass. Flow tops are fine grained and all have amygdules filled with alteration mineralization, primarily chlorite, epidote, quartz and calcite. Major and trace element analysis (INAA and XRF) is being conducted across the flow stratigraphy from Dresser west to the Taylor's Falls area to: 1) delineate differentiation trends across the successive Chengwatana flows and, 2) characterize the Chengwatana sequence in the overall stratigraphy of the Keweenawan rift.

The flows exposed in the quarry were erupted episodically, with the exception of the fifth/sixth flow boundary which exhibits a remarkable example of interflow sedimentation of the flowtop breccia type as described by Jirsa (1984). This surface represents the deposition of fluvial sediments over the rough brecciated, top of flow five and is composed of angular fragments of subjacent flows and fine grained, cross-bedded sand. The fluvial sediments are well exposed on the western wall of the quarry, where they reach a maximum thickness of 5-8 meters before tapering off on either side of the central paleochannels.

The lava flows in the quarry have undergone very low to low-grade metamorphism, as well as hydrous alteration. The flows contain significant amounts of epidote, chlorite, and actinolite; many of the flow tops having become epidosite. The plagioclase present in significantly altered samples has been converted to albite indicating metamorphism in the low grade albite-actinolite-chlorite facies. Hydrothermal alteration has caused the alteration of pyroxenes to uralite, a semi-fibrous variant of hornblende; and the dominant epidotization overprint exhibited in nearly every sample. Previous studies have indicated a depth of burial of at least 2 km and temperatures approaching 440°C (Cordua, 1989).

The outcrop structures in the volcanic flows are straightforward and include the following features: 3 systematic joint sets (N-S, 90°; E-W, 90°; N-S, 45°E), and a conjugate thrust fault pair (N-S, 45°E and N-S, 35°W) which are not crosscut by the

(older) joints. All the joint surfaces are commonly filled with calcite and/or quartz which has been plastically deformed. Both vertical joint sets commonly preserve sub-horizontal striations with dextral stepping directions (and minute offsets). The east-dipping thrust faults are quite numerous, whereas only one west-dipping thrust fault has been observed which is preserved as a .5 m width quartz zone. Within this gouge zone we have observed epidote-filled en echelon fractures, striated and stepped chlorite-quartz-epidote, S-C structures, and late-stage syntaxial calcite fillings. All of these kinematic indicators document hangingwall motion as up and to the east; this fault displacement also offsets the other thrust faults (N-S, 45°E) and is interpreted as being younger. The gouge zone is composed of quartz+chlorite+epidote+adularia+calcite+hematite (+opaques) and represents a green schist metamorphic assemblage (~400°C, ~4 kb) that is similar to the metamorphic grade in the host volcanic rocks.

Calcite and quartz are abundant as secondary minerals filling joint and fault surfaces, and contain mechanical twins or deformation lamellae, which allowed us to characterize the state of stress in these rocks after mineralization. Quartz containing deformation lamellae was observed only associated with the thrust fault gouge zone whereas twinning was observed in all phases of calcite. These deformation lamellae bracket the differential stress magnitudes as >10 MPa (calcite) and >50 MPa (quartz), respectively. Twinning in calcite allows for a detailed strain analysis with the caveat that the age of the calcite is not known. Our results include strain analyses of calcite fillings in joints and thrust faults; calcite amygdules were rare: *joint set I* (N-S, 90°; sub-horizontal shortening trend: N45°E), *joint set II* (E-W, 90°; shortening trend: N5°E), *thrust fault I* (N-S, 45°E; shortening trend and plunge: N90°E, 40°), *thrust fault II* (N-S, 45°E; shortening trend and plunge: N4°E, 70°E). These complex twinning strains are best interpreted as representing regional stress and strain field changes over a long time period (e.g., joint-filling deformation, then thrusting), rather than as variations in the stress field within the area of 1 square km. A regional interpretation of these thrust faults, in conjunction with the detailed flow stratigraphy, is in progress to characterize the extent of thrust faulting along the Keweenaw-Lake Owen-Hasting fault (Middleton, 1991; McGovern et al., 1993).

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Environmental geochemistry of Proterozoic black shales in eastern Finland: a pilot study

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The Precambrian geology of Finland is comparable in many aspects to that of the Lake Superior region. In particular, both areas contain black shales and the environmental geochemistry of these may be directly compared because of similarities in climate.

Thick (20-400 m) formations of S- and C-rich black schists occur in eastern Finland (black schist = metamorphosed black shale). Median concentrations of both graphitic carbon and sulfur are 6-9%. These black schists are spatially associated with the disrupted remnants of 1.96-1.97 Ga ophiolites, occurring over 250 km of strike length along a probable former rift zone in the Kainuu and Outokumpu areas. The thickest black schist formations occur at Talvivaara, where 300 Mt of black schist with Ni+Cu+Zn > 0.8% are present.

The Talvivaara deposit is syngenetic in origin and the main part of the contained metals were precipitated in organic-rich mud during deposition. The primary fine-grained spheroidal pyrite (<0.01 mm) contains 0.3-0.4% Ni which has, during recrystallization, been incorporated in pyrrhotite and pentlandite. The deposit has undergone amphibolite facies metamorphism and tectonic deformation. The deposit included Mn-rich horizons and up to 17% interlayered black calc-silicate rocks.

The Ni-Cu-Zn-rich black schist is easily weathered when in contact with surface waters. The background concentrations of the black schist area have been compared with those of different bedrock, namely the Late Archean granite gneiss areas adjacent to the Talvivaara area. The Hg concentrations of pike (a large northern predatory fish) seem to correlate with bedrock geochemical characteristics:

Lake	Hg in pike (ppm)	Distribution of black schists
Kolmisoppi	0.96	Abundant Hg-rich schists
Jormasjärvi	0.76	Black schist interlayers in mica schist
Älänne	0.33	No black schists
Average in 67 Finnish forest lakes	0.56 (Verta, 1990)	

Chemical concentrations of stream and lake waters, ground water and stream and lake sediments are compared. Spring water results of pilot sampling committed in August 1993 (*n* = number of samples):

	Black schist area	Granite gneiss area
Cu	> 4.08	0.71 - 1.08
Zn	> 97.3	4.17 - 6.39
Ni	> 69.90	0.65 - 0.96
Co	> 3.33	0.20 - 0.41
Pb	> 0.15	0.31 - 0.64
Cd	> 0.25	< 0.02
Mn	> 183	38.5 - 90.4
Al	> 390	244. - 272.
SO ₄	> 7.3	1.0 - 1.7
pH	< 4.8	5.2 - 1.7
<i>n</i>	12	4

Sampling is continuing this year, but these results already indicate that the natural background values are dependent on bedrock geochemical characteristics in the Talvivaara area. The bedrock at Talvivaara contains anomalous Cu, Zn, Ni, Co and Mn, elevated Cd and Hg, but in most places not elevated Pb concentrations, which can also be seen in the chemical composition of spring waters.

PETROLOGY AND WHOLE ROCK ANALYSES OF THE CENTRAL PORTION OF A
LARGE EARLY PROTEROZOIC DIABASE DIKE, EASTERN LAKE OF THE
WOODS, ONTARIO - A PRELIMINARY REPORT

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The dike under study, part of the 2100 m.y. Kenora-Kabetogama (Southwick and Day, 1983) dike swarm, extends at least 60 km from the Pipestone-Cameron Fault on the northwest through the center of Whitefish Bay and Kakagi Lake to southern Godson Township; it is informally named the Whitefish Bay-Kakagi Lake (WBKL) dike in this report. The objective of this study was to use field observations as well as mineral and rock chemistry to constrain the intrusive history of the dike.

In Whitefish Bay the WBKL dike is 70-80 m wide with well-developed chill borders in contact with the Archean granitic country rocks; no chill borders were observed within the dike. The intrusive contact with the granite is irregular with apophyses of basalt at the mesoscopic scale while the regional strike and dip is constant at 140° vertical over the area studied. Igneous layering characterized by modal variation in plagioclase, pyroxene, and magnetic opaques is noticeable between 10 and 30 m from the dike border. The layering is often distorted and/or truncated. The massive central part of the dike is a low-quartz-content diorite which contains small well-developed cross-cutting mafic pegmatites.

Microscopically, the chill border is characterized by altered phenocrysts (up to about 1 mm in diameter) of pyroxene, unaltered to partly altered phenocrysts of zoned plagioclase (an_{60-70}), and smaller opaque minerals in a brown-green cryptocrystalline groundmass of devitrified tachylite. The groundmass contains xenocrysts of quartz and K-feldspar indicating interaction with the country rocks. Proceeding into the interior of the dike, the grain size gradually coarsens (over about 5 m) to 3-7 mm. In the center of the dike, (1) vapor-phase alteration of plagioclase and pyroxene is severe, (2) the plagioclase shows complex oscillatory zoning and, (3) up to 10% quartz is present along with micrographic to symplectic intergrowths of quartz and feldspar.

Whole-rock chemical analyses (by XRAL) presented below show the dike margin samples to be chemically very similar both to one another and to the N-1 dikes analyses of earlier workers. Sample 5 from a plagioclase layer shows predictably higher Al, Ca, and Na and lower Mg and Fe. Sample 6 from the dike center shows higher Si, Al, and Na and lower Ca, Mg, Fe, and Ti as well as a higher LOI indicative of a more felsic composition and of more vapor-phase alteration.

Spl no:	1	2	3	4	5	6	7
SiO ₂	49.3	47.8	48.5	48.4	48.8	54.1	47.9
Al ₂ O ₃	12.5	13.0	12.7	12.8	16.0	15.4	12.5
CaO	9.28	10.1	8.65	9.66	9.64	6.91	8.26
MgO	6.12	5.45	5.52	5.42	4.30	1.82	5.57
Na ₂ O	1.72	1.88	1.96	2.01	2.31	3.24	2.68
K ₂ O	0.28	0.26	0.32	0.37	0.59	0.78	0.84
Fe ₂ O ₃	16.5	18.0	18.0	17.7	14.9	13.9	17.0
MnO	0.21	0.24	0.25	0.25	0.21	0.20	0.25
TiO ₂	2.15	2.30	2.24	2.22	1.96	1.49	2.16
P ₂ O ₅	0.21	0.24	0.22	0.21	0.20	0.47	0.22
LOI	1.80	0.75	1.70	1.10	1.35	1.95	1.65
TOTAL	100.1	100.1	100.1	100.2	100.3	100.4	99.11

Samples - locations and minor element data available from FRL.

1. LW87-1-1a, diabase 1 cm from west contact.
2. LW87-1-1b, diabase 0.3 m from west contact.
3. LW87-1-1c, diabase 1 m from west contact.
4. LW87-1-1e, diabase 3 m from west contact.
5. LW87-1-2a, plagioclase-rich diabase from the layered diabase.
6. LW87-4-3, deuterically altered quartz diabase from mid-dike.
7. LW87-4-11c, diabase 3 cm from east contact.

The WBKL dike was a major feeder to early Proterozoic flood basalts. The distorted and truncated igneous layering and the oscillatory-zoned plagioclase record a complex history of intrusion/extrusion, quiescence, and back-flow causing distortion, re-melting, and/or erosion of the crystallized border of the dike. The increase in quartz in the dike interior shows magmatic evolution as lava extrusion proceeded. Alteration of the dike interior is interpreted as deuteric because of (1) stronger alteration in the interior, (2) the presence of the mafic pegmatites, and (3) a lack of hydrothermal alteration cross-cutting the margin of the dike. Many of these observations and conclusions support those of Southwick and Day (1983).

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ON THE ORIGIN OF MANGANESE OXIDES IN IRON-FORMATION OF THE CUYUNA NORTH RANGE, EAST-CENTRAL MINNESOTA- NEW EVIDENCE FROM THE U.S. BUREAU OF MINES GLORIA DRILL SITE

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The Trommald Formation on the Cuyuna North Range is unique in that it contains the highest reported manganese values of any Early Proterozoic iron-formation in the world, and as such is the largest resource of this metal in the United States. Traditionally, the Trommald has been divided into a lower thin-bedded facies containing Fe-Mn-Mg-Ca carbonates, Fe silicates, magnetite and chert, and an upper thick-bedded facies composed of granular chert, hematite, magnetite, manganese hydroxides, and minor silicates and carbonates (Schmidt, 1963). Near the Merritt mine, uncommon Na-, Mn- and Ba-rich silicates indicative of hydrothermal fumarolic processes occur near the contact between thin- and thick-bedded rocks (Morey and others, 1992). To further elucidate the complex history of the manganese oxides and to investigate the possibility of their in situ leaching, the U.S. Bureau of Mines drilled a long inclined core at the Gloria mine, approximately 1.5 km to the northeast of the Merritt site (Dahl, 1992). That core was drilled to an inclined depth of 366 m (304.8 m below the surface) and intersected a complete section of Trommald Formation (true thickness of 168 m) as well as short intervals of the overlying Rabbit Lake and underlying Mahanomen Formations. Dahl and others (1992) divided the Trommald into an upper oxidized interval separated from a lower unoxidized interval by an oxidation boundary at a depth of 234 m below the surface. The oxidized part was further subdivided into a thin-bedded facies, a mixed thin- and thick-bedded facies, and a thick-bedded facies. In that scheme, the thick-bedded and part of the thin-bedded facies were thought to have been oxidized and leached during subsequent ore-forming events. We observe that some of the thin-bedded rocks contain primary hematite and are chemically akin to thick-bedded rocks. The core is presently being investigated at the Minnesota Geological Survey in terms of mineralogy and geochemistry, and some preliminary results are presented here.

The Mahanomen Formation consists of sericite-biotite quartzite interlayered with thin layers or lenses of tourmalinite. Beds of chlorite-bearing oxide (hematite) iron-formation mark the base of the Trommald Formation. They are overlain by approximately 40 m of thin-bedded strata containing abundant carbonates, silicates and magnetite. Features indicative of syndepositional reworking, possibly under shallow-water conditions, include granule-rich layers, breccias, and pebble-size conglomerate. The silicate-carbonate iron-formation also contains considerable sulfides (pyrite, pyrrhotite, chalcopyrite, arsenopyrite), commonly in irregular, discordant, composite veins—along with quartz, carbonates, and stilpnomelane—in stratiform layers and lenses, or as inclusions in intercalated beds of chert. The sulfides are typically replaced by magnetite, which in turn is martitized. Mafic tuffaceous material, as well as tourmaline-bearing sericite schist, is intercalated with the iron-rich strata. Preliminary data imply that the silicate-carbonate iron-formation is poor in Mn (< 2 wt.% MnO) which is at variance with similar rocks from the Merritt site. In turn, there are higher contents of Ca, P, and S observed in the thin-bedded facies of the Gloria mine.

A transitional interval of approximately 4 m separates thin-bedded silicate-carbonate iron-formation below from thin-bedded oxide iron-formation above. Individual laminae contain chert, primary hematite, stilpnomelane, and limonite. Carbonates are rare, and magnetite where present is martitized. Individual layers of nearly monomineralic chert are interlayered throughout. A highly brecciated interval contains intercalations of argillized shale or tuffitic sediments. Manganese-rich layers first appear in thin-bedded oxide iron-formation about 75 m (true thickness) above the Mahanomen Formation. These massive, concordant hematite-goethite-Mn-oxide-bearing intervals as much as 4 m thick are partly enveloped by brecciated oxides, and have maximum MnO (total)

values of 12 wt.% and Mn-Fe ratios of about 0.2. The latter is similar to the Mn-Fe ratios in unoxidized thin-bedded rocks at the Merritt site.

Mn values increase markedly about 110 m above the base, and stay above 5 wt.% for about 55 m (true thickness). As such this zone straddles the boundary between thin-bedded and overlying thick-bedded strata. Mn-oxide-rich layers in thin-bedded strata have brecciated or "gnarled ore" textures and are conformably interlayered with intervals of decomposed iron-formation containing abundant secondary limonite. Mn-oxide-rich layers in thick-bedded strata are interlayered conformably with thick beds of admixed chert having a relict micronodular texture, and with secondary limonite. The layers typically occur as brecciated rubble zones that exhibit numerous discordant textural features. Manganese minerals include manganite, cryptomelane, and pyrolusite (Dahl, 1992). Whole-rock assays over 1.5-m intervals show that Mn-rich layers in thick-bedded strata contain as much as 50 wt.% MnO, and Mn/Fe in places > 1. The zones also have elevated Ca, Mg (attributed to secondary carbonates), and P values and are enriched in Ba (as much as 1.8 %), Pb, Sr, Ag, and As.

The uppermost 12 m of Trommald Formation consists of thick-bedded, oxide iron-formation where primary hematite is abundant but where manganese oxides are lacking. Mn-Fe ratios are generally less than 0.01. The overlying Rabbit Lake Formation differs considerably; beds of sulfide (pyrite) iron-formation are intercalated with thick beds of oxide iron-formation, carbonaceous shale, and thin layers of tuffaceous material. The sulfide iron-formation (35.7 wt.% Fe₂O₃, 26% S) contains elevated values of Au (31 ppb), As, Cu, Co, Ni, Pb, Sr, V, Mo, and Se (230 ppm).

Several features in the Trommald Formation in the Gloria drill core are unique, and it seems to be of special importance that no direct correlation can be made with the well-documented drill core of the nearby Merritt mine. Granular fabrics, extensive syngenetic deformation textures, and extensive sulfide mineralization have been documented for the first time in the thin-bedded facies of the Trommald Formation. Paragenetic relationships among the various iron and manganese oxides are difficult to interpret because of several superimposed oxidation events in the upper part of the Trommald Formation. However, we have found no evidence that the major elements were significantly redistributed on a scale larger than tens of meters. Therefore the manganese oxides, along with other enriched elements, seem likely to be syngenetic precipitates derived from a hydrothermally influenced source of uncertain affinity and redistributed on a small scale to form the present enriched zones.

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GEOLOGY OF THE "GREATER" BEAVER BAY COMPLEX, NORTHEASTERN MINNESOTA

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The Minnesota Geological Survey recently completed an 8-year mapping project, supported in part by the USGS's COGEOMAP program, whose main objectives were to delineate the multiple subvolcanic intrusions of the Middle Proterozoic Beaver Bay Complex (BBC) of northeastern Minnesota and to characterize its transition into the more plutonic environment of the Duluth Complex (DC). These objectives have largely been accomplished and the results are set forth in the form of three 1:24,000-scale geologic maps (Miller, 1988; Miller, Green and Boerboom, 1989; Miller, Green, Boerboom, and Chandler, 1993), the imminent publication of two others (Miller, Boerboom, and Jerde, in prep.; Boerboom and Miller, in prep.), and an open-file map of the Little Marais quadrangle, also in preparation. These maps, which we present in our poster as a mosaic compilation, include all or parts of eleven 7.5' quadrangles and cover a 440-square-mile-area (Fig. 1). Although this area covers what has been historically called the BBC (Grout and Schartz, 1939), reconnaissance mapping to the east and interpretation of aeromagnetic data over covered areas to the west suggest the need for an expanded definition of the BBC.

Twelve major intrusive (lithodemic) units were identified within the mapped area of the BBC, which represent at least six major emplacement events of mafic to less common felsic magmas into the central part of the North Shore Volcanic Group. This numerical disparity between map units and intrusive events reflects the composite nature of some events and the uncertainties of correlating units over such an extensive area. Because of these correlation problems, it is convenient to subdivide the BBC into southern and northern parts. The southern BBC contains, in order of successive emplacement, the *Lax Lake gabbro* and the separate but correlative(?) *Blesner Lake diorite*; the *Finland Radar Station granophyre*; the layered mafic *Sonju Lake intrusion*, the *Victor Head diabase* sill, and the extensive dikes and sills of *Beaver River diabase* with its anorthosite inclusions and composite bodies of the ferrogabbroic *Silver Bay intrusions*. Although the Beaver River diabase and its composite intrusions can be traced throughout the BBC, a distinct suite of intrusions occurs north of about 47°30' latitude. From oldest to youngest, the northern BBC units are the *Shoepack Lake inclusion-rich diorite* (see Boerboom, this volume), the *Cabin Creek porphyritic diorite*, the *Upper Manitou River gabbro*, the *Wilson Lake ferrogabbro*, the *Houghtaling Creek troctolite*, and again, the *Beaver River diabase*, together with several composite intrusions. The *Upper Manitou River gabbro* is probably correlative with the *Lax Lake gabbro*/*Blesner Lake diorite* units of the southern BBC, because all are irregular in form, lack internal structure, are strongly altered, and have a similar range of rock types. A possible comagmatic relationship between the *Houghtaling Creek troctolite*, a 2- to 3-km-wide, northeast-trending, keel-shaped intrusion, and the lower section of the *Sonju Lake intrusion*, a well-differentiated, 1-km-thick, sheet-like body, is suggested by the similar textures and compositions of their olivine-plagioclase cumulates. More discussion of petrologic and tectonomagmatic relationships of the BBC are given in Miller and Chandler (in review).

General criteria that distinguish the Beaver Bay and Duluth complexes are the shape, cumulate character, and environment of emplacement of individual mafic intrusions. Whereas DC intrusions are typically thick tabular bodies of mostly mafic cumulates emplaced adjacent to other intrusive rocks, BBC intrusions tend to be thinner (<2km) sheet-like bodies or dikes of typically non-cumulate mafic rocks that commonly are in contact with volcanic country rock. The boundary between BBC and DC in the map area is a northeast-trending, 5- to 8-km-wide transition zone bounded by the *Houghtaling Creek troctolite* to the southeast and by gabbroic anorthosites of the DC to the northwest. Within this zone is a complex, heterogeneous mixture of DC and BBC rock types, from oldest to youngest, (1) strongly metamorphosed to partially remelted volcanic rock, (2) highly contaminated mafic intrusions of *Shoepack Lake inclusion-rich diorite*, (3) large granophyre plutons, (4) plagioclase-phyric mafic intrusions, and (5) mafic dikes and layered cumulates of the *Wilson Lake ferrogabbro*. Plagioclase phenocryst compositions and textures and the ferrodioritic matrix composition of the *Cabin Creek porphyritic diorite* are consistent with its being a hypabyssal equivalent of the deeper DC gabbroic anorthositic rocks. If so, this would imply that DC and BBC magmatism were, in part, contemporaneous. Recently acquired U-Pb ages (Paces and Miller, 1993) bracket DC and BBC magmatism between 1099 Ma, the age of DC gabbroic anorthosite, and 1096 Ma, the age of the *Sonju Lake intrusion* and a *Silver Bay intrusion*, but do not reveal whether the magmatism overlapped.

It is apparent from Figure 1 that an extensive band of subvolcanic intrusions occurs in the North Shore Volcanic Group from Duluth to Grand Portage. Although these intrusions fit the general criteria distinguishing them from the Duluth Complex, it will require more work to determine how much of this band should be considered part of the BBC. Miller and Chandler (in review) suggest that the intrusive rocks near the lakeshore between Tofte and Grand Marais be included in the BBC (eastern BBC, Fig. 1). The main intrusive unit there is anorthosite-bearing diabase which can be traced by its aeromagnetic signature directly to *Beaver River diabase* in the northern BBC. Another phase is the *Leveaux porphyry*, a plagioclase-phyric diorite that is very similar to the *Cabin Creek porphyritic diorite* of the northern BBC. More must be learned of the well-exposed but incompletely mapped subvolcanic intrusions farther northeast of the project area to determine whether they too should be included in the BBC. West

and southwest of the study area, thick glacial cover makes interpretation tenuous. However, aeromagnetic data integrated with shallow drilling and rare outcrop in a large area covering the central Duluth Complex (CDC, Fig. 1) suggest the presence of BBC-like sheeted intrusions. These intrusions, informally termed the Cloquet Lake layered series, seem to be enclosed in volcanic rock and seem to merge, in part, with the Houghtaling Creek troctolite. A preliminary 1:100,000-scale geologic map of this area will also be shown at the poster session. Very little is known of the hypabyssal rocks tentatively mapped farther southwest.

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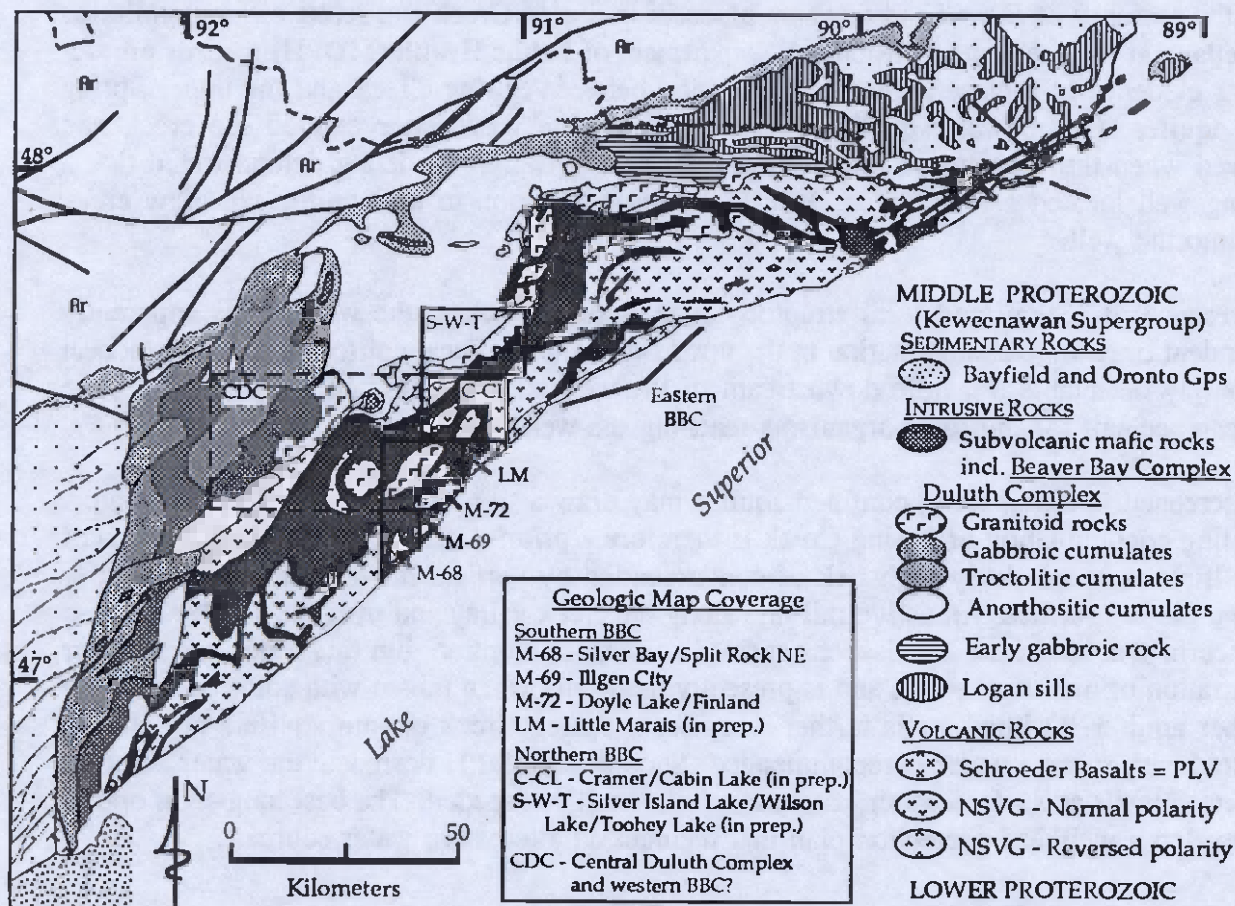


Figure 1. Generalized geology of northeastern Minnesota showing the location of maps covering the Beaver Bay Complex. Solid outlines show areas of 1:24,000 geologic maps (published MGS Miscellaneous Map Series are indicated by M-number). Dashed outline shows the central Duluth Complex study area for which a 1:100,000 geologic map is in preparation.

ASSESSMENT OF SPRING CREEK AQUIFER VULNERABILITY TO POLLUTION USING DRASTIC, WATER TESTING, GROUNDWATER MODELING, AND HISTORICAL RECORDS: A PROJECT OF THE MTU REGIONAL GROUNDWATER EDUCATION IN MICHIGAN (GEM) CENTER

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The Spring Creek wellfield supplies approximately one-half of the public drinking water supply for the City of Ironwood and Erwin Township in Michigan and the City of Hurley, Wisconsin. The origin of *E. coli* contamination in two of the wells was investigated by the Michigan Technological University Regional Groundwater Education in Michigan (GEM) Center. ARC/INFO and ERDAS geographic information systems (GIS) aided data analysis and presentation.

A DRASTIC aquifer vulnerability map, implemented on ARC/INFO GIS, was created to provide a regional perspective on relative vulnerability of aquifers to pollutants originating at the ground surface. The seven DRASTIC parameters are Depth to water, Recharge, Aquifer type, Soil, Topography (slope), Impact of the vadose zone, and hydraulic Conductivity. Potential sources of pollution were mapped to identify areas of particular concern. Surface water testing established the presence of *E. coli* and fecal streptococci in Spring Creek and septic effluent pollution in a wetland at the headwaters. Michigan Department of Public Health (MDPH) records provided clear evidence of a close hydraulic connection between Spring Creek and the upper Spring Creek aquifer. Groundwater quality declined when mine wastewater entered the creek and improved when the wastewater was diverted. MODFLOW 2-D modeling demonstrated that a pumping well located close to a creek in hydraulic connection to the aquifer can draw creek water into the well.

The presence of *E. coli* and fecal streptococci in Spring Creek at the wellfield is apparently independent of sewage contamination in the upstream wetland. Fecal coliforms and streptococci were barely detectable 3/4 mile downstream of the wetland. Wildlife and livestock along the creek can account for indicator organisms reaching the wellfield.

Wells screened in the upper unconfined aquifer may draw a significant amount of creek water. Preventing contamination of Spring Creek is therefore a priority. The DRASTIC map indicates the wellfield is at relatively high risk of contamination by vertical movement into the aquifer from the ground surface. An active rail line along the creek valley and over the aquifer is cause for concern. Drawing from the deeper confined aquifer is an option, but this water has a higher concentration of dissolved solids and is presently used only when mixed with softer water from the upper aquifer. Drilling wells farther away from Spring Creek or into aquifers not closely connected with surface water is recommended. Should the MDPH designate the water entering the affected wells as surface water, a treatment plant will be needed. The best long-term option is to develop a wellhead protection plan that includes an alternative water source.

A POSSIBLE METASOMATIC ORIGIN FOR THE LONGNOSE OXIDE-RICH ULTRAMAFIC BODY

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The Longnose body is a titaniferous oxide-rich ultramafic body hosted by the Partridge River intrusion of the troctolite series of the Duluth Complex. The body is located 83 km north of Duluth in section 30, T. 59 N., R. 13 W. It lies along the trace of a normal fault that cuts two other oxide-rich ultramafic bodies, the Longear and 'Section 17' (Fig. 1). This fault offsets sedimentary stratigraphy, but not the Partridge River igneous units, bringing the Biwabik Iron Formation into contact with the Virginia Formation (Severson, 1988).

Linscheid (1991) described the Longnose body as an asymmetrical funnel, 760 m long, up to 490 m wide, and with a maximum thickness of 167 m. The body is gradationally zoned inward from an oxide clinopyroxenite to an oxide peridotite to an oxide dunite, which hosts discordant massive oxide zones (>80% oxides). In many cases, olivine is completely replaced by serpentine-group minerals. The ilmenite-to-magnetite ratios vary among the distinct units within the Longnose and within the massive oxide unit itself, but ilmenite is the dominant oxide mineral. Most magnetite grains show exsolution lamellae of spinel_{ss} and ilmenite. Secondary hydrous mineral assemblages occur in all rock types and are not limited to zones of intense fractures.

There are many questions regarding the origin of the Longnose body. If the Longnose body is an intrusion, what is the source of the low-SiO₂, high-Fe-Ti melt? If it is not an intrusion, does it represent igneous material that was reworked while still a crystal mush or after crystallization was complete? Whether there was a crystal mush or solidified material, fluids must have been present in the reworked areas. What are the composition and origin of these fluids?

Although the Longnose body has no known appreciable concentration of platinum-group elements, it resembles the platiniferous dunite pipes of the Bushveld. Both the pipes of the Bushveld and the Longnose body consist of Fe-rich dunite cores, which host massive oxide zones, and marginal pyroxenitic and gabbroic rocks. The composition of olivine from the Bushveld pipes ranges from Fo₅₀ to Fo₈₄; in the Longnose, it ranges from Fo₆₀ to Fo₆₆ (Linscheid, 1991). Schiffries (1982) suggested that the Driekop pipe in the Bushveld formed by infiltration metasomatism, one of the most important characteristics of which is the formation of a monomineralic rock such as dunite (Korzhinskii, 1970). The Longnose body has a conspicuous dunite core, which grades outward to pyroxenite and is in turn surrounded by troctolitic rocks. In this context, it seems reasonable to suggest a metasomatic model for the Longnose body and to explore possible lines of evidence.

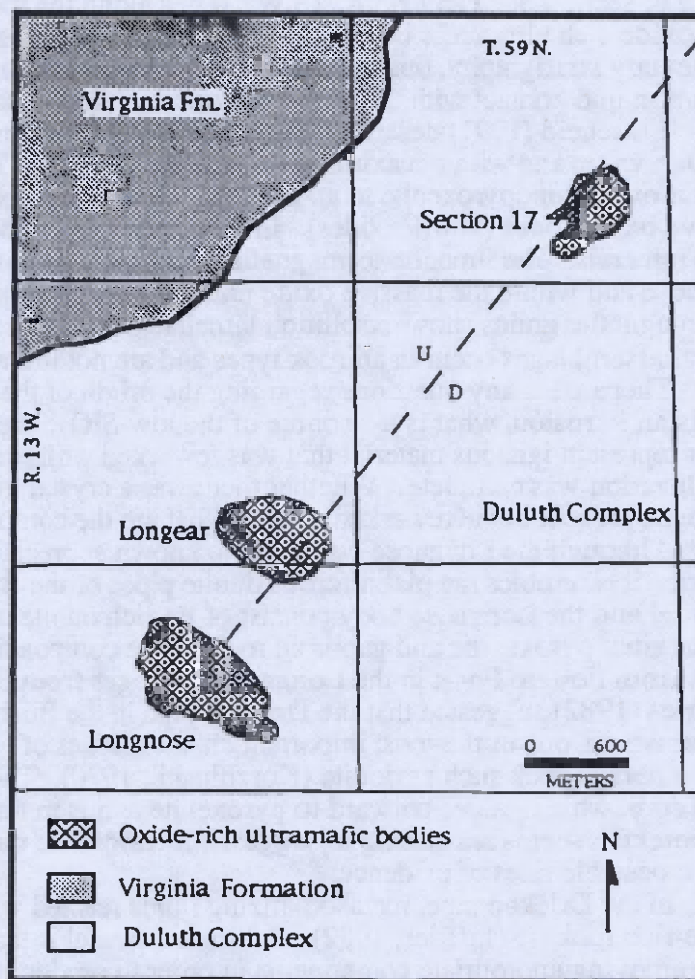
In the Driekop pipe, metasomatizing fluids reacted with noritic host rocks and produced olivine-rich rocks (Schiffries, 1982). Schiffries' model is that fluids passed through the troctolitic rocks removing appropriate components in order to produce dunite. These components were transferred to secondary minerals. In the Longnose body, the occurrence of such secondary minerals as chlorite, serpentine, amphibole, and Ti-rich clinopyroxene indicate the presence of a fluid that transported at least calcium, iron, titanium, and water.

If metasomatizing fluids were involved, then how were their effects concentrated in one area? One possible answer lies in the existence of a normal fault that connects three oxide-rich, ultramafic bodies. On one side of this fault is the Biwabik Iron Formation, which could be a source of Fe-rich fluids. Also, Linscheid (1991) has noted the presence of <2 cm wide actinolite veins in the area surrounding the Longnose body. In the drill core from the Longnose body there are numerous millimeter-scale fractures and cross-cutting features. All of these fractures could serve as conduits for percolating fluids.

Present research on the Longnose body is focused on: possible correlation of ilmenite-to-magnetite ratios with respect to rock type and spatial position within the body, electron microprobe

analyses on exsolved and unexsolved ilmenite and magnetite grains to provide T-fO₂ estimates of the formation and reequilibration conditions in the Longnose body, and electron microprobe analyses of secondary minerals to place temperature and compositional constraints on the possible metasomatizing fluids.

Fig. 1. Location of three oxide-rich ultramafic bodies along the trace of a normal fault (after Severson, 1988).



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HEAVY MINERALS FROM GLACIOFLUVIAL SEDIMENTS IN MINNESOTA

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A study which analyzed the heavy-mineral fraction of northeastern provenance glaciofluvial sediments was conducted by the Minnesota Department of Natural Resources, Division of Minerals, in cooperation with the U.S. Geological Survey, Branch of Geochemistry, Denver, Colorado. Eighty-eight samples were collected from gravel pits across a broad area of Minnesota, sieved to pass 0.83mm, separated (sp gr ~2.85) into three heavy-mineral fractions and then examined geochemically and mineralogically.

A summary of the sampling strategy, the methods of sample preparation and analysis, the geological characteristics of the samples, and the geochemical and mineralogical data for the heavy-mineral concentrate and the paramagnetic and nonmagnetic heavy-mineral fractions is presented in Open-file Report 284 (Nelson and others, 1992).

The geochemical and mineralogical data were analyzed by statistical techniques including basic statistics, correlations, histograms, and multivariate factor analysis of the individual data sets and by glacial lobe within the data sets. Spatial data plots portraying the geochemical and mineralogical data and the statistical results were prepared.

Fairly strong evidence of the local derivation of a significant fraction of the heavy minerals, particularly those in the nonmagnetic fraction, are indicated in the spatial data plots. Many of the patterns of variation in the geochemical and mineralogical data define discrete clusters of samples with similar characteristics. The platinum group, with fire assay gold values, forms an anomaly which is most consistently enriched along and southwest of the contact of the Duluth Complex. High concentrations of andalusite or sillimanite occurred only in samples straddling the contact of the intrusive Duluth Complex with the adjoining metasediments. Several results show samples rich in precious, base metals, and/or associated multi-element associations clustering along and just to the west of the Mississippi River. Three "hot spots" were identified: 1) sample number 23960 is enriched in elements and minerals usually associated with extremely differentiated granites, 2) sample number 23935 has extreme characteristics that would be attributed to base metal deposits, and 3) sample number 23908 has values which exhibit typical anomalous characteristics for the platinum group assemblage. Many of the discrete clusters defined in the results exhibit characteristics expected from bedrock in the vicinity. The results also show surprisingly strong geochemical and mineralogical evidence for mineralization in several areas previously not known to be mineralized.

A report that will present an interpretation of the results from the geochemical and mineralogical data, the statistical data analysis, and the resultant spatial data plots is being prepared as a cooperative effort by a team of scientists from the DNR and the USGS. This report will be available in July 1994 from the DNR, Division of Minerals, Hibbing, Minnesota.

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Geochemistry of the Kallander Creek Volcanics, 1.1 Ga Midcontinent Rift System, Wisconsin and Michigan

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The Kallander Creek Volcanics (KCV) is the younger of two units that compose the Powdermill Group, the earliest volcanic rocks to be erupted from the 1.1 Ga Midcontinent rift system (MRS) in Wisconsin and Michigan. The older volcanic rocks in the Powdermill Group are the Siemens Creek Volcanics (about 1.5 km thick), dominated by high-alumina flood basalts which were probably fissure fed. The KCV overlies the Siemens Creek Volcanics and are composed of a sequence of basalt, andesite, and rhyolite 2-4 km thick. The KCV has been postulated to be the partly eroded remnant of a central volcano erupted between about 1108 and 1102 Ma (Cannon and others, 1993). The outcrop belt extends more than 100 km along strike, but the true extent of the formation is unknown because it is overlain by younger rocks at both ends.

The basalts and basaltic andesites of the KCV have average SiO₂, P₂O₅, and FeO contents somewhat higher than for the underlying basalts of the Siemens Creek Volcanics and the overlying basalts of the Portage Lake Volcanics and Porcupine Volcanics, whereas MgO and CaO contents are somewhat lower. The most striking characteristic of the KCV is the high average TiO₂ content (about 3.5 wt %) compared to that of the Siemens Creek Volcanics (about 1.5-2.5 wt %), Portage Lake Volcanics (about 1.7-2.7 wt %), and Porcupine Volcanics (about 2.2 wt %). There appear to be no large compositional gaps in SiO₂ content from basalt through the intermediate and more felsic volcanic rocks of the KCV. Average trace element compositions of Kallander Creek basalts and basaltic andesites show significant differences in comparison to average basalt compositions of the Siemens Creek, Portage Lake, and Porcupine Volcanics. The KCV have lower contents of compatible trace elements such as Cr and Ni and higher contents of incompatible trace elements such as Nb, Y, REE, Hf, and Th than many other basalts, except for a few individual flows in both the Porcupine Volcanics and the basal Siemens Creek Volcanics.

In detail, distinctive trace element characteristics make it possible to recognize two suites of volcanic rocks within the Kallander Creek Volcanics. Both suites range from basalt to intermediate rocks and rhyolite and are indistinguishable in major element composition. The lowermost 1.5 km of the KCV consist of basalt with minor andesite and rhyolite, all of which have steep straight REE patterns (basalts and andesites have (Ce/Yb)_n = 8.0-10.6; rhyolites have (Ce/Yb)_n = 11.2-11.4). The upper part of the Kallander Creek contains all three rock types as well, but andesites dominate. The slopes of these REE patterns are much less steep and L-shaped (basalts and andesites have (Ce/Yb)_n = 2.9-5.8; rhyolites have (Ce/Yb)_n = 3.4-7.7). Similar distinctions between the upper and lower suites can be made by using other trace element ratios. For example, the lower group of basalts and andesites

have $Y/Nb \approx 0.8$ and $Ta/Th \approx 0.6$, whereas the upper group of basalts and andesites have $Y/Nb \approx 2.0$ and $Ta/Th \approx 0.3$.

This work, in conjunction with previously gathered Nd and Pb isotopic data, documents fluctuations in magma sources and eruptive style during development of the MRS in Wisconsin and Michigan. Volcanism began with the eruption of a thin discontinuous group of basalts that contain clinopyroxene phenocrysts and are generally rich in incompatible trace elements, including TiO_2 . These rocks form the basal unit of the Siemens Creek Volcanics and are postulated to be fissure-fed flood basalts derived by small degrees of partial melting within the mantle plume that led to the development of the MRS (Nicholson and Shirey, 1992). Overlying this basal unit, most of the Siemens Creek Volcanics comprise flood basalts, which are poorer in incompatible trace element abundances and which were most probably derived from plume melts probably augmented by the addition of melts from another source, possibly subcontinental lithosphere (Nicholson and Shirey, 1992).

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Geochemistry of the Kallander Creek Volcanics, 1.1 Ga Midcontinent Rift System, Wisconsin and Michigan

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EXPLORATION AND MINING ACTIVITY IN NORTHWESTERN ONTARIO

O' BRIEN, Mark S., Ministry of Northern Development and Mines,
Suite B002, 435 James St. South, Thunder Bay ON P7E 6E3
The mineral sector in Ontario provided an estimated 18,244
direct jobs and produced products with a total Canadian dollar
value of \$5.1 billion in 1993.

Four of the top gold producers in Canada in 1993 were from
northwestern Ontario: Williams Mine (492,251 oz), Golden Giant
Mine (422,528 oz), Campbell Mine (300,472 oz) and the David Bell
Mine (215,188 oz).

This poster displays the producing mines and advanced
mineral exploration projects in the northwestern portion of the
Province of Ontario. The base map is a collage of the Bedrock
Geology Map of Ontario. Currently there are 7 producing gold
mines, 2 base metal mines, 1 platinum group metal mine, 6
quarries, 2 peat moss producers, 5 amethyst mines and 9 amethyst
producers in the region employing approximately 2700 people.
Quarry producers consist of 2 dimension stone, 1 crushed
granite, 1 quartz, 1 diabase and 1 soapstone producer. There
are also 5 projects in the advanced exploration stage.
Representative samples of Northwestern Ontario are on display.

A statistical summary booklet that tabulates regional data
such as reserves, grades, location, ownership and development is
available free of charge. Many other free brochures are also
available.

PRELIMINARY SOURCE-ROCK AND MATURITY EVALUATION OF THE
PRECAMBRIAN NONESUCH FORMATION IN THE TERRA PATRICK #7-22
BOREHOLE, MIDCONTINENT RIFT SYSTEM, BAYFIELD COUNTY, WISCONSIN

PALACAS, James G. and BURRUSS, Robert C., U.S. Geological Survey, Box
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A wildcat well, Terra Patrick #7-22, about 8 mi (13 km) west of Ashland, Wisconsin, was recently drilled to test the petroleum potential of Middle Proterozoic Keweenawan rocks in the Midcontinent Rift System. Rock-Eval pyrolysis analysis was performed on 25 samples, 22 of which were from the 436-foot (133 m) section of the Nonesuch Formation. Each sample was a composite of a 10-foot (3 m) interval. Total organic carbon (TOC) content ranged from essentially zero to 0.44 wt. % and averaged about 0.1 wt. %. The above values, however should be considered minimum. Although special care was taken to remove drilling mud contaminants and larger sized chips of reddish brown (oxidized) caved particles, variable amounts of the oxidized, caved material remained in the samples, causing in some cases serious dilution effects. This is illustrated by analysis of a duplicate sample that was high-graded by meticulously picking out each individual dark-gray, fine-grained particle. The results showed an increase in TOC from 0.1 to 0.44 wt. %. It is possible that relatively thin (about 0.5-2 ft; 0.2-0.6 m) organic-rich silty shales that have TOC of from 1.0 to 2.5 wt. %, which have been analyzed by others in nearby mineral exploration coreholes and outcrops, are also present but completely masked by a combination of oxidized caved materials and thicker, very organic lean, indigenous rock units. We speculate that the average TOC content may be as high as 0.4 wt. % but certainly not higher than 0.5 wt. %.

Of the 25 samples analyzed only 3 gave reliable Tmax values. These ranged from 436°C to 441°C and averaged 438°C, maturity values indicative of the early phase of oil generation for Type II kerogen. This maturity ranking is consistent with maturity values obtained for comparable Nonesuch rocks by previous workers.

In conclusion, the maturation level for the Nonesuch is favorable for oil generation but the source-rock potential for this particular drillhole sample set, based solely on TOC content, is rated poor to at best fair. On the other hand, as shown on the mud log, the presence of methane gas, averaging about 1,000 ppm by volume, and lesser volumes of ethane to butane gases occurring throughout most of the Nonesuch Formation indicates some hydrocarbon potential.

DUAL IMMISCIBILITY OF DOMINANTLY AQUEOUS FLUIDS IN ROCKS OF THE SOUTHWESTERN FOOTWALL OF THE DULUTH COMPLEX, NE MINNESOTA

PASTERIS, Jill Dill; HARRIS, Teresa N.; SASSANI, David C., Dept. Earth & Planetary Sciences, Washington University, Campus Box 1169, St. Louis, MO 63130-4899

Microthermometric and Raman microprobe analyses were made on about 150 fluid inclusions in 6 rock sections from drillhole FHL-2, which sampled the Fish Lake area of the Duluth Complex 25 km northwest of Duluth. The inclusions, which were investigated in quartz and apatite grains in troctolitic to gabbroic rocks, consist only of aqueous fluid (vapor bubble in liquid+solid phase), a single volatile phase ($\text{CH}_4\pm\text{N}_2\pm\text{CO}_2$), or both aqueous and volatile phases. This work is focussed on the aqueous inclusions, which contain 0 to 48 wt. % total dissolved salts with $\text{CaCl}_2/(\text{NaCl} + \text{CaCl}_2)$ weight ratios ranging up to 0.9. Homogenization temperatures of the aqueous inclusions range from 100° to 400°C (see figures).

The attached plots of homogenization temperature vs. total dissolved salt suggest that different rocks encountered fluids of different compositions and that individual rocks interacted with more than one fluid during their history. Most of the rocks that were investigated have mineral assemblages that indicate their interaction with a fluid phase, for instance, mats of chlorite and amphibole replacing pyroxene and olivine, and K-feldspar replacing plagioclase; many of the fluid inclusions lie along secondary trails in (late-crystallizing) quartz and (early- and late-crystallizing) apatite.

The ranges in values of salinity, homogenization temperature, and $\text{CaCl}_2/(\text{NaCl} + \text{CaCl}_2)$ ratio indicate the complexity of the igneous, magmatic-hydrothermal, and post-magmatic processes that interacted in these rocks; our group and others have provided evidence of both strong magmatic and sedimentary/metasedimentary components in the aqueous and volatile fluids. Thus, the data on the accompanying figures could be interpreted as representing such a diverse array of fluid sources and timings as to defy their tracking.

We believe that a more reasonable alternative model is that many of the inclusions were trapped when the system was in a field of two coexisting fluids, i.e., a field of fluid immiscibility. There are two possible regions of such immiscibility in the general chemical system $\text{H}_2\text{O}-(\text{C}-\text{O}-\text{H}-\text{N})$ gases-salt: brine-brine immiscibility at high temperatures and brine-vapor at lower temperatures (Bowers and Helgeson, 1983). In the inclusion parameters (see figures), the main lines of evidence for an immiscibility model are the bimodal distribution in salinity, lack of correlation between homogenization temperature (T_h) and either salinity or composition, differences in T_h between pairs of adjacent inclusions (particularly those representing extremes in salinity), and pairing of high salinity with low gas content in mixed aqueous-volatile inclusions.

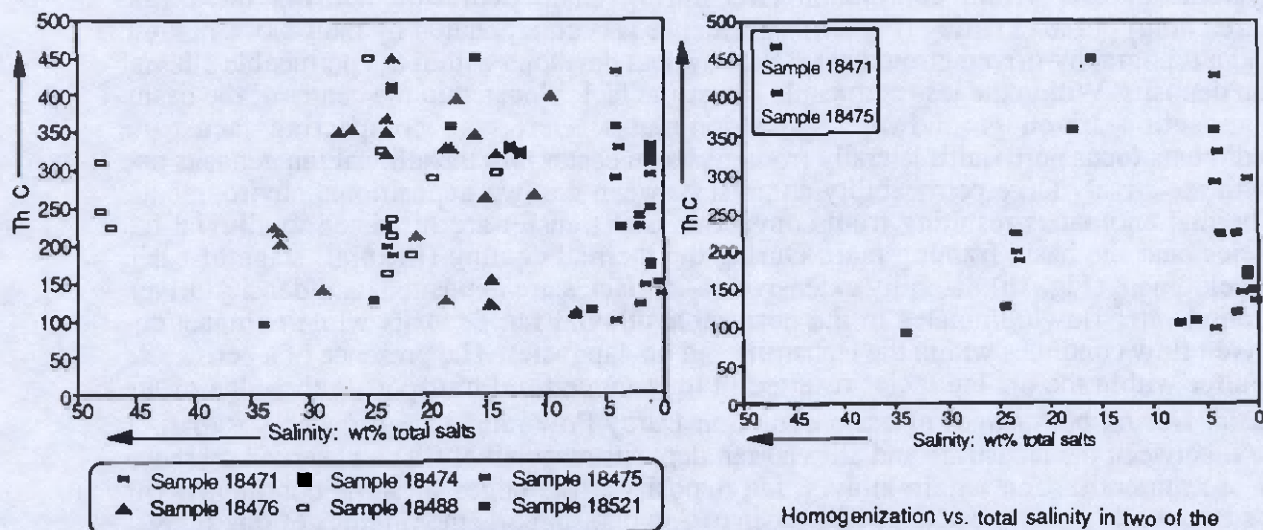
A model of brine-brine immiscibility alone does not account for all of the above features, however, in that salinity and density do not co-vary; in fact, all but a few of the aqueous inclusions homogenize to the liquid. In other words, there is a lack of evidence for the one-step segregation of the system at high temperature into a coexisting saline brine and a lower-density, much less saline aqueous fluid. Further refinement of an immiscibility model is required to explain the formation of coexisting liquid-dominated aqueous inclusions that have similar liquid:vapor ratios but widely ranging salinities and $\text{CaCl}_2/(\text{NaCl} + \text{CaCl}_2)$ ratios.

Immiscibility could have occurred in two stages, initially by the segregation of C-O-H-N volatiles from brine and subsequently by the segregation of two brine-like fluids. This model of dual immiscibility requires that the bimodal salinity distributions noted in the figures do not just reflect sampling statistics and that the physical parameters, such as wetting properties, of the immiscible fluids precluded them from interacting chemically and physically within the

extensive fracture system in the rocks.

Dual immiscibility requires much more stringent geological conditions than does one-step, brine-brine immiscibility. The physical properties (e.g., fractures) and chemical reactivity (e.g., susceptibility to hydration) of the Duluth rocks, as well as the rift environment of the Complex, were critical in the development of dual episodes of fluid immiscibility. In the first stage of immiscibility, some combination of factors moved the bulk composition of the late-stage, magmatic-hydrothermal fluid into the field of liquid + vapor; multiple episodes of physical segregation of brine and volatiles probably occurred, enhanced by the periodic drops in pressure during rifting. This depletion in volatiles moved the aqueous component of the original bulk fluid toward the H_2O -salt "binary", eventually inducing the second stage of immiscibility. Two coexisting brines developed, with contrasting salinities and densities. If these two aqueous fluids remained physically segregated within the fracture system of the host rocks during isobaric cooling (e.g., system evolution at fixed depth) or isothermal increase in pressure (e.g., change from hydrostatic to lithostatic pressure after rifting), then both fluids would increase in density. Trapping of these fluids would produce two populations of liquid-dominated brines with contrasting salinities, like those seen in the figures below.

Several distinctive petrologic features of drillhole FHL-2 and many other portions of the Duluth Complex can be explained by a mobile, high-salinity brine that interacted with the melt and host rock during subsolidus cooling: pegmatoidal zones, the gradational nature of the contacts between inferred igneous stratigraphic zones (Severson and Hauck, 1990), enrichment in anorthite content in the rims of plagioclase grains, bulk-rock concentrations of up to 3200 ppm chlorine (Dahlberg and Saini-Eidukat, 1991), and iron-rich compositions of pyroxenes and olivines.



Homogenization temperature vs. total salinity for all 6 samples investigated in this study.

Homogenization vs. total salinity in two of the samples shown at the left. Note the bimodal distribution in salinity. All inclusions in both diagrams homogenize to the liquid phase.

HYDROLOGIC MODELS OF SEDIMENT-HOSTED ORE FORMATION WITHIN CONTINENTAL RIFT BASINS

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Much attention has recently been placed on the interrelationship between compressional tectonics and the paleohydrology of sedimentary basins (Bethke and Marshak, 1990; Oliver, 1992; and Sverjensky and Garven, 1992). These studies have proposed that during orogenic events, uplift of the land surface and tectonic shortening can induce regional subsurface flow systems capable of transporting significant quantities of heat and fluid mass over hundreds of kilometers. Such transient flow events, which remain active until erosional processes incise the landscape (Garven and Freeze, 1984a,b) or compressional stresses wane (Ge and Garven, 1992), are thought to have formed economic metal ore deposits and petroleum accumulations at the edges of foreland and intracratonic sag basins (Garven, 1989 and Garven et al., 1993). To date, however, little attention has been given to understanding the interrelationship between extensional tectonic events and the paleohydrology of continental rift systems (Person and Garven, 1992, 1994). This study attempts to fill this gap by presenting a series of generic mathematical models of hydrothermal fluid flow within actively rifting basins. The numerical experiments illustrate the important control of permeability and water table configuration in determining which driving-force on fluid motion (compaction, density, or topography) will dominate during basin evolution. The idealized models also help to infer the role of groundwater flow in the formation of sediment-hosted, hydrothermal ore deposits within continental rift basins. The unique stratigraphic relations, heat flow and tectonic conditions associated with continental rifts warrants quantitative analysis.

Assuming that rift basin subsidence and basal heat flow can be represented using a 'standard' geodynamic model (Garner and Turcotte, 1986), two distinct groundwater flow systems evolve within continental rifts during basin evolution. During the initial (stretching) phase of rifting (Fig. 1a), subsidence is accommodated by fault block motion, and a topography-driven groundwater flow system develops within the permeable alluvial fan deposits. Within the less permeable lacustrine facies located in the center of the basin, compaction-driven groundwater flow dominates. Here, the compacting lacustrine sediments focus pore fluids laterally from the basin center into the alluvial fan deposits due to the relatively large permeability contrast between the two depositional environments. Thermal anomalies resulting from convective heat transfer are restricted to alluvial fan facies near the basin framing fault. During the thermal cooling (flexural) stage of basin development (Fig. 1b), laterally extensive on-lap facies are deposited, and density-driven groundwater flow dominates in the permeable alluvial fan deposits while compaction-driven flow continues within the lacustrine and on-lap facies. The presence of a permeable aquifer within the on-lap facies resulted in long-range fluid transport to the edge of the basin. During both stages of basin evolution Darcy flow rates varied from 10^{-5} to 10^{-1} m/y. between the lacustrine and alluvial fan deposits respectively. The observed presence of ore mineralization within alluvial fan deposits at the edges of some continental rift systems, such as the Cretaceous Rift Basin of Angola, supports the findings of this study.

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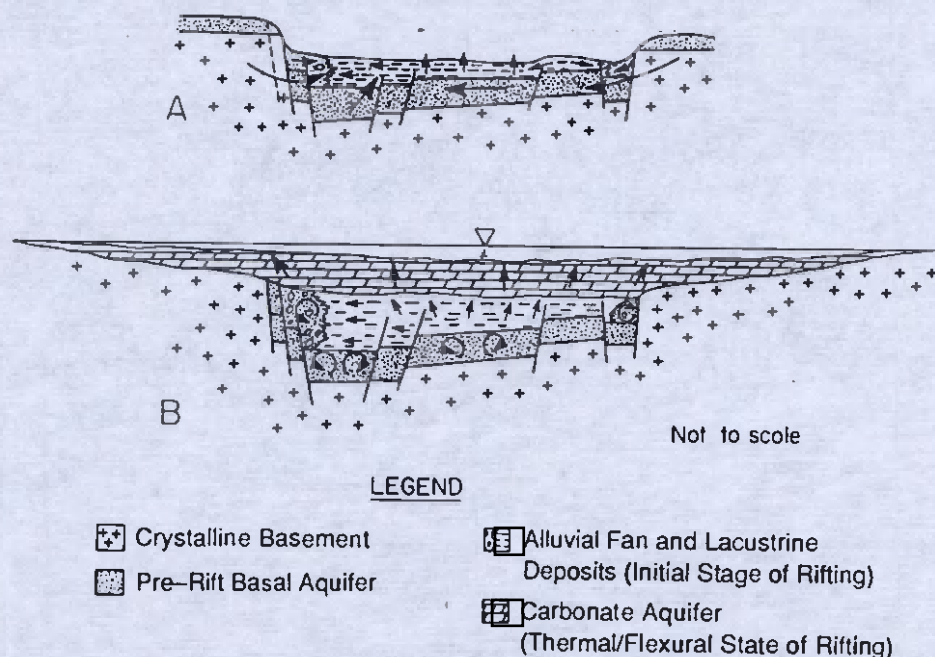
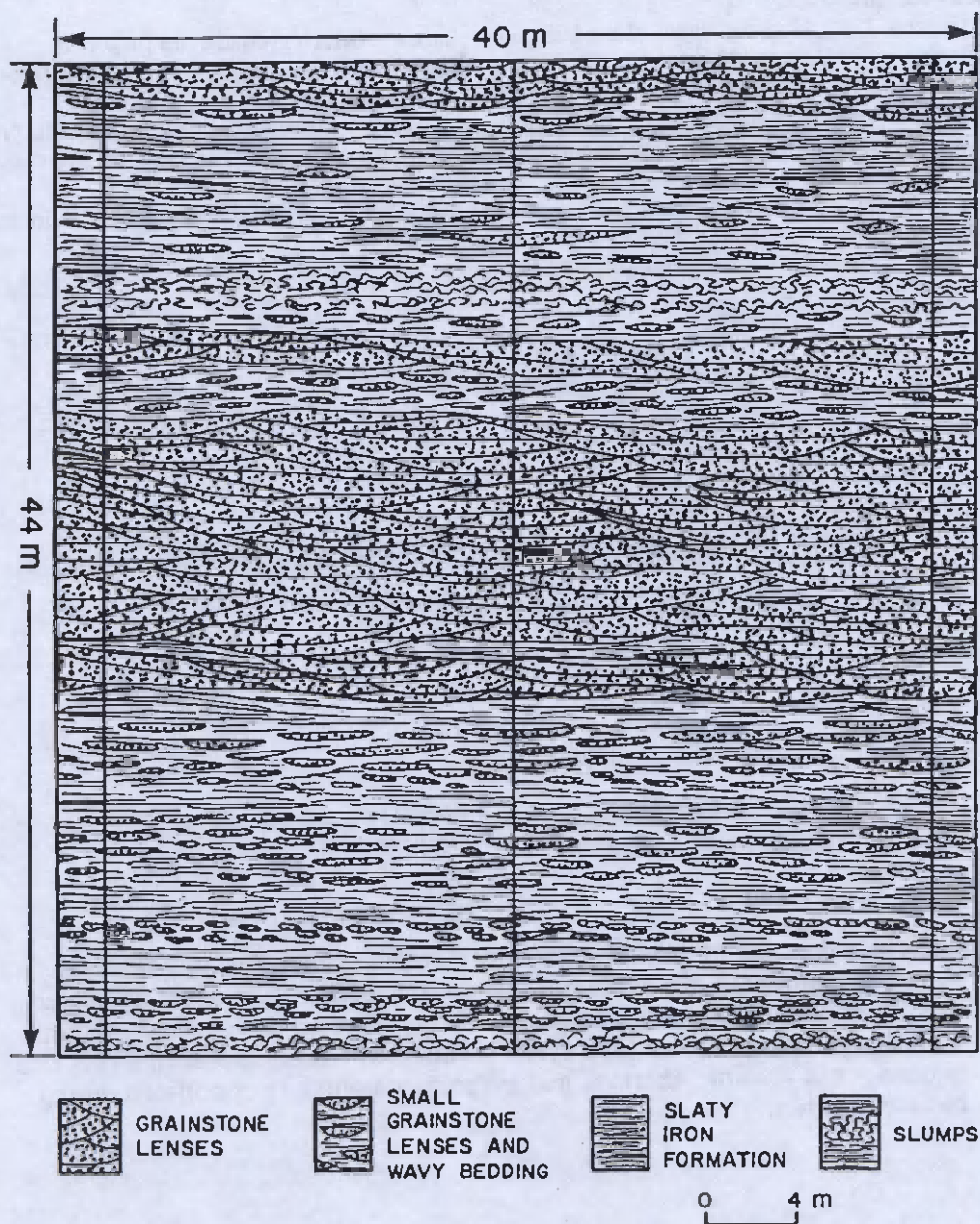


Figure 1. Conceptual model of groundwater flow system during initial and flexural stages of continental rift evolution. Arrows depict direction of groundwater motion due to topography-, density-, and compaction driven flow systems. Two distinct groundwater flow systems can form within continental rifts due to changes in tectonic, thermal, and hydrologic boundary conditions during basin evolution.

DEPOSITIONAL CONTROLS ON SHALLOW WATER IRON FORMATION ACCUMULATION, GOGEBIC RANGE, WISCONSIN.

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Well exposed, glacially polished iron formation outcrops near the town of Mellen, Wisconsin. These units form a portion of the western Gogebic iron range which strikes east-west through the area. Iron formation exposure of this calibre is unusual in the Lake-Superior region and provides an opportunity to investigate physical and chemical sedimentary controls on accumulation of this type of sediment.



A 40 x 40 m section of iron formation composed of trough cross-stratified chert grainstones and parallel laminated slaty iron formation was mapped in detail (Figure 1). The sequence is composed of three distinct stratigraphic units. The first comprises 12 m of parallel laminated slaty iron formation with small chert lenses appearing at the bottom of the section. The second is a 15 m thick succession of large trough cross-stratified grainstone lenses, some extending laterally 10-12 m. The third unit lies immediately above the grainstone succession and is composed of 8 m of slaty iron formation. Paleocurrent data is dominantly unidirectional from the north.

Slaty iron formation is dominated by parallel laminated beds 2-5 mm in thickness. In regions where slaty iron formation coexists with small grainstone lenses the characteristic parallel lamination gives rise to wavy bedding. Ripple lamination is present in the lowest stratigraphic unit. Many beds are both physically and chemically graded. Variations in the distribution of Al, Mn, Fe and Mg are seen within individual beds and throughout the entire span of the section. Mineralogically the dominant phases are hematite, magnetite and chert with minor amounts of greenalite, apatite and manganese oxide.

The trough cross-stratified chert grainstone lenses are composed of rounded chert and hematite grains ranging in size from 0.1 to 2 mm. Many chert grains are coated with hematite, suggesting rolling by bottom currents through iron-rich muds. A few of the largest hematite grains possess cores composed of ilmenite. The matrix is dominantly chert & calcite with traces of stilpnomelane. Lenses range from 2 to 40 cm thick and may extend laterally 0.70 to 15 m. The smallest grainstone lenses appear at the base of the section within slaty iron formation. The largest lenses are found in the succession of trough cross-stratified grainstones. Ripups of slaty iron formation, 1-3 cm in length, are common at the base of the largest lenses (30 cm thick, 8-11 m wide) at the top of the succession.

The section is characterized by a coarsening upwards sequence in which muddy shelf deposits pass through ripple laminated fine sand into a succession of cross-stratified dunes. This sequence is characteristic of offshore bars. The thin ripple lamination in slaty iron formation in the lowermost slaty unit may represent sands moved by storm produced currents. The dominantly unidirectional paleocurrent pattern is also indicative of storm enhanced currents. Slumping is suggested throughout the sequence by the presence of extensive convolute bedded slaty iron formation.

The offshore bar complex composing the Upper Cretaceous Sussex Sandstone in the Powder River Basin, Wyoming is similar to the chemical sedimentary succession described above. The sedimentological controls forming the carbonate sequence in Wyoming should therefore closely parallel those governing sedimentation on the shallow shelf present during deposition of the slaty and cherty iron formation. The offshore bar sequence in Wyoming also grades gradationally from silty claystone through interbedded sandstone and claystone to sandstone and contains a sequence of sedimentary structures similar to that present in the iron formation. The Sussex sandstone also demonstrates an asymmetrical distribution of facies resulting in a steeper depositional slope which endured higher depositional energies, and underwent periodic slumping probably similar to that observed in the Proterozoic bar succession.

HYDROGEOLOGIC INVESTIGATIONS OF PETROLEUM CONTAMINATION IN KARST, CENTRAL UPPER PENINSULA OF MICHIGAN

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BACKGROUND

Hydrogeologic investigations have been conducted in response to fuel contamination of residential water supply wells in a small Upper Michigan community (due to litigation, the location cannot be disclosed). An initial investigation identified some possible sources and poorly defined hydrogeology. A subsequent investigation refined the source identification and provided better definition of the vertical and horizontal extent of the contaminant plumes.

GEOLOGIC SETTING

The site lies on the Northwest edge of the Michigan basin, near the contact between the Michigan Basin Paleozoic sediments and the Precambrian metamorphics of the Canadian Shield. At the surface are Wisconsinan-aged thin, medium textured glacial tills (ground moraine) (Farrand and Bell, 1982). Underlying the drift is the Middle Ordovician Trenton Group; a gray, brown, or buff colored, fine grained, limestone or dolomite, with thin gray shale partings, sometimes fossiliferous, fractured, vuggy with some calcite crystals or pyrite in vugs (Ostrom and Slaughter, 1967, Sinclair, 1960 and Vanlier, 1963). Underlying the Trenton Group (estimated to be at least 250 feet thick in this area) are the Black River Limestone, the Prairie du Chien formation and the Late Cambrian Munising Sandstone (Sinclair, 1960 and Vanlier, 1963). Regional groundwater flow is to the Southeast, generally parallel to the dip of the bedrock structure.

DISCUSSION

Surficial deposits are glacial till: light brown, brown or reddish-brown, fine to medium clayey sand, sandy clay or clayey silt, with trace to some fine to coarse gravel, ranging from 3 to 9 feet thick. Gravel percentage increases with depth; cobbles of bedrock are incorporated just above the bedrock surface.

The bedrock is fairly homogeneous to at least 60 feet below ground level (bgl), the total depth of investigation. It is grayish-brown to buff dolomite, microcrystalline, fractured with some dissolution features, containing few to some vugs and few to some thin (<2" thick) zones or beds of shaley dolomite to shale, generally occurring below a depth of 20 feet bgl. The vugs commonly are filled with calcite crystals or pyrite, fractured, which often are filled with reddish-brown silty clay. Please refer to the core and drill log for MW-110D.

Groundwater flow is strongly influenced by the secondary permeability (fractures). The depth to groundwater in the 40 monitor wells (Figure 1) ranges from 0.5 to 29 feet bgl, with a corresponding range in ground surface elevations of only 18.5 feet. Water levels fluctuate widely with seasonal changes, with as much as 18.25 feet noted from May to September in one well, MW-111D.

Initial attempts to contour the groundwater elevation data were frustrating (Figs. 2 & 3). It was apparent that several wells were responding differently to changing conditions, so well hydrographs of elevation versus time were prepared (Figs. 4-6). In the hydrographs it is obvious that some wells do not reflect changing groundwater elevations in concert with the majority of the wells. These "anomalous" wells probably are screened in zones hydraulically isolated from the rest of the aquifer. They were not used in subsequent

interpretation, resulting in potentiometric surface maps (Figs. 7 & 8) that agree well with the observed contamination plumes (Figs. 9 & 10).

A groundwater high is found at the Western edge of the study area, roughly corresponding to a bedrock and topographic high, with groundwater flowing off the high to the North, East and South (Fig. 7). This high is not reflected deeper in the aquifer, where groundwater follows the regional flow to the Southeast (Fig. 8). Horizontal hydraulic gradients vary around this high, from 0.022 to 0.028 ft/ft to the North, 0.012 - 0.015 ft/ft to the East and 0.026 - 0.031 ft/ft to the South, with little to no seasonal fluctuations. Although the vertical hydraulic gradient is downward, little contamination was found in the deep wells: 1 detection of a single compound, at trace levels, on only one sampling date each in 2 of the 12 deep wells, and one of those detections was not repeated in a duplicate sample.

A total of 24 slug tests were performed on 14 monitor wells (8 shallow). Hydraulic conductivities range from 1.37×10^{-4} to 4.25×10^{-2} cm/s, with an average of 1×10^{-3} cm/s. A 24-hour constant rate pumping test yielded comparable hydraulic conductivity values of 2.35×10^{-4} to 1.52×10^{-3} cm/s, with a Transmissivity of 1.92 to 12.4 m²/day and Storage Coefficient of 1.06×10^{-3} to 1.26×10^{-3} (the smaller numbers are from MW-6 and the larger from MW-112D).

A marked seasonal fluctuation in the contaminant plumes is evident. The plumes reach a maximum in the spring (Fig. 9) when snow melt and heavy rains flush residual contaminants into the aquifer. Later in the year (Fig. 10), lesser recharge is reflected in the greatly reduced plume sizes, to the point where discrete sources become evident. Since all known leaking fuel storage tanks have been removed, these contaminant sources probably are either residual fuel in the drift or in sediments filling the epikarst, or LNAPL trapped in fractures above the high water table.

CONCLUSIONS

Carbonate hydrogeology, even in young regimes such as the recently glaciated Midwest, often is strongly influenced by karst development which may be so subtle as to be unnoticeable in rock cores. It is suggested that, if potentiometric flow maps prove difficult to interpret, innovative data handling techniques may be needed.

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ORIGIN OF THE EARLY PROTEROZOIC KENORA-KABETOGAMA MAFIC DIKE SWARM

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The Early Proterozoic Kenora-Kabetogama dike swarm intrudes over 90,00 km² of northern Minnesota and southern Ontario. Dikes were sampled from outcrops throughout the exposed eastern portion of the swarm, from the Mesabi Iron Range, north to Kenora, Ontario. Samples from dikes buried beneath glacial cover in northwestern Minnesota were obtained from drill core. The swarm is composed of thousands of dikes, ranging from 1-120 m wide, some of which can be traced for over 100 km. Phyric basalt at the quenched margins of the dikes coarsens to diabase and gabbro in the cores of large dikes (>20 m in width). Rare composite dikes are composed of a similar marginal basalt and have medial felsic granodiorite intrusions. Dike margins are porphyritic, with plagioclase, pyroxene, and rare Fe-Ti oxide phenocrysts in a groundmass of plagioclase microlites, pyroxene, magnetite, and green hydrous silicates; the margins are believed to best represent the composition of the primary intruded magma. Alteration within dikes is variable, and is believed to have been largely deuteric in nature. It was not accompanied by significant chemical compositional changes, and mobilization of elements was restricted to K, Rb, Sr, Ba, Ca, and Mn.

All dikes of the KK swarm are composed of Fe-rich quartz normative basalts following a tholeiitic trend on the AFM diagram. Dike margin rocks have nearly constant silica contents and exhibit a wide range in magnesium index (Mg/Mg+Fe), typical of continental tholeiitic rocks. Coherent trends of Mg depletion and Ti, P enrichment with differentiation are seen on major element bivariate diagrams. Our data set shows a distinct grouping of samples into high Mg-low Ti, and low Mg-high Ti groups, similar to that seen by Southwick and Day (1983).

Trace element analyses of the dikes have been studied to better constrain the trends in both within-dike and inter-dike variation. Most gabbro core rocks can be successfully modelled from their basaltic margins using major element mixing and trace element fractionation models. In the composite dikes, the extremely differentiated granodiorite portions have trace element patterns exhibiting both fractionation and contamination processes. Large negative Ta anomalies, and highly enriched incompatible elements including Th, require an upper crustal component of contamination in addition to extreme differentiation to produce the granodiorites (Figure 1). The negative Ti, P, Zr, Sr, and Ba anomalies in the extended trace element patterns of these felsic samples are due to large degrees of fractionation including accessory phases of apatite, zircon, ilmenite, amphibole, and potassic feldspar.

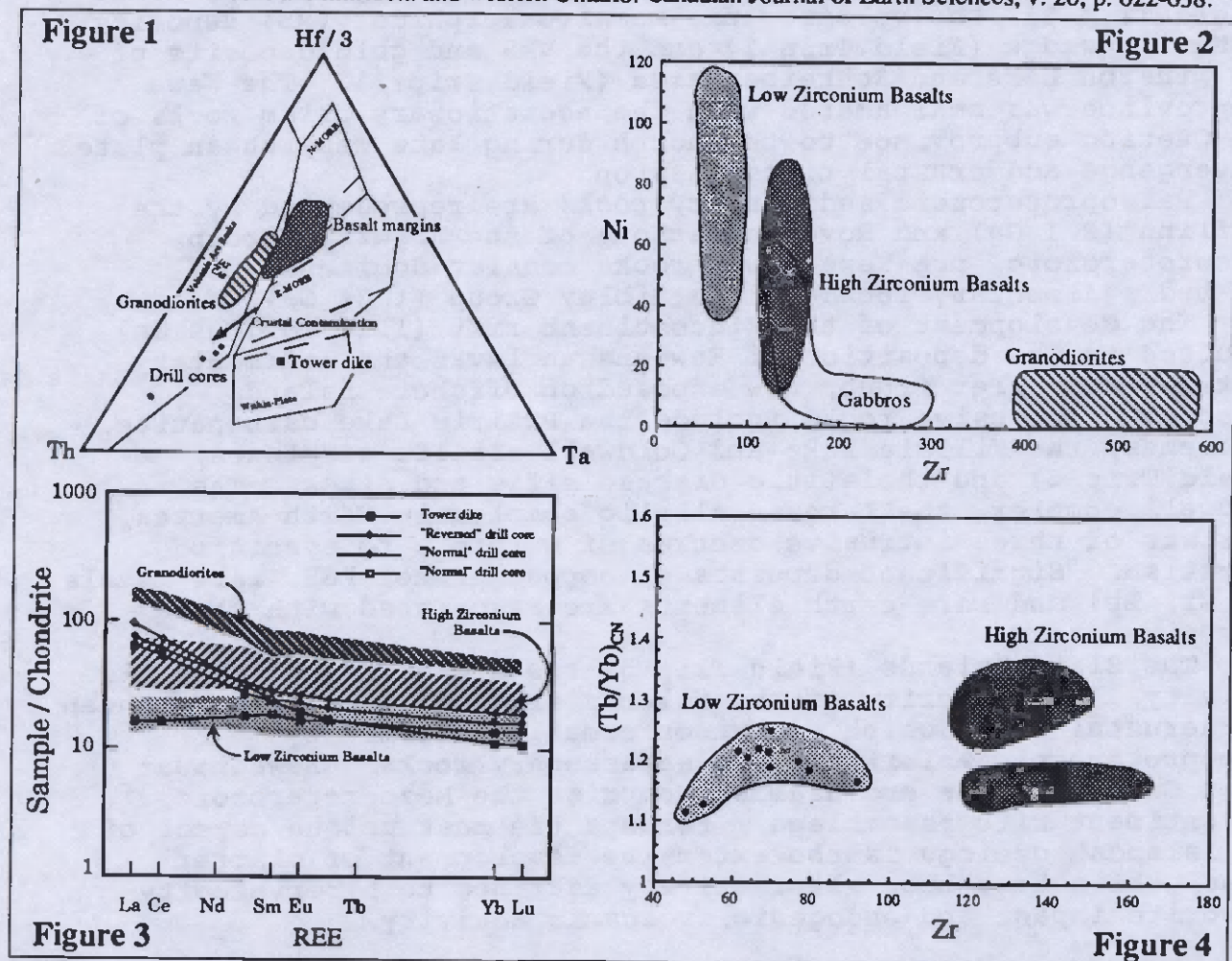
Inter-dike variation has been studied using analyses from the margins of dikes. Margin rocks fall along two distinct arrays in plots of compatible elements (Ni, Cr, Co) versus Zr (Figure 2). These two trends correspond to the groupings based on major element chemistry. REE patterns of both groups are essentially parallel over large variations in HFSE (Zr = 48-162 ppm). Both groups of dikes have flat MORB-like chondrite-normalized REE patterns [e.g. (La/Sm)_{CN} = 0.86-1.07] with absolute abundances of 15 to 60x chondrite. The total absolute REE abundance is clearly correlated with the high and low-Zr groups (Figure 3). A distinctive difference in the slopes of the HREE is the basis of Figure 4, which divides the high-Zr group into two subgroups; these two subgroups are believed to represent different magma series and possible differences in source. Within each subgroup, the REE and extended trace element patterns suggest a fractionation series. Eu anomalies become progressively larger with increasing enrichment, suggesting fractionation of plagioclase, consistent with major element modelling and petrographic evidence. Patterns within the low-Zr group do not illustrate a clear differentiation sequence, but share similarities with both high-Zr groups.

Extended trace element patterns of the dike margin samples are well correlated with the exception of the highly incompatible mobile alkali elements, Cs, Rb, K, and to some extent Ba. Low abundances of the highly incompatible elements are similar to MORB and indicate a depleted source. Little evidence of crustal contamination is seen, as indicated by minor Ta-anomalies, and low (Th/La)_{CN} (0.47-0.85) ratios. Samples of KK dikes plot in the N-MORB field of Figure 1, with very few samples pulled along a vector of crustal contamination. This diagram illustrates the distinct composition of dikes near Tower, MN, and those found in drill core from northwestern MN.

A dike near Tower, MN with a trend and field characteristics similar to those of the KK swarm is seen to have a very different trace element chemistry. It has enriched, OIB-like REE and extended trace element patterns, and plots within the OIB field of the Hf/3-Th-Ta diagram. It also shows a low degree of crustal contamination. The Tower dike represents a melt from a different magma source not observed elsewhere in the KK swarm, and might be related to a different magmatic event (i.e. Keweenaw Rift).

While the thousands of NW-trending dikes observed in northwestern MN by aeromagnetics have been previously assumed to be of KK affinity, the six samples of four drill cores analyzed have trace element patterns that are distinct from the rest of the KK swarm (Figure 3). Two of the dikes sampled appear to have reversed polarity aeromagnetic signatures. The three samples from these "reversed" dikes have similar REE and extended trace element patterns: highly enriched in incompatible elements, similar to OIB, with large negative Ta and P anomalies suggesting crustal contamination. The other two dikes have "normal" polarity. Samples from one dike have OIB like patterns highly enriched in incompatibles and show signs of extreme crustal contamination. A sample from the other "normal" dike is highly altered, but has a distinct flat trace element pattern similar to MORB. These dikes from northwestern MN might be representatives of one or more different dike swarms. Conversely, they might be part of the Kenora-Kabetogama swarm, with their different compositions a function of extreme crustal contamination, or the tapping of different mantle sources.

Reference: Southwick, D.L., and Day W.C., 1983, Geology and petrology of Proterozoic mafic dikes, north-central Minnesota and western Ontario: Canadian Journal of Earth Sciences, v. 20, p. 622-638.



A GEOLOGICAL MARATHON: THE ROCKS OF THE NORTH SHORE OF LAKE SUPERIOR

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The north shore of Lake Superior is underlain by a variety of Precambrian rocks and hosts numerous economic mineral deposits. The 41st Institute on Lake Superior Geology, hosted by the Town of Marathon in 1995, will highlight the area's exceptionally varied geology.

Neoproterozoic greenstone belts and granitoid plutons of the Wawa subprovince underlie most of the region. The supracrustal rocks (2.77 to 2.70 Ga) consist of komatiitic to tholeiitic basalt, calc-alkalic basalt to rhyolite, clastic sedimentary rocks and iron formation. They have been tectonically juxtaposed, deformed and intruded by massive to gneissic granite, granodiorite and tonalite. Greenstone belt rocks host the gold deposits at Hemlo (Field Trip 1), the volcanogenic massive sulphide (VMS) deposits at Manitouwadge (Field Trip 2) and the VMS and gold deposits of the Winston Lake and Schreiber area (Field Trip 3). The Wawa subprovince was amalgamated with the accretionary prism rocks of the Quetico subprovince to the north during late Neoproterozoic plate convergence and crustal transpression.

Paleoproterozoic sedimentary rocks are represented by the Gunflint (2.1 Ga) and Rove formations of the Animikie Group. Mesoproterozoic, pre-Keweenaw rocks consist dominantly of red-bed sedimentary rocks of the Sibley Group (1.34 Ga).

The development of the Midcontinent rift (1.11 to 1.09 Ga) resulted in the deposition of Keweenaw lavas and sedimentary rocks of the Osler Group, now exposed on offshore islands. Associated intrusive rocks include the Prairie Lake carbonatite, diatremes, the Killala Lake and Coldwell alkalic complexes, (Field Trip 4) and tholeiitic diabase sills and dikes. The Coldwell complex, the largest alkalic complex in North America, consists of three intrusive centres of gabbroic to syenitic magmatism. Significant deposits of copper-nickel-PGE, rare metals (Y, Zr, Be) and rare-earth elements are associated with these intrusive rocks.

The Slate Islands (Field Trip 5) are a crucible of geologic activity. The majority of the islands are underlain by Neoproterozoic supracrustal rocks which are unconformably overlain by Paleoproterozoic Animikie Group sedimentary rocks. Keweenaw Osler Group basalts and diabase comprise the Mesoproterozoic, Midcontinent rift assemblage. Perhaps the most unique aspect of the islands' geology is the extensive development of shatter cones, which have been alternatively ascribed to hypervelocity meteorite impact and endogenic, volcanic activity.

UPDATE ON THE GEOLOGICAL CORE AND SAMPLE REPOSITORY - MARQUETTE, MICHIGAN

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The Michigan DNR's Geological Survey Division (GSD) maintains the Geological Core and Sample Repository at Marquette, Michigan. This "Rock Library" collection of core and samples currently represents 36 of the 83 counties in the state; however, the majority of the materials are from the western one-half of the Upper Peninsula. Thus, Precambrian aged rocks are more represented than the Paleozoic aged materials.

As of the end of 1993, the Geological Core and Sample Repository collection contains 778 complete drill hole cores totaling 236,436 feet, filling 17,135 boxes; drill cuttings from 195 holes representing 64,154 feet of drilling contained in 507 boxes; 386 holes represented by abbreviated core from 131,855 feet of drilling, held in 1,907 boxes; 174 boxes of miscellaneous materials (chip samples, soils, overburden drilling materials, outcrop samples, assay pulps, etc.) including 4,498 feet of represented overburden drilling. This gives a collection total of 1,404 drill holes representing 436,943 feet (82.75 miles) of drilling plus other samples, all contained in 19,723 boxes of materials.

The core and sample collection continues to grow in an effort to better represent the geology of the state. Materials are submitted to the Repository from a number of sources: 1) As a partial requirement of fulfilling state metallic and non-metallic mineral leases; 2) From various state sponsored projects; 3) Through company donations of single holes on up to large collections; 4) From other state and federal government agencies, such as the U.S. Bureau of Mines.

In 1993, 146 holes totaling 34,639 feet of drilling in 3,677 boxes were added to the collection. Much of the core was donated by Western Mining Corporation and Resource Exploration, Inc. Besides the many drill holes of Nonesuch Shale drilling, known as the Western Syncline, or Presque Isle deposit, Resource Exploration, Inc. donated 125 boxes of outcrop samples, soil samples, assay pulps, splits, etc. along with hundreds of assay results from previous work in the U.P. This all helps our collection be more useful.

Some Core and sample materials are on-loan to several universities for research. Additionally, material is reviewed on-site or borrowed for short term studies periodically by consultants, exploration and mining companies, academia and individuals.

The Repository is also the storage site for the G.S.D.'s Metallic Mine Map and Data Collection. During 1993, the balance of the inventoried collection was moved from Lansing to Marquette. Additionally, we obtained a collection of M.A. Hanna's Michigan materials and several years ago we also received a large collection of USX (U.S. Steel) mine maps and cross sections, etc. These materials assist with understanding of the geology and the mine subsidence potential in specific areas of the state, thus they also are an aid to the public safety.

The facility is open for visitors to study the core and cuttings, by appointment on weekdays between 8:30 a.m. and 4:00 p.m., Eastern time. Some sampling can be arranged for on a case-by-case basis. Copies of data derived from the study of the collection are to be submitted to be made part of the public record for future use. For information or an appointment, call Bill Swenor or Milt Gere at 906-228-6561.

Additionally, the GSD maintains all well logs and thousands of selected well cuttings for oil and gas wells in Lansing. Water well records for the entire state are also kept in Lansing by the GSD. Call 517-334-6907 for information. Copies of all Upper Peninsula, Region I, water well records and selected well cuttings are maintained by the GSD at the DNR's District 3 Office near Escanaba. Call Frank Chenier at 906-786-2351 for more information.

GOLD POSSIBILITIES IN MICHIGAN'S LATE ARCHEAN HEMLOCK FORMATION,
AND THE PAINT RIVER GROUP IS STILL A USEFUL STRATIGRAPHIC TERM.

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Almost everyone seems to believe that the Hemlock Formation is Proterozoic. However, a Late Archean age for the Hemlock is suggested by Francis Pettijohn's field mapping (1951, USGS OF) of T.42N., R.30W., Dickinson County, by Dave Paddock's gravity survey (1982, MSU MS Thesis) of the Iron River-Crystal Falls Basin showing that the Hemlock and the Badwater both underlie the Basin, by Jim Trow's (1989, MGS 1st Symposium) using USGS aeromagnetic data to trace three magnetic horizons (Mansfield member of the Hemlock, East Kiernan Sill, and Skunk Creek I-F) from Iron County S and E along strike into the Late Archean Dickinson Group Six-Mile Lake and Solberg strata in Dickinson County, and by Warren Beck's and Rama Murthy's (1991, USGS B1904-I) recent Hemlock Nd error-chron with an age of 2.7 ± 0.5 Ga.

To reconstruct palinspastically to an early Penokean pattern, the Amasa Oval and related domes are translated back 5 miles SSW along the Bush Lake Fault, and rotated back 60° counterclockwise to appear to be almost E-W Archean trends. The now-northern end of the gneissic core of the Amasa Oval appears to have originated near present Iron River. Wen-long Ueng and Dave Larue (1988, *Tectonics*, v. 7, no. 3) envisaged a somewhat similar rotation.

At the turn of the century, placer gold panned from the Iron River at Iron River led nowhere when traced NW upstream. However, if traced NE up-ice in the Langlade Pleistocene Lobe (with SW glacial motion) it leads back to the northern half of the Hemlock of the Amasa Oval. Bill Cannon's $1^\circ \times 2^\circ$ Iron River Quadrangle (1985, USGS Map I-1360-A) shows airborne EM anomalies in this area and in the southern half of the Amasa Oval, which Warren Peterson's $1^\circ \times 2^\circ$ Iron River Quadrangle (1985, USGS Map I-1360-C) suggests occur in the area of W and NW glacial-motion vectors of the Green Bay Lobe.

If the Hemlock is Archean, then Paul Sims (1992, USGS Map I-2185) cannot use its supposed correlation with the Proterozoic Badwater Greenstones to justify correlating the Paint River Group with the Michigamme Formation, although the latter correlation is plausible for Marquette County, where Clarksburg may equal Badwater, and the Bijiki I-F may equal the Riverton I-F. However, that correlation does not square with observations to the south where an almost complete Marquette Supergroup section can be traced WSW within the Calumet Trough (and its westward extension) from the Randville Dolomite at the Calumet Iron Mine, sec. 8. T.41N., R.28., Dickinson County, stratigraphically upward to Commonwealth, Wisconsin, drill holes and exposures of Paint River Group rocks. This conformable sequence exposes no Hemlock, as illustrated in the accompanying stratigraphic column. Here, the thick Michigamme graded-bedded graywackles underlie the Badwater and the entire Paint River Group, as suggested by Hal James (1958, USGS P314-C).

This north/south stratigraphic dilemma may be reconciled by sedimentology: If Marquette Supergroup sedimentary basin development migrated northward, as the Penokean orogeny soon thereafter rolled northward, then the appropriate environment for the thick Michigamme graded-bedded graywackes in Iron and Dickinson Counties may have occurred in Baraga "time", whereas that environment may not have existed until late Paint River "time" near Lake Michigamme, in Marquette County. This involves merely fine tuning excellent Survey work.

The meat and potatoes bottom line of this paper is this: A long-unrecognized Archean greenstone belt (Hemlock) probably contains gold. Let's go!

Pre-Keweenaw Rocks in Iron and Dickinson Counties, Michigan, by Jim Trow, M. S. U.

<u>Iron County</u>		<u>Dickinson County</u>	
Intrusive Peavy Pond Complex		Granite, Diorite, Pegmatite Metagabbro	
EARLY PROTEROZOIC MARQUETTE SUPERGROUP	Paint River Group	Fortune Lakes Slate	
		Hiawatha Graywacke	
		Riverton Iron-Formation	
		Dunn Creek Slate (with Wauseca Pyritic Member)	
	Baraga Group	Badwater Greenstone	Badwater Greenstone
		Michigamme Formation	Michigamme Formation
	Menominee Group	Vulcan Iron-Formation	Vulcan Iron-Formation
		Felch Formation (slate, graywacke, quartzite, arkose plus Bayley's 1959 B1077 p. 14-17 magnetic greenschist of his Dickinson Group)	Felch Formation (quartz-mica schist, garnet- grunerite schist, quartzite, feldspathic quartz-mica schist plus Lamey's 1961 PP310 p. 131- 133 amphibolite)
		Quinnesec Horizon?*	
	Chocoma Group	Randville Dolomite	Randville Dolomite
		Sturgeon Quartzite	Sturgeon Quartzite
		Fern Creek Formation (including some arkose)	Fern Creek Formation
LATE ARCHEAN	Dickinson Group	Kiernan Sills and other Metagabbros	Gneissic Granite and Banded Gray Gneiss
		Unnamed Graywacke ?? Fence Lake Strata in SE Baraga Co.	Metagabbro (Amphibolite)
		Amasa-Fence River Iron-Forma- tions	Unnamed Graywacke (See James, 1961, PP310, p. 25.)
		Hemlock Formation (including Bird and Mansfield Iron- Formations)	Grunerite Zone in Six-Mile Lake Amphibolite
		Quartz-Sericite-Magnetite Schist, Skunk Creek Iron- Formation, and Porphyritic Red Felsite	Six-Mile Lake Amphibolite
		Magnetic low may be East Branch Arkose or Porphyritic Red Granite	Solberg Schist (including Skunk Creek Iron Formation)
EARLY ARCHEAN	Margeson Creek Gneiss of Amasa Oval		East Branch Arkose
			Red Granite Gneiss of Norway Lake area

*Outside area discussed, Quinnesec Formation overlies Randville Dolomite in Wisconsin in Menominee River ESE from Pembine (Trow), and overlies marbles, arkosites, quartzites, and schists on W, N, and E sides of Dunbar gneiss dome (Schulz, 1982, Inst. on L. Superior Geology, p. 43)

PETROGRAPHY AND DIAGENESIS OF THE UPPER CAMBRIAN MT. SIMON SANDSTONE, SE MINNESOTA.

URIBE, Rubén D., Department of Geology, University of Minnesota-Duluth, Duluth, MN 55812.

The Mt. Simon Sandstone is the lowermost formation of the Dresbachian stage (Upper Cambrian). The unit rests unconformably on a wide variety of Precambrian rocks in southeastern Minnesota. Its average thickness is about 260 feet. The Mt. Simon Sandstone is dominantly a white to gray, medium-to fine-grained quartz sandstone ($Q_{95.4}F_{4.1}L_{0.5}$) with sporadic thin shale beds. A noticeable feature of the unit is the abundance of authigenic potassium feldspar. The presence of authigenic feldspar may be correlated with mineralization of midcontinent Mississippi Valley-type lead-zinc deposits.

Petrography and microprobe analysis were used to identify the framework and matrix constituents of the Mt. Simon Sandstone and to determine the diagenetic textures, paragenetic sequence and chemical composition of authigenic minerals. A total of 95 thin sections were studied and point counted with 600 points on each (Table 1). All samples were from drill holes.

The sandstone has undergone a varied diagenetic history, which includes precipitation and dissolution of authigenic minerals, dissolution of unstable detrital grains, and compaction. Potassium feldspar is the most common authigenic mineral in the Mt. Simon Sandstone. The feldspar is present in almost all the samples as euhedral to subhedral overgrowths on detrital grains, ranging from 0.2 to 23.5 volume percent in the thin sections. The overgrowths are not in optical continuity with the detrital cores, and are usually pure orthoclase in composition, as evidenced by electron microprobe analysis. Quartz cement is present along detrital quartz contacts and in very few cases as distinct overgrowths. Authigenic dolomite exhibits two different textures: 1) Euhedral, sand-sized rhombic-shaped crystals with considerable zonation showing iron-rich (red) and iron-poor (clear) dolomite, and 2) Rhombic fine-grained subhedral crystals replacing illitic matrix. Poikilotopic calcite is found in a few samples partially replacing detrital and authigenic minerals. Calcite is also present as isolated patches filling pore spaces. Kaolinite cement is present in nearly all samples. Two texturally different types of kaolinite occur: 1) Well-crystallized vermicular aggregates in pore spaces and 2) Micron-sized particles finely laminated around detrital grains, displaying a wavy-looking pattern parallel to the stratification. Other secondary authigenic minerals found in the unit include hematite, pyrite and leucoxene, present as grain coatings and pore fillings.

The total average porosity for all the samples taken from the Mt. Simon Sandstone is 15.5 percent; part of it is secondary porosity which is evidenced by dissolution of cements and labile detrital grains throughout the unit.

The final objective of this study is to describe the paragenetic sequence of the authigenic minerals. This part of the study is presently in progress.

		H1A	B1	SQ9	SCH & KAN	V669	TOT AVE
NUMBER OF SAMPLES		16	21	18	18	22	
	COMMON	59.3	62.8	51.2	62.7	66.5	60.51
	POLYCRYSTALLINE	2.0	1.6	3.1	0.6	4.1	2.30
QUARTZ	VEIN (?)	0.1	0.8	1.9	1.0	2.1	1.17
	MULTICYCLE			5.3			1.05
	TOTAL QTZ	61.4	65.3	61.5	64.3	72.7	65.03
	ORTHOCLASE	2.2	1.9	0.5	1.4	1.0	1.42
FELDSPAR	MICROCLINE	1.0	0.3		0.1	0.3	0.34
	PLAGIOCLASE	0.5	3.1		1.0	0.6	1.05
	TOTAL FELDSPAR	3.7	5.4	0.6	2.6	1.8	2.81
	PLUTONIC		0.1		0.0	0.4	0.12
ROCK FRAG.	SEDIMENTARY				0.3		0.07
	METAMORPHIC			0.6			0.13
	TOTAL ROCK FRAG		0.2	0.6	0.3	0.4	0.31
MICA	MUSCOVITE	0.4	0.1				0.12
	BIOTITE		0.1				0.03
MATRIX	ILLITIC (?) CLAY		1.6	3.7	1.4	1.0	1.551
	QUARTZ	3.9	1.9	2.7	1.9	2.4	2.56
	FELDSPAR	9.7	5.0	0.8	3.2	3.1	4.35
	DOLOMITE	1.3		2.9	3.6		1.59
	CALCITE	0.1	0.7	4.6		0.9	1.28
CEMENT	SIDERITE			0.4			0.08
	KAOLINITE	0.5		8.3		0.1	1.78
	PYRITE		1.3			0.4	0.34
	HEMATITE	1.3			4.1		1.09
	LEUCOXENE	1.4					0.27
FOSSILS	COLLOPHANE	0.4	0.2	0.2	1.4	0.7	0.59
	PYRITE REPLACED		0.2			0.2	0.07
GLAUCONITE				0.6	2.6		0.63
PORES		15.9	18.2	13.0	14.5	16.0	15.54
	QUARTZ (Q)	94.3	92.2	98.1	95.7	97.0	95.42
CLASSIFICATION	FELDSPAR (F)	5.7	7.6	0.9	3.8	2.4	4.12
	LITHICS (L)		0.3	1.0	0.5	0.6	0.46

Table 1: Petrographic summary for the Mt. Simon Sandstone, based on 95 thin sections from 5 drill holes in southeastern Minnesota. Drill hole locations are listed below.

Northern Natural Gas
Hollandale 1-A (H1A)
SE1/4SW1/4 sec.7,T.103N,R.19W.
Freeborn County

New Jersey Zinc B-1
NW1/4SW1/4 sec.25,T.104N.,R.9W.
Fillmore County

Pan Ocean Oil, Ltd. SQ-9
SE1/4SW1/4 sec.1,T.104N.,R.32W.
Martin County

Minnegasco KAN-1
SW1/4SW1/4 sec.4,T.108N.,R.22W.
Waseca County

Minnegasco SCH-1
NW1/4NE1/4 sec.6,T.108N.,R.22W.
Waseca County

Northern Natural Gas
Vermillion 66-9 (V66-9)
W1/4NW1/4 sec.11,T.114N.,R.18W.
Dakota county

ECHO LAKE GABBRO, HOUGHTON COUNTY, MICHIGAN
WAGGONER, T. D., Cliffs Mining Services Co., Ishpeming, MI 49849

The Jacobsville sandstone between Lake Gogebic and Keweenaw Bay has long been thought to cover the Powder Mill Group (extrusive volcanics) which form the southeastern flank of Midcontinent Rift Basin. The relative magnetic and gravity highs were interpreted as fault blocks of the Group at shallow burial.

Jacobsville thicknesses range from 0 to +3600 feet based on outcrop and drilling information. Further geophysical data suggest thickness in excess of 9000 feet in some areas.

Based on the geological interpretation and seeking knowledge of the copper potential in the lower flow units, an exploration hole was completed in 1975. The hole, Echo Lake #1, was collared 990'N, 1480'W of the SE corner of Section 22, T49N, R37W, Houghton Co., Michigan. Collar elevation was +1375'. The hole encountered 95 feet of glacial till followed by 805 feet of Jacobsville sandstone. At 900 feet, the hole entered weathered olivine gabbro for 20 feet and was terminated at 1315 feet in fresh olivine gabbro. Minor zones of more basic rock approaching a picrite are present.

Shattering normal to the vertical hole is evident in both core and thin section, affecting both labradorite and olivine. Serpentinization of the olivine along the fractures is common. Specific gravity of the gabbro ranges from 2.94 to 3.11. Magnetite occurs as thin (mm) bands normal to core angle in the upper part of the hole, and the magnetic iron content at 1025' measured 4.3%.

The core was devoid of sulfides and the Pt/Pd analysis did not exceed background.

Both the magnetic and gravity signature can be reinterpreted as an elongate plutonic body similar in shape to the Mellen Gabbro and possibly with a granophyric component. It can also be postulated that at depth near the lower Proterozoic contact, base metals may occur.

Paradigms are guide lines or rules used for solving problems and interpreting data within the confines of that paradigm. Paradigms are an integral part of any scientific discipline, and geology is no different. The prevalent paradigm of today is that the anorthosites of the Duluth Complex along the north shore of Minnesota are igneous cumulates. Why? Well, they have an obvious igneous texture and besides, they are not associated with metamorphic rocks like the slates and greenstones near Virginia and Ely Minnesota (Phinney, 1966, p. 142). Plagioclase crystals from the gabbroic magma simply floated towards the top of the intrusion, settled to the bottom, or sometimes both (Phinney, 1966, p. 135). Besides accumulating as phenocrysts in magmatic chambers, anorthosites are also observed as inclusions within dikes, sills, and flows. Where present, nearly all of these inclusions are rounded (Phinney, 1966, p. 135). Anorthosites also occur as lenticular masses within the surrounding gabbro. Temperature estimates for anorthosites are based on O^{18}/O^{16} ratios from several samples and suggest that most anorthosites crystallized under conditions of about 1000° to 1100°C with a water fugacity between 500 bars to 2000 bars (Isachsen, 1966, p. 439).

Study and sampling was done at the large disused anorthosite quarries at Carlton Peak (SE 1/4 of NE 1/4 of Sec 20, R4W, T59N). At this site anorthosite dominates the quarry but is spotted with hundreds of gabbroic inclusions. When viewed from the proper orientation these gabbro spots appear as elongate lenses which are oriented parallel to one another. Many of these spots can be found with a deep red rim of hematite surrounding them. These samples are extremely friable and needed to be dipped in epoxy glue in order to cut, polish and thin section. Without this epoxy, the samples simply could not have been thin sectioned. Air bubbles rising from fractures in the gabbroic spots as well as plucking of the entire thin section sample was a common occurrence. Obviously, these samples are highly fractured. The gabbro spots themselves are the most severely fractured/friable and in many cases these spots are parallel

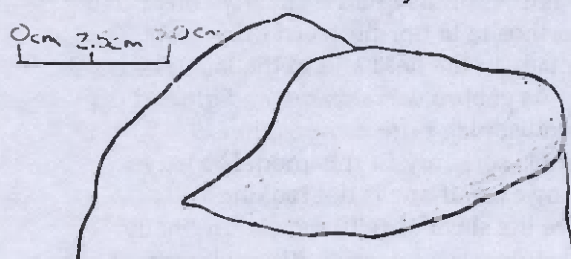


FIGURE 1: Gabbro spot showing diagnostic tail, a typical shear structure shape.

to major fractures within the samples. In addition to this, several rounded spots had visible "tails" to them (Fig. 1) which are identified by Carol Simpson as shear structure geometries (Simpson, 1986, p. 250). Another feature worth note in this paper is the apparent grain of the rock which, when broken, runs subparallel to the gabbro spots and not along the shortest path as would be expected.

If the large scale features and hand samples were suggestive of shear zone genesis, then the thin section evidence is overwhelming. The first step was to thin section the anorthosite itself, without the gabbro spots. The first striking thing about the anorthosites of this area is that even they are highly fractured. Most fracture fills are chlorite, yet there are many more that have plagioclase as a fracture fill itself. Also common in the anorthosites are plagioclase crystals that have both very typical angular crystal faces and very atypical rounded and curved crystal faces. Both of these features can be found within the same crystals. Where the crystal faces are smoothly rounded the crystal boundary appears very fuzzy. Upon closer examination, one can see a series of fractures that are subparallel to the crystal face. Also present within the anorthosite thin sections are several examples of shear structures. One such feature is a plagioclase crystal, rounded and exhibiting tails, as an inclusion within another plagioclase crystal (Fig. 2). Moving from the

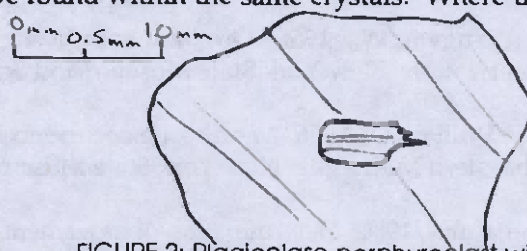


FIGURE 2: Plagioclase porphyroblast with tail inside another plag crystal.

anorthosite to the gabbroic spot inclusions, one can see an interesting trend. Many of the spots in the anorthosite are highly fractured while others are more massive. Beginning with the more massive samples (which still needed to be epoxied for thin sectioning) one can observe plagioclase and pyroxenes. The pyroxene has been slightly to moderately altered along its fractures and exhibits a vermicular texture at these points. The main alteration minerals are chlorite and hematite. Within many anhedral pyroxenes are perfectly rounded plagioclase crystals. Within many anhedral plagioclase crystals there are rounded

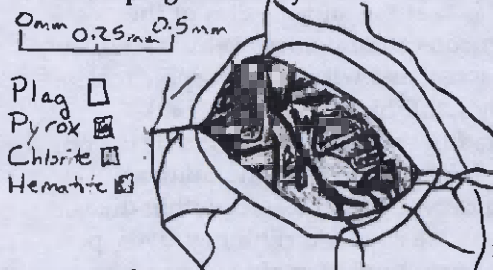


FIGURE 3: Circular fracture patterns surrounding rounded pyroxenes.

pyroxene crystals which are highly altered to chlorite and hematite. Several more pyroxenes show an almost perfect textbook quality porphyroclast with tails. Many of the more circular and rounded pyroxenes have curious fracture patterns which change direction and circle around the pyroxene crystals (Fig. 3). Moving to the more fractured spots, the pyroxenes appear much more heavily altered. Within many of these heavily altered pyroxenes are more circular plagioclases. And within these plagioclases are chlorite fracture fills encased within (Fig. 4). Moving to the most highly fractured material within the anorthosites, one can hardly recognize the altered pyroxenes anymore. Many still encase round plagioclase with chlorite and hematite present. As with the other two spot samples there are the rounded pyroxenes, circular fracture patterns, rounded plag crystal faces, chlorite fracture fills, pyroxenes altered entirely to chlorite, and more shear structure patterns.

pyroxene crystals which are highly altered to chlorite and hematite. Several more pyroxenes show an almost perfect textbook quality porphyroclast with tails. Many of the more circular and rounded pyroxenes have curious fracture patterns which change direction and circle around the pyroxene crystals (Fig. 3). Moving to the more fractured spots, the pyroxenes appear much more heavily altered. Within many of these heavily altered pyroxenes are more circular plagioclases.

And within these plagioclases are chlorite fracture

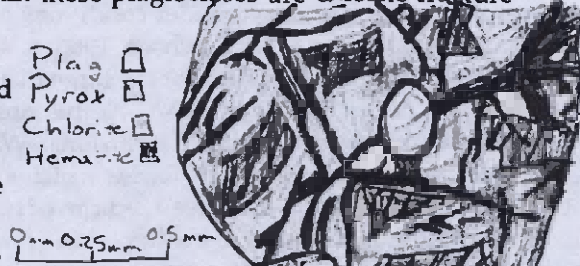


FIGURE 4: Rounded plag within highly altered pyroxene. Note the chlorite fracture fills.

The question that needs to be asked now is; if this is truly an igneous cumulate, can these things be present? And the answer is unequivocally "No". Phinney had difficulty constructing a theory that could explain all four occurrences of anorthosite in northeastern Minnesota. An igneous model just does not agree with observations made in the field and in the lab. The north shore anorthosites are metamorphosed gabbroic rocks. As gabbro was sheared and ground up water flux removed and deposited minerals until an almost plag pure composition recrystallized from it. The lenses and rounded inclusions certainly fit this model. Many anorthosite bodies do not exhibit shear geometries. However, if one is not looking perpendicular to the sense of shear, one cannot observe the shear structures. Additionally, preliminary geochemical evidence we have conducted supports a metasomatic environment. For those who are restricted by their paradigm and cannot accept the observations themselves, then there are dozens of ad hoc's which can be added to the cumulate theory. However, the more exceptions there are to a rule or theory, the less and less that theory is capable of making predictions. If a theory cannot make predictions, it is useless. If a paradigm cannot allow someone to problem solve accurately, then that paradigm is also useless. The real genesis of the north shore anorthosites is by no means resolved by this paper. What cannot be denied, however, is the inability of the cumulate model to hold up even under common observational techniques. It is time for another paradigm.

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USE OF RUNOFF- AND SEDIMENT-CONTROL MODELS IN THE DESIGN OF MINE HYDROLOGIC CONTROLS

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ABSTRACT

Control of runoff and erosion at mine surface facilities is an important aspect of environmental protection. Regulations regarding the installation and maintenance of runoff- and sediment-control facilities at coal mines have been in place over 15 years since implementation of the Surface Mining Control and Reclamation Act of 1977. Similar laws governing environmental controls at mineral mines are currently being considered on a Federal level.

Several models have been developed for the design of runoff- and sediment-control facilities at mining and industrial operations. These models range from simple analytical and empirical approaches to detailed computer codes. Models have been developed to estimate rainfall-runoff relations, sediment yield, the erosion potential of channelized streamflow, and the sedimentation characteristics of control structures. These models will be reviewed, along with examples of their implementation.

**BIODEGRADATION OF
ENVIRONMENTAL CONTAMINANTS
UTILIZING WHITE ROT FUNGUS**

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ABSTRACT

White rot fungi are a common, naturally-occurring class of wood-degrading fungi that evolved to degrade lignin. Extensive research conducted since early 1980s has shown that many of the same mechanisms utilized by the fungi for lignin degradation also promote the degradation of several carbon-based environmental contaminants. These contaminants include polycyclic aromatic hydrocarbons, pesticides, herbicides, wood preservatives, chlorinated solvents, PCBs, explosives, cyanide, dyes, and others.

The fungi utilize an extra-cellular, free-radical, non-specific mode of degradation which allows them to degrade both soluble and insoluble contaminants, whether they are absorbed or in solution. The extra-cellular substance secreted by the fungi include several enzymes (which catalyze the initial oxidation of contaminant molecules), hydrogen ions (to maintain a slightly acidic pH), electrons (to maintain a charge balance and to reduce contaminants through the breaking of chemical bonds), and hydrogen peroxide (a highly effective oxidizer). In addition, the fungi secrete veratyl alcohol (a free-radical mediator which catalyzes reductions) and oxalate (an organic acid which is a highly effective reductant).

Application of white rot fungi for the remediation of contaminated soils involves mixing fungal-inoculated substrates with the soil. The materials are moistened during mixing to provide an environment which is conducive to fungal growth. The soil/substrate mixture is then placed in a biocell and aerated to promote contaminant degradation. Case histories of bench-scale tests and field applications are presented.

MAKING THE MOST OF IT: COMBINING FIELD, MICROSCOPIC AND BIBLIOGRAPHIC FINDINGS TO INTERPRET SHOWINGS AROUND LAKE SUPERIOR

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Electronic Education:

A project has been initiated to present geological information in an accessible manner for research and learning purposes, using multimedia educational software tailored to a broad audience. The eventual aim is to produce a PC-compatible product on CD-ROM, with a wide range of data enclosed within a "shell" structure of menu options, help screens and indices. The information to be offered in this system can be divided into four elements:

1. A bibliographic database, with $\approx 30,000$ annotated entries,
2. An image bank, with hundreds of colour photographs and other figures,
3. A book on computer databases in Earth and environmental science applications, and
4. A set of "tutorials" illustrating selected themes, one example being the geology of the Superior region.

The Lake Superior Tutorial:

The Lake Superior region provides excellent examples of many facets of Archean and Proterozoic geology. A partial listing includes banded iron formations, metavolcanic rocks, mafic-ultramafic and alkaline intrusions, and deposits of copper, silver, gold and platinum group elements (PGE). Products of progressive deformation, metamorphism, the emplacement of minor intrusions and veins, hydrothermal alteration and mineralizing events can all be examined in the field. Selected features of Superior geology (in an area within 100 km of the shore) have been integrated into a sequential "tutorial" presentation.

The Superior tutorial comprises 30 frames, each consisting of an image (with a brief caption) or a short paragraph of text. The viewer can browse through the screens, which are analogous to a slide show. If further information is required, a second screen can be revealed with an explanatory paragraph, and perhaps a selection of references. The visual approach, combined with a "layered" access to information, is designed to hold appeal for both casual and specialized viewers, and will hopefully promote worthwhile discussion! Follow-up queries can be addressed to a database which (in old-style terms) functions as a cross-linked card index. Areas referred to in the tutorial, proceeding anticlockwise around the lake from Sault Ste. Marie, are as follows:

1. The Wawa area
2. The Hemlo gold camp
3. The Coldwell alkaline complex
4. Iron formations and gold in the Beardmore-Geraldton belt
5. The North Shore of Superior
6. Silver Islet: native silver
7. Lac des Iles: PGE in mafic-ultramafic rocks
8. Kakabeka Falls
9. The Duluth complex
10. Keweenaw Copper Country

Field Geology and Petrography:

The site selection is dictated more by the availability of materials than by any systematic aim to define the "top ten" features of the regional geology. In the Lake Superior tutorial, deposits of three native elements (Au, Ag and Cu) are included, while volcanogenic massive sulphides are omitted. In the wider context of the CD-ROM project, this is compensated for by the use of examples from other parts of the world. The initial selection is divided roughly 2:1 between field items (outcrops, landscape features) and photomicrographs of rocks and ores.

Bibliographic Database:

Although it is anticipated that image files will fill 80-90% of the capacity of the CD-ROM, the driving force behind the project is to make available the heavily-annotated MINLIB database (Wilson, 1991), and to present it in conjunction with a review of the use of computer databases in the Earth sciences (coincident, in part, with Wilson, 1992a,b). MINLIB is not designed to compete with major databases such as GeoRef, which have broader thematic and systematic coverage, nor to supplant material compiled by regional surveys (including mineral deposit inventories and assessment files) and other geographically specialized publications (e.g., Sheahan, 1984). It is intended to cover a broad range of topics, but with clear emphasis on aspects of economic geology, mineralogy, petrology and structural geology. A relatively intensive selection of keywords (up to 30 lines per record) facilitate recovery of articles with diverse combinations of subject matter. Within the current contents ($\approx 28,000$ records), there is significant coverage for many geological features in the Lake Superior region. Examples include the Wawa subprovince (230 references), the Keweenaw (110), the Gunflint iron formation (50), the Hemlo gold camp (200), the Silver Islet mine (20), the Coldwell complex (80), the Duluth complex (120), and the Lac des Iles complex and associated PGE mineralization (80). In terms of the cumulative literature, coverage of these subjects varies from sketchy to substantial. Available material is weighted towards recent articles (MINLIB was initiated in 1983, and only 18% of records concern items published prior to that year).

While the thrust of MINLIB will appeal especially to economic and "hard-rock" geologists and mineralogists, several hundred "popular" articles are included, and it is hoped that these, in conjunction with the image bank and tutorials, will be of broad appeal to high-school students, rockhounds, and to others interested in extending their knowledge of the natural world. The wider audience for the tutorial approach and the supporting imagery may appreciate material in the "popular" category of the database (≈ 1 in every 40 records). This includes books on local mining history (recent examples would be Barr, 1988; Lefolii, 1987; Smith, 1986), certain field guides (e.g., Pye, 1968) and articles in non-technical publications such as *Canadian Geographic* and *National Geographic*.

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CHALCOCITE MINERALIZATION IN THE PORTAGE LAKE VOLCANICS, KEWEENAW PENINSULA, MICHIGAN

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Seven chalcocite deposits occur in the Michigan copper district in the western part of the Upper Peninsula of Michigan, a region better known for native copper mineralization. The chalcocite deposits, mostly discovered in the 1970's, range in tonnage from 0.1 to 4.5 million metric tons, and most have average grades from 2.5% to 3.0% Cu. The chalcocite deposits are within the 1.0 Ga Portage Lake Volcanics near the northeast tip of the Keweenaw Peninsula, restricted to an area 2 km by 13 km, stratigraphically below the Bohemia Conglomerate and just above the Keweenaw fault (Figure 1).

On a regional scale copper mineralization in the Keweenaw Peninsula can be subdivided into three types or districts, each with a characteristic style of mineralization: (1) native copper in fissure deposits in basalt, (2) native copper in lode deposits in both basalt and conglomerates, and (3) chalcocite in basalt. The chalcocite district is along strike and stratigraphically lower than the native copper lode district and is directly stratigraphically below the native copper fissure district (Figure 1). Although these three districts are adjacent to one another, there is little overlap, suggesting that the three styles of mineralization are interrelated and part of a regional mineralizing system. We have attempted to define the mineralizing process for the chalcocite deposits and to determine the genetic connection between chalcocite mineralization and native copper mineralization.

In all the chalcocite deposits, the predominant sulfide is chalcocite. In most, bornite in trace amounts is the only other sulfide. One exception is the Mt. Bohemia deposit which contains chalcocite in addition to a replacement sequence of pyrite-chalcopyrite-bornite-chalcocite, in which Fe-sulfides were replaced by successively more Cu-rich sulfides (Robertson, 1975). The chalcocite deposits occur in fragmental tops of basalt flows in much the same style as native copper lode deposits. Chalcocite occurs as an amygdale mineral, as open-space fillings around basalt fragments, disseminated in altered basalt, and in veinlets cutting basalt. Related alteration minerals include epidote, quartz, hematite, pumpellyite, chlorite, albite, K-feldspar, laumontite, and titanite.

$\delta^{34}\text{S}$ values for chalcocite from six of the deposits are all less than 0‰, ranging from -0.1‰ to -21‰. Although basalts in the rift are sulfur-poor because of degassing during eruption, sulfur and copper were derived by hydrothermal alteration of the underlying volcanic section during burial metamorphism down-dip from the deposits. Individual deposits have a restricted range of $\delta^{34}\text{S}$ which is roughly correlated with the tonnage of copper ore in the deposit: the largest deposit has the highest $\delta^{34}\text{S}$ values (-0.1‰ to -4.2‰) and the smallest deposit has the lowest (-15.6‰ to -6.6‰). This correlation can be interpreted as indicating that chalcocite was deposited during progressive oxidation of a mineralizing fluid, which probably carried a limited amount of sulfur along with abundant copper complexed as bisulfide and/or copper chloride. Because of the large isotopic fractionation between sulfide and sulfate, oxidation of sulfide in the fluid would result in residual aqueous sulfide becoming increasingly isotopically depleted in ^{34}S . This is further indicated by late native copper-bearing veinlets in one deposit, which have the most depleted values of any samples from that deposit, indicating that most of the sulfide had been oxidized before the deposition of the veinlets, but the copper remained in solution.

The lower tonnage of deposits with lower sulfur isotope values is consistent with a diminution of the ability of the fluid to precipitate copper sulfide due to the progressive oxidation of the mineralizing fluid. After all sulfur was stripped from the fluids by oxidation, abundant

dissolved copper remained in residual fluids and was available for deposition as native copper. We believe that chalcocite mineralization consumed the limited supply of sulfur in the regional system as a precursor to native copper deposition.

Negative sulfur isotope values for chalcocite occur throughout the Keweenaw district, as evidenced by $\delta^{34}\text{S}$ values of -6.7‰ to -9.4‰ for chalcocite in veins cutting the Baltic native copper lode (Livnat, 1983), and second-stage chalcocite mineralization at the White Pine deposit (Mauk and others, 1992), showing that oxidation of sulfide-bearing fluids was widespread. The zonal arrangement of deposit types on the Keweenaw Peninsula suggests that other chalcocite deposits might be found elsewhere in the Keweenaw volcanic section, peripheral to native copper mineralization.

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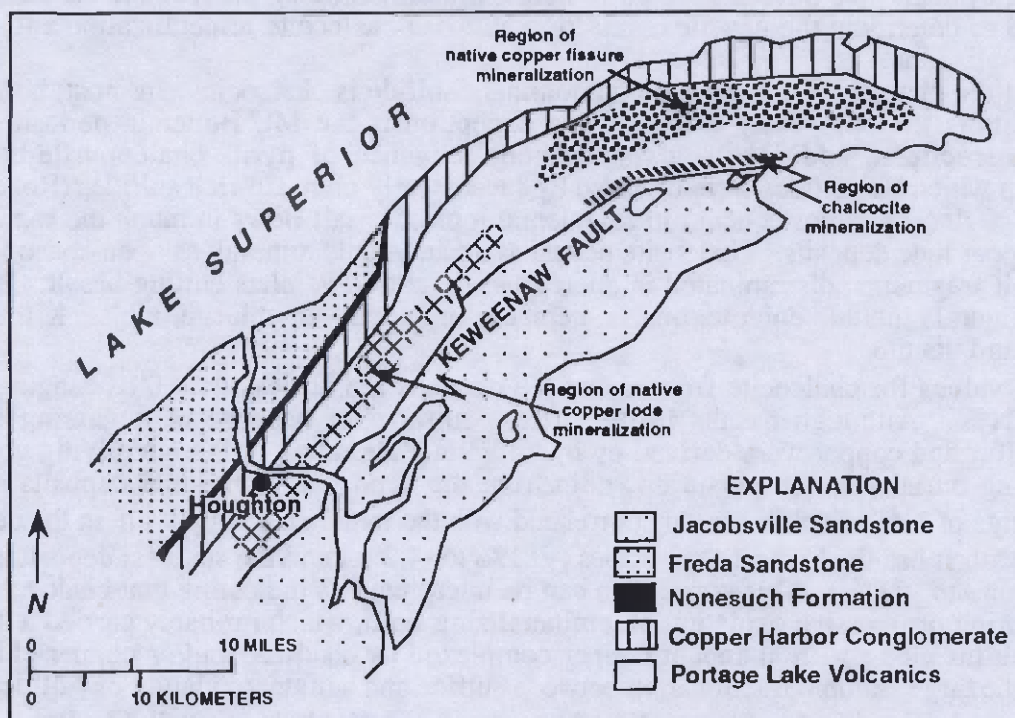
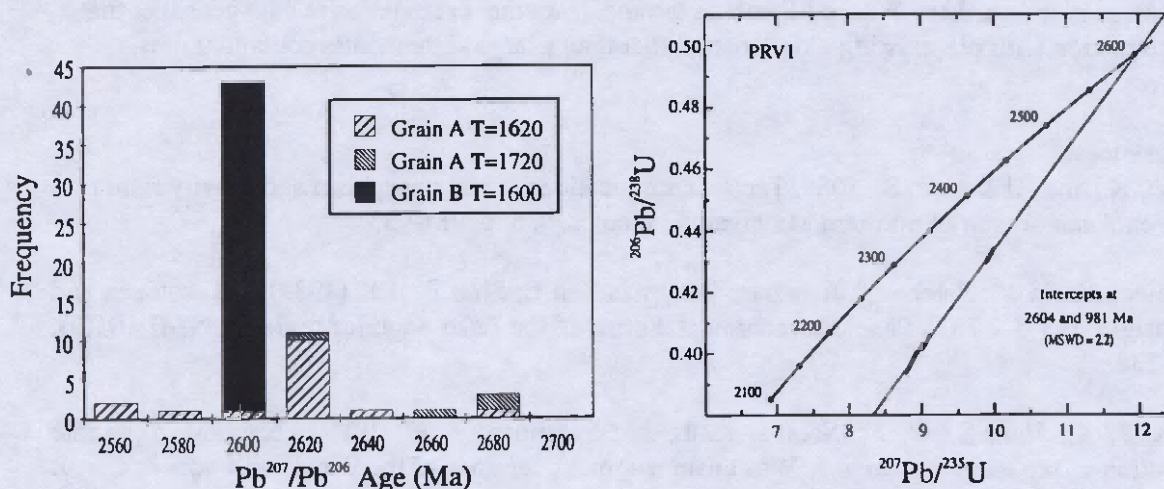


Figure 1. Generalized geologic map of the Keweenaw Peninsula, Michigan. Region of chalcocite mineralization contains seven small, high-grade chalcocite deposits.

Archean crust in the Wausau-Pembine Terrane; Continental underthrusting, or island arc basement?

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Conventional U/Pb and single zircon evaporation data on zircons from a strongly deformed gneiss located 20 km south of the mapped trace of the Niagara Fault (N45.78286°, W88.68963°), within the Wausau-Pembine Terrane (Sims et al. 1989), yield a simple concordia plot with an upper intercept age of 2604 Ma, and a lower intercept age of 590 Ma. Single zircon evaporations from three separate grains all give single plateau Pb/Pb ages at 2610 Ma. Together these data indicate a crystallization age of 2610 ± 7 Ma.



The Nd whole rock isotope composition ($T_{DM} = 2.99$ Ga and $\epsilon(T)_{\text{Nd}} = -2.5$) is typical of true Archean basement. Feldspar common Pb (6/4=16.08, 7/4=15.76), similarly indicate an old age for this sample. The high 7/4 ratio is in good agreement with the proposed end-member model lower crust required for the Penokean mixing model described by Van Wyck and Johnson (1993) and requires remobilization of Archean lead into feldspars. One possible interpretation of the feldspar Pb data is that the strong gneissic fabric and outcrop scale folding are related to a Penokean high grade metamorphic and fabric forming event, and therefore may be of use in deciphering the Penokean kinematic history of this area. Alternatively, the relatively simple zircon systematics and lack of a Penokean lower intercept age argues against a high grade Penokean metamorphism, and in turn suggests that feldspar lead was not a closed system during the Penokean. Under this scenario, the structures recorded at this outcrop could be Pre-Penokean.

Collectively these data argue for the presence of Archean crust within the Wausau-Pembine terrane. This is the first reported presence of crust of this age in what has been previously thought to be a juvenile package of rocks; this leads to the following possible interpretations:

a) The Superior province is underthrust at least 20 km to the south, as has been implied by the gravity data of Attoh and Klasner (1989). This crust is now exposed as a basement culmination, and one would predict that structures such as the Dunbar Gneiss Dome, along strike to the east, may be similarly cored by Archean crust. The timing and mechanism for the exposure of these

deeper crustal levels are unknown, but analogies with deep crustal exposures produced by extensional tectonics are appealing.

b) Alternatively, this age is from basement to the Wausau-Pembine terrane, which has been previously thought to consist of juvenile crust formed in an island arc environment.

In either case, the feldspar common Pb and $^{143}\text{Nd}/^{144}\text{Nd}$ ratio measured in this sample offers an appealing explanation for the high Pb207/204 signatures of galenas and feldspar leads reported for this region, as well as the reported trend of increasingly negative ϵ_{Nd} values for Penokean intrusives versus distance from the Superior Province. On account of the absence of reported old crust in the Wausau-Pembine terrane, Barovich et al., (1989) have suggested that mantle contamination by Superior Province derived sediments explained the low ϵ_{Nd} Penokean intrusives in the northern Wausau-Pembine terrane. Another explanation is now possible; that of interaction with pre-existing older crust, rather than a large scale mantle contamination process.

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Zircon age data

Zircon fraction	206/204 Meas.	206*/238	207*/235	207*/206*	206*/238 Age (Ma)	207*/235 Age (Ma)	207*/206* Age (Ma)
100-75 μ	5398	0.396274	8.86105	0.162177	2151.86	2323.8	2478.48
100-75 μ	5096	0.400454	8.95252	0.16214	2171.13	2333.17	2478.11
100-75 μ	4124	0.398362	8.89045	0.161862	2161.49	2326.82	2475.21
LM2 Abd	6476	0.431821	9.9453	0.167037	2313.92	2429.72	2528.17
LM2 Abd	4834	0.403347	9.06484	0.162997	2184.43	2344.57	2486.99

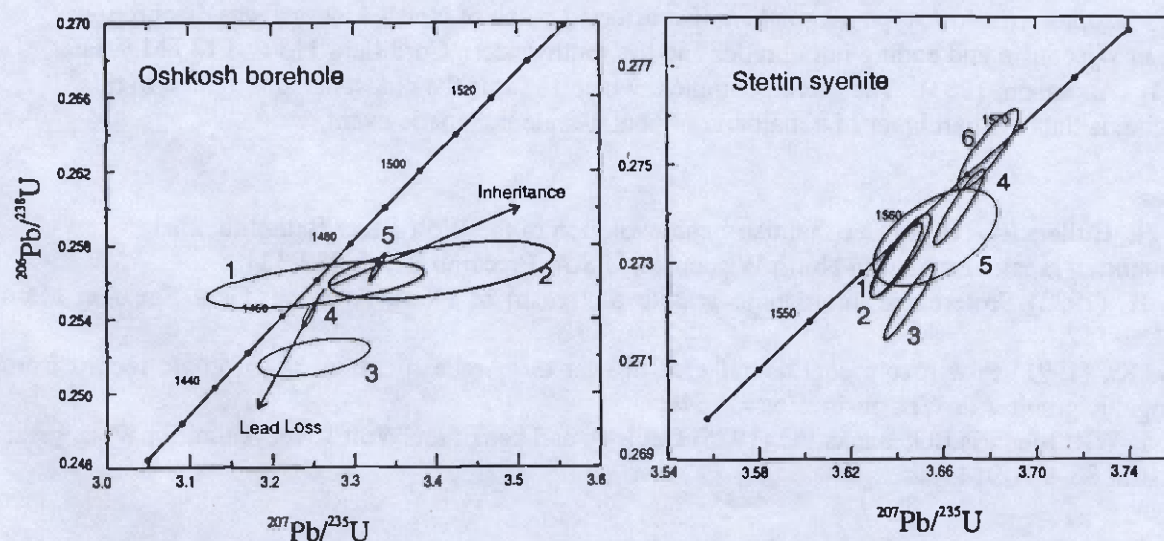
The Wolf River A-type Magmatic Event in Wisconsin: U/Pb and Sm/Nd Constraints on Timing and Petrogenesis

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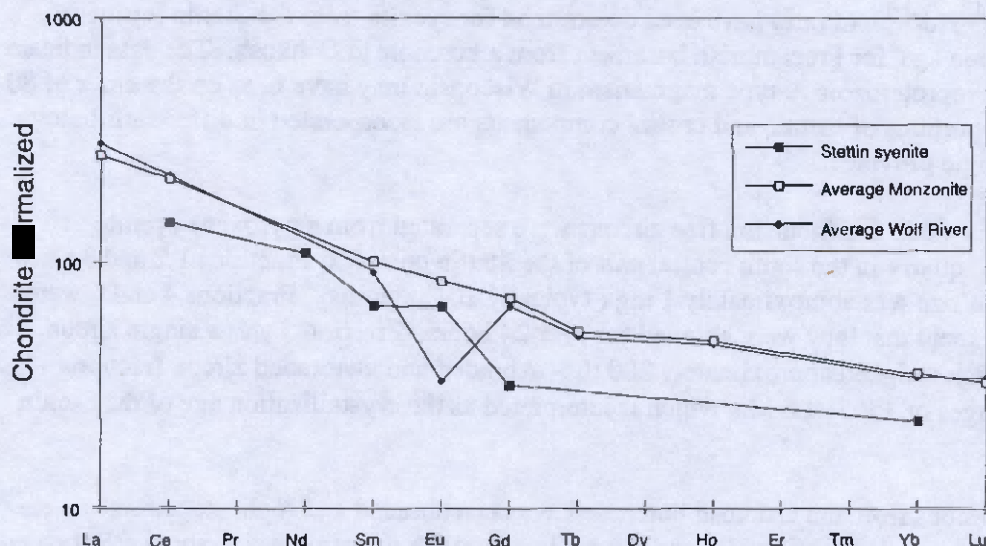
A U/Pb zircon age and $^{143}\text{Nd}/^{144}\text{Nd}$ ratio have been determined for syenite from the Stettin intrusive complex, and a U/Pb zircon age, for Precambrian basement from a borehole at Oshkosh. The data indicate that duration of Early Mesoproterozoic A-type magmatism in Wisconsin may have been on the order of 80 m.y. and that various proportions of mantle and crustal components are incorporated in different lithologies of the Wolf River petrologic province.

Abundant euhedral, diamagnetic and inclusion free zircons were separated from a pyroxene syenite collected at an abandoned quarry in the south central part of the Stettin complex. Fractions 1,2 and 3 were unabraded and the sample size was approximately 1 mg (typically 20-30 grains). Fractions 4 and 6 were identical to 1 through 3 except that they were abraded for over 24 hours. Fraction 5 was a single zircon crystal, also abraded, which weighed approximately 200 μg . Abraded and unabraded zircon fractions together give concordia ages of 1565 ± 3.5 Ma, which is interpreted as the crystallization age of the Stettin syenite.

Diamagnetic, euhedral zircons from the Oshkosh borehole have been abraded and replicate analyses were performed over a one year period. Fractions 1,2 and 3 were less than 0.5 mg sample size and were abraded for 15 hours. All fractions, except for 1, do not lie on concordia and are difficult to interpret. Although three fractions (1,2, and 5) give consistent $\text{Pb}^{206}/\text{U}^{238}$ ages of approximately 1471 Ma, it is more likely that these zircons have experienced lead loss from a slightly older age of approximately 1475 Ma, which is well within error of the previously published age for the Wolf River of 1485 ± 15 Ma (Van Schmus et al 1975). An additional complication maybe zircon inheritance. Fractions 4 and 5 were analyzed one year later and are 1 mg sized samples. One zircon population is dark brown in color, in comparison to the majority of zircon grains, which were clear to light colored. Fraction 4 has had the darker grains removed shows no indication of inheritance. Fraction 5, which contained approximately 10% dark brown grains, does show an inheritance component. Unfortunately the data can not resolve whether it is Archean or Penokean inherited zircons, which will require detailed single zircon analysis.



REE concentrations for Stettin pyroxene syenite are slightly lower than those for Wolf River adamellite and monzonite, but the chondrite-normalized REE patterns are similar, with LREE enrichment and relatively flat HREE (for syenite, $(\text{Ce/Tb})_{\text{CN}} = 4.90$, and $(\text{Tb/Yb})_{\text{CN}} = 1.31$). $\epsilon(\text{T})_{\text{Xal}}$ for syenite is +2.9, suggesting derivation from a mildly depleted subcrustal lithospheric source, in contrast to Wolf River granitic rocks, in which epsilon Nd_T ranges from -0.3 to -4.0 (Nelson, 1991), indicating significant amounts of crustal contributions. Nd model ages also differ for the Stettin complex and Wolf River batholith, being 1.65 Ga and 1.9 to 2.1 Ga, respectively.



Geochemical differences between the Stettin complex (syenite and nepheline syenite, isotopically depleted) and the Wolf River batholith (predominantly adamellite, isotopically enriched) reflect evolving magma compositions due to increasing mantle-crust interactions in an A-type igneous cycle. The Wolf River magmatic event was initiated by mantle upwelling (plume?) and generation of the Stettin complex at 1565 Ma by partial melting of mildly depleted lithosphere. Later mantle-derived melts were contaminated with crustal material to form the Wausau complex (quartz syenite and granite) at 1517 Ma (Van Schmus, pers. comm.). Thermal maturation, magma ponding, and crustal anatexis culminated at 1485 Ma (Van Schmus et al., 1975) in production of the voluminous Wolf River batholith.

The Early Mesoproterozoic A-type magmatism that affected much of North America was diachronous, beginning in Wisconsin and ending in Labrador and the southwestern Cordillera 115 and 135 M.y. later, respectively (Anderson, 1983). The Stettin complex, which so far is the oldest dated intrusion in this igneous suite, is thus the harbinger of a major, continental-scale magmatic event.

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A COMPENDIUM OF MINERAL RESOURCE INFORMATION, EAST-CENTRAL MINNESOTA

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The administration of state-owned lands includes the management of those lands for mineral resources. The Minnesota Department of Natural Resources Minerals Division administers state-owned mineral rights for the benefit of schools, the university, local units of government and the public. As a part of this responsibility, the Minerals Division has maintained mineral resource records and information. This compendium of minerals information for east-central Minnesota is provided by the Minerals Division for all people who work in the field of land management, both within various levels of government and outside government. It is intended to serve as a guide to available information, by providing maps showing the location of known mineral resources and the geographic extent of information sources, and listing a knowledgeable contact person for each theme. Further, it is intended to document the presence of some known subeconomic mineral resources, which may have a higher value in the future, and therefore should be considered in current planning. It does not contain a map of speculative resource locations for all commodities, because that would require a complex evaluation and presentation. This compendium is intended to be a starting point for all who need or want access to mineral resource information in east-central Minnesota.

Three mineral commodities are currently being extracted in east-central Minnesota - peat for horticultural applications, aggregate for construction purposes, and dimension stone for buildings or monuments. There have been over 70 years of mining of two other mineral commodities - iron and manganese, from Crow Wing County and adjacent areas. Moreover, large quantities of iron and manganese resources are still present here, having been identified by past drilling.

It is reasonable to assume that mining for the above five commodities, as well as other minerals, could be proposed in the future in this region. The geologic setting suggests that other plausible minerals could include industrial minerals such as graphite, garnet or other abrasives, barite, beryllium, phosphate; or metallic minerals such as gold, silver, copper, lead, zinc, bismuth, chromium, platinum, nickel, or rare earth metals. There are known mineral occurrences for almost all of these commodities, but not in sufficient, known quantities for extraction. As a result, these "other" minerals are referred to here as speculative mineral resources, which would have to be discovered in larger quantity and quality to warrant development evaluation work. The private sector initiates such development evaluation, primarily spurred by market demand in the form of favorable commodity prices. All future development proposals would be subject to the compendium of law applicable to the environmental review and permitting process.

The study area (see the first map) covers the part of Minnesota that very nearly corresponds to Minnesota's Department of Natural Resources administrative region III. Our study area differs from DNR Region III boundaries in that we use county boundaries for the border with two minor exceptions. Because most of our minerals databases contain county designations, it was more practical to use entire county boundaries as much as possible. The two exceptions are small areas within Itasca and Anoka counties, which were included to accommodate the entirety of DNR Region III.

The minerals information in this compendium is presented primarily in the form of maps, and is organized around seven general themes: State-Owned Lands and Mineral Leasing, Peat, Industrial Minerals, Sand and Gravel, Iron Ore and Manganese, Other Speculative Minerals, and Mineral Exploration Data (see Table 1).

A common package is presented for each theme, and contains an explanation, a bibliography or digital database reference, and a set of index maps. No part of the package was intended to stand alone. The explanation defines what is included in the theme, describes it and the maps, and summarizes the information. Each bibliography was created from those references judged most helpful. The maps for

three themes were created from existing digital databases, and do not have bibliographies (see Table 1). A specialist with extensive knowledge of each theme has written the explanation, created the bibliography, and designed the theme maps. It was not practical to illustrate all of the references on all the maps.

The following maps were created by overlaying mineral resource data on a base map assembled from the Minnesota Land Management Information System (MLMIS) 100 database. MLMIS is a grid-cell based database of Minnesota's natural resources, public land survey, and ownership. The database was designed for use with EPPL7, a raster-based GIS package developed by the Land Management Information Center, Minnesota Office of Planning.

The data for MLMIS were captured from maps ranging in scale from 1:24,000 to 1:1,000,000 through grid-overlay techniques and digitizing. MLMIS was designed to be used in regional and statewide planning, not for site specific work, and is divided into two databases, based on cell size: MLMIS40 and MLMIS100. The cell size of MLMIS40 is 40 acres and is available as statewide files. The cell size of MLMIS100 is approximately 2.5 acres (the length of each side of the cell is 100 meters) and is the spatially corrected version of MLMIS40. MLMIS100 is available as county files and enables the user to better match geographically referenced data from other sources.

For this study of east-central Minnesota, staff used the public land survey files of MLMIS100 to map their "occurrence" data that were stored in tabular database formats as township, range, section, and sometimes forty. The references were mapped through digitizing the reference boundaries or by matching the township, range, and sections covered by the references with the MLMIS100 files.